The NA62 experiment at CERN for $K^+ \to \pi^+ \nu \bar{\nu}$

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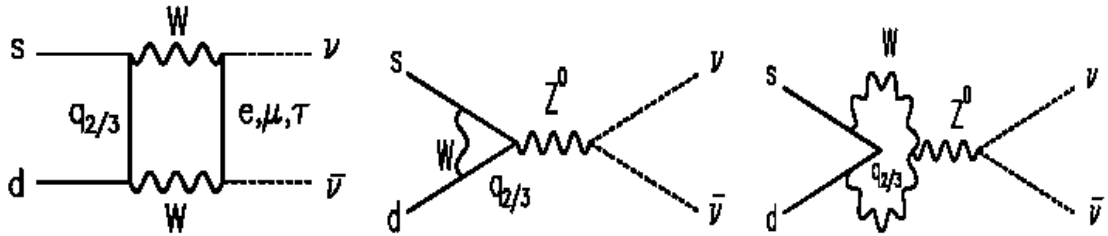
KAON '09 - Tsukuba 12/06/2009

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

- 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):

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (8.5 \pm 0.7) \times 10^{-11} \quad [m_c = (1286 \pm 13) \text{ MeV}/c^2]$$

$$BR(K_L \to \pi^0 \nu \bar{\nu}) = (2.76 \pm 0.40) \times 10^{-11}$$

- Experimental results:

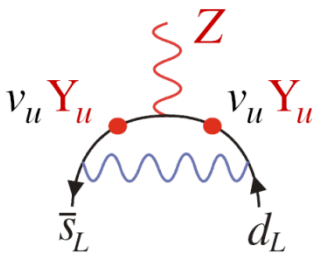
$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10} \quad [E787,\ E959\ '08]$$

$$BR(K_L \to \pi^0 \nu \bar{\nu}) \leq 6.8 \times 10^{-8} [E391a\ '08]$$

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

(courtesy by C. Smith)

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

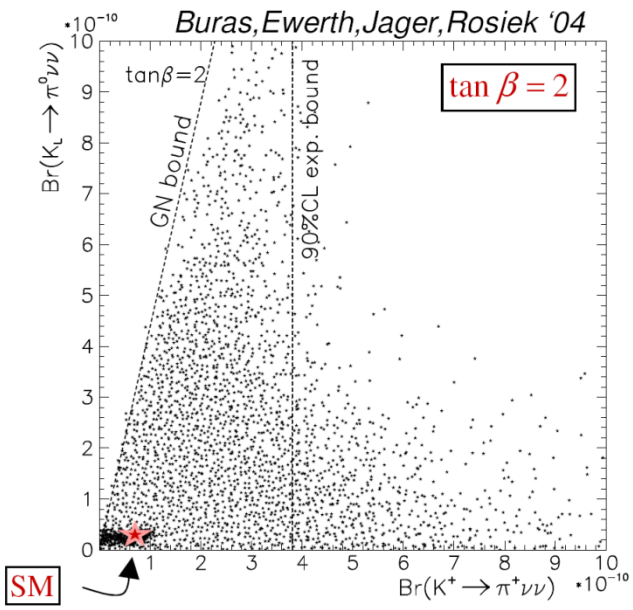


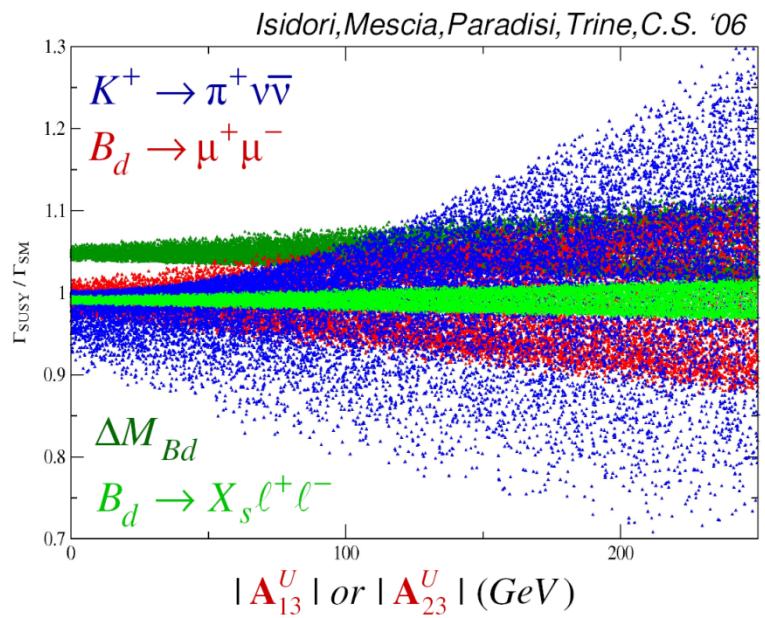
- $SU(2)_L$ breaking: $SM: v_u^2 Y_u^{*32} Y_u^{31} \sim m_t^2 V_{ts}^* V_{td}$

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

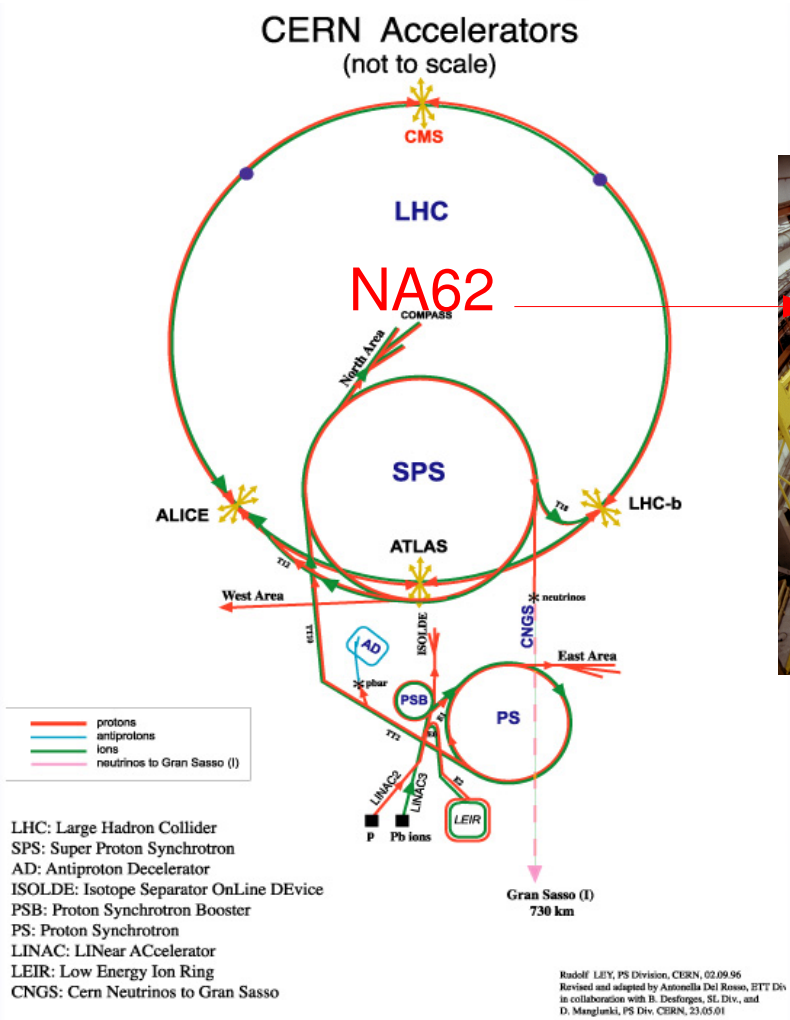
$$MFV: v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 V_{ts}^* V_{td} \left| A_0 a_2^* - \cot\beta\mu \right|^2 .$$

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





The NA62 Experiment

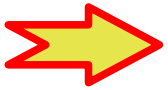


former NA48 exp hall

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

- Goals:
  - $O(100)\,K^+ \to \pi^+ \nu \bar{\nu}$ events
  - ~10% background



  - BR(SM) ~ 8.5×10^{-11}
  - Acceptance: 10%
  - K decays: ~10^{13}

- Principles:
  - "High" momentum K^+ beam: easier rejection of the π^0 induced background
  - Decay in-flight technique: beam-backgrounds suppressed wrt stopping kaon experiments

- Experimental techniques to exploit:

  (1) Kinematic rejection: against 2-body and 3-body backgrounds

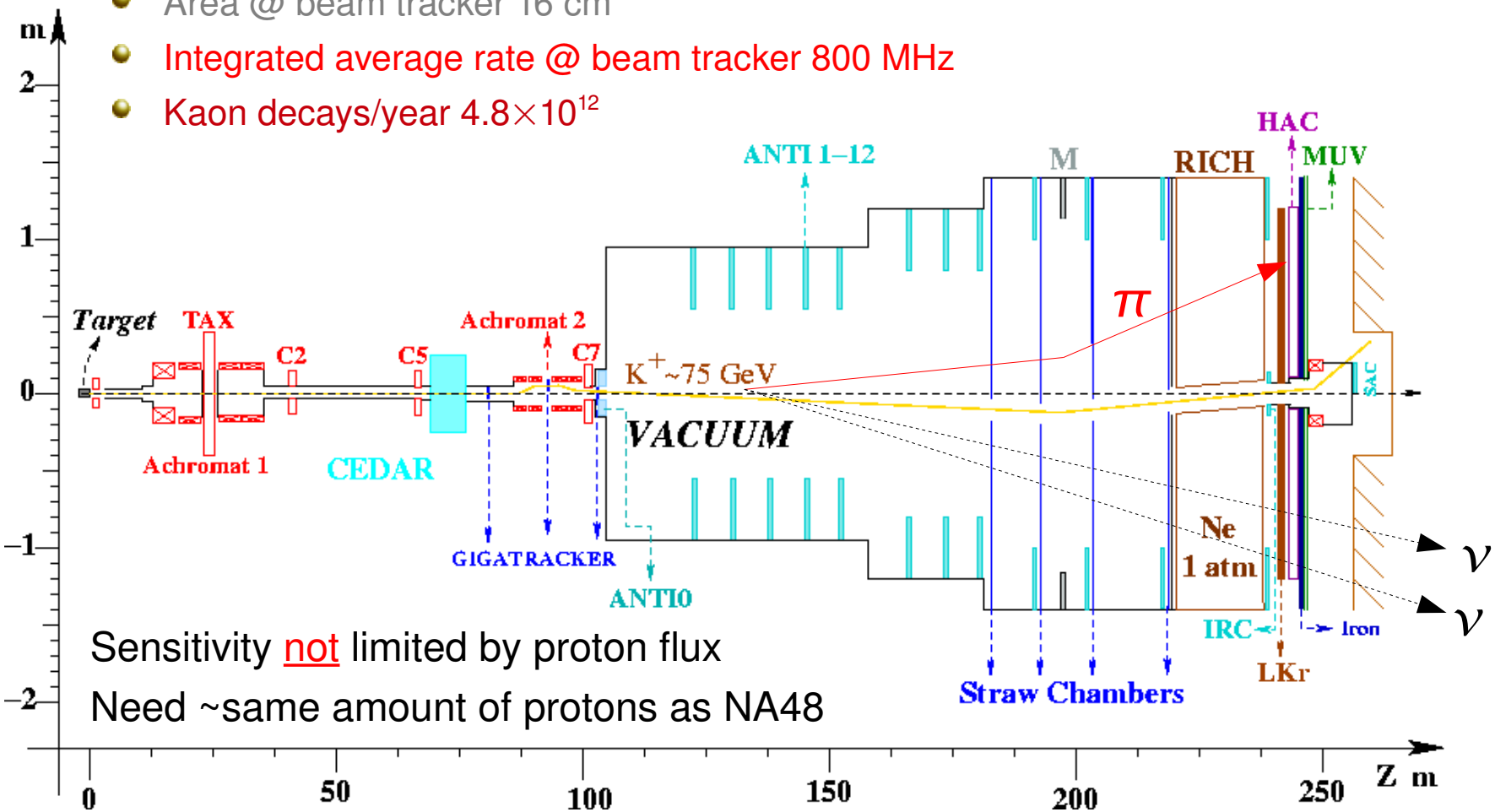
  (2) Precise timing: matching of the outgoing π^+ with the correct parent K^+

  (3) Vetoes: rejection of events with γ and μ in final state

  (4) Particle Identification: K/π (in the primary beam), π/μ (final state)

Detector Layout

- SPS primary protons @ 400 GeV/c ⇨ Unseparated secondary charged beam
  - 75 GeV/c ($\Delta P/P \sim 1\%$)
  - p/π/K (positron free, fraction of K ~6%)
  - Area @ beam tracker 16 cm^2
  - Integrated average rate @ beam tracker 800 MHz
  - Kaon decays/year 4.8×10^{12}

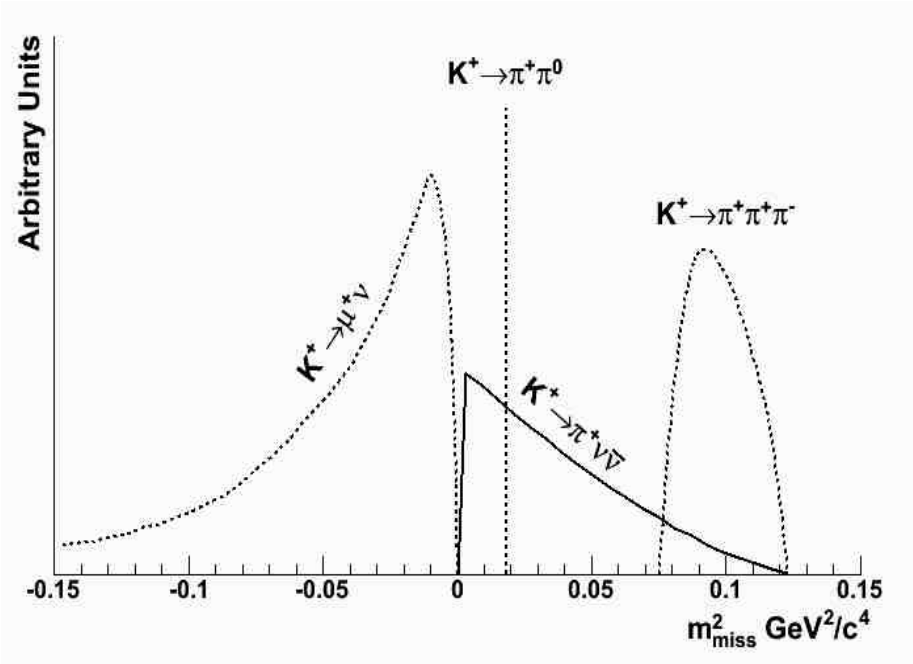


Sensitivity not limited by proton flux

Need ~same amount of protons as NA48

1) Kinematic Rejection

- Background constrained by kinematic

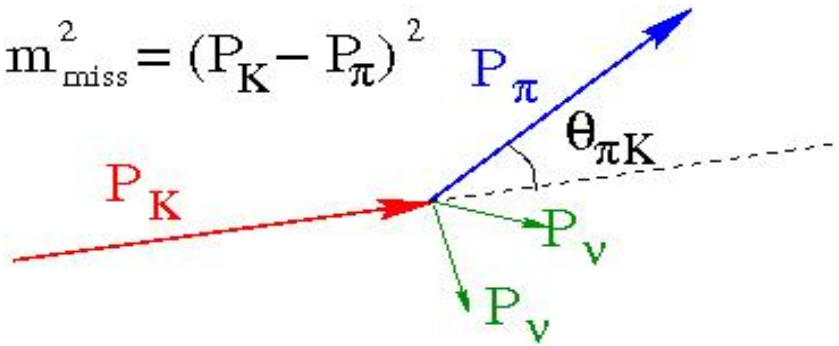


~92 % of the total K decay BR

- Two regions almost "background" free, separated by the $K^+ \rightarrow \pi^+\pi^0$

- Signal signature

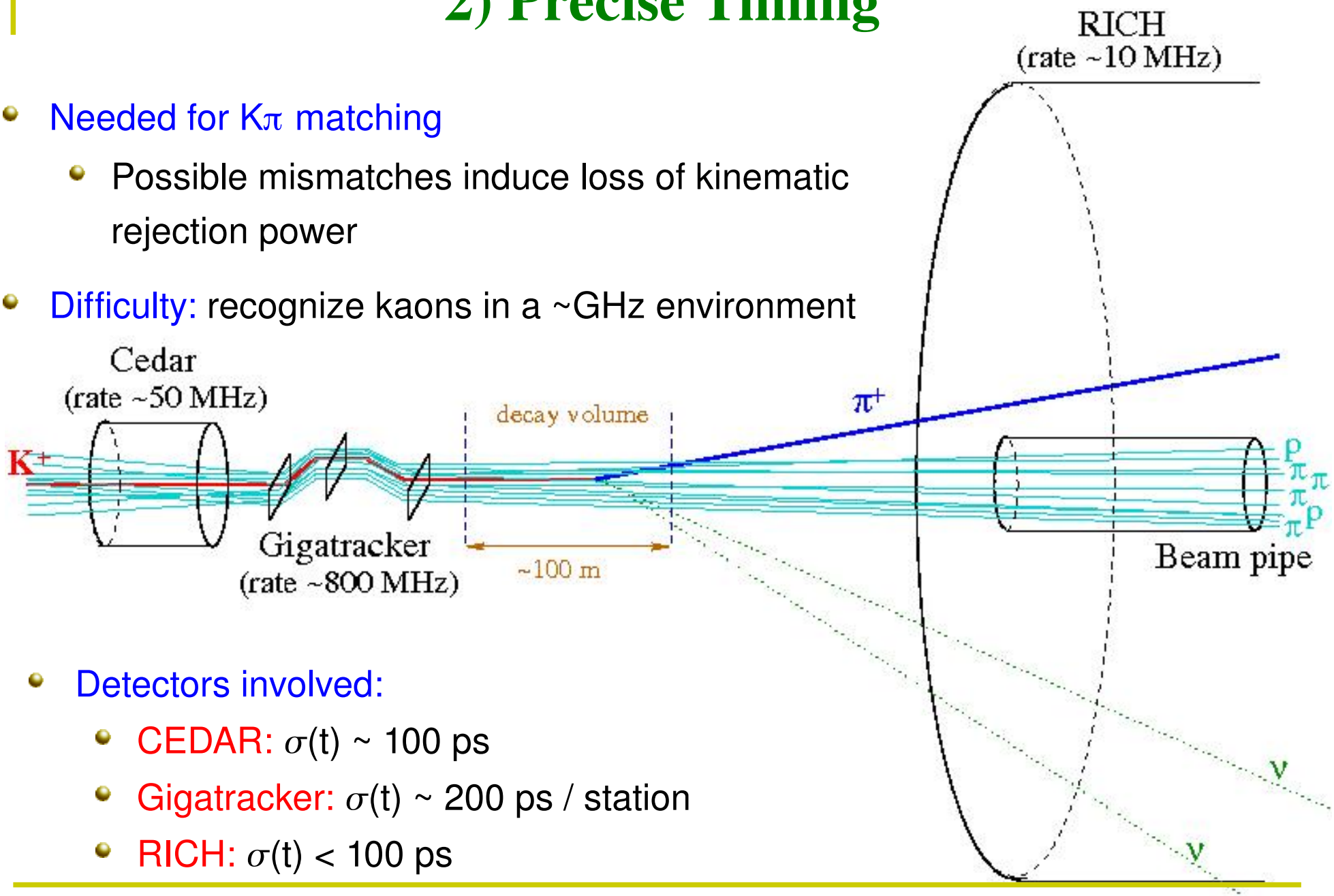
$$m^2_{miss} = (P_K - P_\pi)^2$$



- Requirements
- Minimization of multiple scattering
  - Low mass trackers for K and π
  - Tracking in vacuum for K and π
- High resolution trackers
  - σ ~100 μm per coordinates
- Detectors involved
  - Gigatracker: Kaon
  - Straw chambers: pion

2) Precise Timing

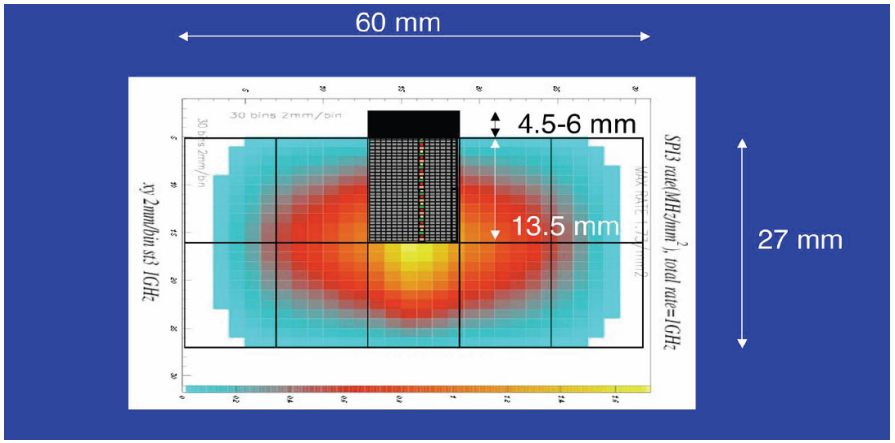
- Needed for Kπ matching
  - Possible mismatches induce loss of kinematic rejection power
- Difficulty: recognize kaons in a ~GHz environment

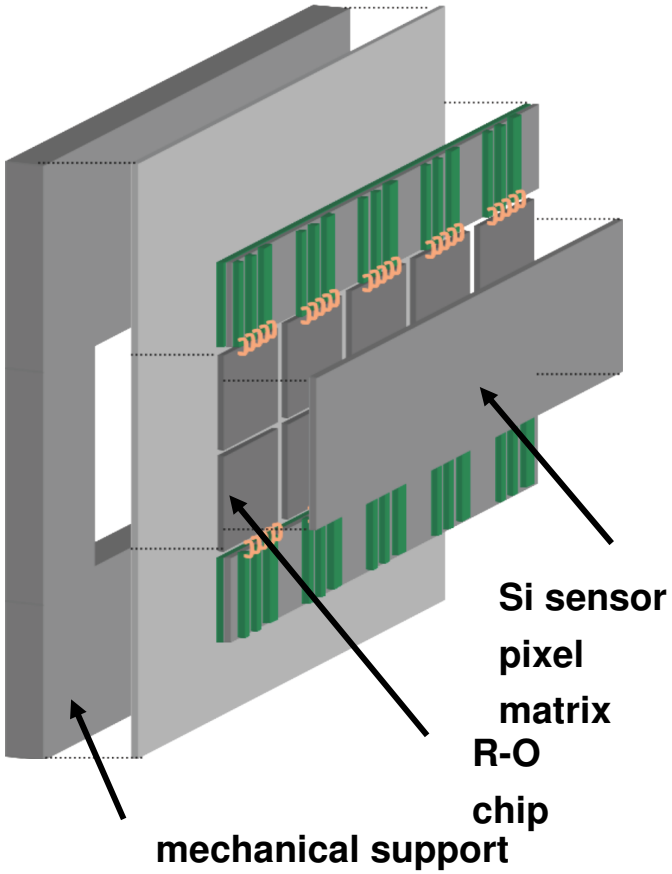


- Detectors involved:
  - CEDAR: $\sigma(t)$ ~ 100 ps
  - Gigatracker: $\sigma(t)$ ~ 200 ps / station
  - RICH: $\sigma(t)$ < 100 ps

Gigatracker

- 3 Si pixel stations before the decay volume
- Geometry matching the beam size

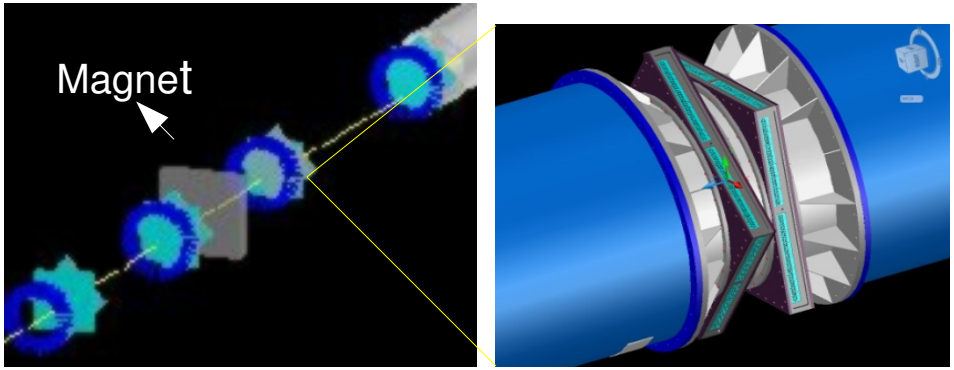




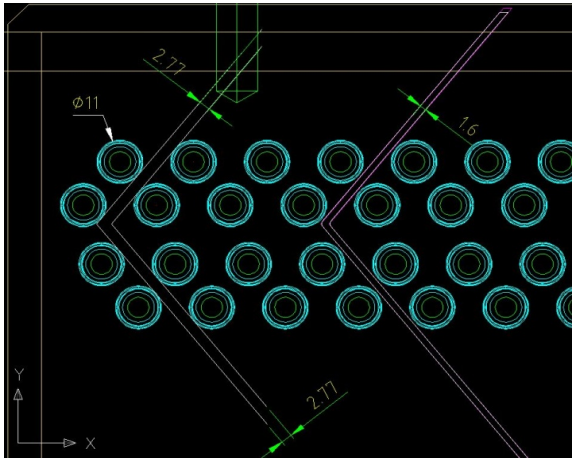
- Requirements:
- High space resolution: 300x300 μm pixels
- Low X/X_0: 200 μm sensor+100 μm chip (<0.5% X/X_0 per station)
- Excellent time resolution: sophysticated RO chip bump bonded on the sensor (0.13 μm technology)

Straw Chamber Spectrometer

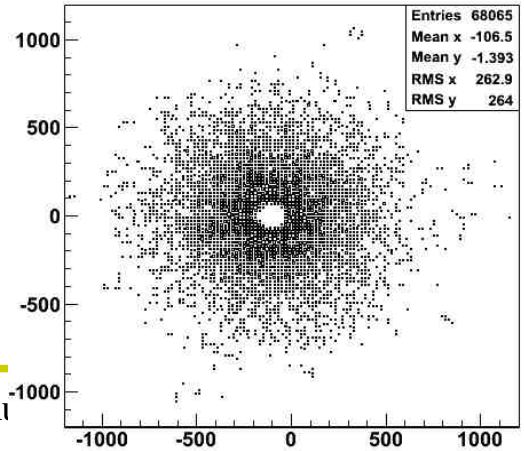
- 4 straw chambers in vacuum + 1 magnet (NA48 magnet, 256 MeV/c P_t kick)



- 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

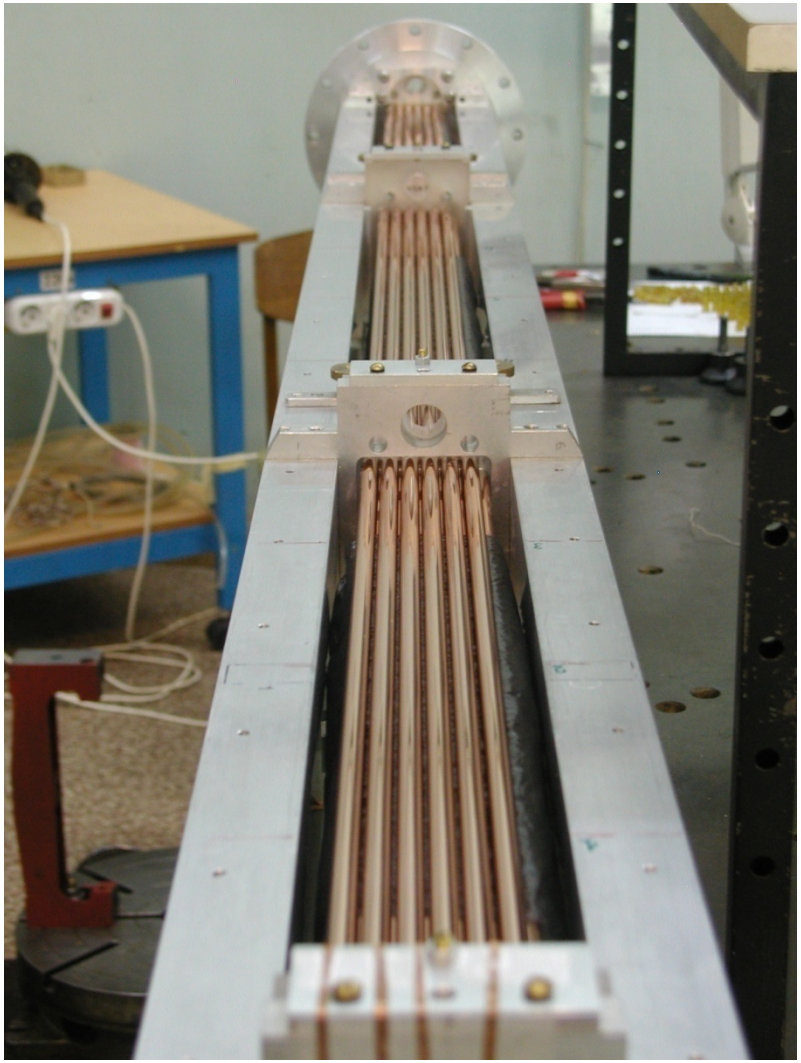


- 6 cm "radius" beam hole displaced in the bending plane according to the 75 GeV/c beam path



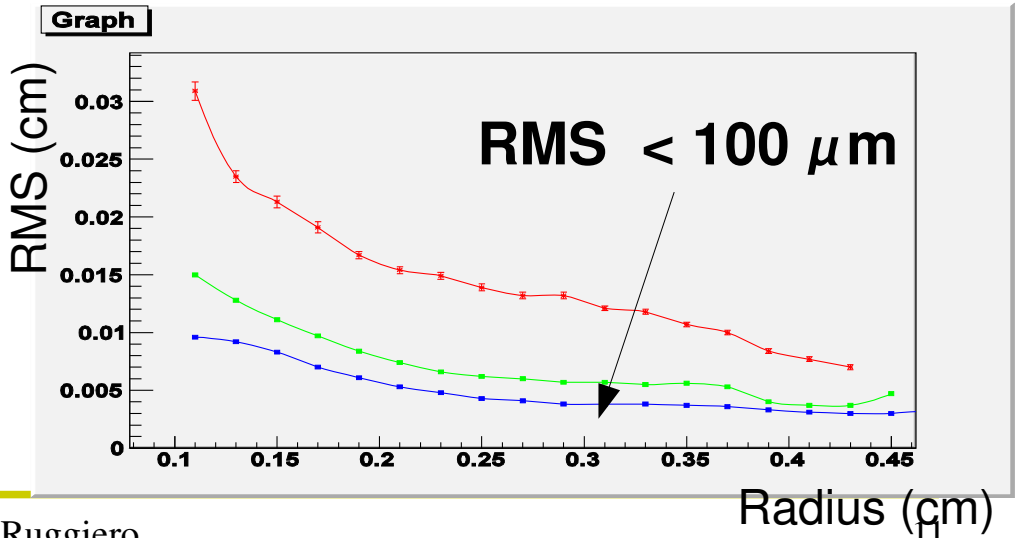
Straw Chamber Spectrometers R&D

- Full length prototipe built in 2007



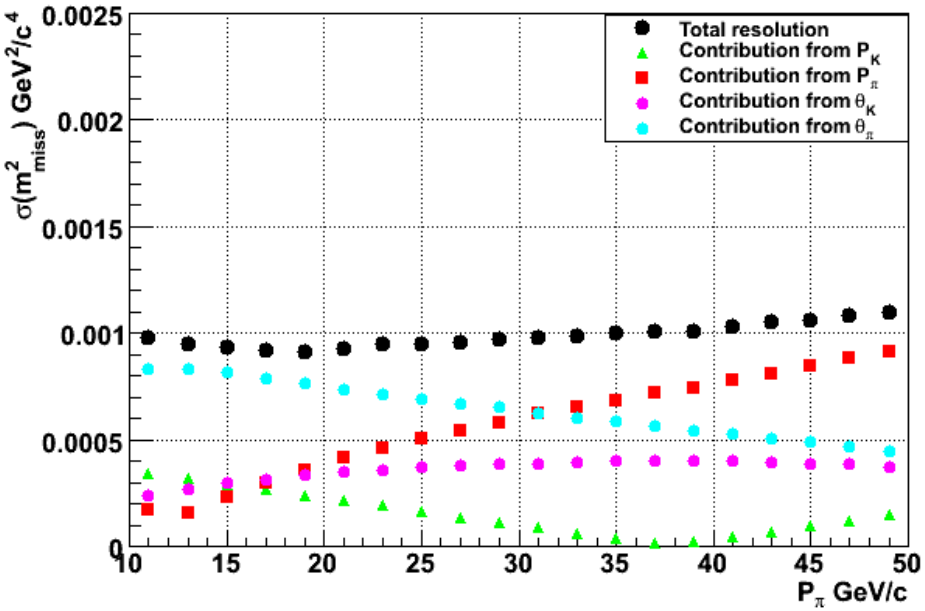
- Placed in vacuum on the beam

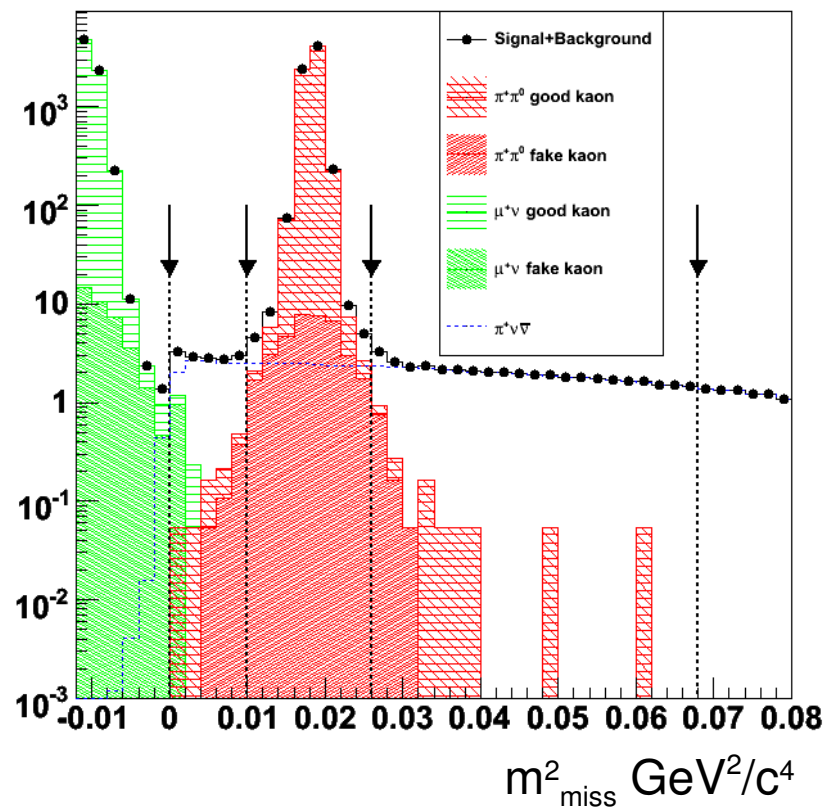
- Resolution from test beam (blue points)



Kinematic rejection capabilities

- Performance of the new tracking system (Geant4 MC):
  - $\sigma(P_K)/P_K$ ~0.2%, σ(dX,Y/dZ)~17 μrad
  - $\sigma(P_\pi)/P_\pi$ ~0.3%$\pm$0.007% P_π, σ(dX,Y/dZ)~45 – 15 μrad
- 2-body rejection power
  - 10^4 ($K^+\to\pi^+\pi^0$), 10^5($K^+\to\mu^+\nu$)
- Sources of inefficiency:
  - MS non guassian tails
  - Kπ mis-match





3) Vetoes

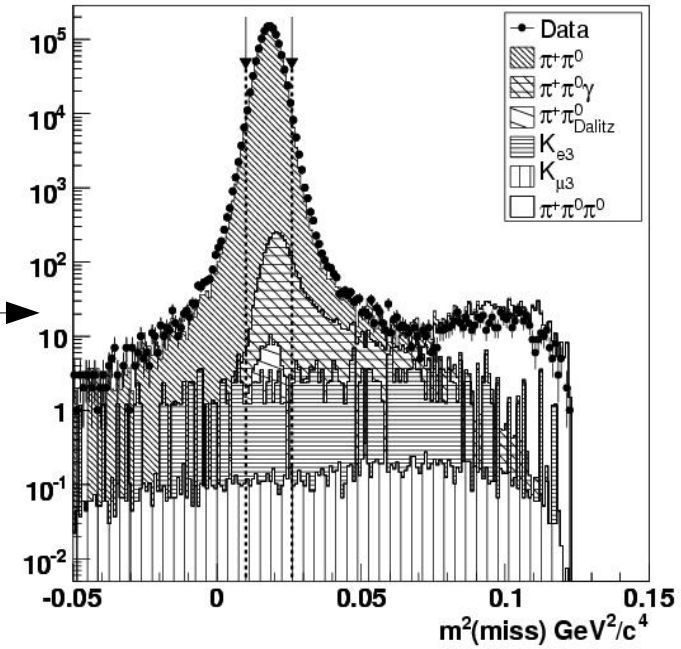
- Photon vetoes:
  - studied to reject $K^+ \rightarrow \pi^+\pi^0$ in conjuction with the kinematic rejection
- Requirements: $O(10^{-8})$ π^0 rejection inefficiency
- Detectors: electromagnetic calorimeters
  - LAV (10-50 mrad)
  - LKr [NA48] (1-10 mrad)
  - SAC, IRC (<1 mrad)

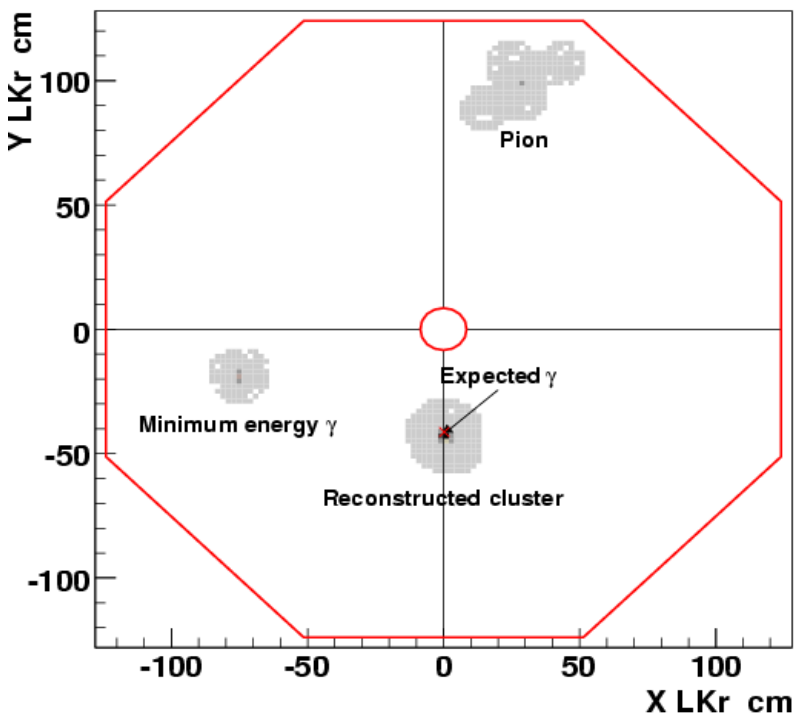
- Key points:
  - Analysis request: $P(\pi^+)<35$ GeV/c $\Rightarrow$ $P(\pi^0)>40$ GeV/c, it can hardly be missed in calorimeters
  - >1 GeV photons hit the liquid Kripton calorimeter
  - 10^{-5} inefficiency of the liquid Kripton calorimeter for >10 GeV photons

- Muon veto:
  - studied to reject $K^+ \rightarrow \mu^+\nu$ in conjuction with the kinematic rejection and particle ID
- Requiremet: $O(10^{-5})$ muon rejection inefficiency
- Detector: hadronic calorimeter + fast pad-scintillator planes
  - Upgrade of the existing NA48 hadronic calorimeter
  - sensitivity to the MIP and em/hadronic shower separation capability

NA48 Liquid Kripton em calorimetry inefficiency

- Inefficiency measured on data
- 2006 bremmstrahlung photon beam (E>2.5 GeV)
- 2004 NA48 data @ 75 GeV (E>10 GeV)
  - $K^+ \rightarrow \pi^+\pi^0$ selected using kinematic only

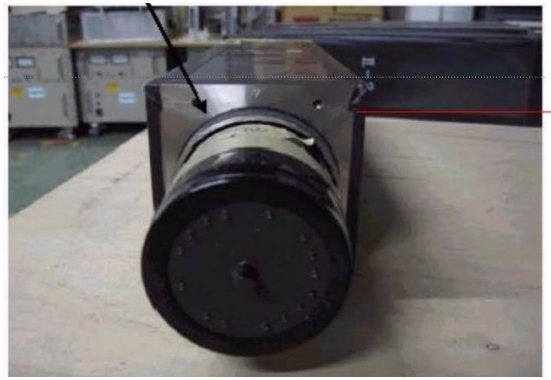


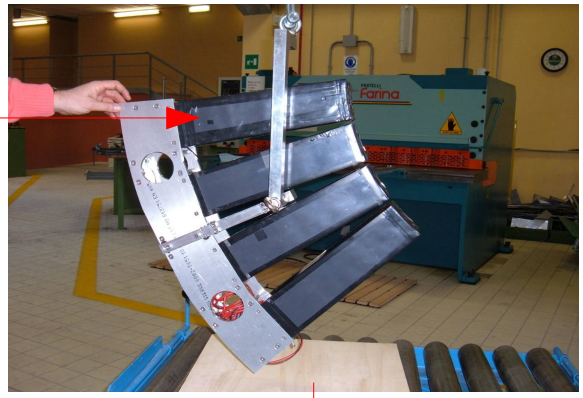


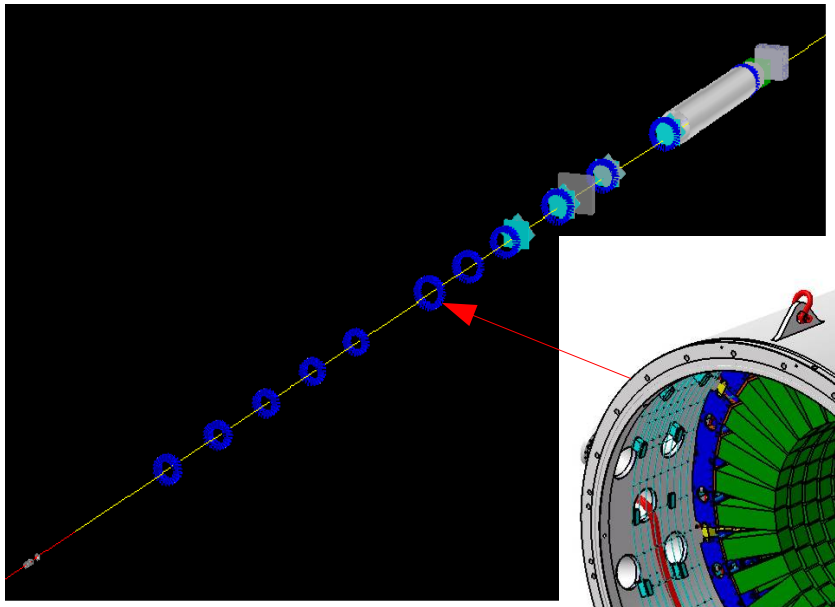
E (GeV)	Inefficiency
2.5 – 5.5	$< 10^{-3}$
5.5 – 7.5	$< 10^{-4}$
7.5 – 10	$< 5\times10^{-5}$
> 10	$< 8\times10^{-6}$

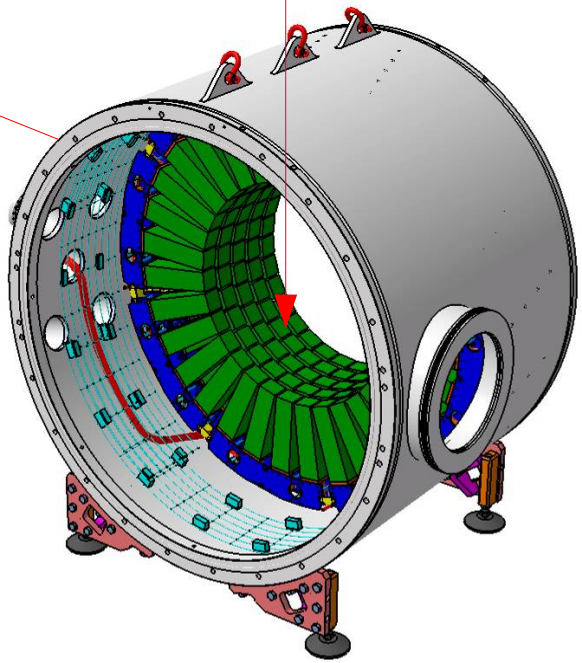
Large Angle Veto (LAV)

- OPAL lead glass:
- 12 rings along the detector line (variable radius) in vacuum
  - 5 staggered plane of modules per ring
- Array of blocks tested @ BTF (Frascati):
  - Inefficiency @ 471 MeV e^+: ~10^{-4} on the whole surface
- Module prototype tested @ CERN in 2008
  - Validation of the operation in vacuum
  - Time resolution ~1 ns
- First ring under construction: will be tested @ CERN in autumn.



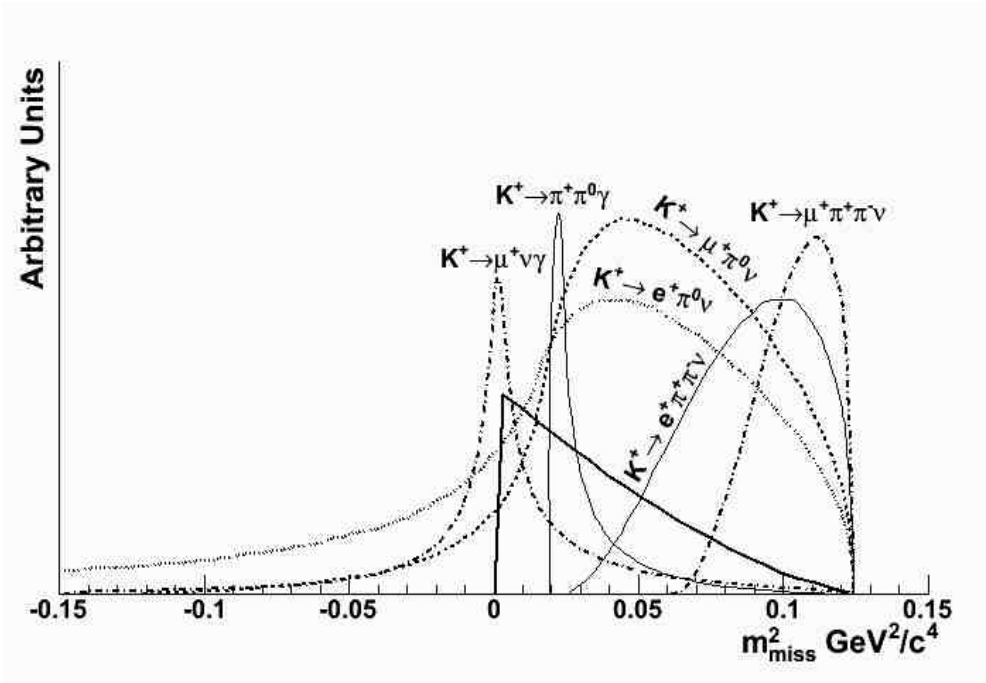






4) Particle Identification

- Physical background not constrained by kinematic
- ~8% of the total K decay BR
- Span across the signal region
- Particle ID + Veto



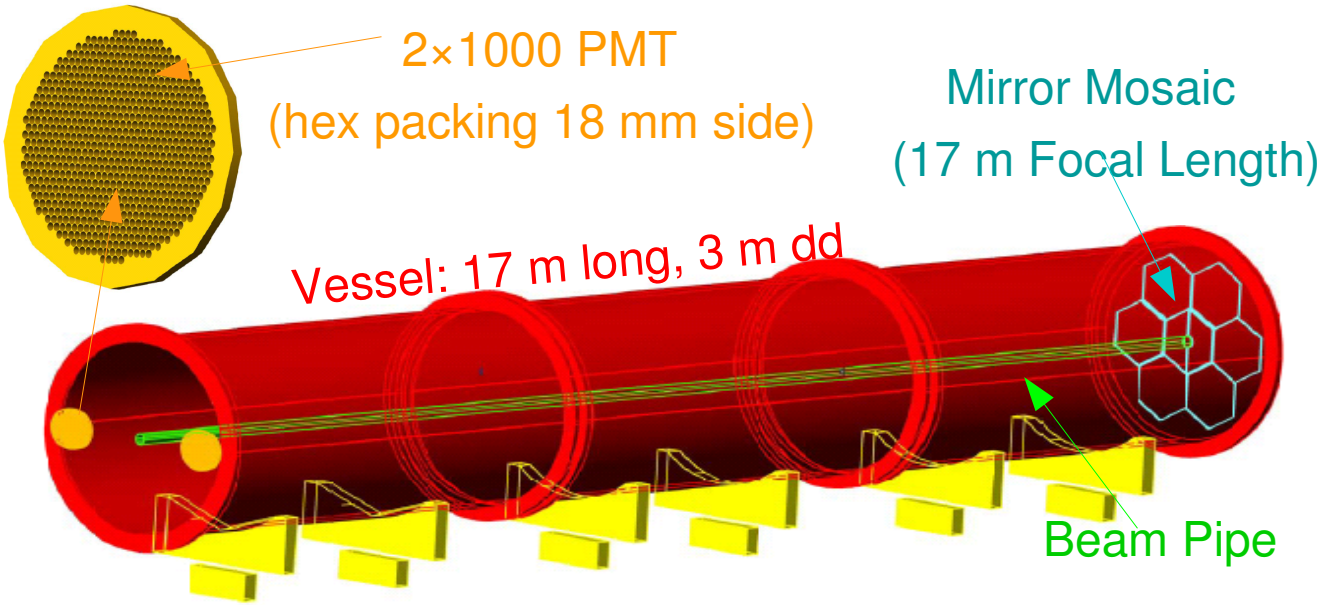
- Beam related background:
- hadronic interaction of the beam particles with the gigatracker stations
- Interactions of the beam particles with the residual gas in the decay volume

- Requirements and Detectors involved:
- ~10^{-2} π/μ separation up to 35 GeV (mainly against $K^+ \to \mu^+ \nu(\gamma)$): RICH
- π/e separation: LKr and RICH
- K identification: CEDAR

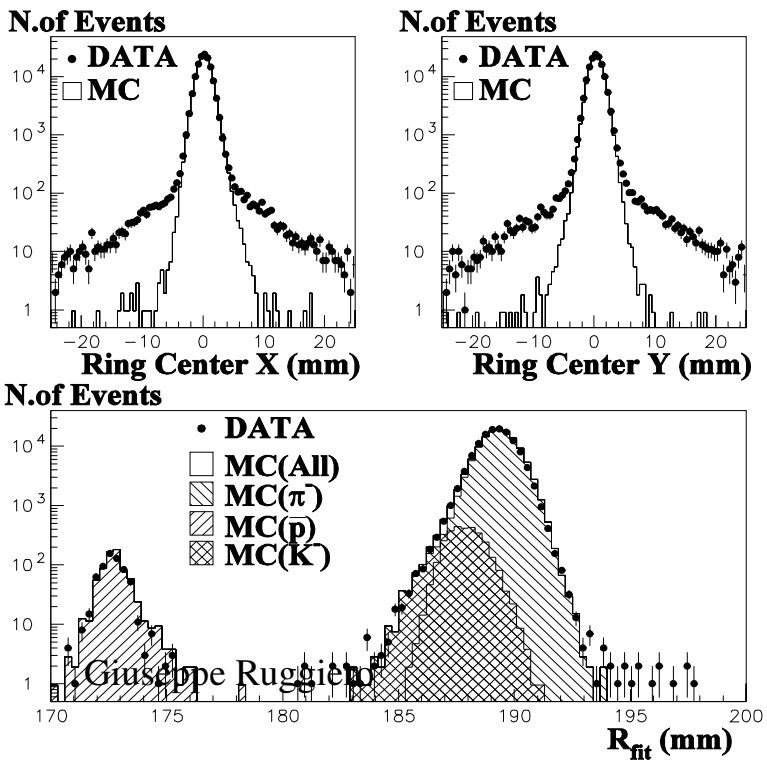
RICH

Radiator: Ne gas at 1 atm

- Purposes
- π/μ separation with low inefficiency and high purity
- Time of the events: excellent time performance
- Main trigger for 1 track events



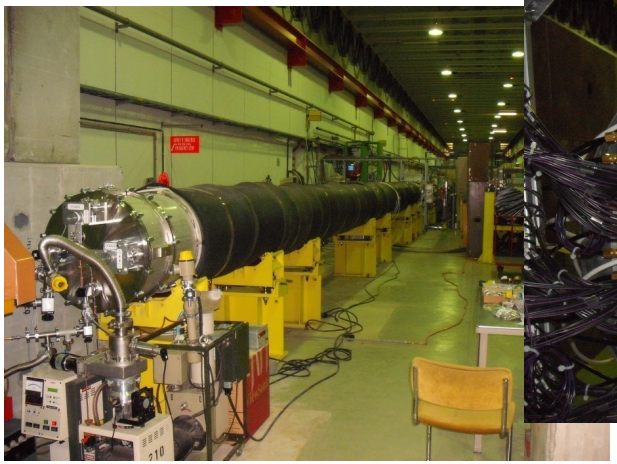
- Test beam 2007
- ECN3 (NA48 cavern) @ CERN
- 200 GeV hadron beam (pion/K)
- Full length prototipe (0.5 m radius)
- 96 PMT Hamamtsu R7400

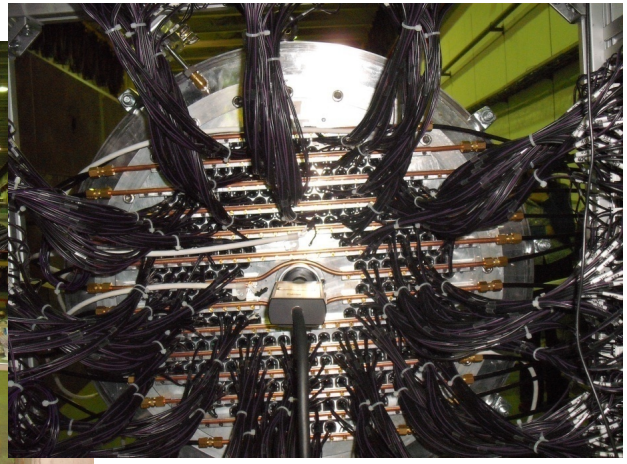


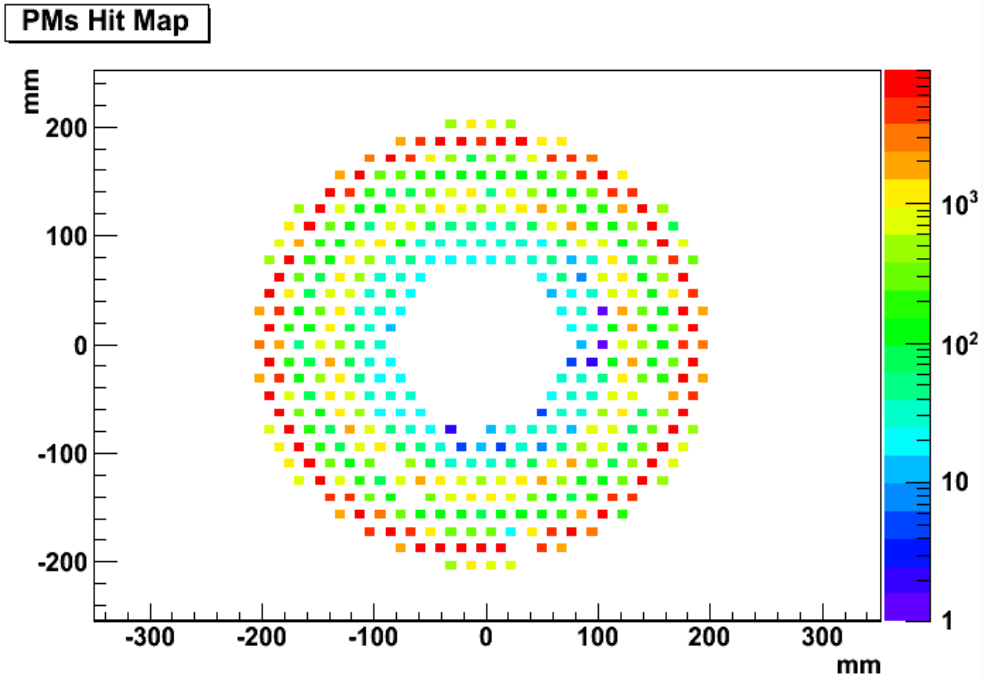
- Results [NIM A 593, 2008]
- N_{hits} ~ 17/event
- Δt_{event} ~ 70 ps
- $\Delta\theta_c$ ~ 50 μrad (biased by PM Geometry)

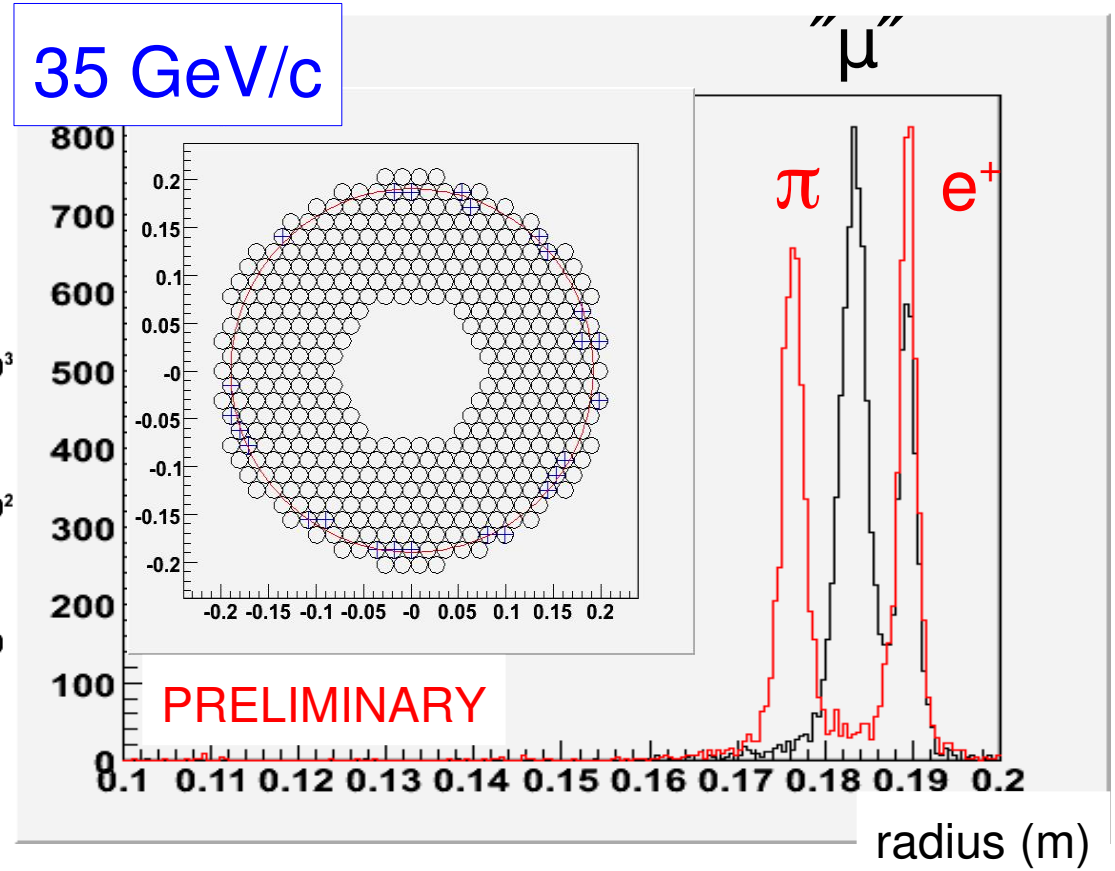
Rich Test Beam '09

- Full length prototype tested on a charged beam at CERN SPS
- ~400 PMT installed
- ~17 photon / positron detected
- HPTDC and TELL1 boards for readout (project developed within the collaboration in the framework of the Trigger R&D)



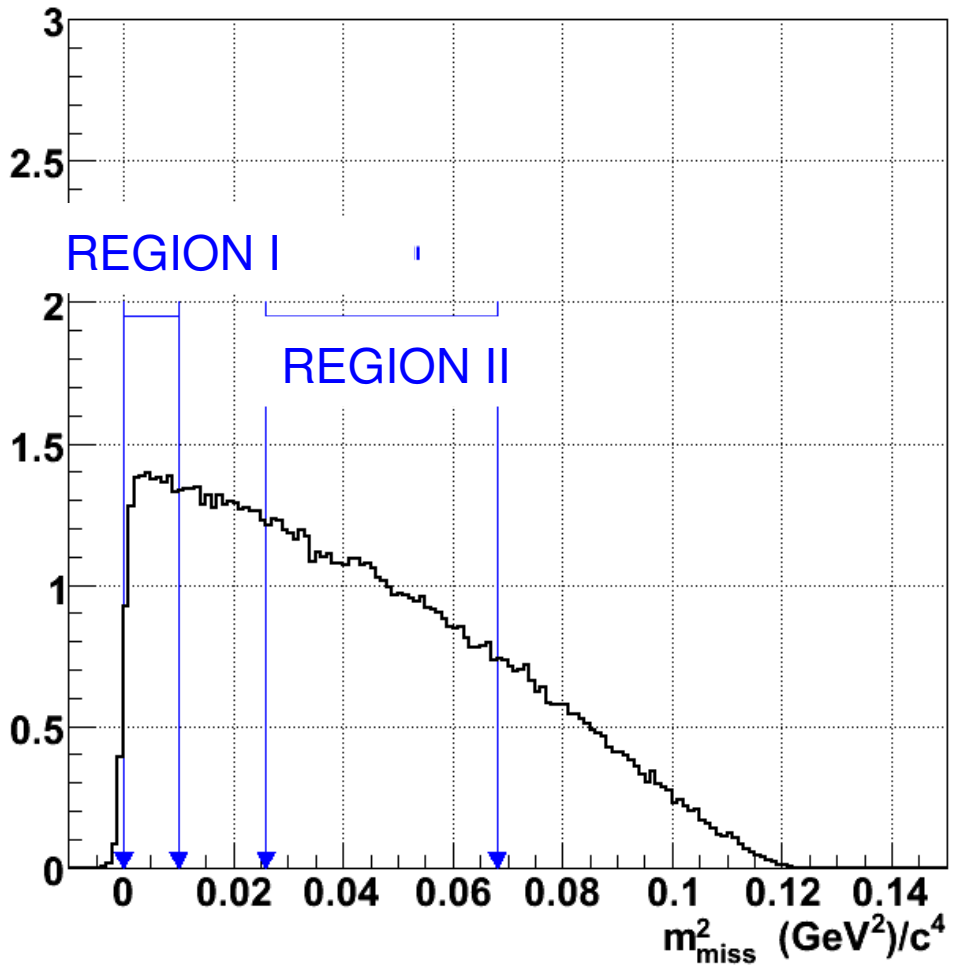






NA62 Sensitivity: signal acceptance

- 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_{π} 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 = 4.8×10^{12} decay/year]*	**55** *evt/year*
$K^+ \to \pi^+ \pi^0$ *[$\eta_{\pi 0} = 2\times10^{-8}$ (3.5×10^{-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

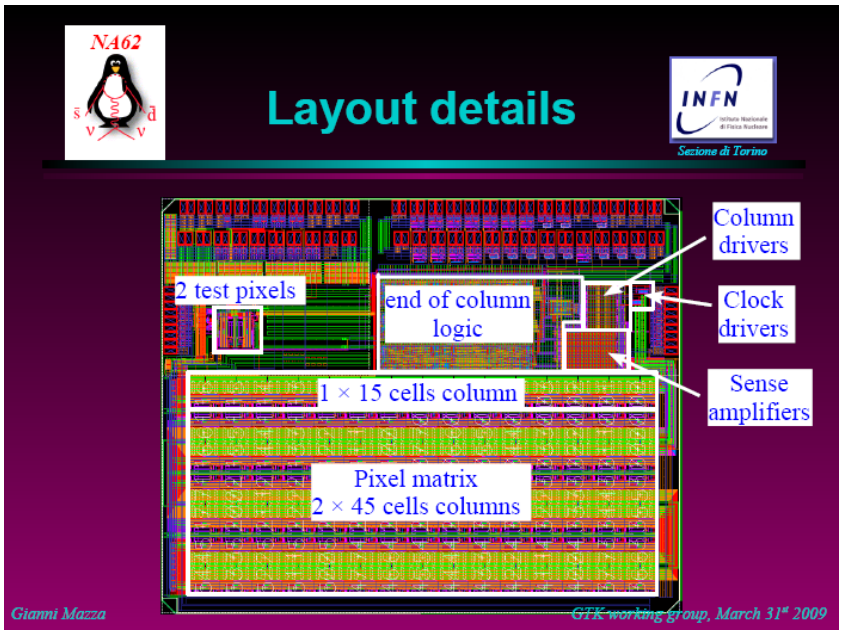
- The physics case to study ultra rare kaon decays at CERN SPS in the LHC era is very strong
- With 2(+1) years of data taking NA62 will provide a 10% measurement of the BR of the $K^+ \to \pi^+ \nu \bar{\nu}$
  - Key points: Excellent resolution, hermetic coverage, strong particle ID
  - x50 Kaon flux with respect to NA48 with ~same amount of protons from SPS
- A rich physics NA62 program can be added to the ultra rare kaon decays
  - precision tests of lepton universality, study of strong interactions at low energy
  - searchs for (e.g.) Sgoldistinos, νMSM Neutral Leptons
- The R&D is close to the end, the construction is already started
  - The construction schedule is mostly resource driven
- The experiment was approved by the CERN Research Board (December 5 2008) ”subject to the definition of resource sharing within the Collaboration”

Spares

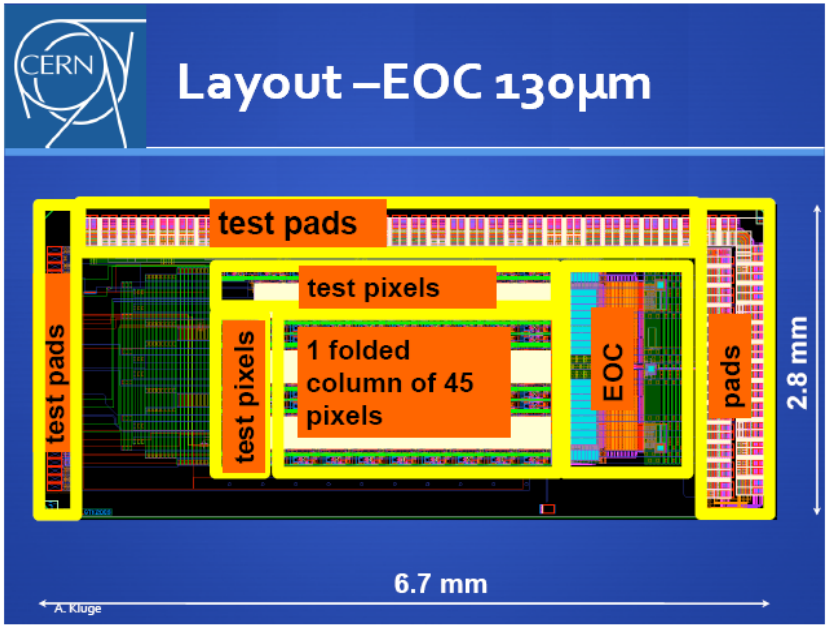
Gigatracker R&D

- Gigatracker R/O prototypes

INFN design: One TDC/pixel



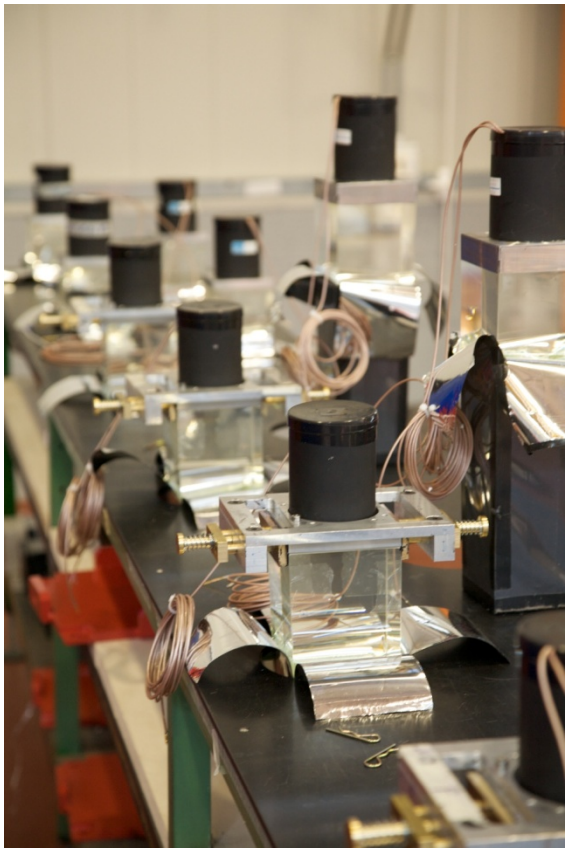
CERN design: end-of-column TDC

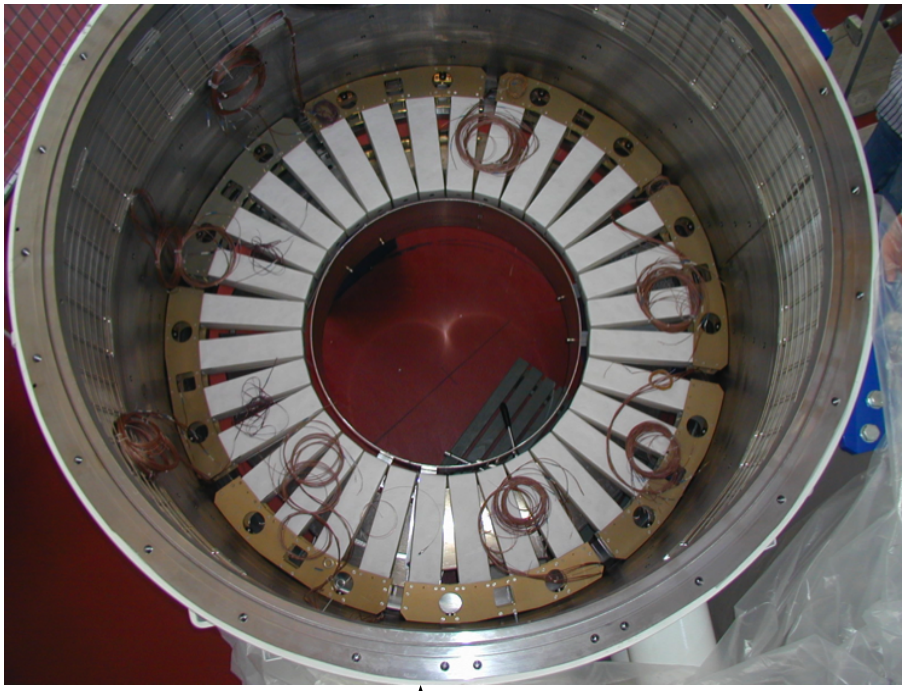


Photon ANTI counters

Large Angle Veto (LAV) R&D

- First ring at LNF (Frascati) for assembly

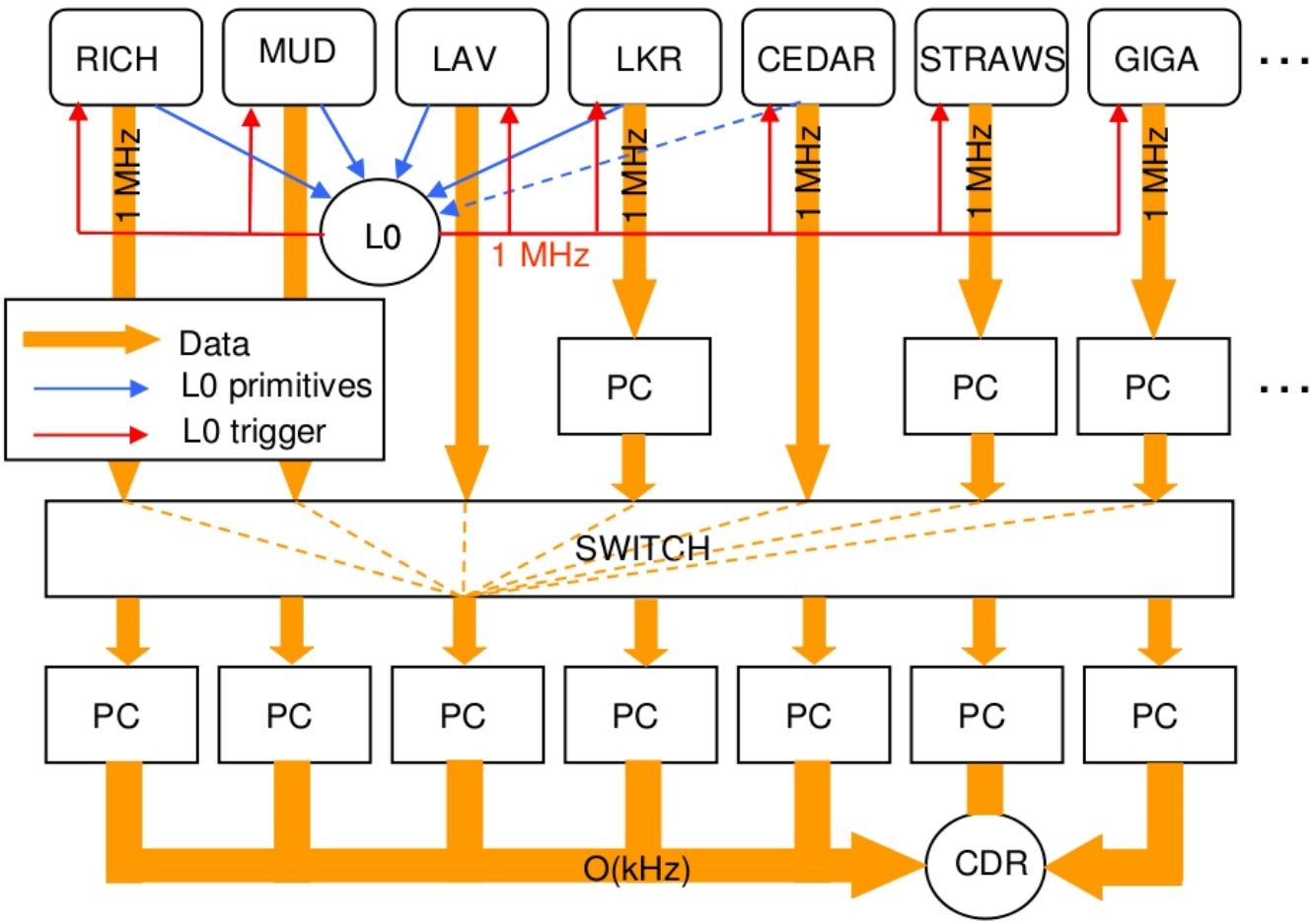




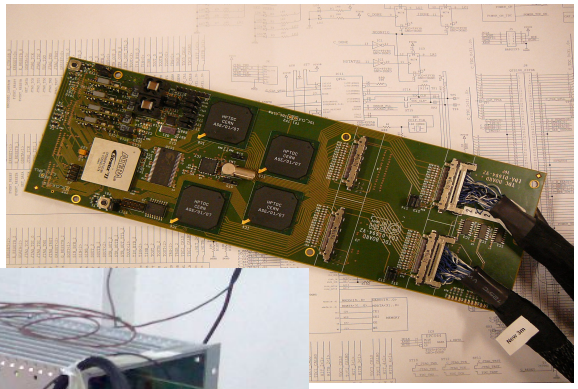
- First layer assembled (may '09)

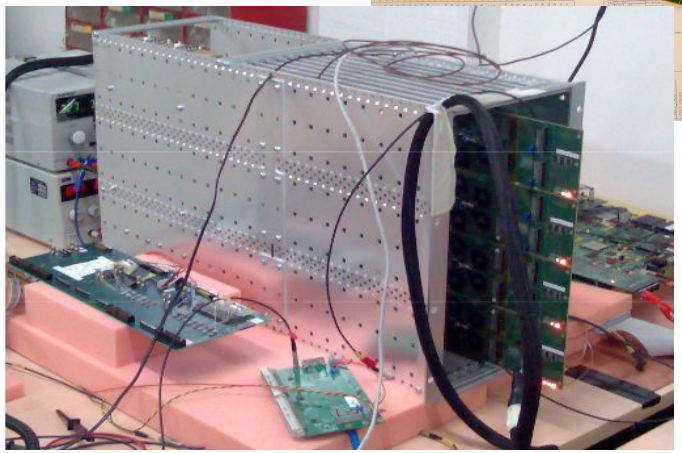
Trigger system

- Sub-detectors R/O and integrated L0 trigger: TELL1/TDC project
  - RICH, MUD, LAV, Straws
  - Gigatracker, LKr , CEDAR: dedicated projects for R/O and L0 trigger
- L0 processor: receives O(40 MB/s), takes a decision delivered to all the detectors.
- L1 (subdetectors), L2 (event) triggers: online farm. Output O(kHz).

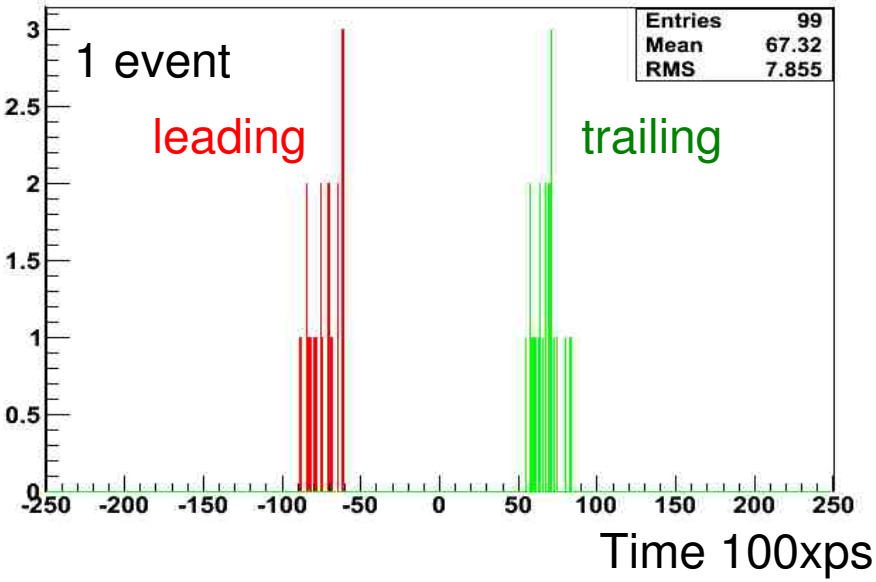


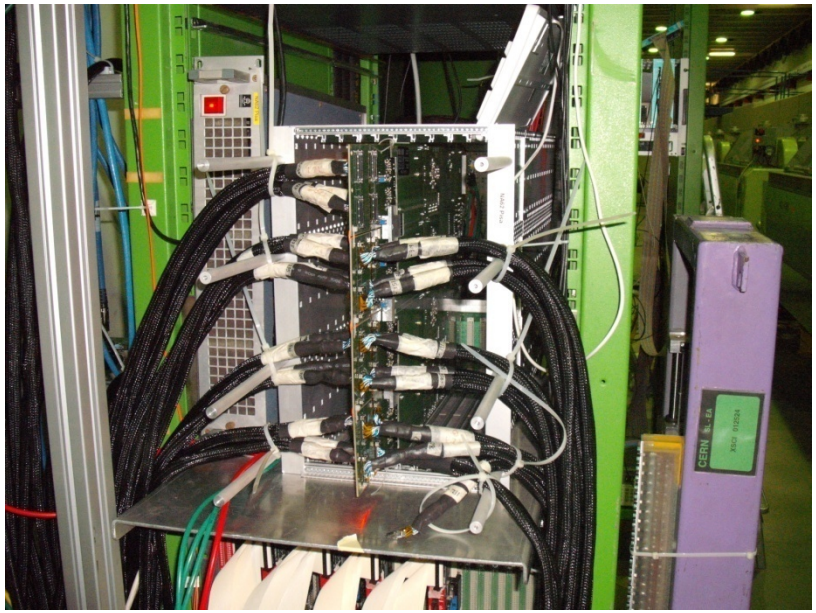
TELL1/TDC R&D





- LHCb TELL1 as underlying carrier board
- High integration TDC daughter card with HPTDCs developed (512ch/TELL1)
- Linear fast preamp/discriminator gives PH information with time-over-threshold
- Local processing and power storage
- TELL1/TDC based R/O system tested successfully during the '09 RICH test





Ruggiero