The NA62 Experiment @ CERN

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On behalf of the NA62 Collaboration

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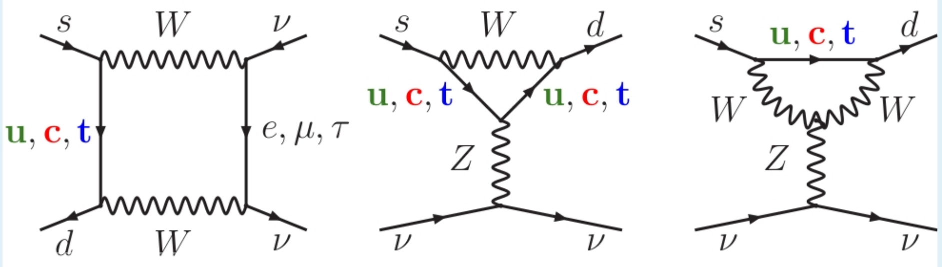
OUTLINE

- The **K → $\pi\nu\bar{\nu}$** decay (SM and beyond)
- The **NA62** experiment:
  - Experimental technique
  - Signal & background
  - Detectors
  - Trigger
  - Sensitivity
- Conclusions

$K \to \pi \nu \bar{\nu}$ decays in SM

- Key role in search for New Physics beyond SM
- FCNC processes mediated by Z penguins and box diagrams only arising at loop level
- Strongly suppressed in SM ($<10^{-10}$) → **good sensitivity to NP**



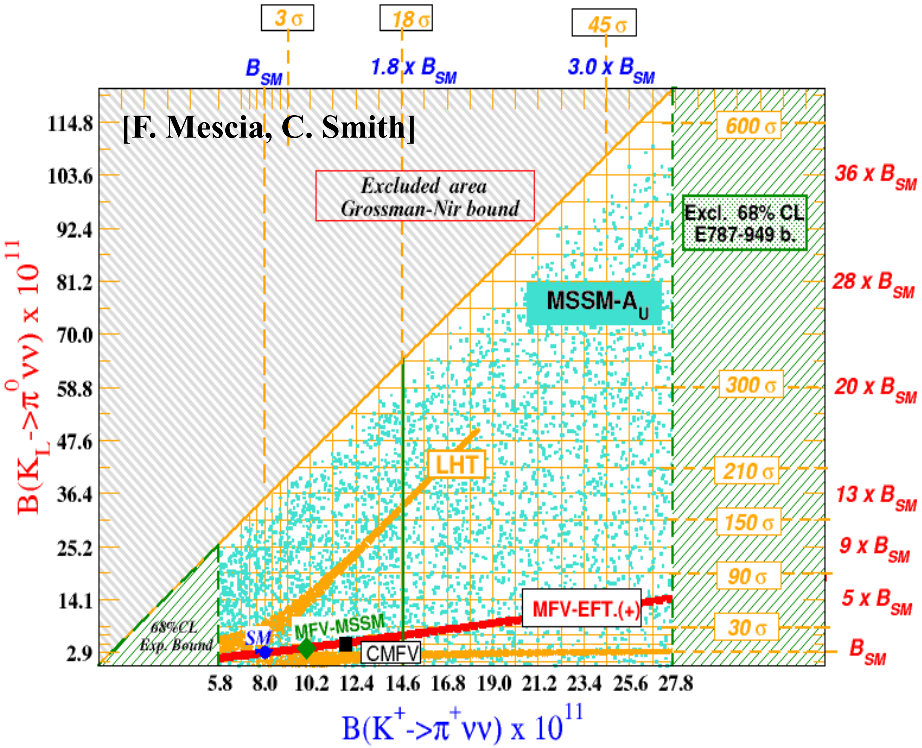
- **SM predictions extremely clean:**
  - Short Distance dynamics dominated, hadronic matrix element from semileptonic decays
  - Main error from experimental uncertainty on CKM matrix elements
  - Clean V_{td} dependence: the BR measurement determines V_{td} without input from Lattice QCD

BR × 10^{10}	SM Prediction	Experiments
$K^+ \to \pi^+ \nu \bar{\nu}$	**0.781 ± 0.075 ± 0.029** [1]	**1.73 + 1.15 – 1.05** [2]
$K^0 \to \pi^0 \nu \bar{\nu}$	**0.243 ± 0.039 ± 0.006** [1]	**< 260** [3]

[1] Brod, Gorbahn, Stamou: PRD83(2011) 034030, arXiv 1009.0947
[2] BNL E787/E949: PRL101 (2008) 191802, arXiv 0808.2459
[3] KEK E391a: PR D81 (2010) 072004, arXiv 0911.4789

K→ π ν $\bar{\nu}$ decays beyond SM

Rare K decays are highly CKM suppressed → leave more chance to NP

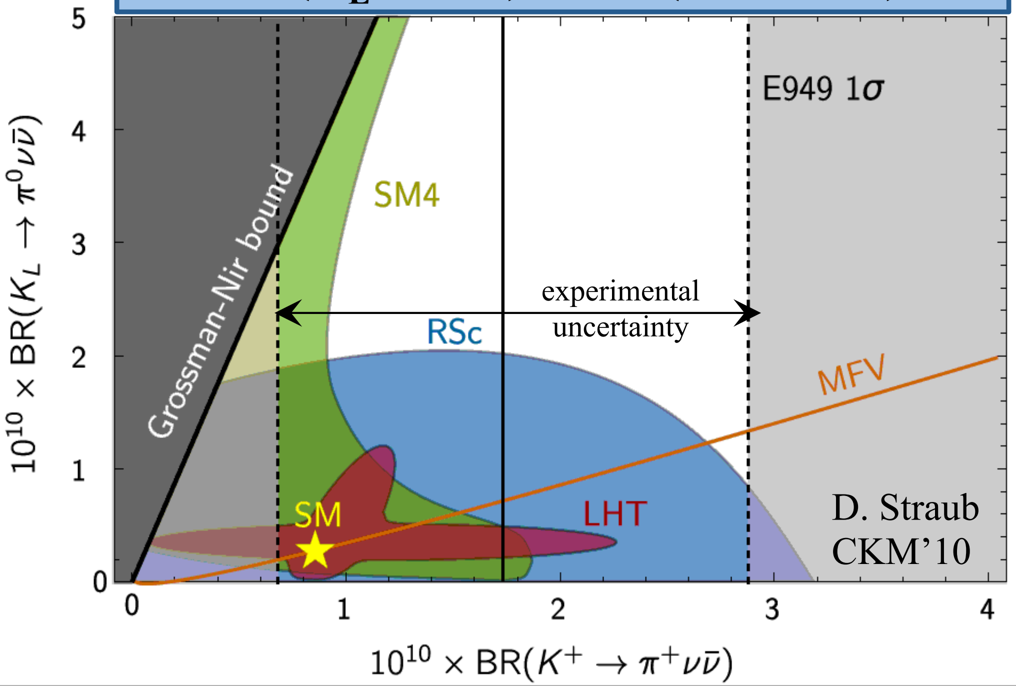


Several SM extensions predict sizeable deviations for the BR wrt SM

Possibility to distinguish among different models :

Chargino / H± loops (MSSM at low/large tanβ),
R-parity violation (non MFV), enhanced EW Penguins,
Little Higgs, extra dimensions, 4th generation, ...

BR($K_L\to\pi^0\nu\nu$) vs BR($K^+\to\pi^+\nu\nu$)



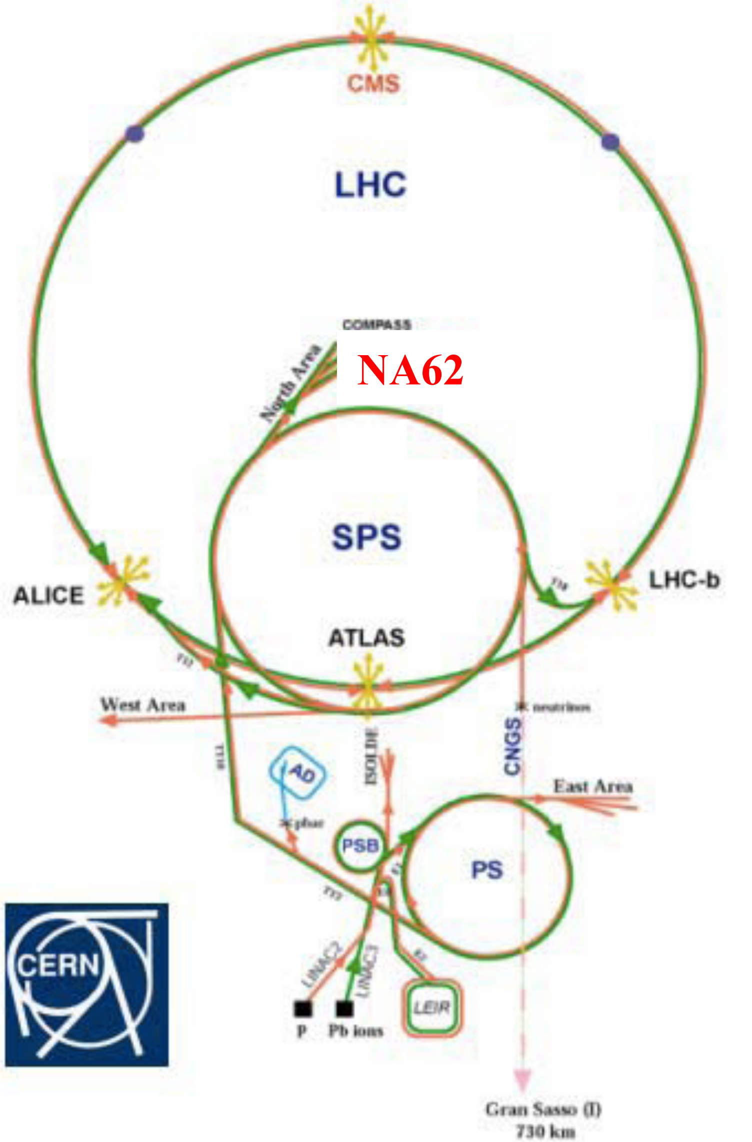
Concrete NP models predicting high deviations from MFV

Randall-Sudrum**, **Littlest Higgs with T-parity,** **SM 4th generation

The NA62 experiment @ CERN

ECN3 hall (same as NA48)

CERN North Area



The NA62 Collaboration

Birmingham, Bratislava, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain, Mainz, Merced, Moscow, Naples, Perugia, Pisa, Protvino, Rome I, Rome II, San Luis Potosi, SLAC, Sofia, Turin

NA62 Experimental Principles

- **GOAL:** **10% precision measurement of the BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)**
  - ★ **O(100) $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events**
  - ★ **O(%) Systematic error**

- **REQUIREMENTS:**

➔ Statistics

- BR(SM) ~ 7.8×10^{-11}
- Acceptance: 10%
- K^+ decays: 10^{13}

➔ Systematics

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

Statistics ⇓ **Kaon intensity & Signal efficiency** ⇓ **High momentum K^+ beam**

Systematics ⇓ **Signal purity & detector redudancy** ⇓ **Decay in-flight technique**

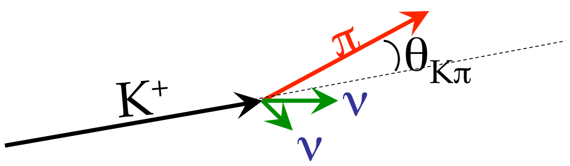
NA62 Experimental Technique

Very challenging experiment:

- Weak signal signature: **$BR_{SM} \sim 7.8 \times 10^{-11}$**
- Huge **background from all K^+ decays**

Kaon decay in-flight technique + High Momentum beams

- Advantages
  - Easy to have high intensity beam
  - Easy to veto higher energy photons
- Disadvantages:
  - Long detector and decay region
  - Event by event measurement of the kaon momentum
  - Unseparable hadron beam



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

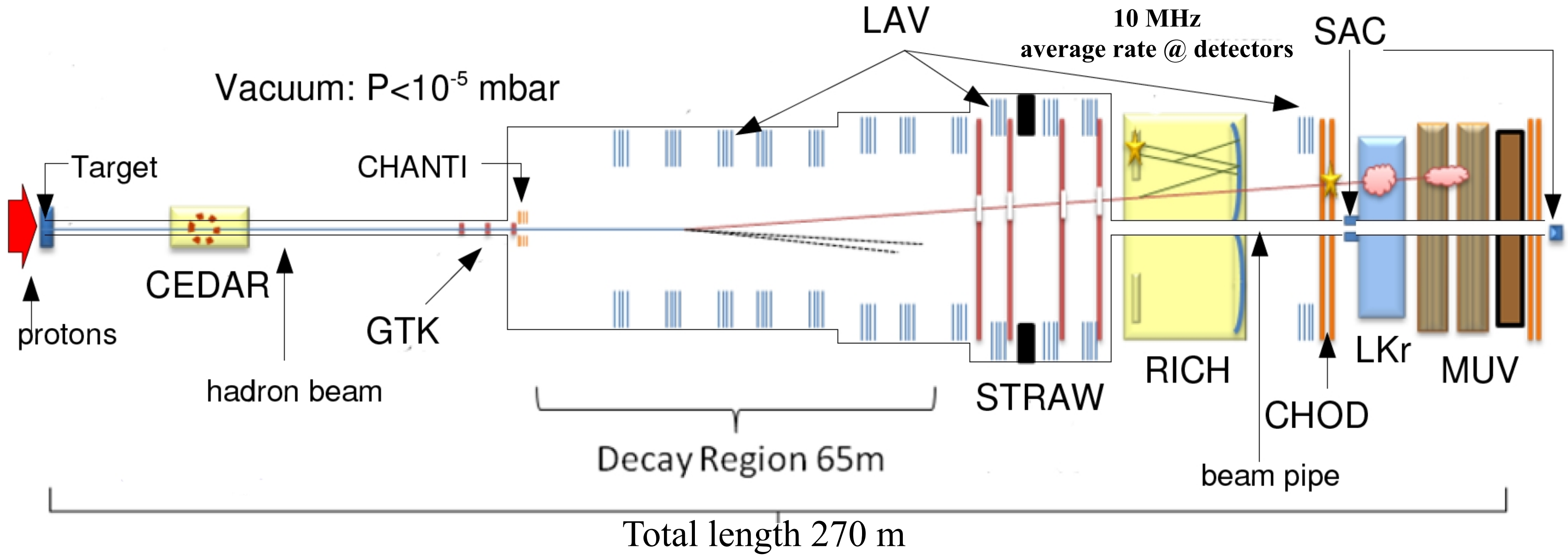
Key points:

- ✓ Kinematic reconstruction
- ✓ Precise Timing
- ✓ Particle Identification
- ✓ Vetos

Decay	BR
$\mu^+\nu$ ($K_{\mu2}$)	63.5%
$\pi^+\pi^0$ ($K_{\pi2}$)	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0e^+\nu$ (K_{e3})	5.1%
$\pi^0\mu^+\nu$ ($K_{\mu3}$)	3.3%
$\pi^+\pi^0\pi^0$	1.8%
$\mu^+\nu\gamma$ ($K_{\mu2\gamma}$)	0.62%
$\pi^+\pi^0\gamma$	2.7×10^{-4}
$\pi^+\pi^-e^+\nu$ (K_{e4})	4.1×10^{-5}
$\pi^0\pi^0e^+\nu$ (K_{e4}^{00})	2.2×10^{-5}
$e^+\nu$ (K_{e2})	1.5×10^{-5}
$\pi^+\pi^-\mu^+\nu$ ($K_{\mu4}$)	1.4×10^{-5}

+ accidental charged particles (beam particle interactions)

Detector Layout



Primary SPS beam

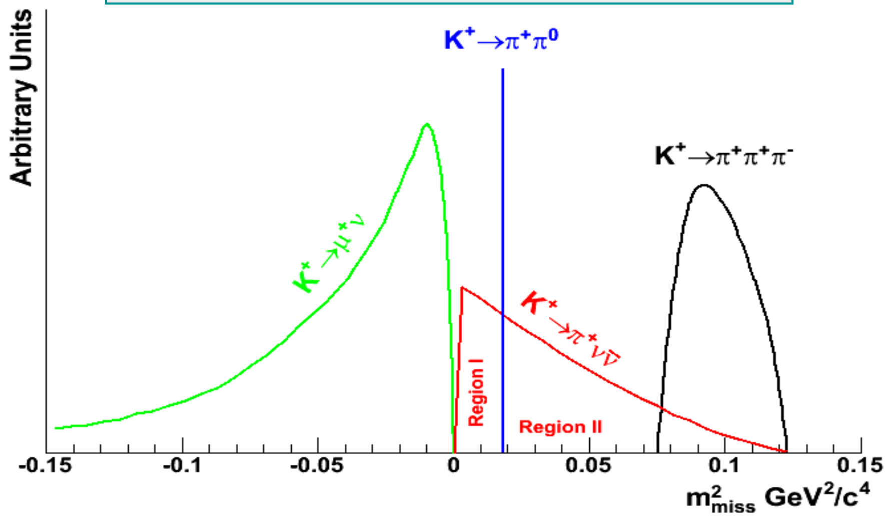
- P proton = 400 GeV/c
- Proton/pulse 3×10^{12} (×3 NA48/2)
- Duty cycle 4.8/16.8 s

Secondary beam

- p_K = 75 GeV/c (ΔP/P ~ 1.1%)
- p/π/K (K^+ ~ 6% , positron free)
- Beam acceptance = 12 μstr (×25 NA48/2)
- Area @ beam tracker = 16 cm^2
- Integrated average rate = 750 MHz
- K^+ decays / year = 4.5×10^{12}

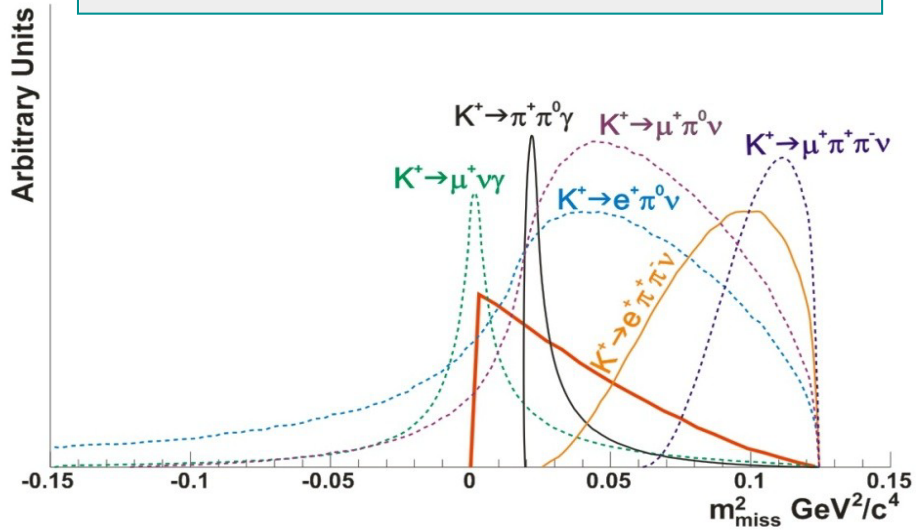
Kinematic & Backgrounds

92% constrained by kinematics



- $m^2_{miss} = (P_K - P_\pi)^2$ defines low bkg signal regions separated by $K^+\to \pi^+\pi^0$ (I and II)

8% not constrained by kinematic



- Span across the signal region: rejection must rely on Veto and Particle ID

- Important to have **high resolution** m^2_{miss} reconstruction
- Need to measure precisely **kaon and pion momenta**
- Keep **multiple scattering** as low as possible

(low mass/high resolution trackers, tracking in vacuum)

Gigatracker (Kaon)

Straw chambers (Pion)

- Suppress $\mathbf{K^+\to \pi^+\pi^0}$ bkg (20.7%)
- Reject offline decays with γ
- $\mathbf{K^+}$ identification in hadron beam
- $\mathbf{10^{-3}}$ π-μ mis-id probability

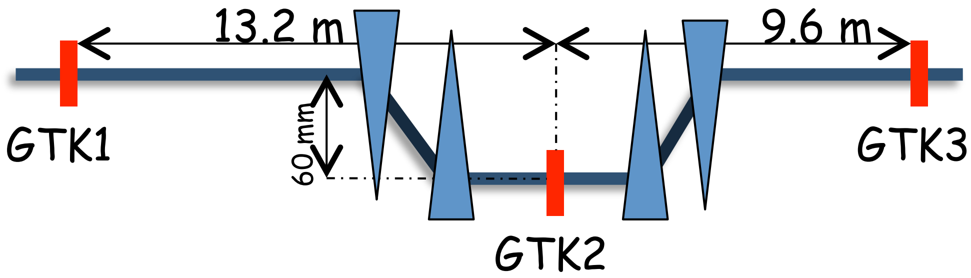
γ/μ Veto

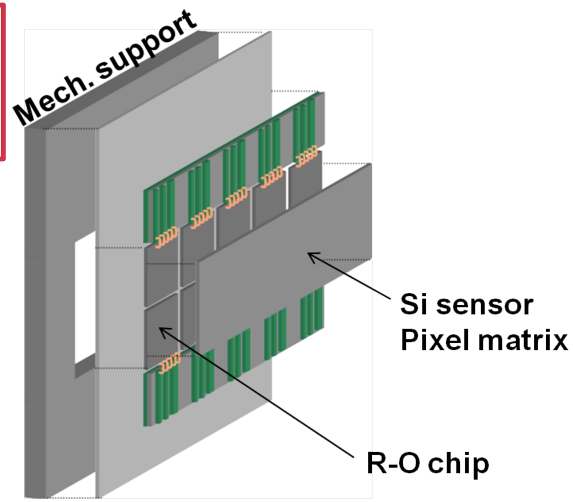
$\pi/\mu/e$ Separation

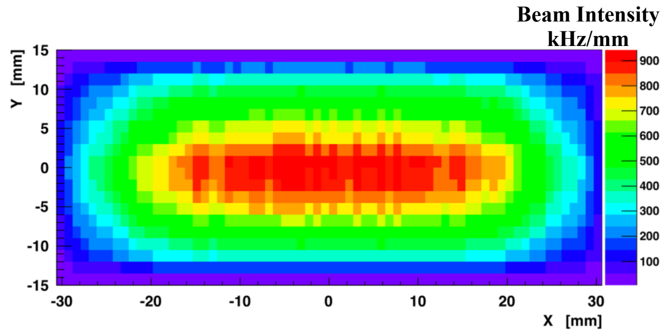
1) Tracking: Gigatracker

The Beam spectrometer: to measure time, coordinates and momentum of individual particles in a **800 MHz** beam

★ **Three Si-pixel stations before the decay volume**







- **geometry matching the beam shape**
- **high space resolution 300x300 μm pixels**
- **excellent time resolution (achieved in test beams)**
- **thin detector → 200 μm sensor + 100 μm readout chip (~ 0.5%X/X_0 per station)**
- **18000 pixels, 150 kHz rate per single pixel in the central part**
- **mounted in vacuum to avoid additional material in the beam path**

◆ $\sigma(t) \sim 150$ ps on single track (test beam)

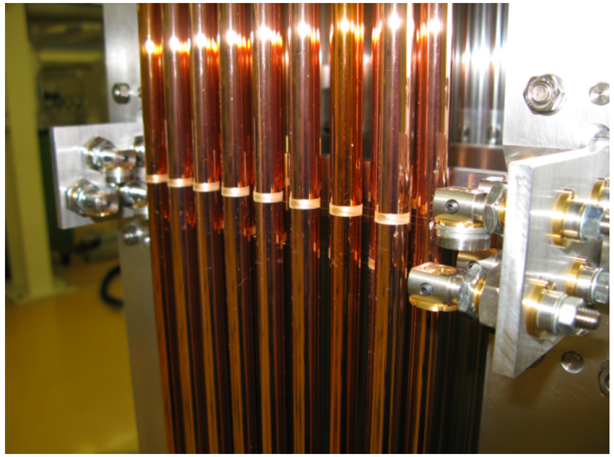
◆ $\sigma(P_K)/P_K \sim 0.2\%$

◆ $\sigma(\theta_K) \sim 16$ μrad

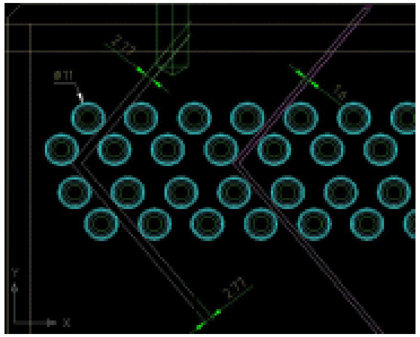
1) Tracking: Straw Spectrometer

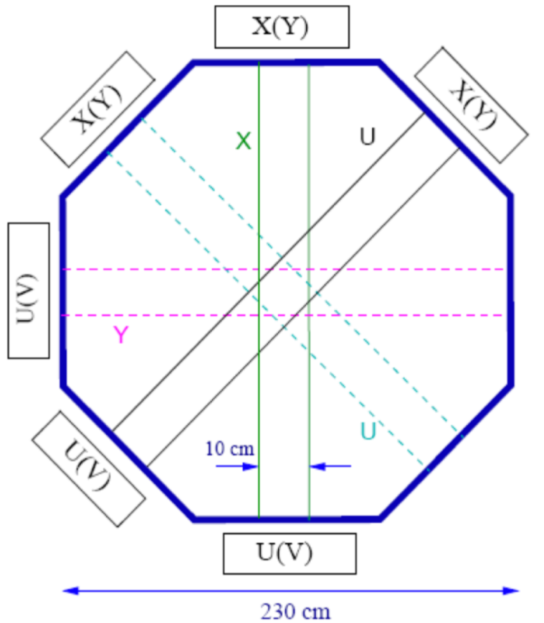
The Downstream Tracker: to measure coordinates and momentum of charged particles originating from decay region with **$\delta p/p < 0.5\%$**

- 4 straw chambers in vacuum
- +1 magnet (256 MeV/c p_t kick)
- 4 views per chamber (XYUV)
- 4 staggered layers of tubes per view
- 2.1 m long, 9.6 mm Ø mylar tubes
- total $X/X_0 \sim 0.1\%$ per view
- central "hole" (6 cm radius)
- operation in a 10^{-6} mbar vacuum



Full length prototype built and tested in vacuum at SPS@CERN in 2007 and 2010



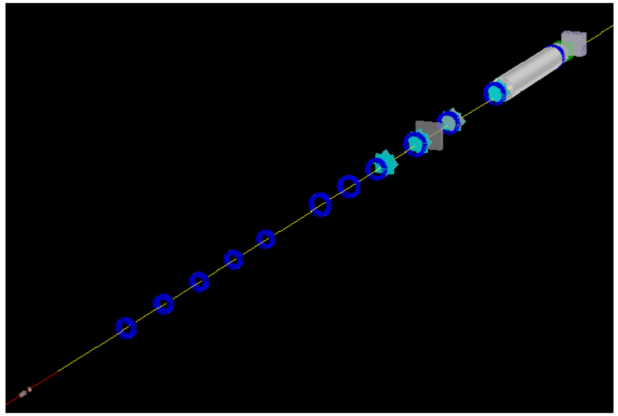


- **$\sigma(P_\pi)/P_\pi \sim 0.3\% \oplus 0.007\% {*} P_\pi$ (GeV/c)**
- **$\sigma(dX/dZ)/(dX/dZ) \sim 45\text{-}15\ \mu$rad**

Expected rejection power: 10^4 ($K \rightarrow \pi\pi^0$), 10^5 ($K \rightarrow \mu\nu$)

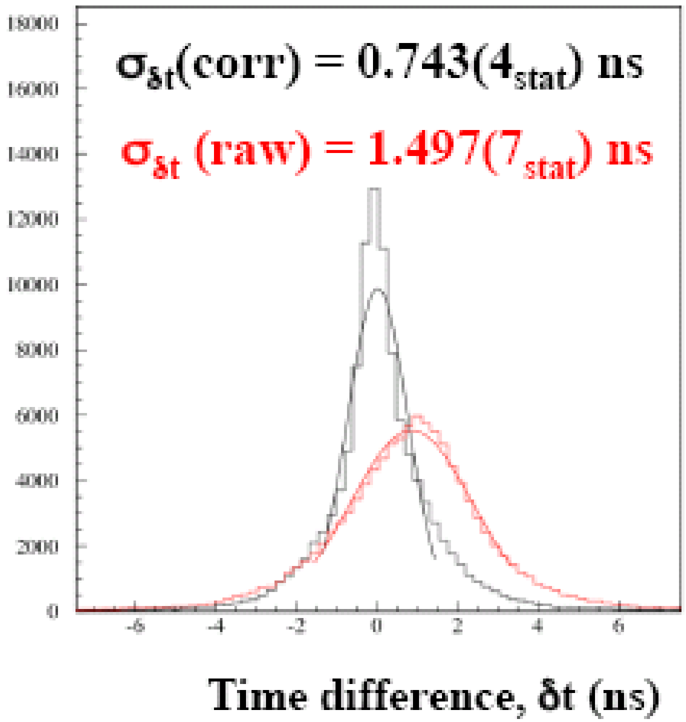
2) Veto: LAV

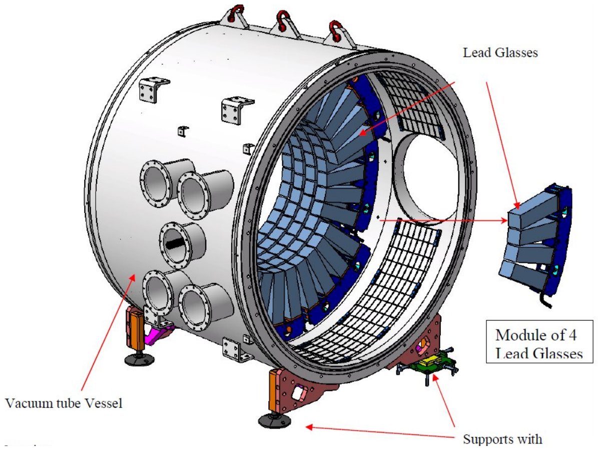
Large angle (**8.5-50 mrad**): inefficiency $<10^{-4}$ for 100 MeV $< E_\gamma < 35$ GeV



- 12 rings along the decay region (in vacuum)
    - 5 staggered rings per station
- Full angular coverage in the 8.5-50 mrad range
- Total depth of 29 to 37 X_0, particles traverse $> 20\ X_0$
- OPAL calorimeter lead glass reused: > 2500 cristals in total

- Block tested at BTF@Frascati:
    - inefficiency $< 10^{-4}$ for 471 MeV e^+
- Tested in vacuum at CERN
- Time resolution: ~ 700 ps
- 5 LAV installed on the blue tube

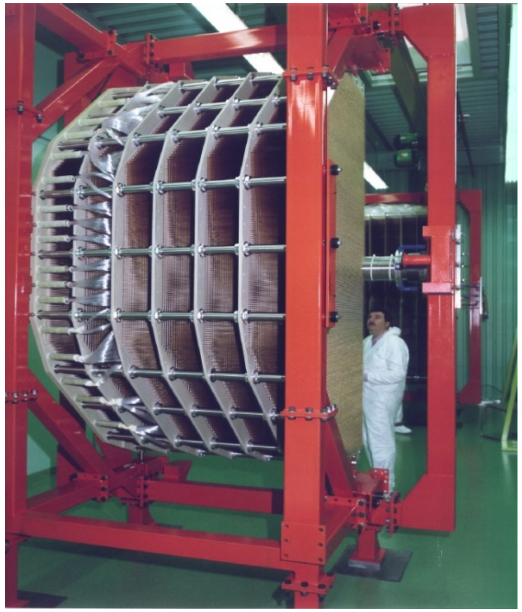




2) Veto: LKR

Medium angle (1-8 mrad): inefficiency $<10^{-5}$ for $E_\gamma > 10$ GeV

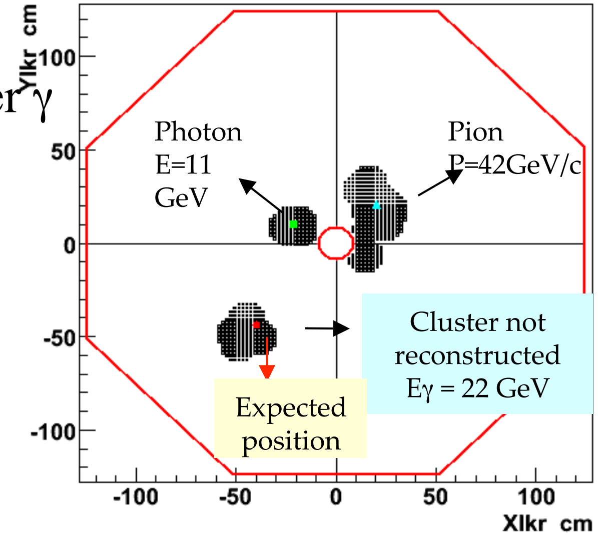
- Liquid Krypton NA48 electromagnetic calorimeter
- Quasi homogeneous ionization chamber
- More than 13000 channels, 2x2 cm^2 granularity
- Depth 1.25 m, 27 X_0
- Excellent energy resolution
- Very good time resolution: 100 ps
- New readout electronics: 14 bits 40 MHz ADC with large buffers



Performance as photon veto

- measured using NA48 data @75 GeV
- $K^+ \rightarrow \pi^+ \pi^0$ selected using kinematics only
- π^+ and lower energy γ are used to predict the position of the other γ

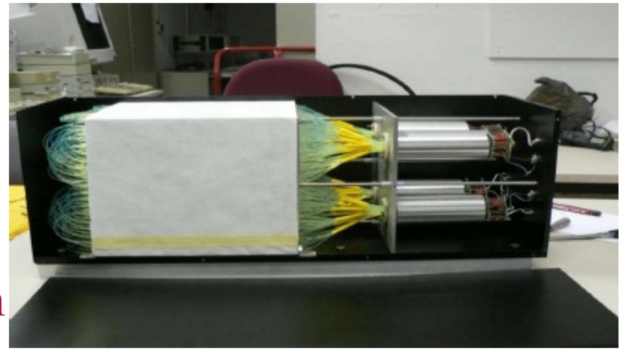
Energy(GeV)	Inefficiency
2.5-5.5	10^{-3}
5.5-7.5	10^{-4}
7.5-10	5×10^{-5}
>10	8×10^{-6}



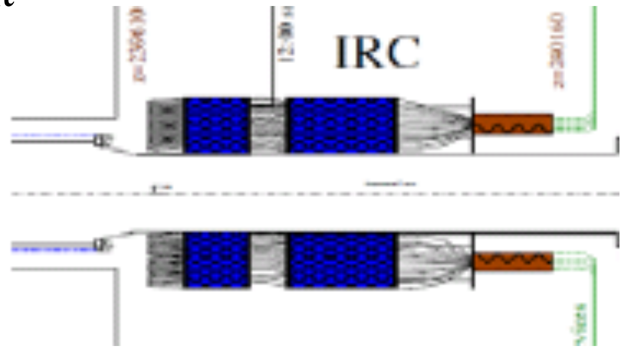
2) Veto: SAC, IRC and CHANTI, CHOD

Small angle (<**1 mrad**): inefficiency $<10^{-3}$ for $E_\gamma > 10$ GeV

- IRC: Inner Ring Calorimeter to increase the acceptance for small angle γ in the region not covered by the LKr
  - Located around the beam pipe, in front of LKr

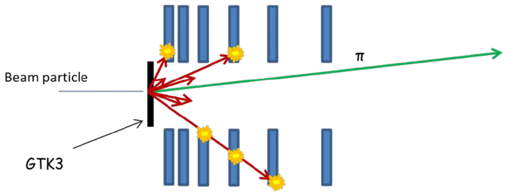


- SAC: Small Angle Calorimeter to detect γ in the beam pipe region
  - Located in the beam dump, at the very end of the experiment



- Both calorimeters of "shashlyk" type

Veto for charged particles



CHANTI required:

➔ to reduce background induced by inelastic interactions of the beam with the collimator and the GTK stations and tag beam halo muons in the region closest to the beam

➔ 6 stations, 2 layers/station, 22 triangular scintillator bars/layer read out by SiPM

CHOD Scintillator Hodoscope:

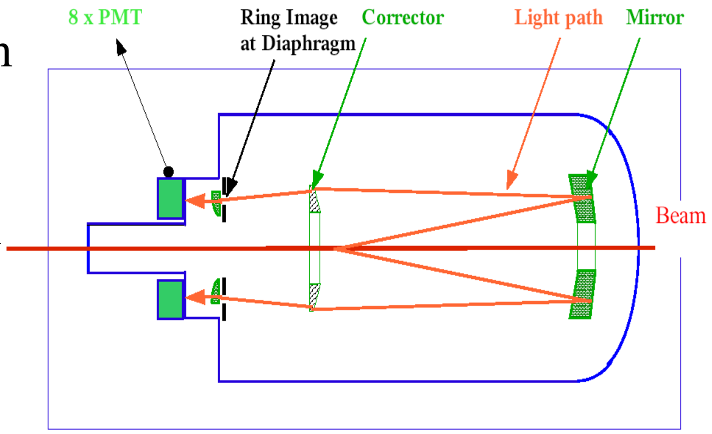
➔ to trigger on charged particles

➔ veto multiple charged particle events

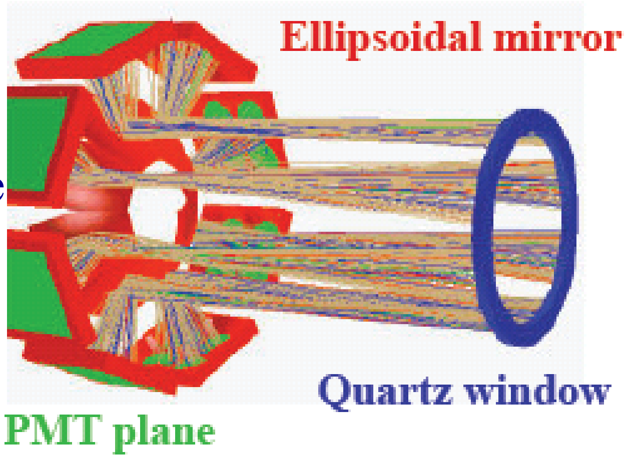
3) PID: Cedar

Differential Cherenkov counter filled with hydrogen gas

- Positive identification of Kaons in a 800 MHz hadron beam
- Excellent time resolution O(100 ps)
- Sustain rate O(MHz/mm^2)
- With 50 MHz kaon rate one must spread the photon rate on many photo-detectors (PMs)

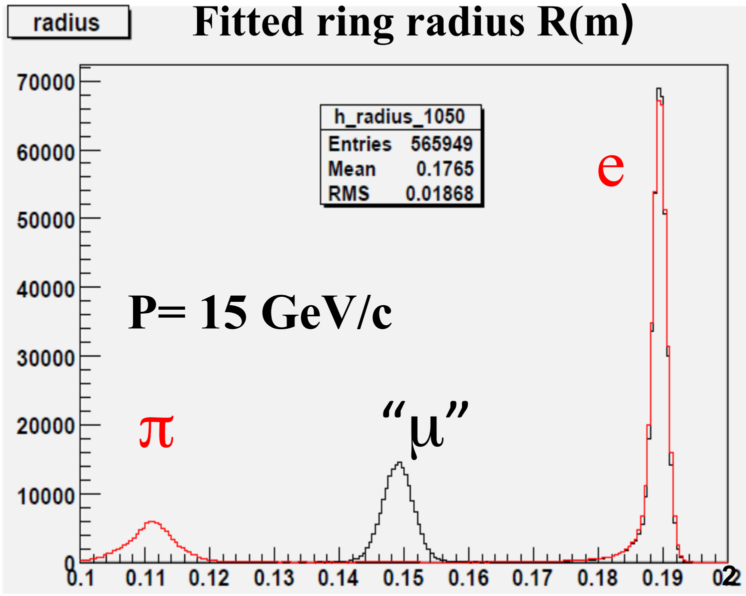


- Upgrade CEDAR built at CERN in the 70's for the SPS secondary beams
- Insensitive to pions and protons
- H_2 to minimize multiple scattering
- Nominal pressure for kaons: 3.85 bar
- New readout (PMs and electronics)
- New deflecting mirrors system to decrease the rate per single channel on the readout

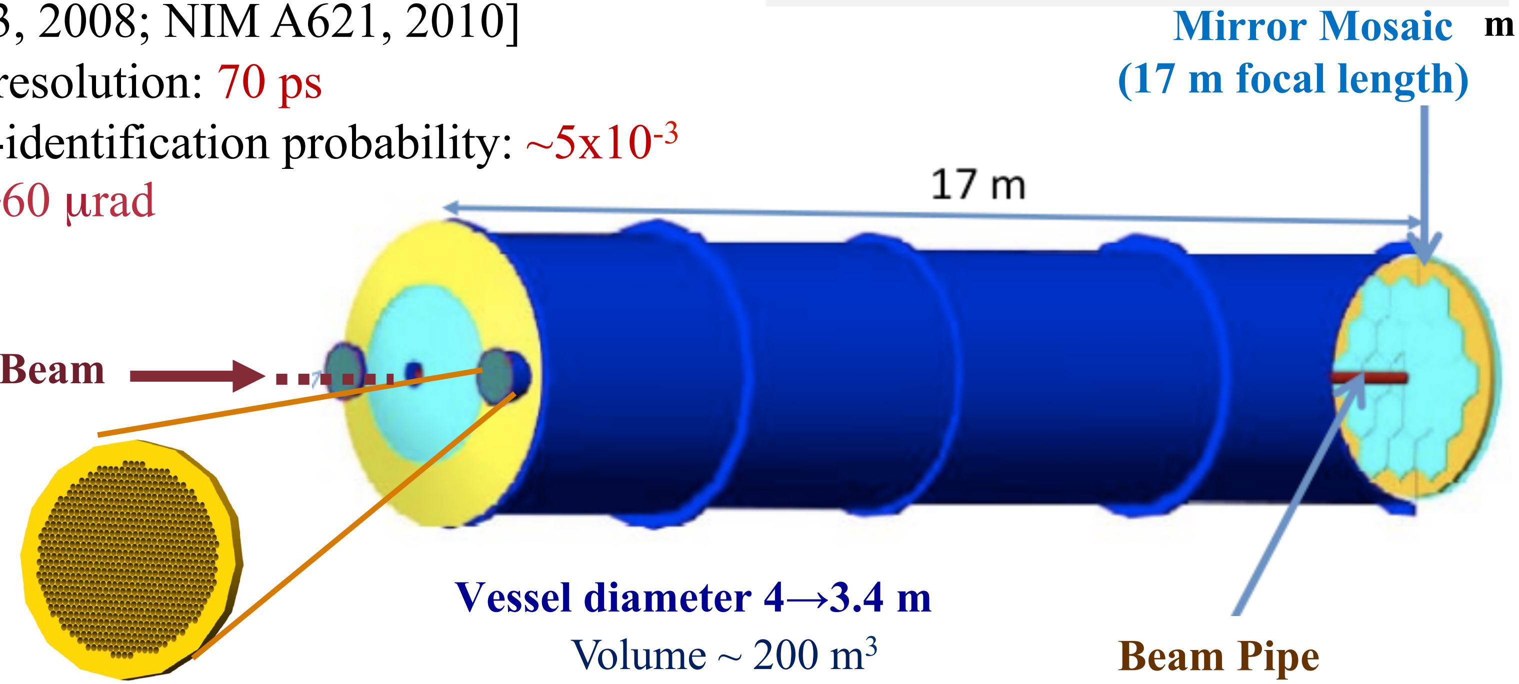


3) PID: RICH

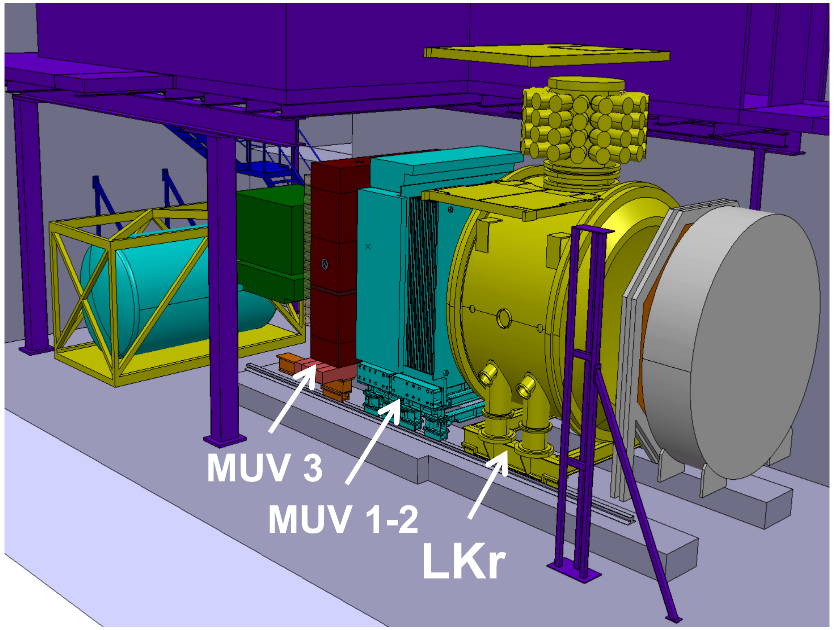
REQUIREMENTS:
- Separate **π-μ** in 15 < p < 35 GeV/c
- Measure pion crossing time with a resolution < 100 ps
- Provide a L0 trigger for charged tracks

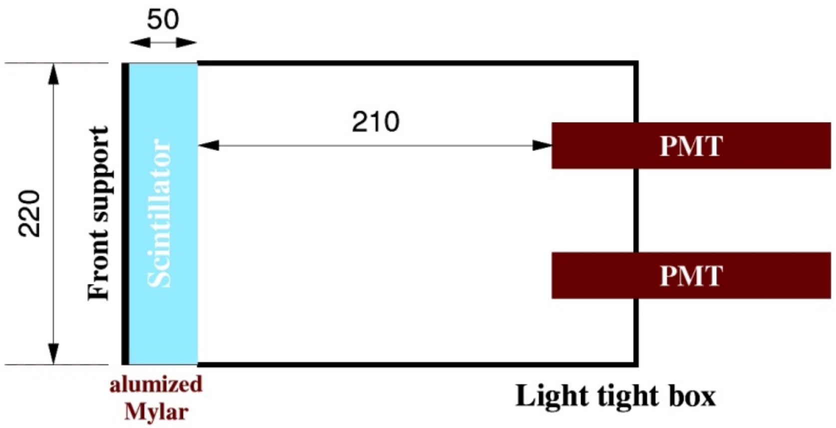


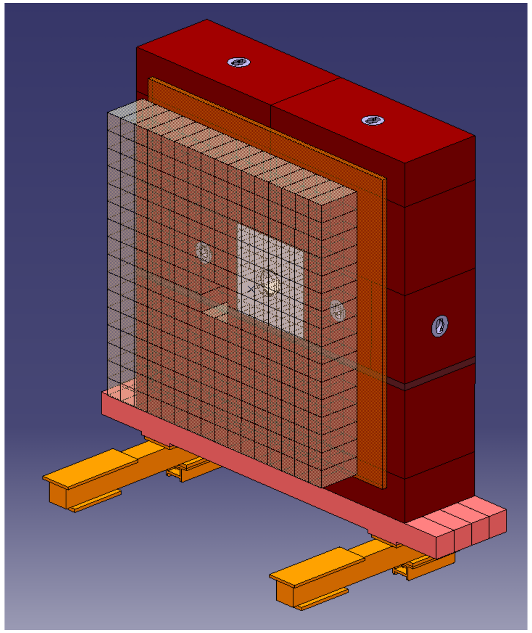
- 17 m long, 3 m in diameter
- Neon gas at atmosferic pressure
- Cherenkov light collected in two spots: 1000 PM each
- Full length prototype tested at CERN in 2007 and 2009
- **Results** [NIM A 593, 2008; NIM A621, 2010]
  - Average Time resolution: 70 ps
  - Integrated mis-identification probability: ~5×10^{-3}
  - θ_C resolution ~60 μrad



3) PID: MUV







- MUV1-2 : to reach a factor of 10^6 in muon rejection (combined with the RICH)
  - NA48 Hadron calorimeter partially reused (25 + 23 layers)
  - Iron and scintillator
- MUV3: fast muon identification plane for trigger
  - after 80 cm of iron, 5 cm thick single layer of scintillator tiles readout with 2 PMs
  - <1ns time resolution achieved in test beam, crucial to cope with 10 MHz integrated rate

TRIGGER and DAQ

Requirements:

- Reduce online 10 MHz rate/detector to 10 kHz
- High data bandwidth
- No zero suppression (for candidate events)
- Very good time resolution to avoid random veto (< 1%)

Solution:

- Integrated Trigger + DAQ
- Completely digital data stream from FE to TDAQ
- Fully monitored system
- Uniformity for most subdetectors
- Custom hardware minimized (offline reproducibility)
- L0 hardware, L1/L2 software
- Flexibility (for additional physics program)

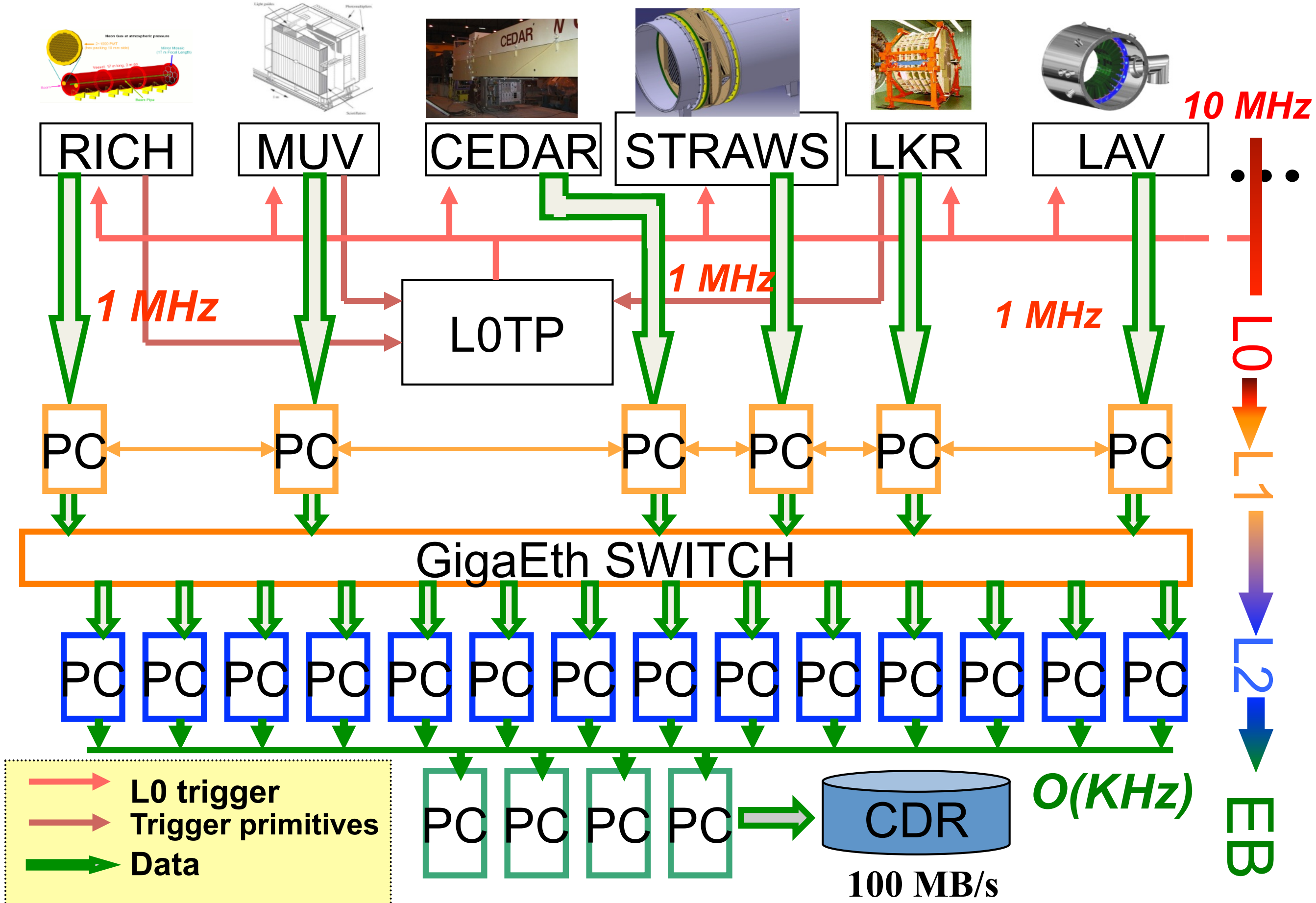
On-line sub-nanosecond time resolution of Veto detectors and RICH crucial for high efficiency (>95%)

L0:
Hardware level. Decision based on primitives produced in the RO card of detectors partecipating to trigger

L1:
Software level. "Single detector" PCs

L2:
Software level. The informations coming from different detectors are merged together

Trigger/Daq General Overview



Detector	Rate (MHz)
CEDAR	50
GTK	800
LAV (total)	9.5
STRAW (each)	8
RICH	8.6
LKR	10.5
MUV	9.2
SAC	1.5

		Input (max)	Output (max)	latency
L0	hw,sync	~10 MHz	~ 1 MHz	1 ms
L1	soft,async	~ 1 MHz	~ 100 kHz	undefined
L2	soft,async	~ 100 kHz	O(kHz)	undefined

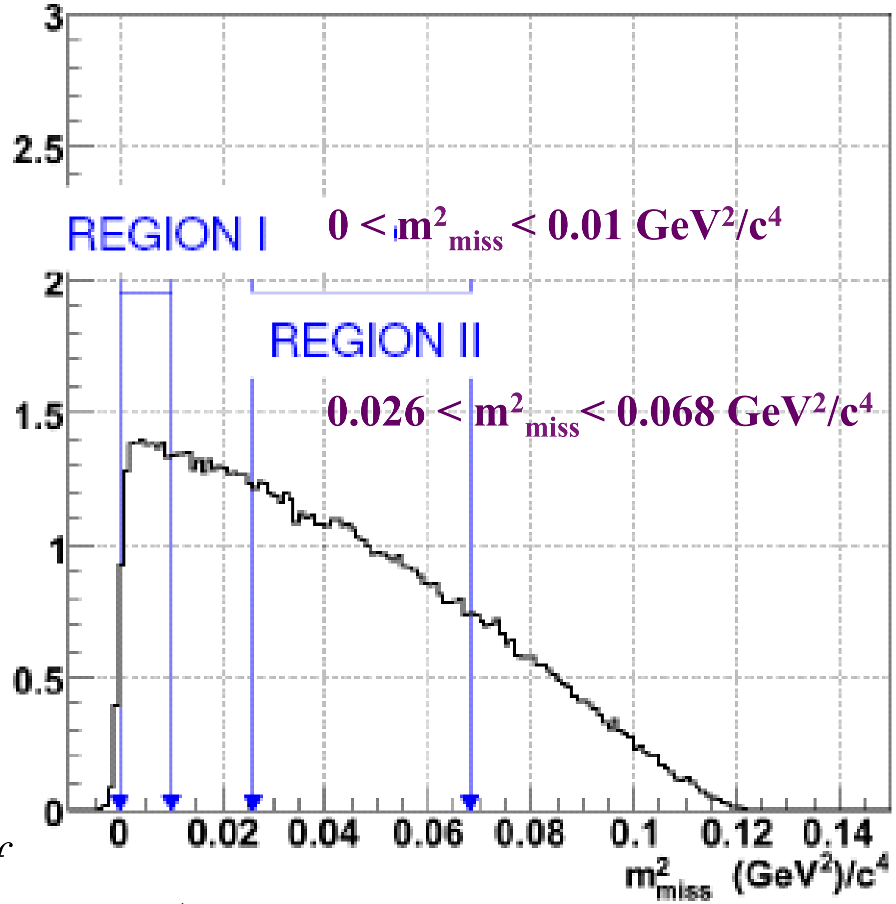
NA62 Signal Acceptance

Analysis:

- Simulation based on G3, G4, Fluka
- Main cut **$15 < P_\pi < 35$ GeV/c**
  - for RICH operational reasons
  - better photon and muon rejection

Acceptance:

- 3.5 % in region I
- 10.9% in region II
- 50% loss due to P_π cut
- expected detector inefficiencies considered



Acceptance: ~ 14.4 % (*To be reduced because of additional losses due to dead time, detector inefficiencies, ….*)

The NA62 experiment matches the goal of 10% acceptance

NA62 Sensitivity

Decay mode	Events / year
Signal: $K^+ \to \pi^+ \nu\bar{\nu}$ *(Flux = 4.8 ×10^{12} decays/year)*	55 events/year
$K^+ \to \pi^+ \pi^0$	4.3% (2.3 evts)
$K^+ \to \mu^+ \nu$	2.2% (1.2 evts)
$K^+ \to \pi^+ \pi^- e \nu$	<3% (1.7 evts)
Other 3-track decays	<1.5% (0.8 evts)
$K^+ \to \pi^+ \pi^0 \gamma$	~ 2% (1.1 evts)
$K^+ \to \mu^+ \nu \gamma$	~ 0.7% (0.4 evts)
others	negligible
Expected background	**<13.5% (7.4 evts)**

CONCLUSIONS

- The $K \rightarrow \pi\nu\bar{\nu}$ decay : precision physics complementary to high-energy approach for NP search

- **NA62:** Very challenging experiment
  - ➔ collect 0(100) events in two years to provide a 10% BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$) measurement
  - ➔ key points: high intensity beams, excellent resolutions, hermetic coverage, Particle ID

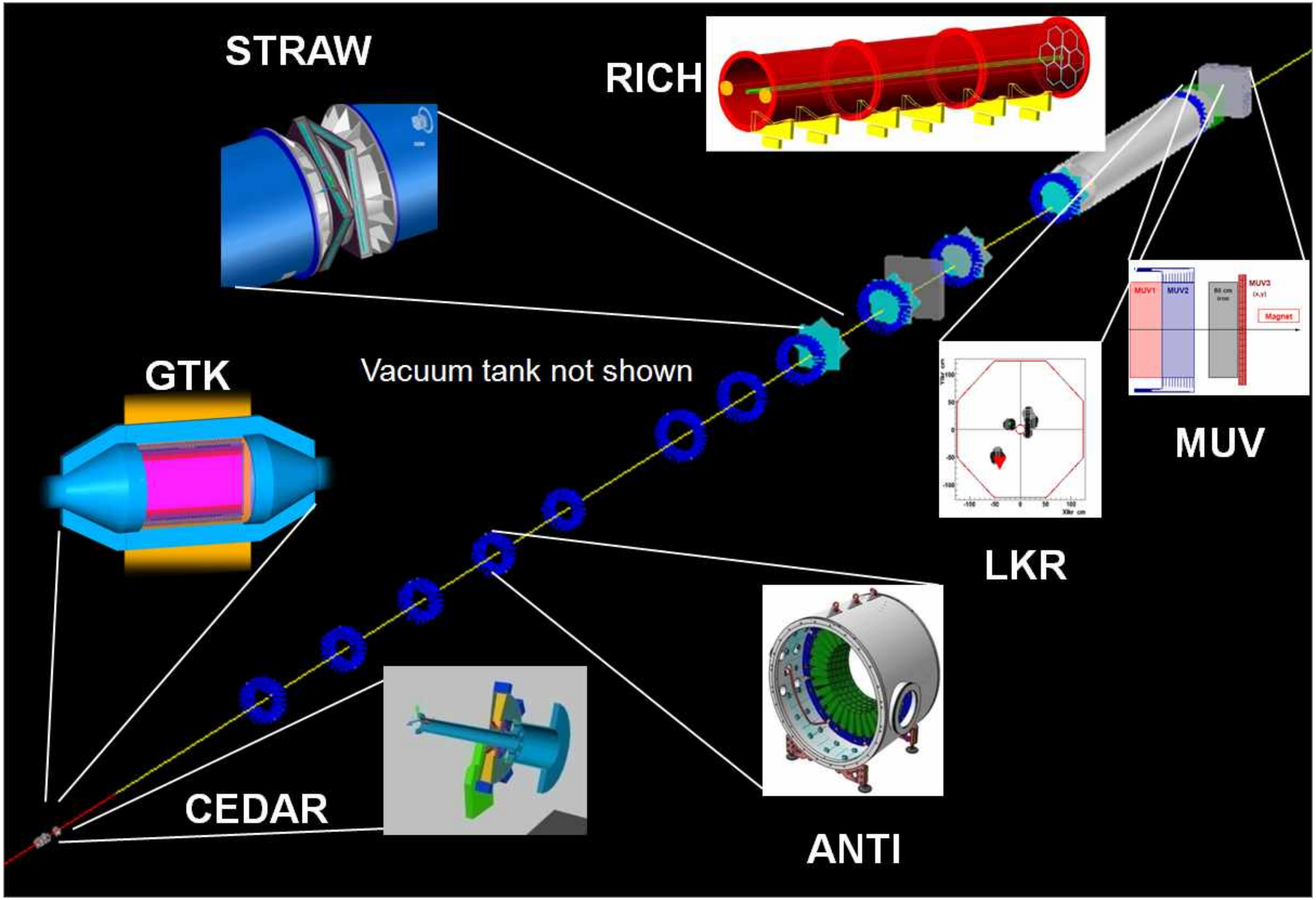
- **Schedule**
  - ➔ Construction in progress (2010-2013)
  - ➔ Dry and Technical runs in summer/falls 2012
  - ➔ Ready to take data after CERN accelerator breakdown

- **More..**

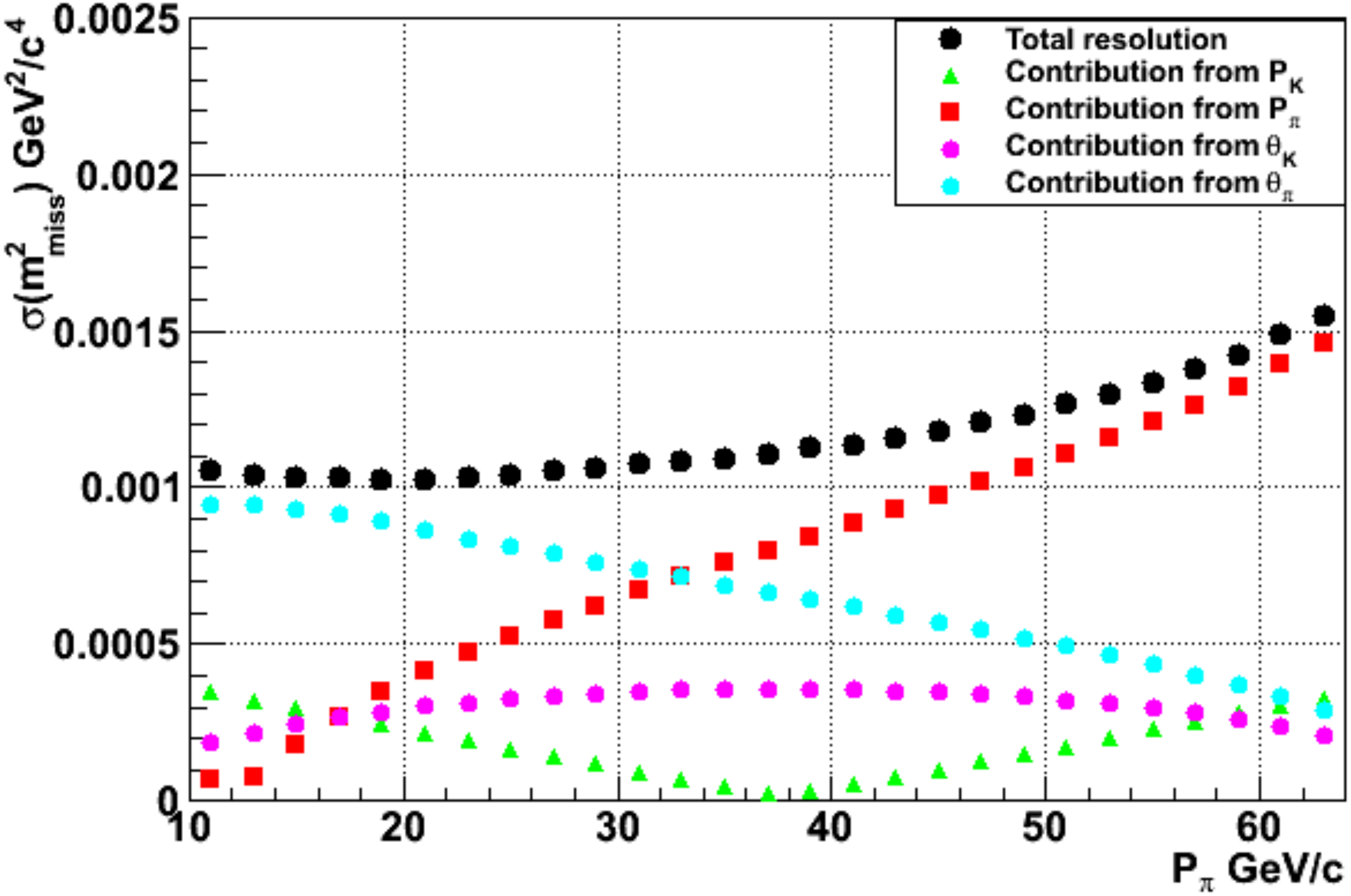
  The high performances of the detectors can also be the building blocks for a further physics program

A very rich program in the near future

SPARES


STRAW
RICH
GTK
Vacuum tank not shown
MUV
LKR
CEDAR
ANTI

Kinematic Rejection



Missing Mass Resolution

General Theme:
Maintain a good signal/background ratio
preserving the signal acceptance
as much as possible

NA62 Main Detectors

- CEDAR
  - It positively identifies the kaons before they enter the decay region. It must tag approx. **50 MHz of Kaons** and be as thin as possible. It must time-stamp the K^+ with an RMS of better than 100 ps in order to improve the association of the the parent K^+ with the daughter π^+
- Gigatracker (GTK)
  - Silicon Pixel tracker to measure direction and momentum on event-by-event basis. The beam rate is almost **one GHz** (hence the detector name…). It must be very thin to avoid too many inelastic interactions…Excellent time resolution is required to time stamp each track **(< 200 ps / hit)**
- Photon Vetoes + LKr Calorimeter
  - A large system of detectors surrounding the decay tank to suppress the π^0 background by about **8 orders of magnitude**
- Straw Tracker
  - Reconstructs the decay charged particles. To reduce the multiple scattering, this large acceptance spectrometer is housed in the vacuum tank. The overall thickness of the 16 tracking views amounts to **less than 1% X_0**
- RICH
  - Pion / Muon identification up to 35 GeV/c is achieved by means of a Ring Imaging Cherenkov Counter (RICH). It also provides the time reference to correlate the pion to the correct incoming kaon track **(100 ps or better)**
- Muon Vetoes
  - To suppress the muons at the trigger and analysis level. They consist of hadron calorimeters made of iron and plastic scintillator and a fast veto plane

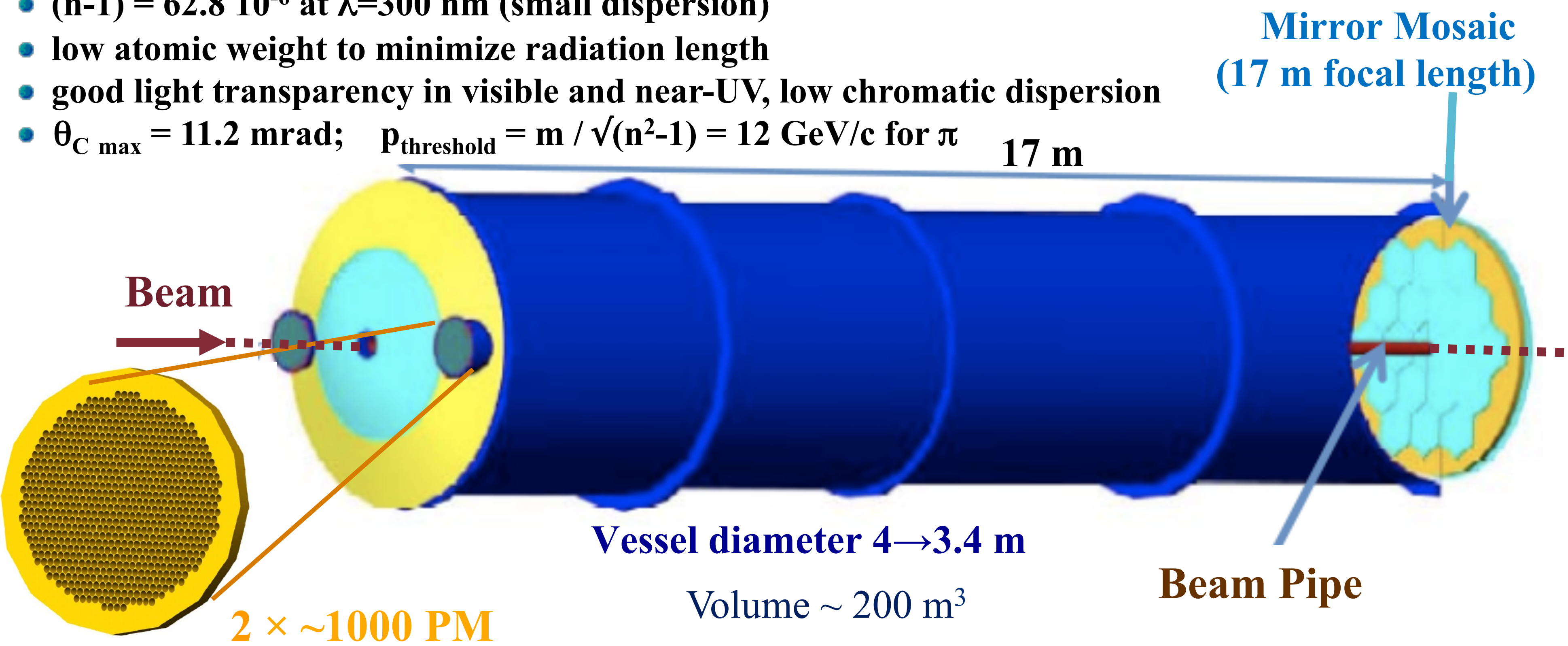
The NA62 RICH Detector

REQUIREMENTS:

- Separate π-μ in $15 < p < 35$ GeV/c with a muon suppression factor better than 10^{-2}
- Measure pion crossing time with a resolution < 100 ps
- Provide a L0 trigger for charged tracks

Radiator: Neon gas at atmospheric pressure (non-flammable):

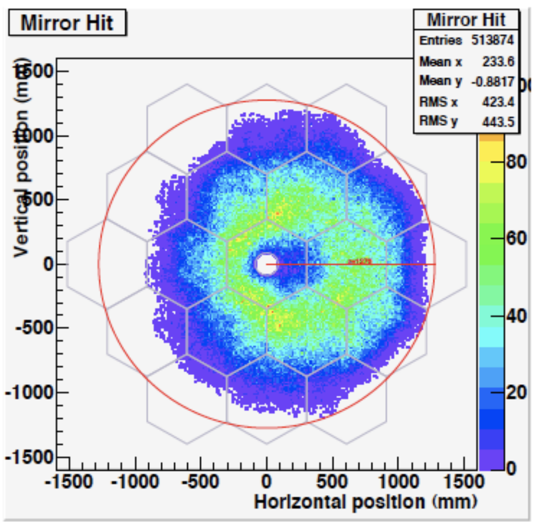
- **appropriate refractive index at atmospheric pressure**
- **$(n-1) = 62.8\ 10^{-6}$ at λ=300 nm (small dispersion)**
- **low atomic weight to minimize radiation length**
- **good light transparency in visible and near-UV, low chromatic dispersion**
- **$\theta_{C\ max} = 11.2$ mrad; $p_{threshold} = m / \sqrt{(n^2-1)} = 12$ GeV/c for π**



Mirror layout

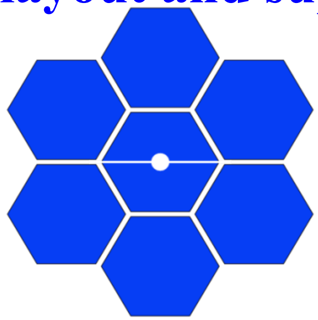
Mirrors from MARCON company

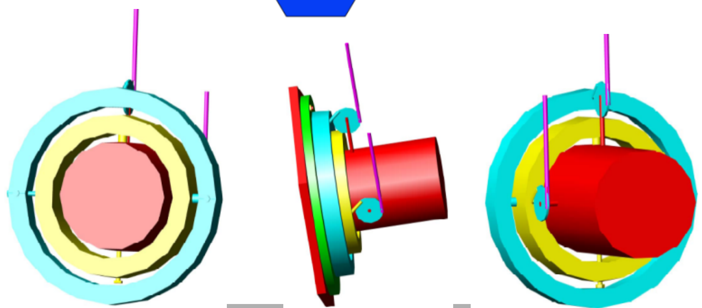
- Spherical mirrors, nominal radius of curvature 34 m (±20 cm maximum), 17 m focal length
- Glass substrate 2.5 cm thick, aluminum coat with thin dielectric film (MgF_2) deposit
- Hexagonal shape (35 cm side): 18 hexagons + 2 half hexagons (beam pipe) 3m diameter
- Average reflectivity better than 90% in 195-650 nm wavelenght range, $D_0 < 4$ mm
- Carbon fiber honeycomb structure for mirror support, piezo actuators for alignment
- Mirrors pointing toward left and right of the beam pipe (2 PM regions)
- Initial alignement with laser, check with data

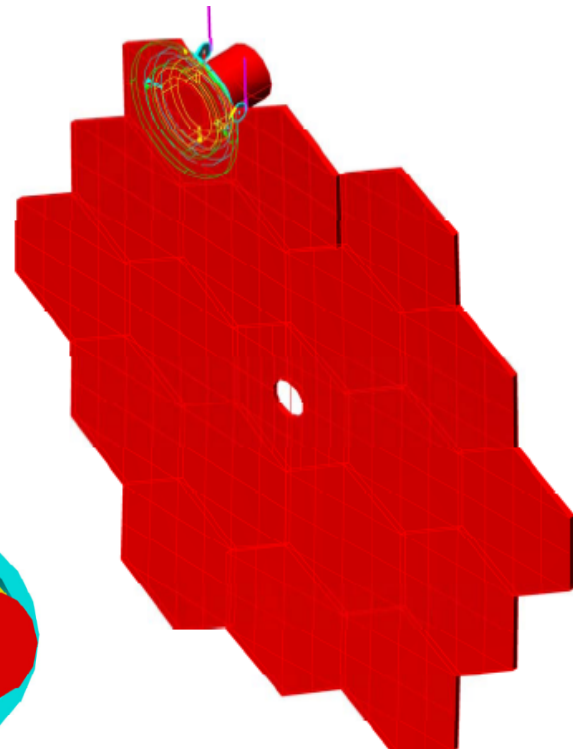


MC Simulation (Geant4): photon distribution on the mirrors (15-35 GeV/c momentum)

Mirror layout and support

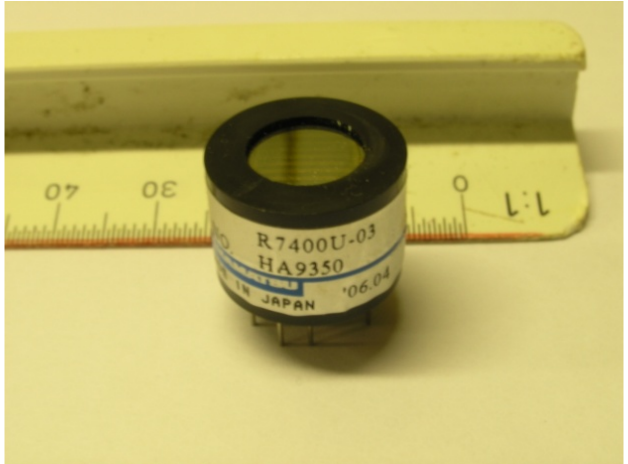




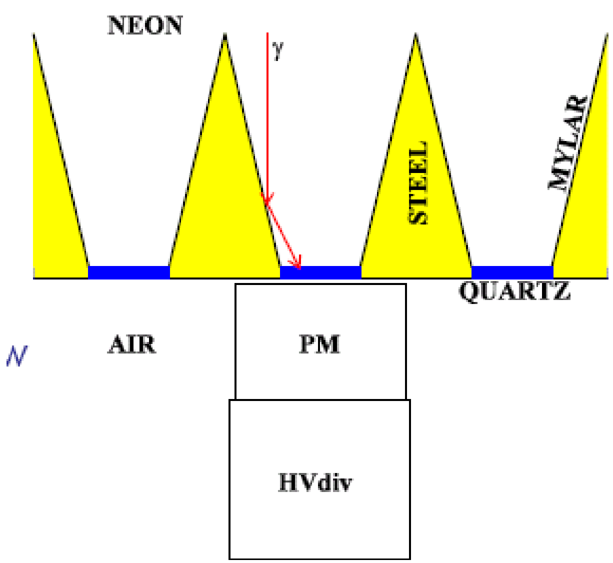


The light detection

Hamamatsu R7400 U03 Photomultiplier

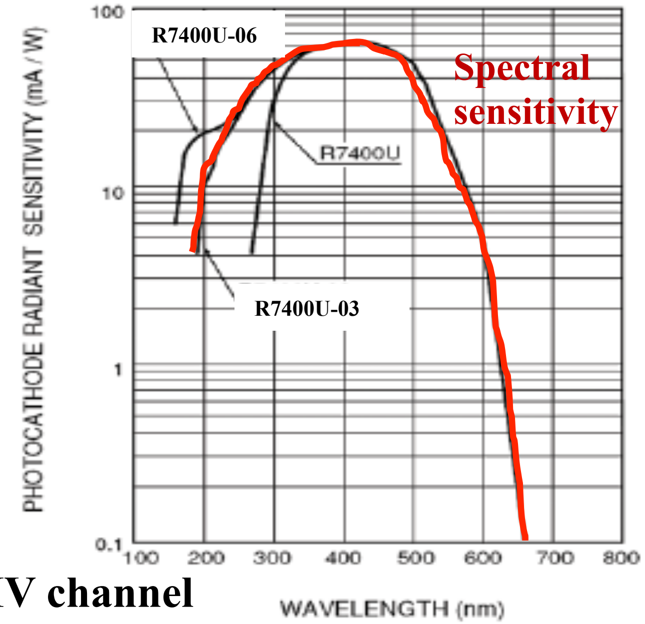


- Fast single anode photomultiplier
- Metal package tube, bialkali cathode, 8 dynodes
- UV glass window, 16 mm ϕ (photocathode 8 mm active ϕ)
- Sensitivity range 185–650 nm, 420 nm peak sensitivity
- Gain: minimum 7×10^5 @800 V ($\sim 1.5 \times 10^6$ @900 V)
- Transit time: 5.4 ns, transit time spread (FWHM): 0.28 ns
- Operating Voltage: 900 V (1000 V maximum)



Light Collection

- Winston Cones covered with aluminized Mylar foils
- 22 mm high
- 7.5 to 18 mm wide
- 1 mm thick quartz window



HV CAEN System

- 4 PMT supplied by a single HV channel
- SY1527 (16 slots), SY2527 (6 slot) main frames
- A1733N (12 ch.) and A1535S (24 ch.) board