# The NA62 Experiment at CERN

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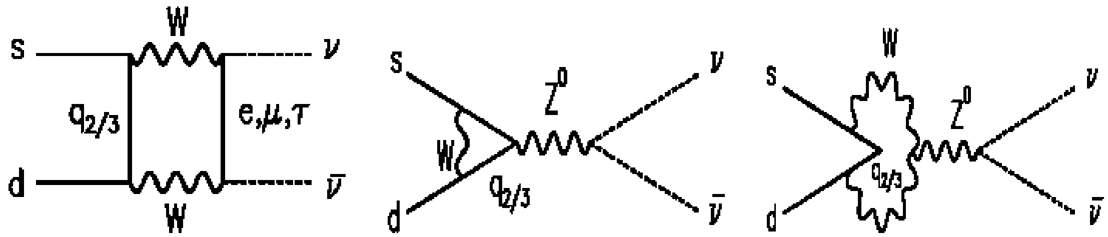
# The $K \to \pi \nu \bar{\nu}$ decays: a clean theoretical environment

- NA62 Physics goal: study of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay mode
- FCNC loop processes: s→d coupling and highest CKM suppression




- Very clean theoretically: SD contributions dominate, hadronic matrix element related to precisely measured quantities

- SM predictions (main uncertainties from CKM matrix elements):

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (8.5 \pm 0.7) \times 10^{-11}, \quad BR(K_L \to \pi^0 \nu \bar{\nu}) = (2.6 \pm 0.4) \times 10^{-11}$$

- Experimental results:

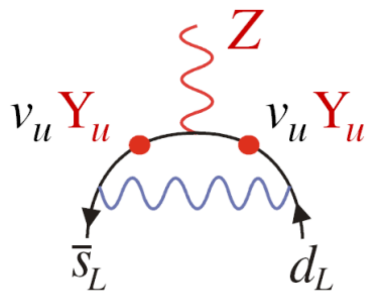
$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10} \; [E787, E959]$$

$$BR(K_L \to \pi^0 \nu \bar{\nu}) \le 2.6 \times 10^{-8} \; [E391a]$$

# NP and The $K \to \pi \nu \bar{\nu}$ decays

(courtesy by C. Smith)

C. The Z penguin (and its associated W box)

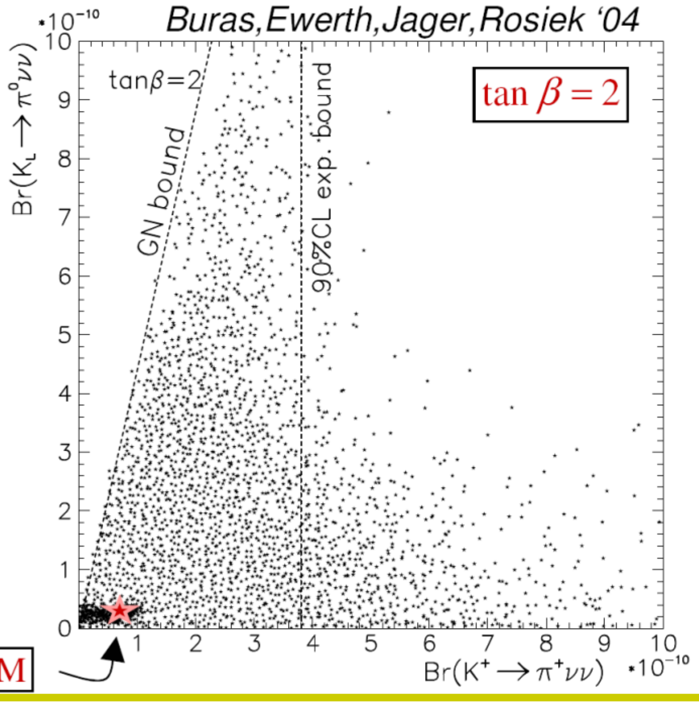


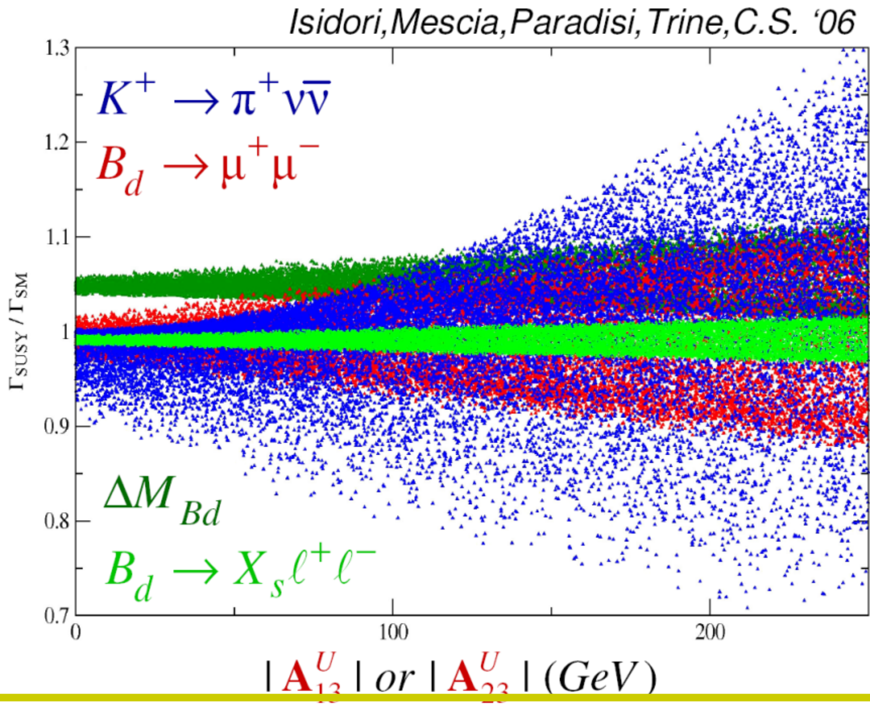

- $SU(2)_L$ breaking: $SM: v_u^2 Y_u^{*32} Y_u^{31} \sim m_t^2 V_{ts}^* V_{td}$

$$MSSM: v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 \times O(1)?$$

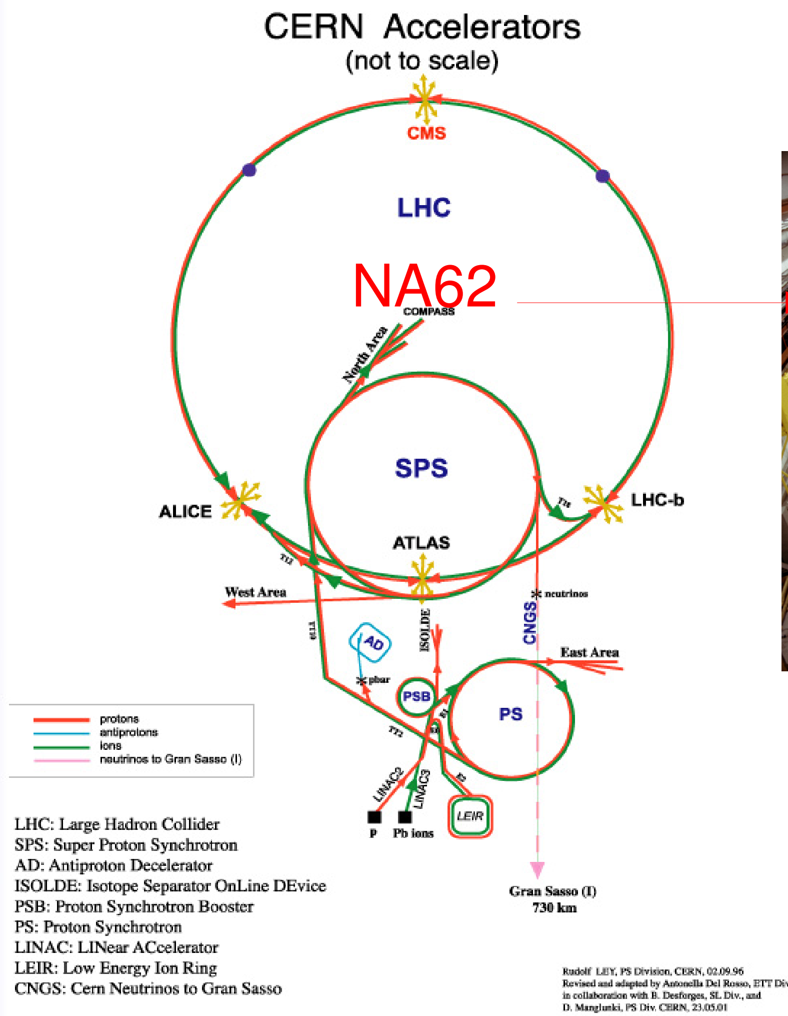
$$MFV: v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 V_{ts}^* V_{td} \left|A_0 a_2^* - \cot\beta\mu\right|^2 .$$

- Relatively slow decoupling (w.r.t. boxes or tree).



# The NA62 Experiment




former NA48 exp hall

NA62 Collaboration: Bern ITP, Birmingham, Bristol, CERN, Dubna, Ferrara, Fairfax, Florence, Frascati, Glasgow, IHEP, INR, Liverpool, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin

# Experimental Principles of NA62

- Goal: 10% precision branching ratio measurement
  - $O(100)\, K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events
  - % level Systematics
- Requirements
  - Statistics:
    - BR(SM) ~ $8.5\times10^{-11}$
    - Acceptance: 10%
    - K decays: $10^{13}$

Kaon intensity - Signal efficiency

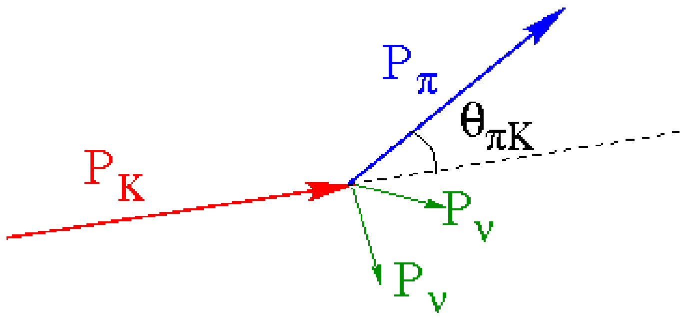
  - Systematics
    - $\geq 10^{12}$ background rejection (i.e. $\leq$10% background)
    - $\leq$10% precision background measurement

Signal purity & Detector Redundancy

- Principles:
  - "High" momentum $K^+$ beam
  - Decay in-flight technique

# Experimental Principles of NA62

- Signal signature:

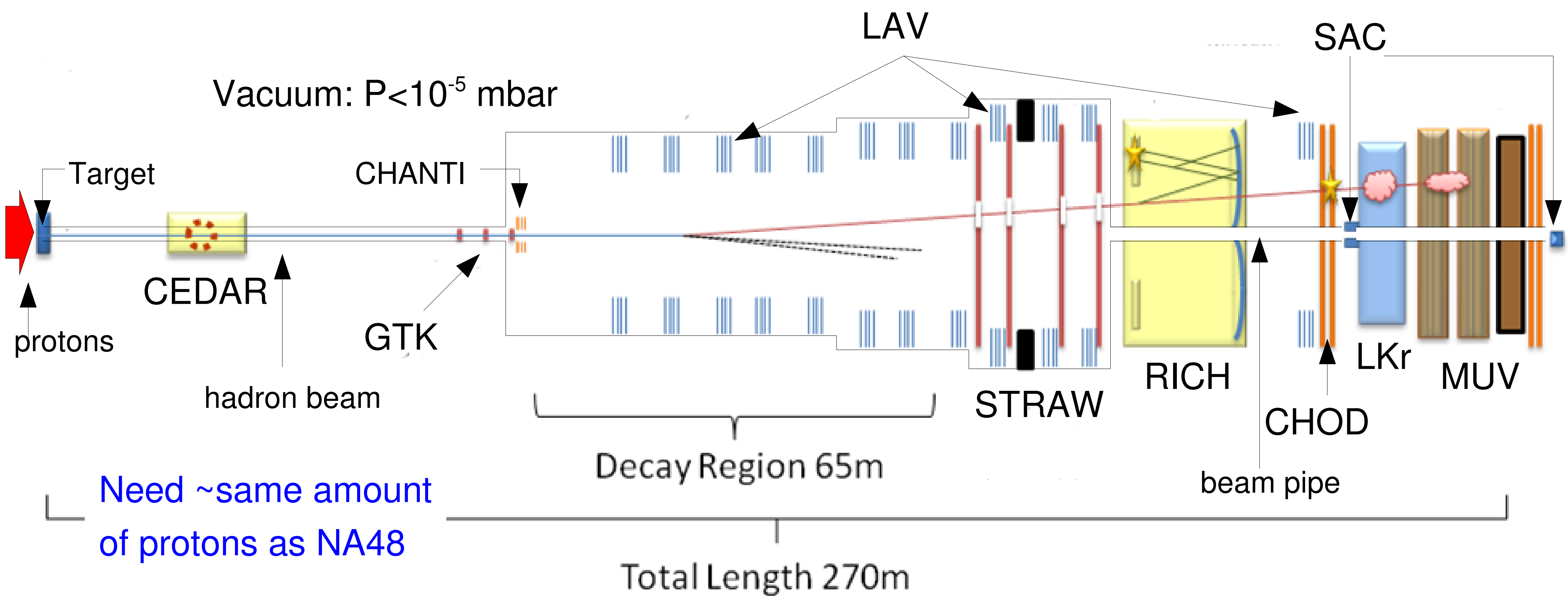



- Background:
  - All the $K^+$ decay modes.
  - Accidental charged particles (beam particle interactions).

- Experimental technique:
  (1) Kinematic rejection
  (2) Precise timing
  (3) Vetoes
  (4) Particle Identification

# Detector Layout

- SPS primary protons @ 400 GeV/c ⇨ Unseparated secondary charged beam
- 75 GeV/c ($\Delta P/P \sim 1\%$)
- $p/\pi/K$ (positron free, fraction of K ~6%)
- Area @ beam tracker 16 $cm^2$
- Integrated average rate @ beam tracker 750 MHz
- Kaon decays/year $4.8 \times 10^{12}$

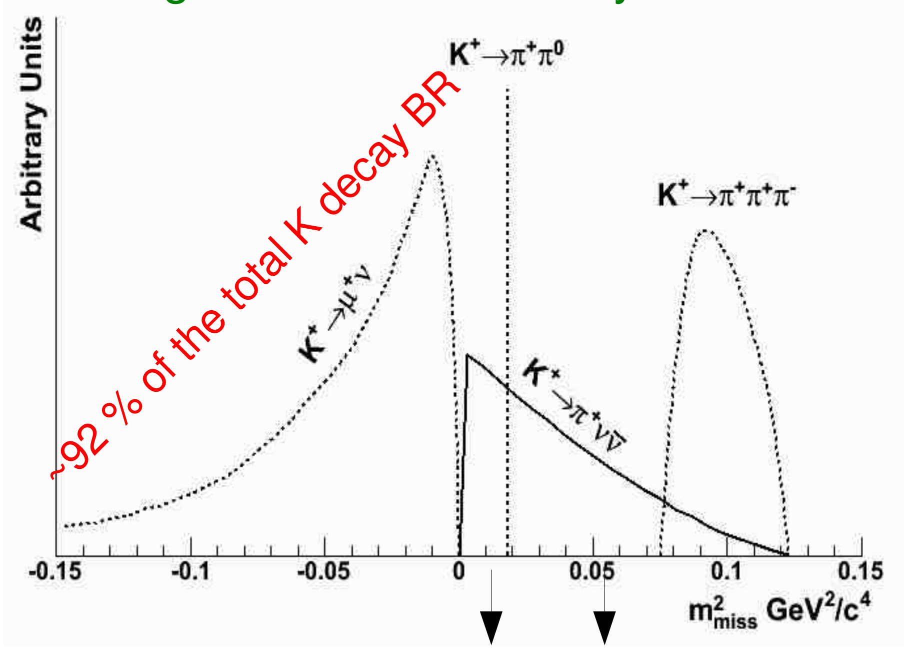



Need ~same amount of protons as NA48

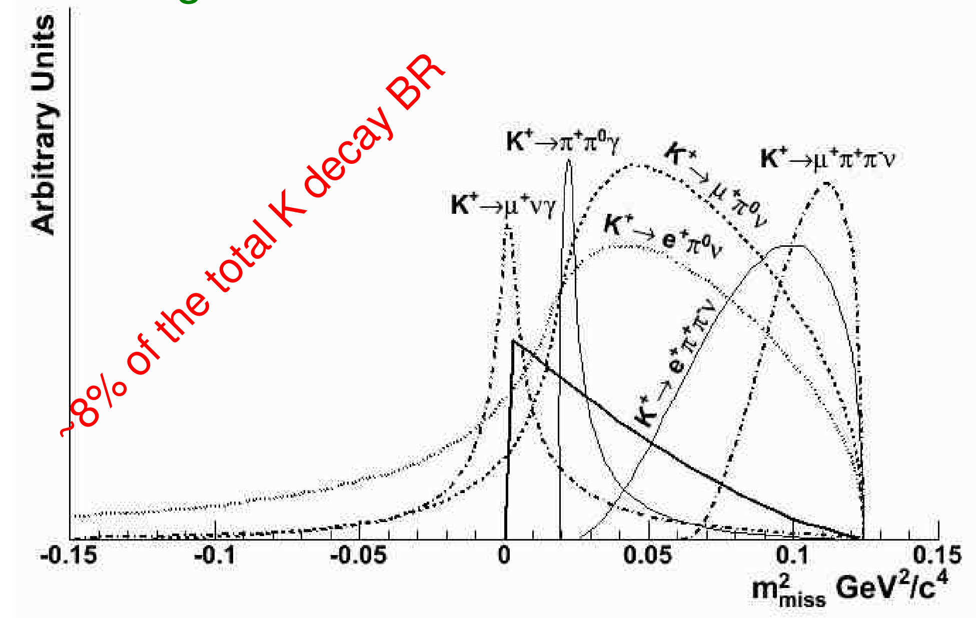
# 1) Kinematic Rejection

- Background from $K^+$ decays: $m^2_{miss} = (P_K - P_\pi)^2$

Background constrained by kinematic




Background not constrained

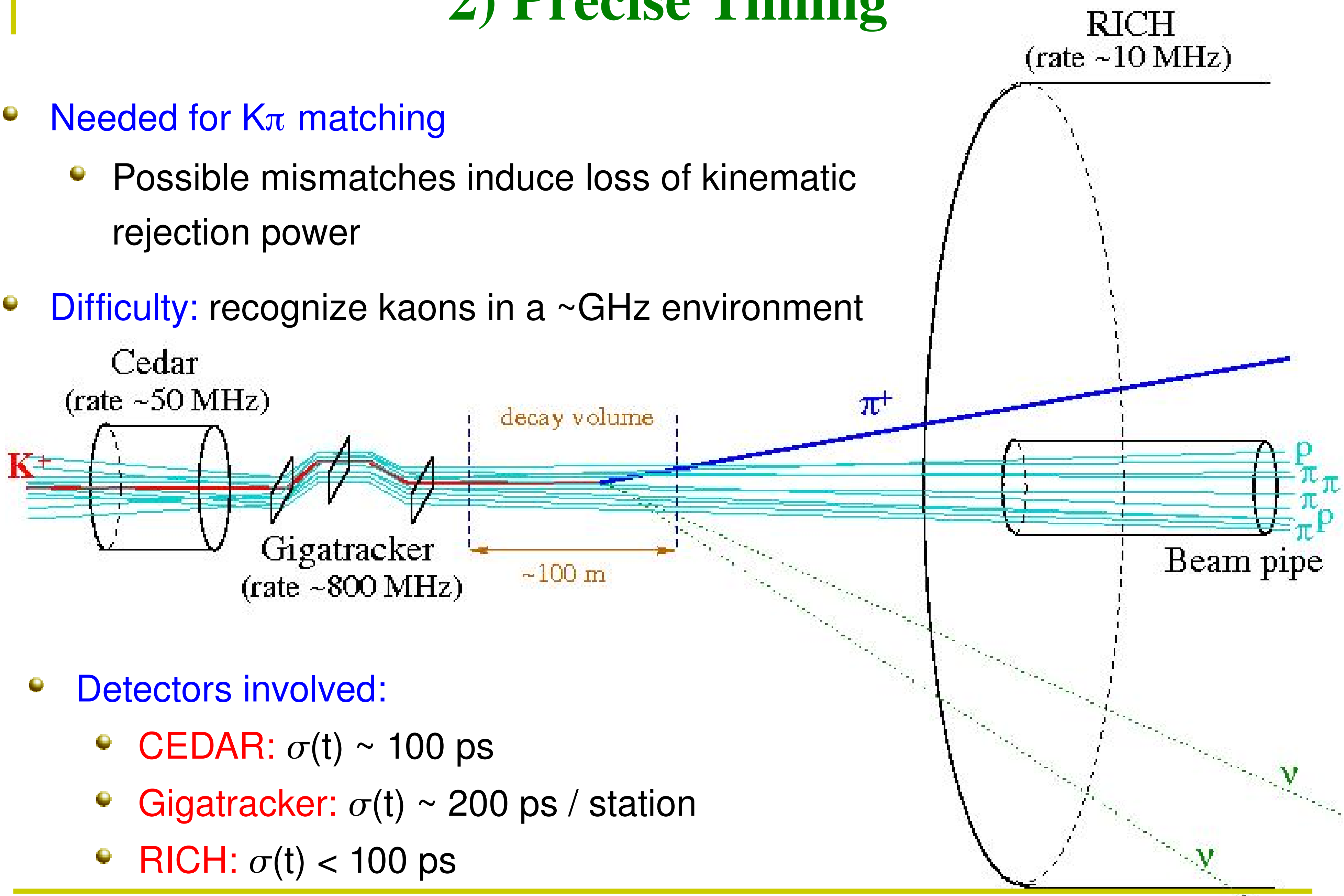



- Two signal regions with a minimum of background, separated by the $K^+ \to \pi^+\pi^0$
- Background from 1) Kinematic resolution 2) Decays "not constrained".

- Requirements: low mass / high resolution trackers → Gigatracker (kaon), Straw chambers (pion)
  - tracking in vacuum, $\sigma$ ~100 $\mu$m per coordinates

# 2) Precise Timing

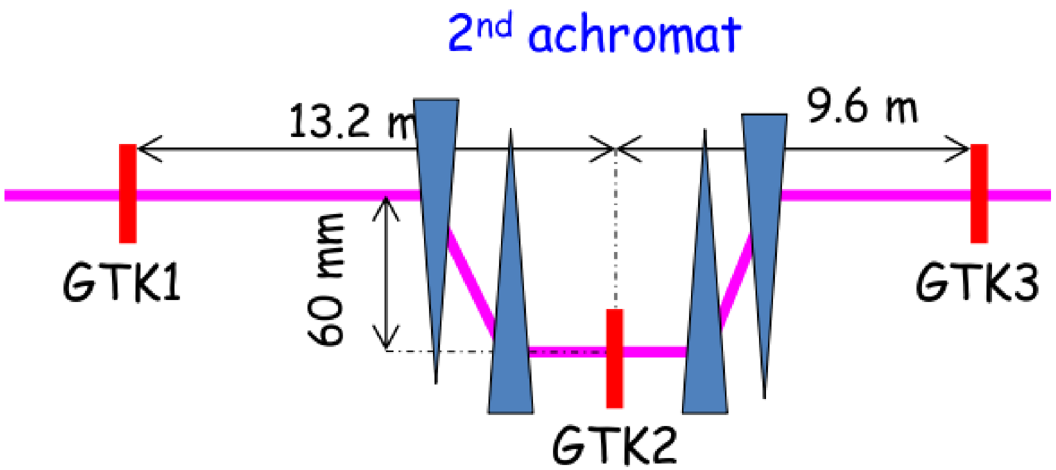
- Needed for K$\pi$ matching
  - Possible mismatches induce loss of kinematic rejection power
- Difficulty: recognize kaons in a ~GHz environment



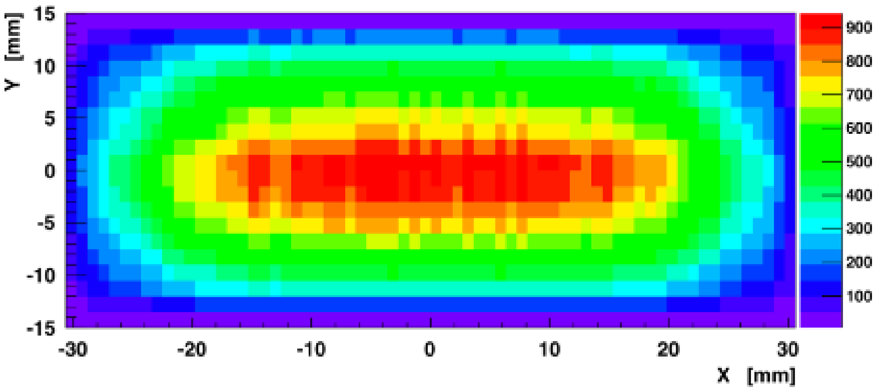

- Detectors involved:
  - CEDAR: $\sigma(t) \sim 100$ ps
  - Gigatracker: $\sigma(t) \sim 200$ ps / station
  - RICH: $\sigma(t) < 100$ ps

# Gigatracker

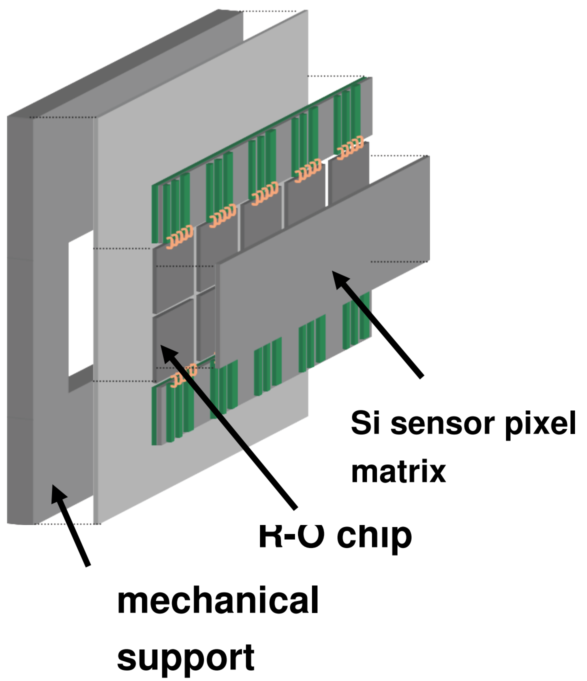
- 3 Si pixel stations before the decay volume




- Geometry matching the beam shape

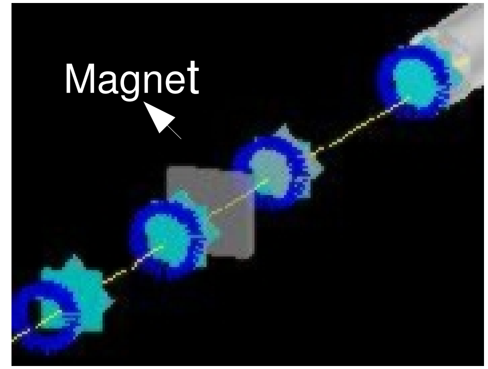


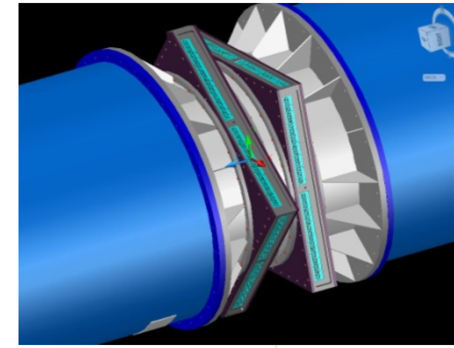

- Requirements:
- High space resolution: 300x300 μm pixels
- Low $X/X_0$: 200 μm sensor+100 μm chip (<0.5% $X/X_0$ per station)
- Excellent time resolution: sophysticated RO chip bump bonded on the sensor (0.13 μm technology)
- First prototype tested on beam at CERN PS last week.

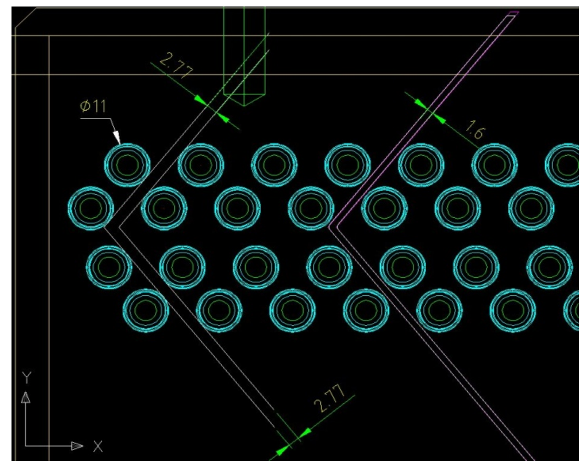


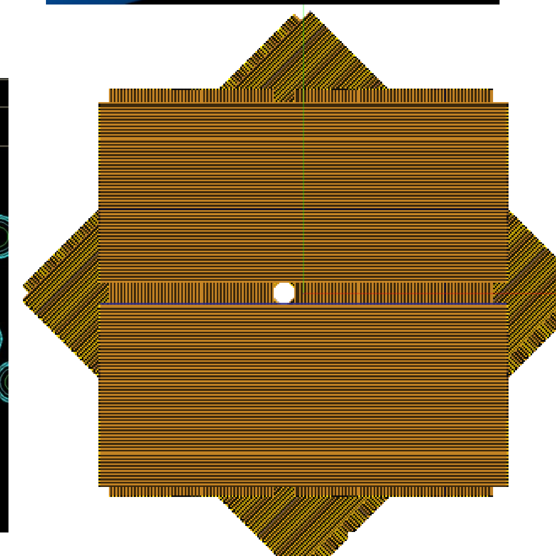
# Straw Chamber Spectrometer

- 4 straw chambers in vacuum + 1 magnet (NA48 magnet, 256 MeV/c $P_t$ kick)
- 4 views per chamber (XYUV)
- 4 staggered layers of tubes per view
- 9.6 mm mylar tubes
- 2.1 m long
- Total $X/X_0$ ~0.1% per view
- 6 cm "radius" beam hole displaced in the bending plane according to the 75 GeV/c beam path

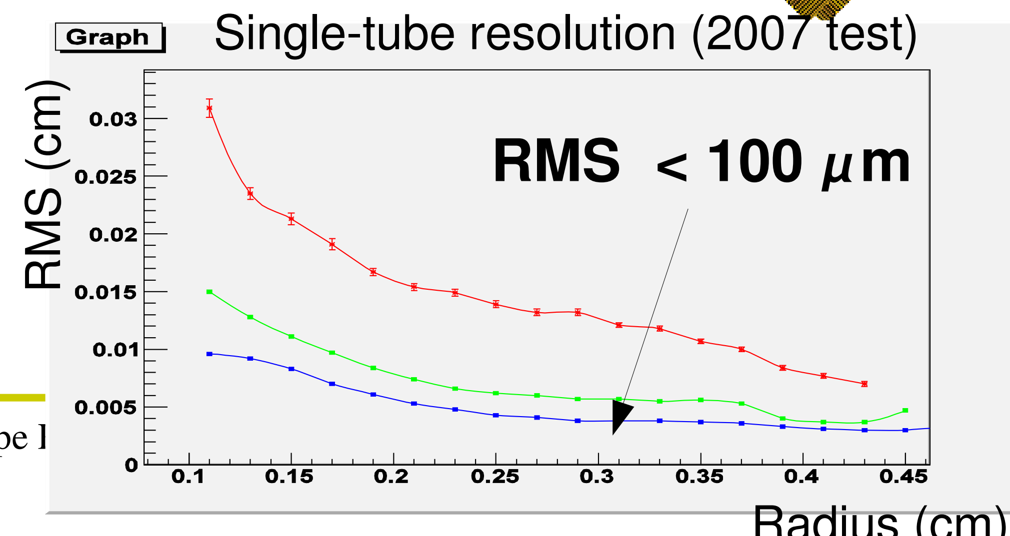




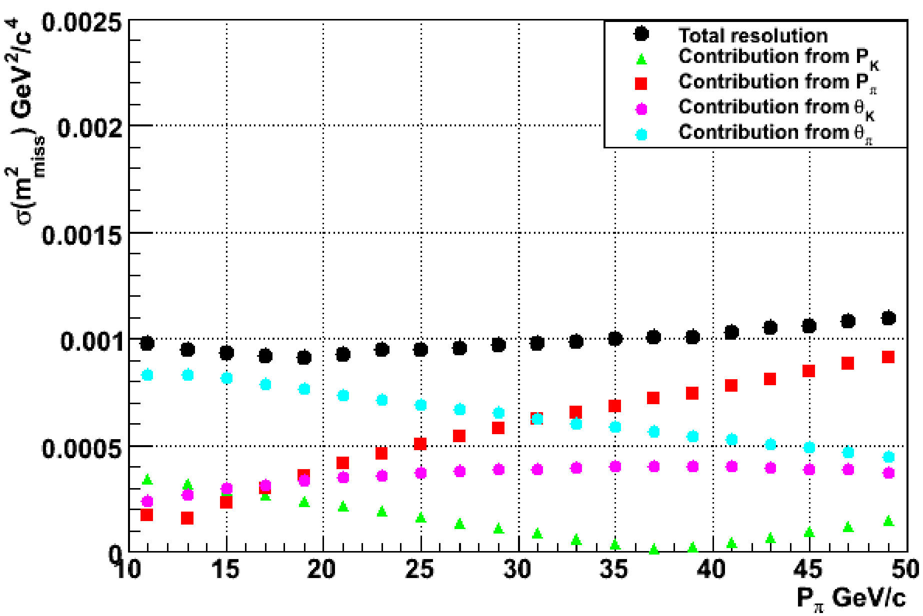



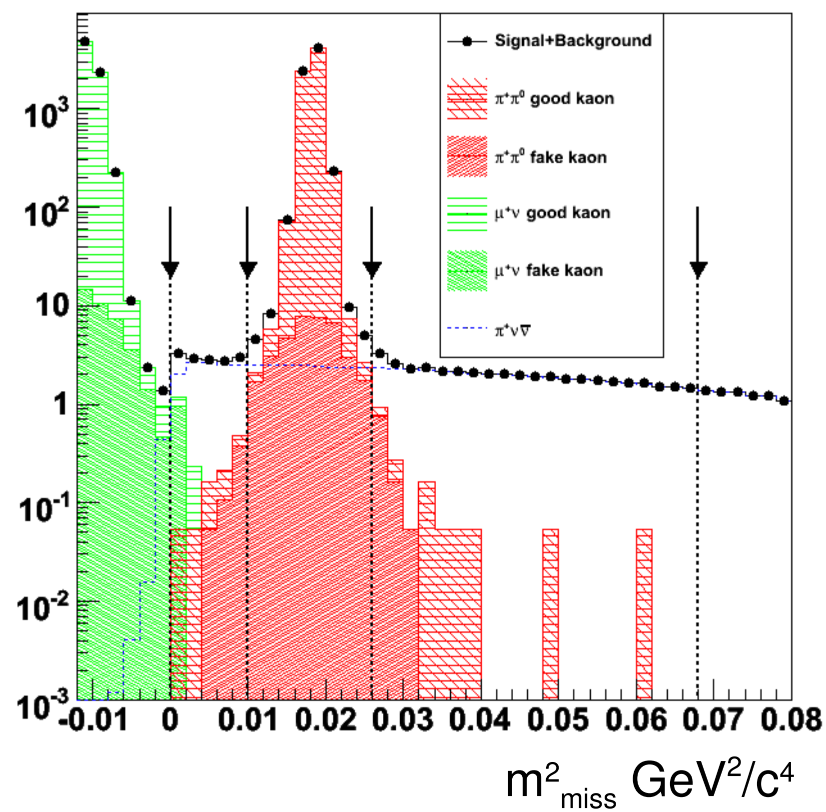
- Full length prototipes built in 2007 and 2010.
- Placed in vacuum.
- Tested on beam in 2007 and 2010.



# Kinematic rejection capabilities

- Performance of the new tracking system (Geant4 MC):
  - $\sigma(P_K)/P_K$ ~0.2%, $\sigma$(dX,Y/dZ)~16 μrad
  - $\sigma(P_\pi)/P_\pi$ ~0.3%⊕0.007% $P_\pi$ (GeV/c) $\sigma$(dX,dY/dZ) ~45 – 15 μrad
- 2-body rejection power
  - $10^4$ ($K^+\to\pi^+\pi^0$), $10^5$($K^+\to\mu^+\nu$)
- Sources of inefficiency:
  - MS non guassian tails
  - Kπ mis-match



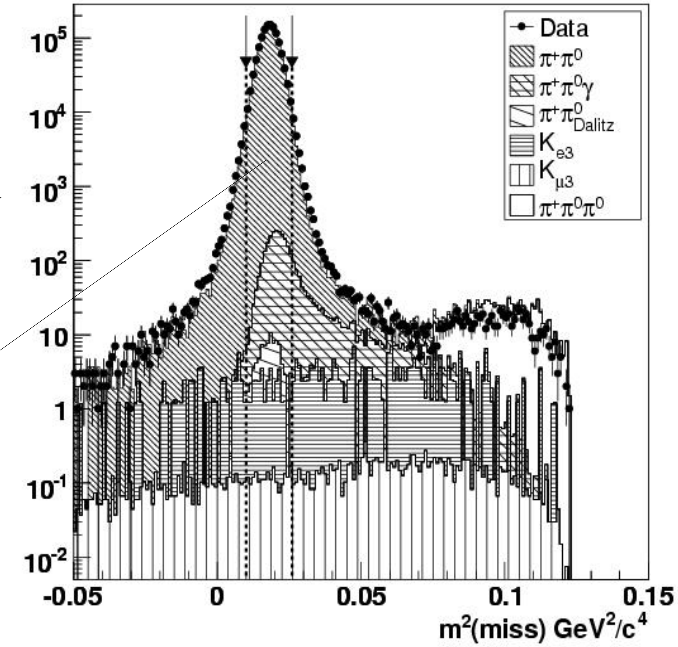



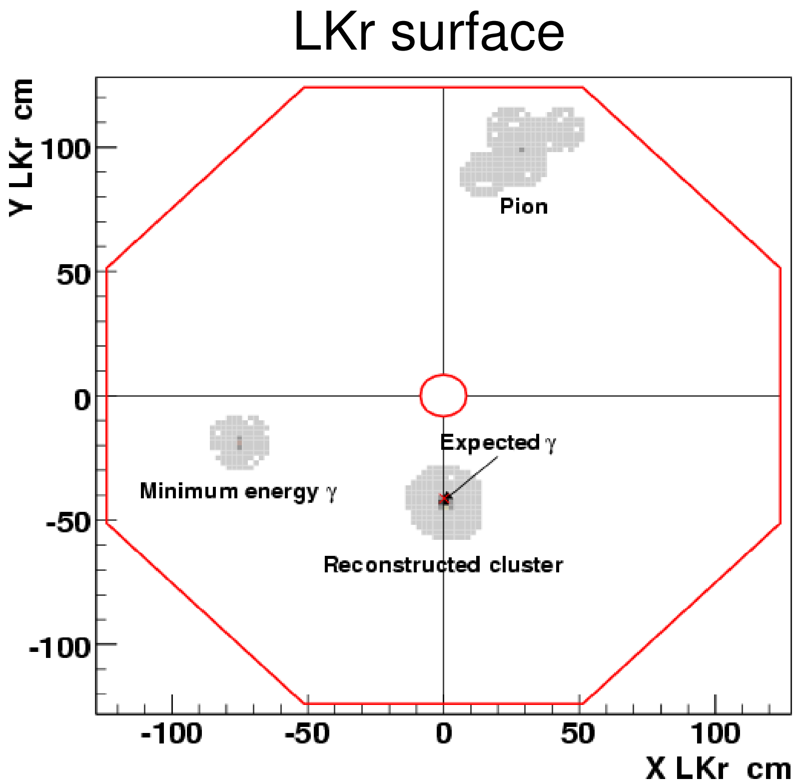
# 3) Photon Vetoes

- Requirement:
  - Veto the $K^+ \to \pi^+\pi^0$ at L0 trigger
  - Support the kinematics in order to reject offline decays with $\gamma$ (e.g. $K^+ \to \pi^+\pi^0$ ).
- Detectors: EM calorimeters
  - NA48 liquid Kripton calorimeter (acceptance: 1-10 mrad): trigger+offline
  - Rings of large angle vetoes (acceptance: up to 50 mrad): offline
  - Small angle calorimeters (acceptance: < 1 mrad): offline
- Key points:
  - sub-ns online time resolution of the LKr (for trigger purposes)
  - >1 GeV photons hitting the liquid Kripton calorimeter.
  - $10^{-5}$ inefficiency of the liquid Kripton calorimeter for >10 GeV photons .
  - Offline requirement: $P(\pi^+)<35$ GeV/c $\Rightarrow$ $P(\pi^0)> 40$ GeV/c it can hardly be missed in calorimeters!
- Rejection Capability:
  - $2\div3.5\times10^{-8}$ $\pi^0$ rejection inefficiency from $K^+ \to \pi^+\pi^0$

# NA48 Liquid Kripton em calorimetry inefficiency

- Inefficiency measured on data
- NA48 data @ 75 GeV
  - $K^+ \to \pi^+\pi^0$ selected using kinematics only

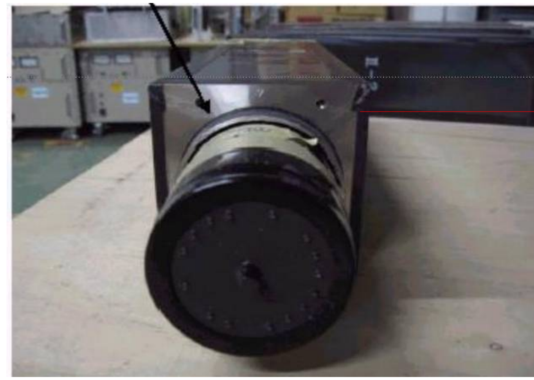


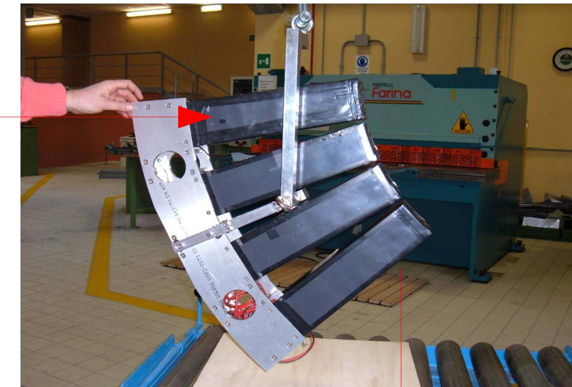



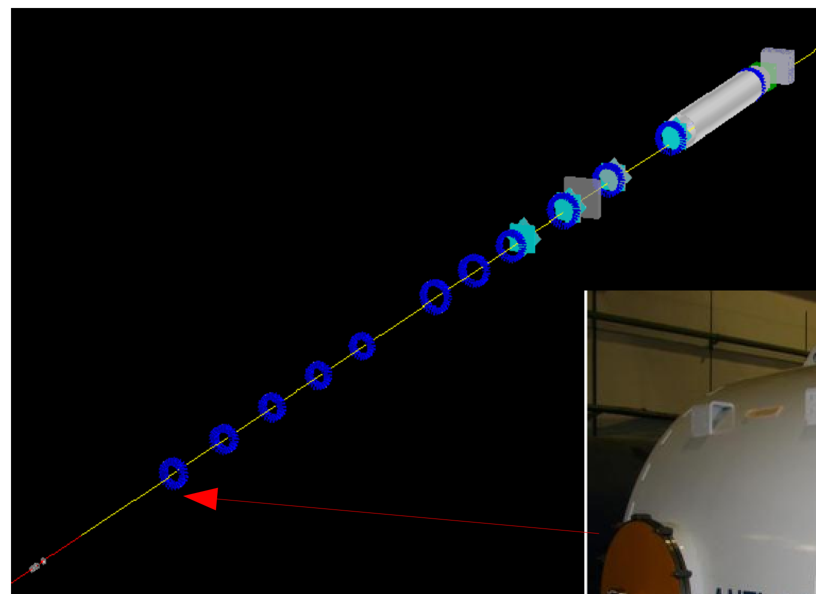

| E (GeV) | Inefficiency |
|---|---|
| 2.5 – 5.5 | $< 10^{-3}$ |
| 5.5 – 7.5 | $< 10^{-4}$ |
| 7.5 – 10 | $< 5x10^{-5}$ |
| > 10 | $< 8x10^{-6}$ |

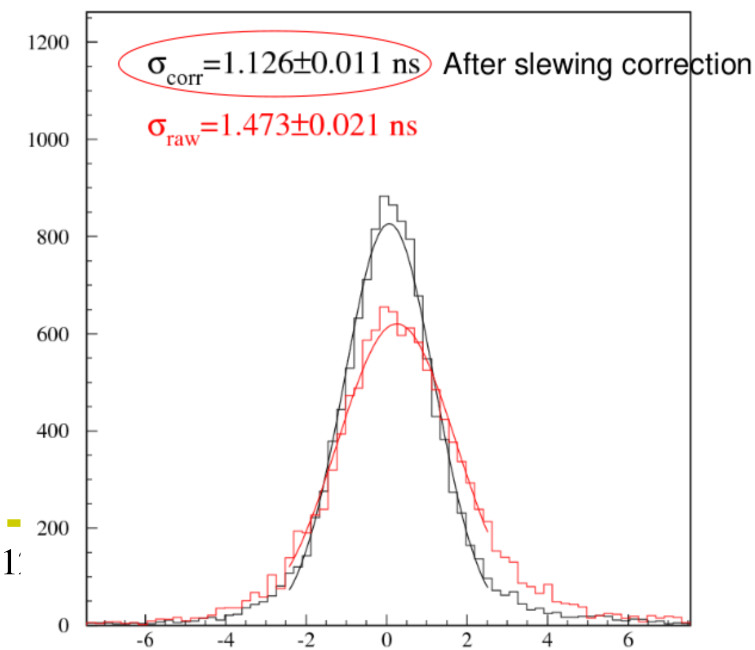
# Large Angle Veto (LAV)

- OPAL lead glass:
- 12 rings in vacuum
  - 5 staggered planes per ring
- Blocks tested @ BTF (Frascati):
  - Inefficiency @ 471 MeV $e^+$: $\sim 10^{-4}$ on the whole surface
- Ring 1 and 2 built in Frascati.
- Tested successfully in vacuum at CERN in 2009 and 2010.
- Ring 3 under construction (Frascati)





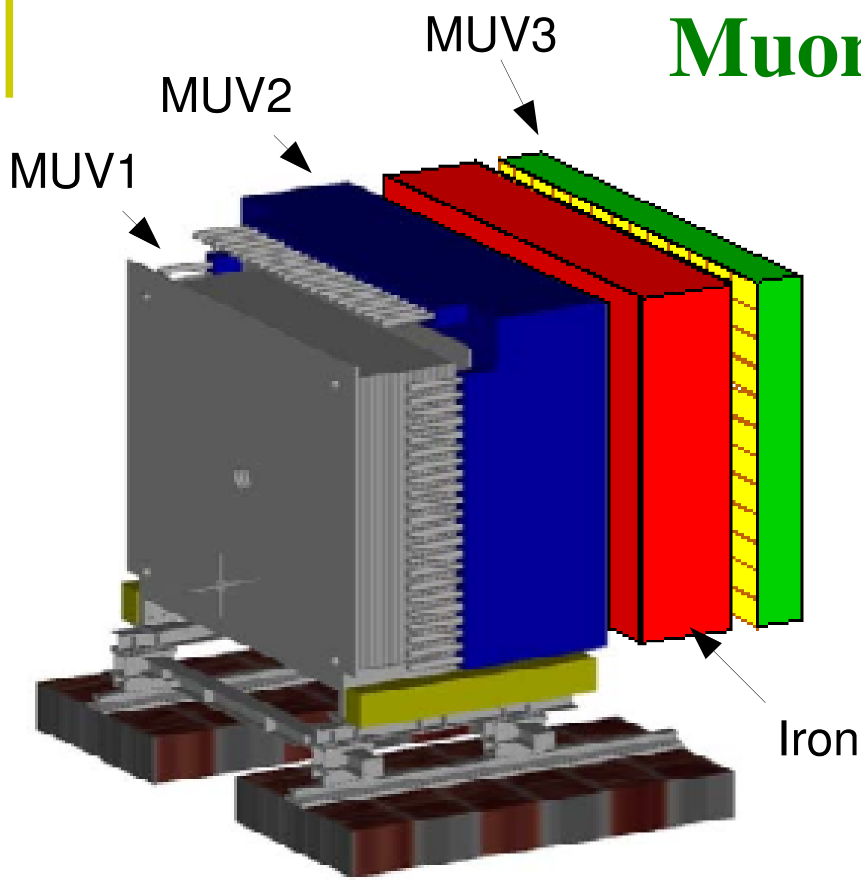


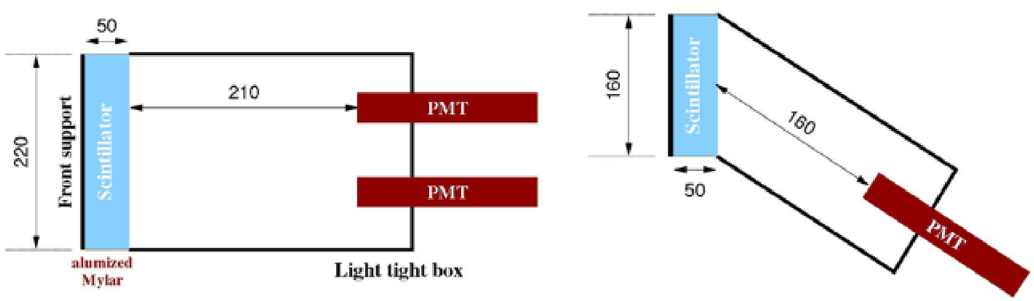
# 3) Muon Vetoes

- Requirements:
  - Veto the decay $K^+ \to \mu^+\nu$ at L0 trigger
  - Support the kinematics in order to reject the $K^+ \to \mu^+\nu(\gamma)$ decay offline.
- Detector
  - 1 plane of fast scintillator behind all the detectors (trigger)
  - Hadronic calorimeter (offline)
- Key points:
  - Online sub-ns time resolution of the fast muon veto plane
    - Integrated rate ~10 MHz
  - EM/Hadronic showers separation
    - Information from both LKr and the hadronic calorimeter
- Rejection Capability:
  - $O(10^{-3})$ muon rejection inefficiency (trigger).
  - $O(10^{-5})$ muon rejection inefficiency (trigger+offline).

# Muon Detectors




- Fast scintillator plane (MUV3):
  - ➔ End of the detector region
  - ➔ Matrix of pads
  - ➔ PMts behind the pad directly connected with the scintillator
  - ➔ Carefull PM arrangement to solve the signal ambiguity due to the Cerenkov light eventually produced by particles in the PM.




- Hadronic calorimeter (MUV 1-2)
  - ➔ 2 modules
  - ➔ Fe-scintillators sampling calorimeter
  - ➔ 24 and 22 layers of scintillator srips

- MUV3 prototype tested on beam in 2010:
  - Online time resolution ~500-600 ps

# 4) Particle Identification

Against $K^+$ decays

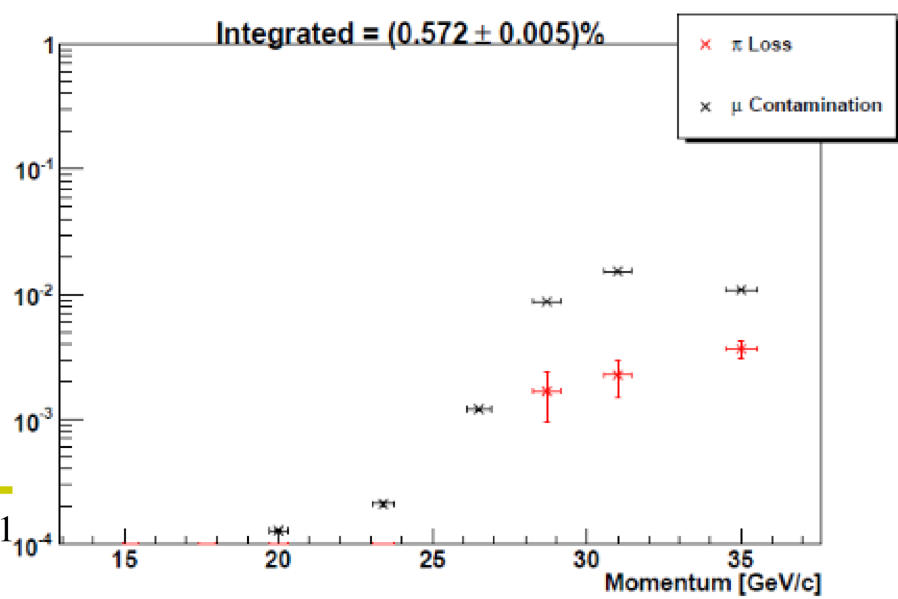
- Requirements:
  - Support kinematics and $\mu$-veto for the ultimate rejection of $K^+ \rightarrow \mu^+\nu(\gamma)$ decays.
  - Rejection of decays with positron/electron
- Detector: RICH and LKr
  - $\pi/\mu/e$ separation
- Performances:
  - RICH: ~$10^{-3}$ / $10^{-2}$ muon mis-identiication probability up to 35 GeV/c
  - LKr: ~$10^{-3}$ positron (electron) mis-identiication probability
    - measured using NA48-NA62/1 data (see A.Sergi talk).
- Redundancy
  - Measurement of the kinematic rejection, muon rejection, positron rejection.

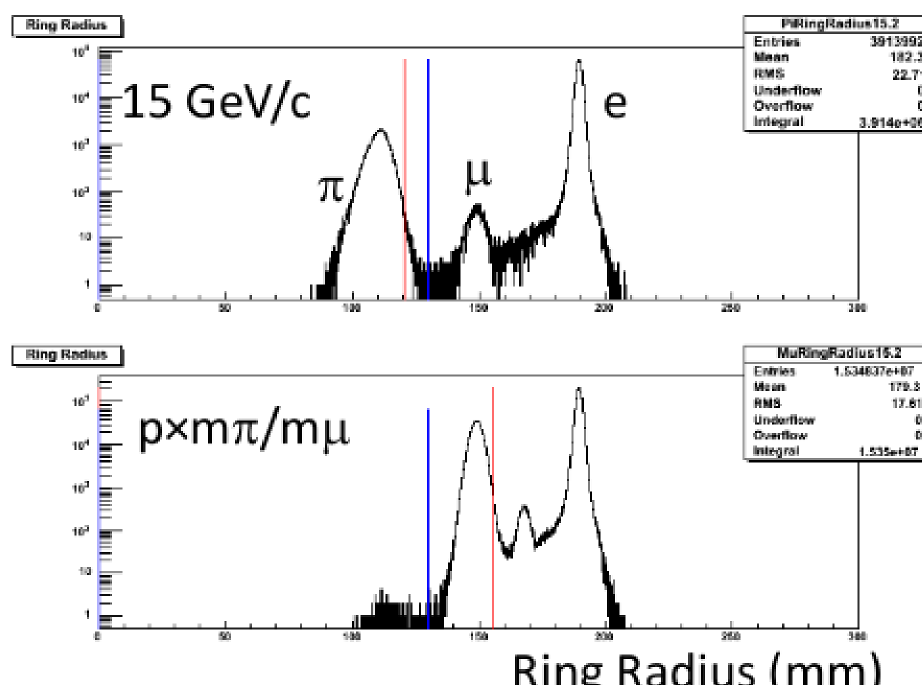
Against beam-induced background

- Requirement:
  - Veto of events with $\pi^+$/p interacting in the beam tracker or in the residual gas.
- Detector: Cerenkov threshold detector (CEDAR) for $K^+$ identification on the beam line.

# RICH

- Purposes:
  - $\pi/\mu$ separation, event time
- Radiator: Ne (1 atm)
  - $P_{\pi}$ > 15 GeV/c (Threshold)
- Tested @ SPS in 2007 and 2009
- Full length prototipe (0.5 m radius)
- 400 PMT Hamamtsu R7400 installed
- Results [NIM A 593, 2008; A 621, 2010]
  - Average time resolution ~70 ps
  - $\pi/\mu$ separation (up to 17 hit PMs):

# Trigger/DAQ system: requirements

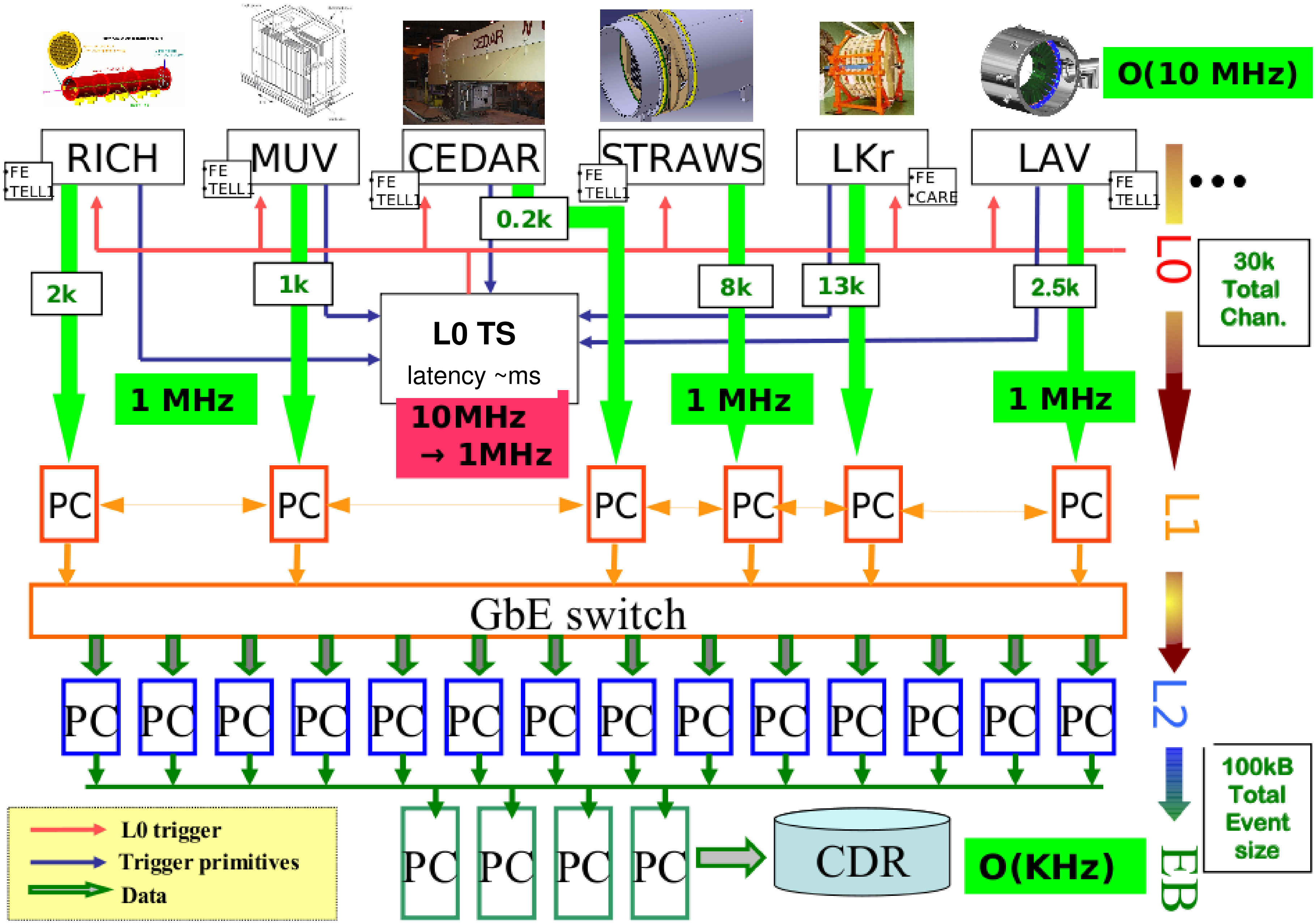
- Requirements:
  - High trigger efficiency (>95%)
  - Low Random Veto (< 1%)
  - High data bandwith
  - No zero suppression (for candidate events)

→

- DAQ reliability (< $10^{-8}$ inefficiency)
- Trigger reproducibility (offline analysis)

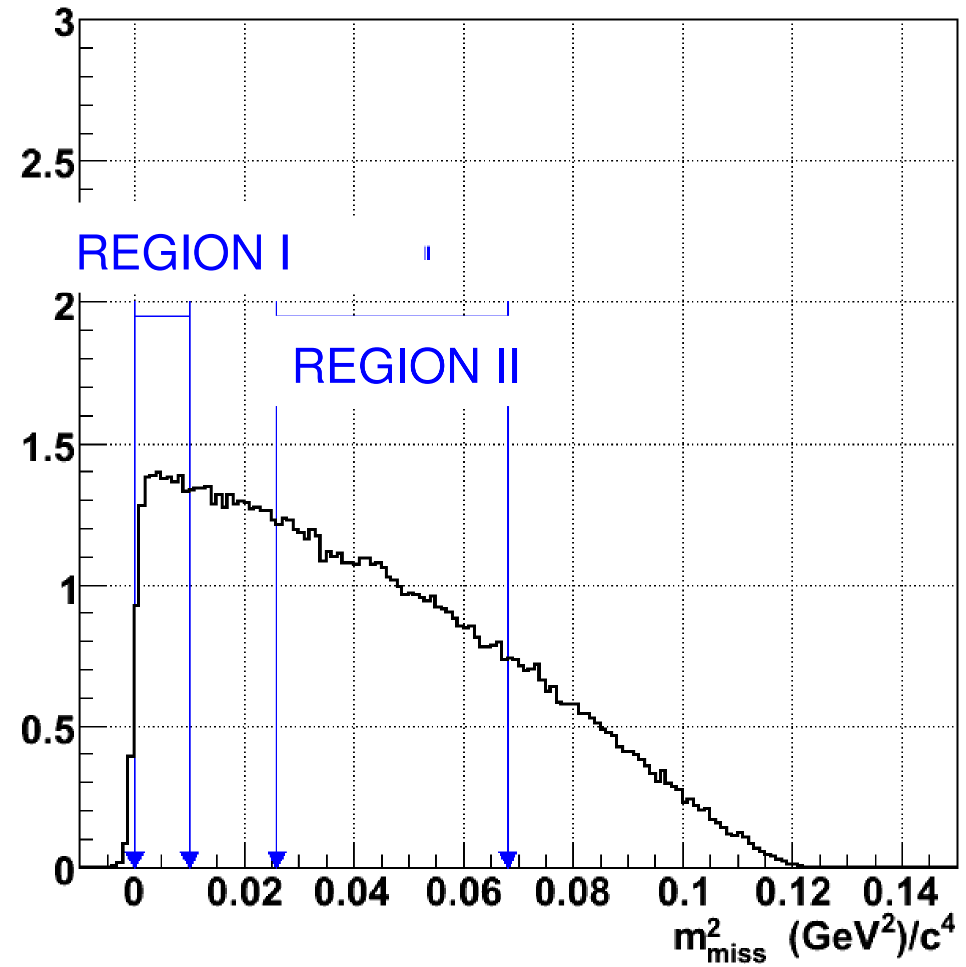
- Solution:
  - Integrated Trigger+DAQ.
  - Completely digital data stream from FE to TDAQ.
  - Fully monitored system (inefficiency and flow control recording).
  - Custom hardware minimized: L0 hardware + L1/2 software.
  - Flexibility (e.g additional physics program).

# Trigger/DAQ system: general overview



# NA62 Sensitivity: signal acceptance

- Simulation of the NA62 apparatus
  - interactions in the trackers simulated using GEANT4
- Most important cut in the analysis: $15 < P_\pi < 35$ GeV/c
  - For photon and muon rejection
  - RICH operational reasons
- Acceptance: ~14.4%
  - 3.5% "region 1", 10.9% "region 2"
  - 50% loss due to $P_\pi$ cut
  - Expected detector inefficiencies considered




- To be reduced because of losses due to dead time, additional inefficiencies...

The NA62 experiment matches the goal of 10% acceptance

# NA62 Sensitivity

| Decay Mode | Events |
|---|---|
| Signal: $K^+ \to \pi^+ \nu \nu$ *[ flux = $4.8\times10^{12}$ decay/year]* | 55 *evt/year* |
| $K^+ \to \pi^+ \pi^0$ [$\eta_{\pi 0} = 2\times10^{-8}$ ($3.5\times10^{-8}$) ] | 4.3% (7.5%) |
| $K^+ \to \mu^+ \nu$ | 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% (≤17%) |

# Conclusions

- NA62 is approved and funded.
- With 2(+1) years of data taking NA62 will provide a 10% measurement of the BR of the $K^+ \to \pi^+ \nu \bar{\nu}$
  - x50 Kaon flux with respect to NA48 with ~same amount of protons from SPS.
  - Key points: Excellent resolutions, hermetic coverage, strong particle ID.
  - The R&D is close to the end and the construction is already started.
- The high performances of the detectors can also be the building blocks for a further rich physics program.