The $K^{+} \rightarrow \pi^{+} \nu \bar{\nu}$ experiment at CERN

P326 – NA48/3 – NA62

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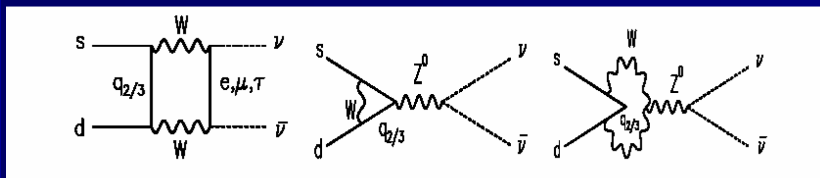
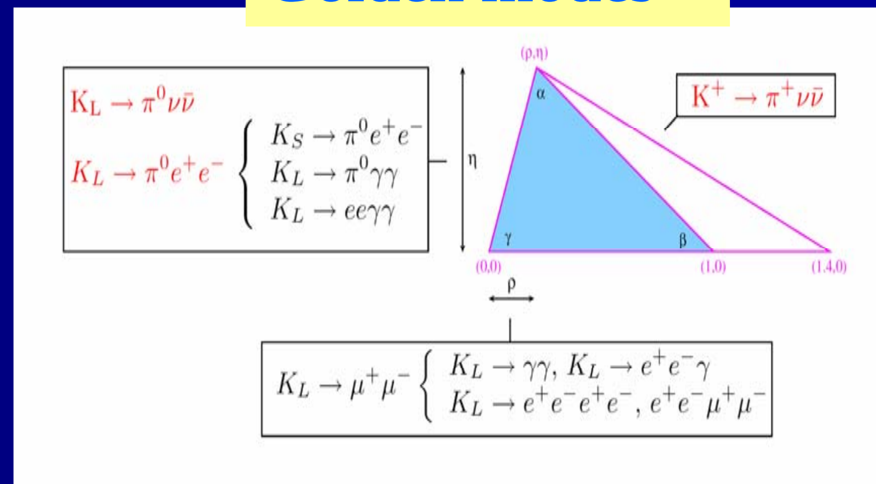
The $K^+ \to \pi^+ \nu\bar{\nu}$ decays: a clean test of SM sensitive to new physics

- Flavor Changing Neutral Current loop process: s→d coupling and highest CKM suppression



Golden modes



- Very clean theoretically: short distance contributions dominate, hadronic matrix element can be related to measured quantities ($K^+ \to \pi^0 e^+ \nu$).

SM predictions (uncertainties from CKM elements):

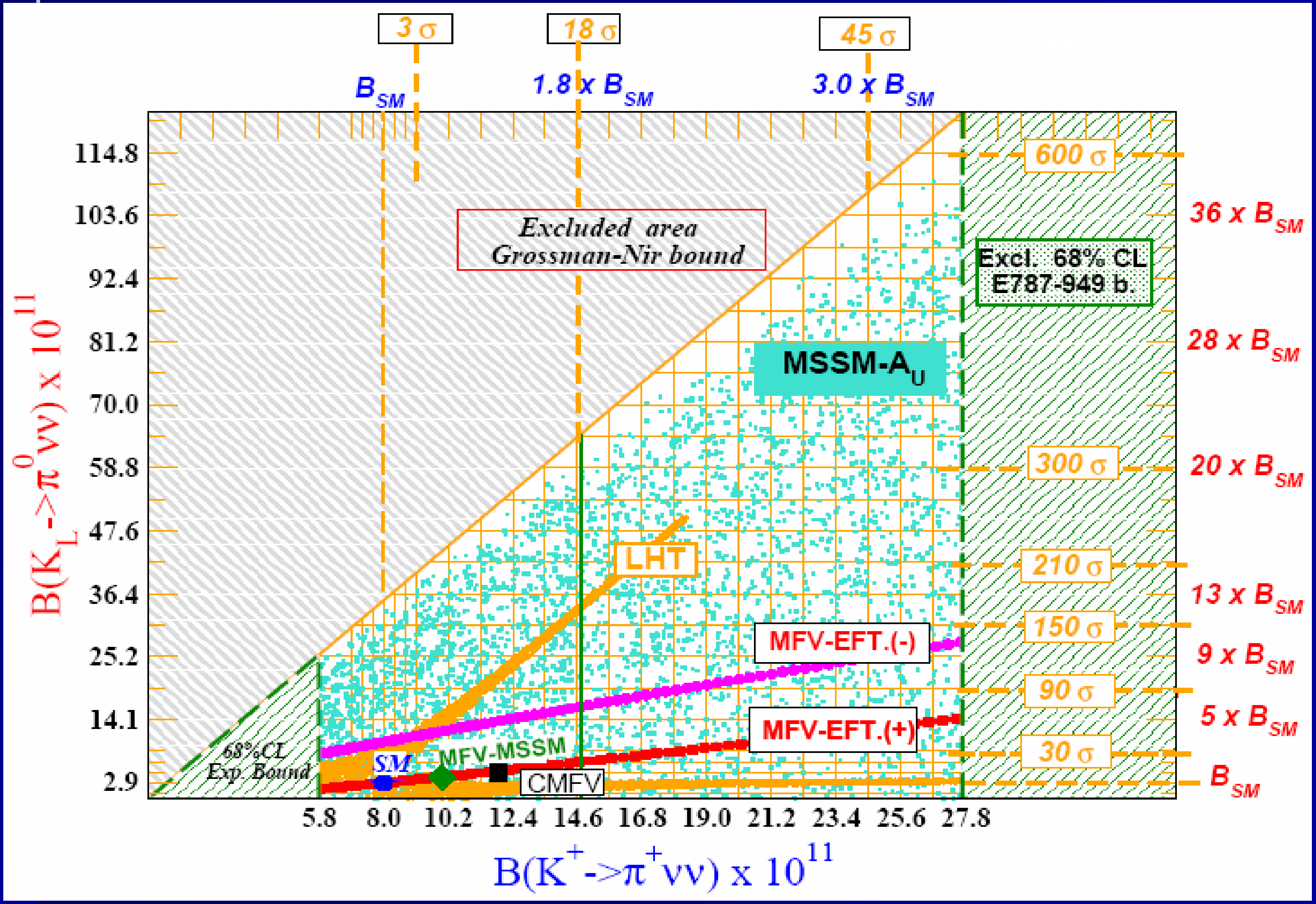
$BR(K^+ \to \pi^+ \nu\nu) \approx (1.6\times10^{-5})|V_{cb}|^4[\sigma\eta^2+(\rho_c-\rho)^2] \to (8.0 \pm 1.1)\times10^{-11}$

$BR(K_L \to \pi^0 \nu\nu) \approx (7.6\times10^{-5})|V_{cb}|^4\eta^2 \to (3.0 \pm 0.6)\times10^{-11}$

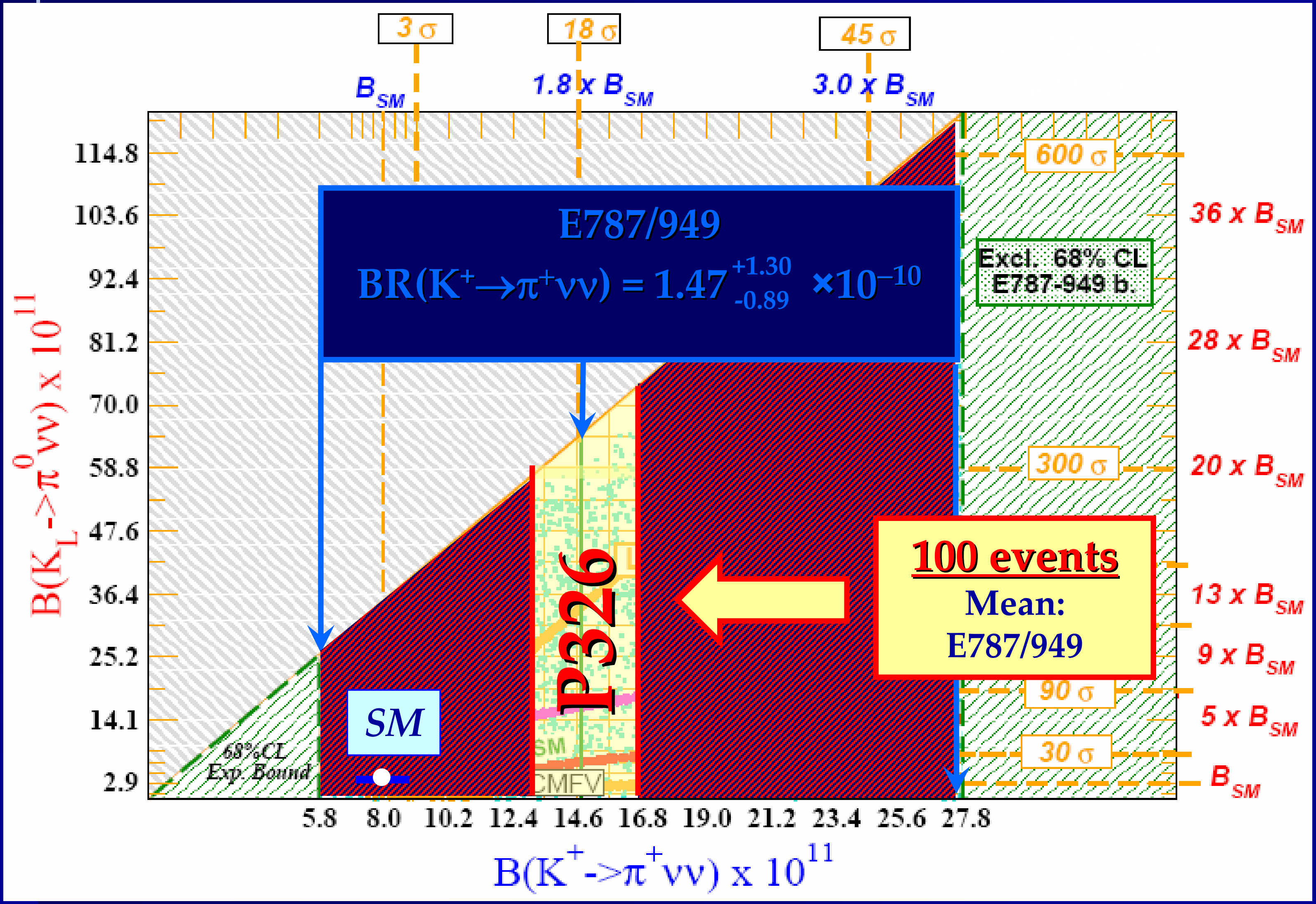
Sensitive to New Physics

Present measurement (E787/949): $BR(K^+ \to \pi^+\nu\nu) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$ **(3 events)**

Effects of new physics on $K \to \pi \nu \bar{\nu}$ decays



Setting the bar for future $K\to\pi\nu\bar{\nu}$ experiments



Proposal to Measure the Rare Decay $K^+\to\pi^+\nu\bar{\nu}$ at the CERN SPS (P326)

CERN-SPSC-2005-013
SPSC-P-326

CERN, Dubna, Ferrara, Florence, Frascati, Mainz, Merced, Moscow, Naples, Perugia, Protvino, Pisa, Rome, Saclay, San Luis Potosi, Sofia, Triumf, Turin

Located in the same hall of NA48

Schedule

- September 2005: presented at CERN SPSC
- December 2005: R&D endorsed by CERN Research Board
- Start of the Gigatracker project
- Start of test beams at CERN in 2006
- 2007: prototypes construction and test at CERN and Frascati beams
- 2008 – 2010: Technical design and construction
- 2011 - Start of data taking

Base of the NA62 (NA48/3)

O(100) $K^+ \to \pi^+ \nu\nu$ events

~ 10% background

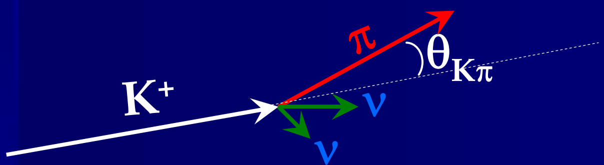
1) **Physics:** BR(SM) = 8×10^{-11}

- **Acceptance 10%**
- **K decays ~10^{13}**

→

- Kaon decay in flight technique
- Intense proton beam from SPS
- High energy K (P_K = 75 GeV/c)
  - Kaon ID

- **Kinematical rejection**



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

→

- Kaon 3-momentum: beam tracker
- Pion 3-momentum: spectrometer
- γ/μ detection: calorimeters
- Charged veto: spectrometer
- π/μ/e separation: RICH

- **Veto and particle ID**

2) **Budget:** …

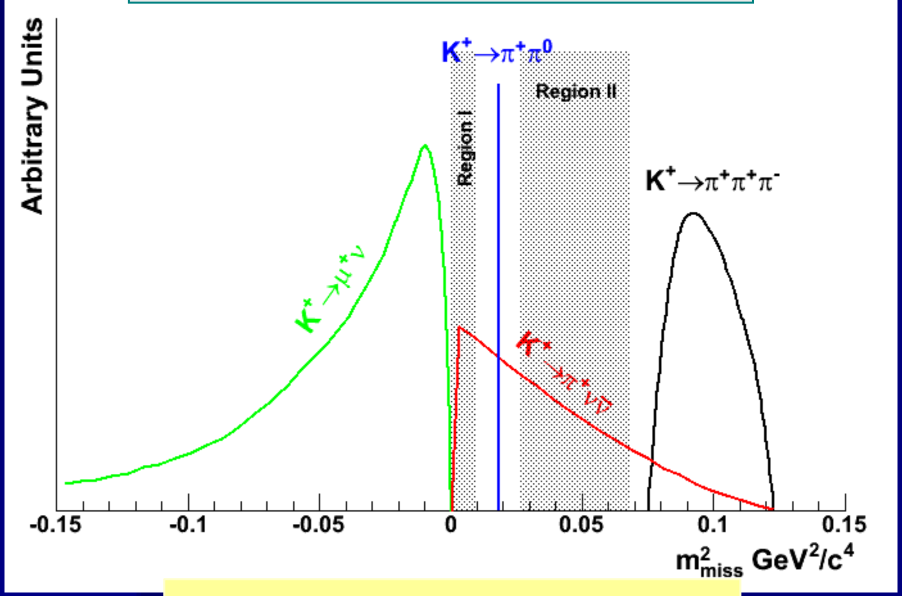
- **Be pragmatic**

→

- Use as much as possible the existing NA48 infrastructures

Backgrounds

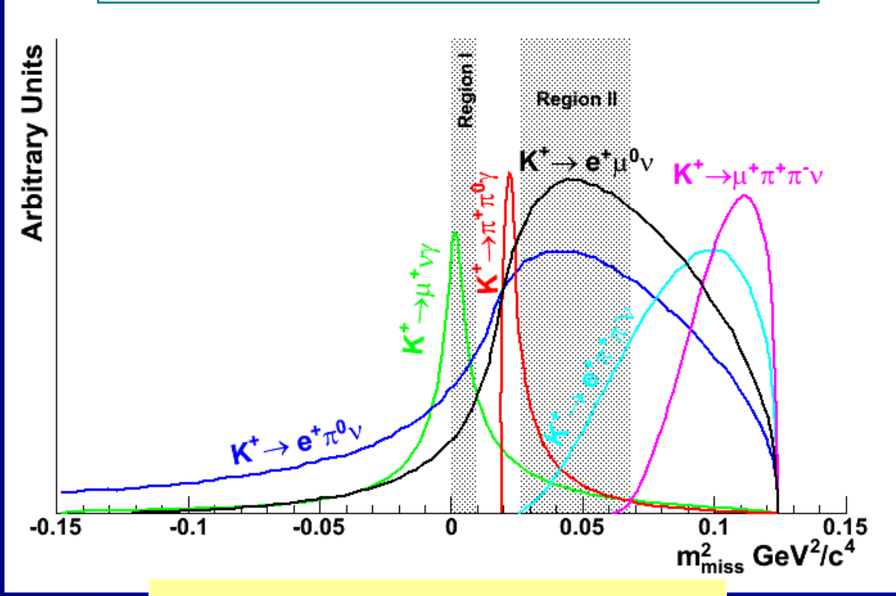
Kinematically constrained



92% of total background

- Allows us to define a signal region
- $K^+\to\pi^+\pi^0$ forces us to split it into two parts **(Region I and Region II)**

Not kinematically constrained



8% of total background

- Span across the signal region
- Rejection must rely on veotes

Largest background rejection

$K^+ \to \mu^+ \nu$ ($K_{\mu 2}$)

Largest BR: 63.4%

Need ~10^{-12} rejection factor

- **Kinematics:** 10^{-5}
- **Muon Veto:** 10^{-5} ⟹ **MAMUD**
- **Particle ID:** 5×10^{-3} ⟹ **RICH**

$K^+ \to \pi^+ \pi^0$ ($K_{\pi 2}$)

2nd largest BR: 20.9%

Need ~10^{-12} rejection factor

- **Kinematics:** 5×10^{-3}
- **Photon Veto:** 10^{-5} per photon

Assuming the above veto inefficiencies and an acceptance of 10%, a S/B > 10 is obtained if $\Delta m_{miss}^2 \sim 8 \times 10^{-3}$ GeV^2/c^4

Resolution requirements:

$P_\pi \rightarrow < 1\,\%$, $P_K \rightarrow 0.3\,\%$, $\theta_{K\pi} \rightarrow$ 50-60 μrad

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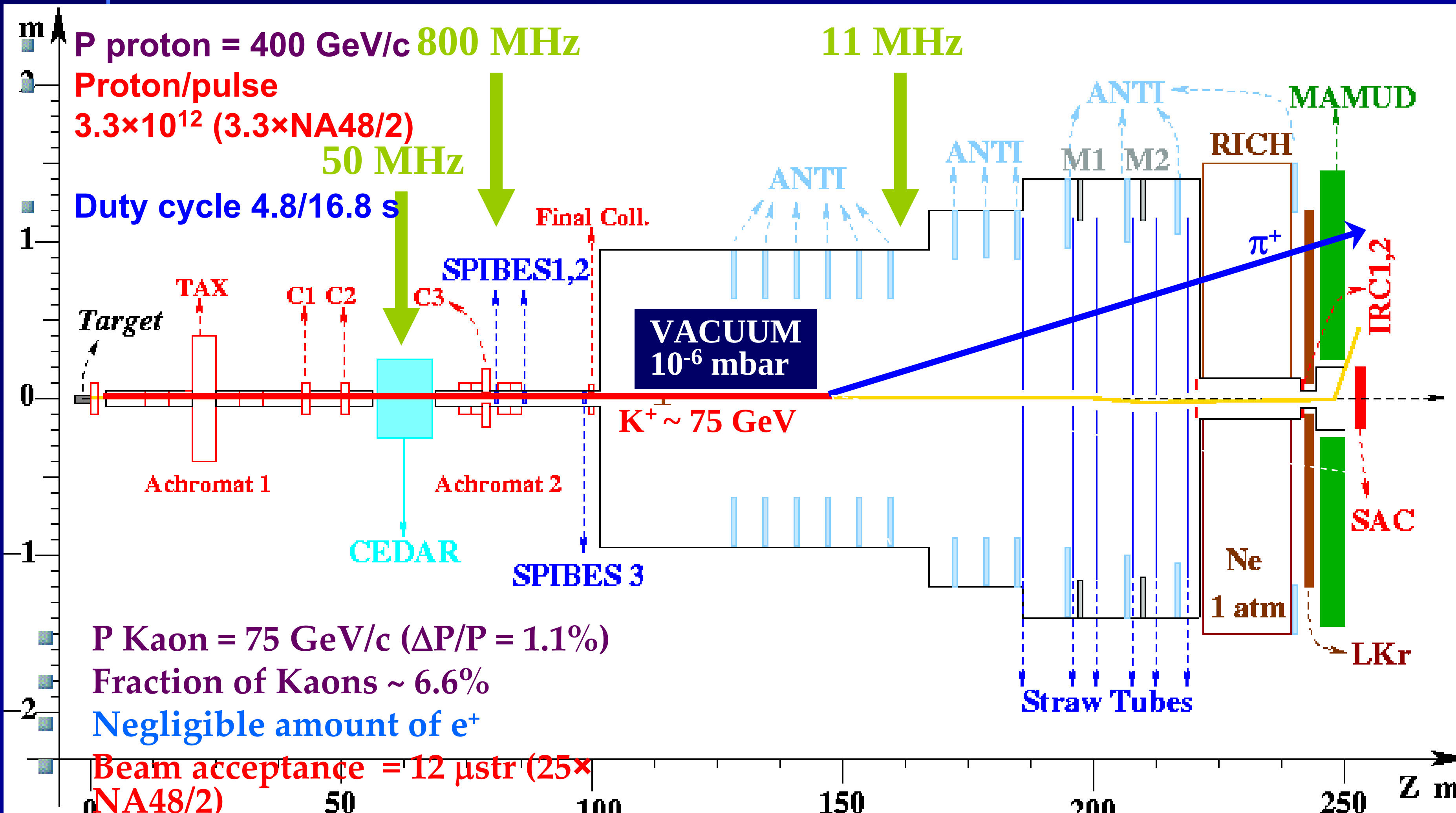
Layout of the experiment

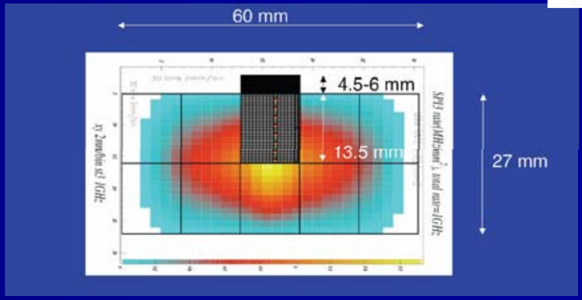


- P Kaon = 75 GeV/c (ΔP/P = 1.1%)
- Fraction of Kaons ~ 6.6%
- Negligible amount of e^+
- Beam acceptance = 12 μstr (25× NA48/2)
- Area @ beam tracker = 58×24 mm^2
- Integrated average rate = 760 MHz
- Kaon decays / year = 4.8 × 10^{12}

The Tracking system: Gigatracker

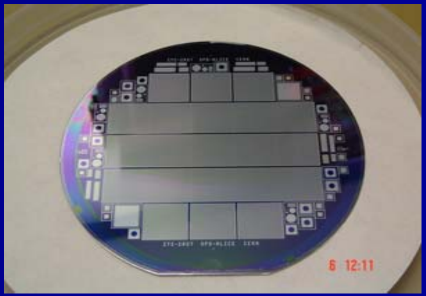
The Gigatracker (*i.e.* the beam tracker)

- 3 Si pixel stations across the 2nd achromat: size 60 × 27 mm^2



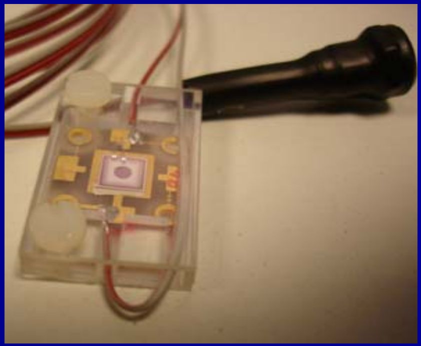
- Rate: 760 MHz (charged particles) ~60MHz/cm^2
- Good space resolution to match the downstream tracker resolution → **300×300 μm pixels** ($\sigma(P_K)/P_K \sim 0.22\%$, $\sigma(\theta_K) \sim 16$ μrad)
- Low X/X_0 not to spoil the beam → **200 Si μm sensor + 100 Si μm chip**
- Excellent time resolution needed for K+/π+ association: **σ(t)~200 ps** per station → **Readout chip bump-bonded on the sensor (0.13 μm technology)**

Readout chip: 1st MPW in 0.13μm technology is ready to test (results by September)



Si diode irradiation tests

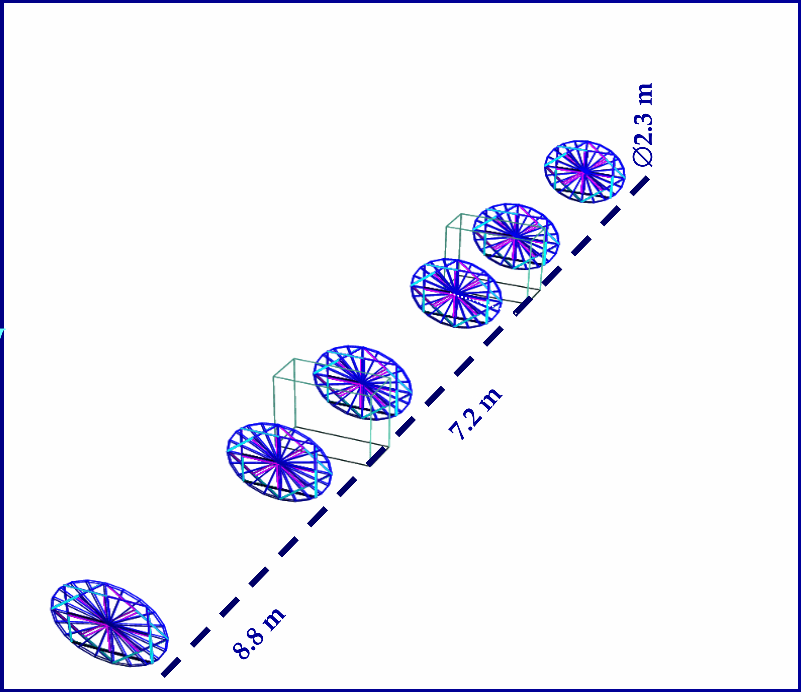
- Prototype wafers (200μm thick) produced by itc-IRST using ALICE pixel layout
- 3 mm × 3 mm and 7 mm × 7 mm test-diodes
- Test diodes irradiated with n and p (Ljubljana, CERN)
- Fluences: 1E12 to 2E14 1MeV n cm^{-2} (range P326)
- Pre and post irradiation measurements (annealing) to study diode characteristics



The Tracking system: Double Spectrometer

The Double Spectrometer (*i.e.* the downstream tracker)

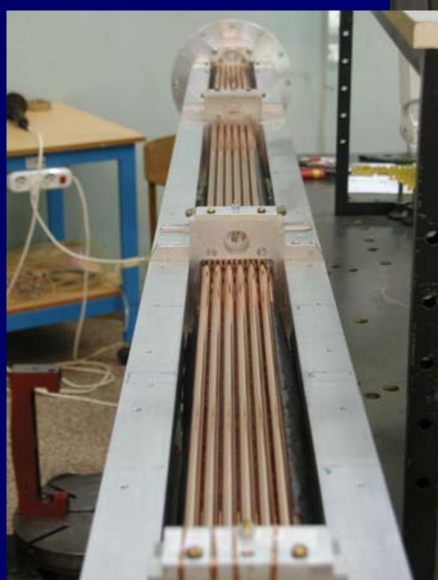
- 6 chambers with 16 layers of straw tubes each

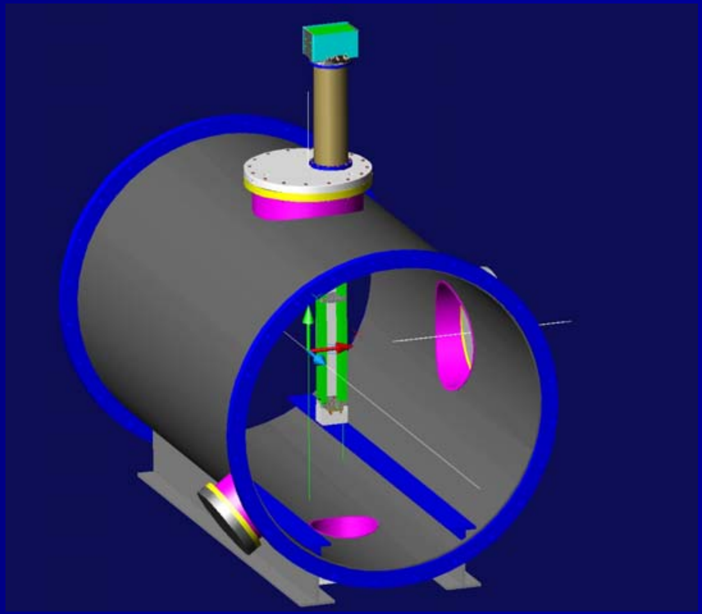


- Rate: ~ 45 KHz per tube (max 0.8 MHz)
- Low X/X_0 → **In vacuum, X/X_0~0.1% per view**
- Good space
- & angle resolution → **130 μm per hit**
- Redundant p measurement → **2 magnets**
- Veto for charged particles → **5 cm radius beam hole displaced in the bending plane**

Straw prototype

- **Design, construction and test of a Straw prototype (Dubna, CERN)**
  - Chosen technology: ultrasound welded gilded mylar tube (36 μm, D=10 mm, L=2.3 m)
  - 48 straw prototype has been produced in Dubna
  - Tests on gas leakage
  - Tests on tube expansion in vacuum
  - Prototype assembled & cosmic ray tests





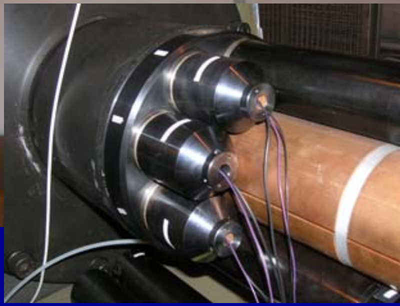
- **October 2007: Prototype integration in NA48 set-up and test on a beam**

The Particle Identification system: CEDAR

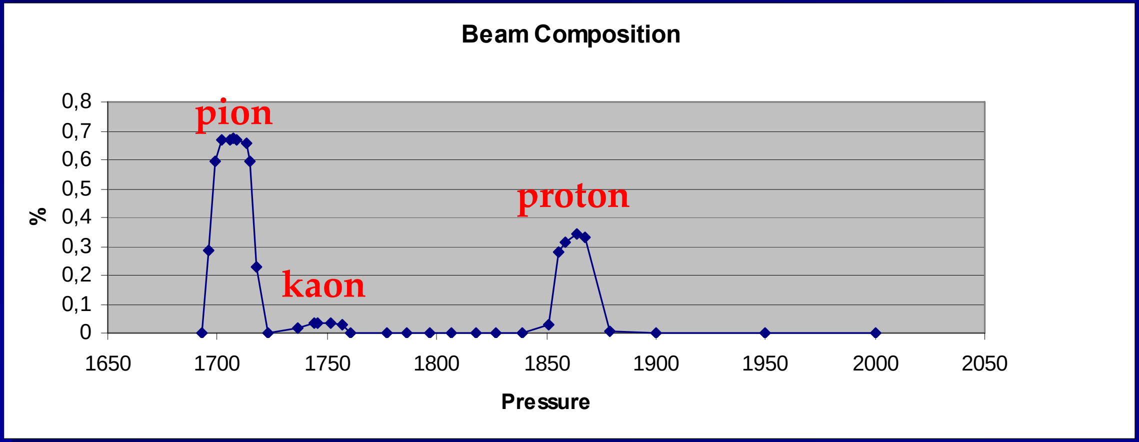
The CEDAR (*i.e.* the kaon ID)

- CEDAR: existing differential Cerenkov counter at CERN to be placed on the beam

- Tagging the kaon to keep the beam background under control
- Minimal material budget → **H_2 instead of Ne**
- Good time resolution → **New phototubes**



- CEDAR W-type filled with Ne tested at CERN in November 2006, using a 100 GeV hadron beam with 10^5 – 10^7 ppp (CERN, Firenze, Perugia).



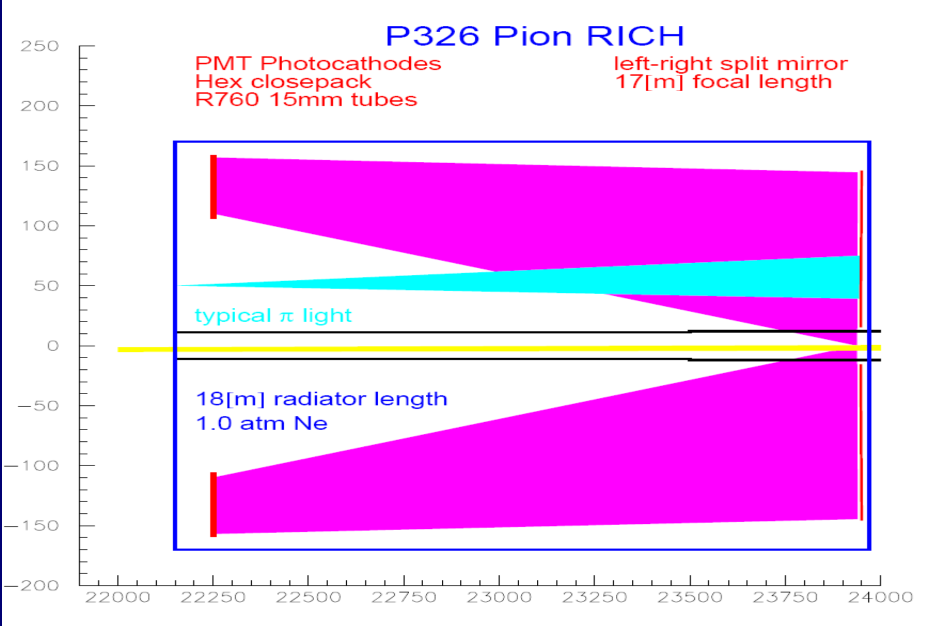
Plan: to test of fast photomultipliers using Cerenkov light.

The Particle Identification system: RICH

The RICH (*i.e.* the pion ID)

- 18 m long tube (2.5 m diamater) filled with Ne @ 1 atm, two 17m focal length mirrors

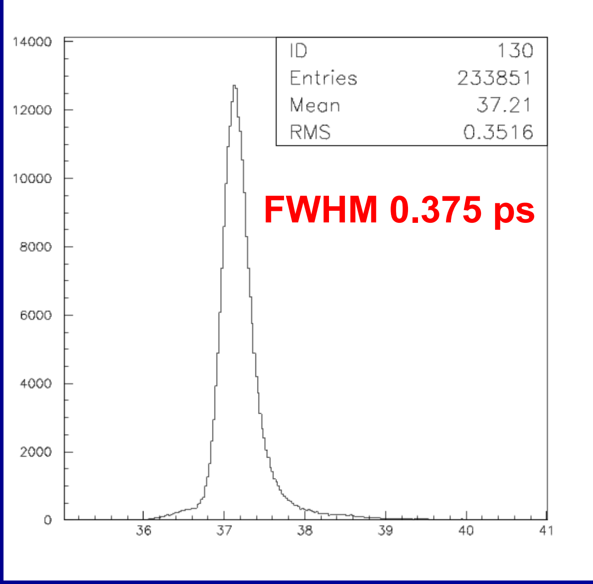
- >3σ pion/muon separation @ 35 GeV/c (13 GeV/c threshold for π) → **High granularity (2000 PMTs) Small pixel size (18 mm PMT)**
- Time resolution 100 ps (track timing) → **Phototubes with very good σ(t)**
- Velocity spectrometer (redundancy)

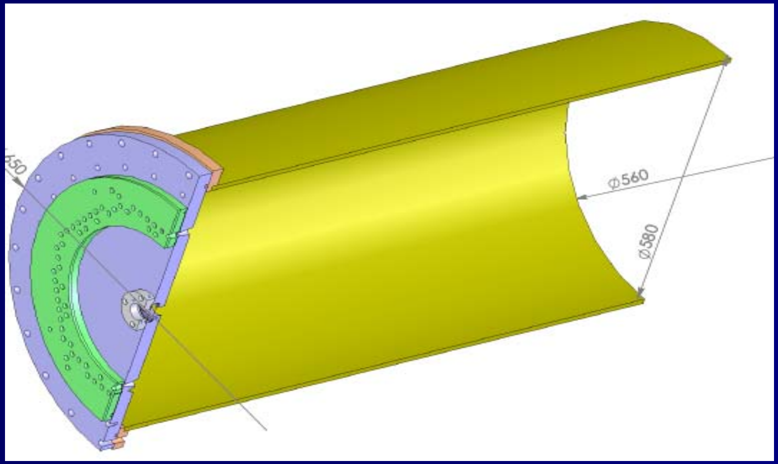


RICH prototype

- **Design, construction and test of a RICH prototype (CERN, Firenze, Perugia)**

- Full length prototype (17 m, 0.6 m diamater, stainless steel tube at CERN)
- Mirror built, delivered and under test in Firenze
- Endcap with 96 Hamatsu PMs readout through Winston's cones
- PMs tested at SPS (2006) and Firenze (with laser)
  - Measured Full Width Half Maximum (FWHM) per single γ per phototube: 390ps (150 ps electronics and 110 ps laser included)





- **November 2007: prototype integration into the NA48 set up and test with beam**

The Veto system

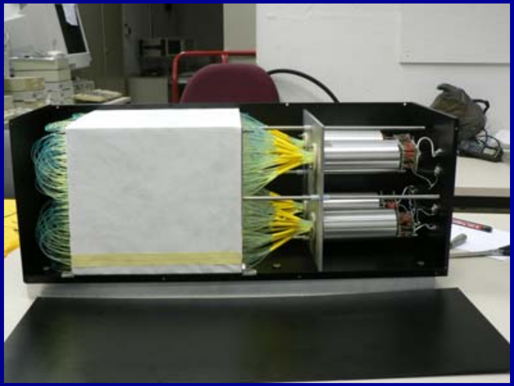
Photon vetoes

- Large angle (10, 50 mrad): Rings calorimeters (in vacuum)
  - Rate: ~4.5 MHz (μ) + ~0.5 MHz (γ)
  - 10^{-4} inefficiency for E_γ in 0.05,1 GeV
  - 10^{-5} inefficiency for E_γ>1 GeV

  → **20 X/X_0 Lead scintillator tiles or Lead scintillator fibers (KLOE-like)**

- Medium angle (1, 10 mrad): LKr calorimeter
  - Rate: ~8.7 MHz (μ)+~4 MHz (γ))+~3 MHz (π) → **New Readout**
  - 10^{-4} inefficiency for E_γ in 1,5 GeV
  - 10^{-5} inefficiency for E_γ>5 GeV

- Small angle (<1 mrad): Shashlik technology →
  - Rate: 0.5 MHz (μ)
  - 10^{-5} inefficiency (high energy photons)



Muon veto

- Extruded scintillator – lead sampling calorimeter 6 m long + magnet for beam deflection
  - Rate: ~7 MHz (μ)+~3 MHz (π)
  - 10^{-5} inefficiency for μ detection

  → **em/hadronic cluster separation. Sensitivity to the MIP**

  - Deviate the beam out from the SAC → **5Tm B field in a 30×20cm^2 beam hole**

Large angle Photon Vetoes

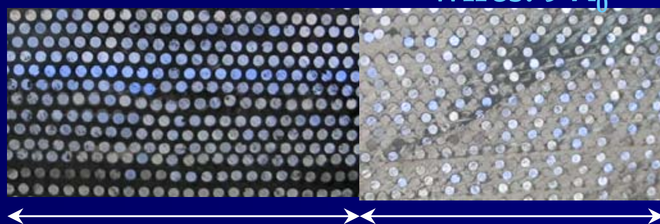
P326

KLOE-type lead/scintillating fiber: prototype constructed in Frascati

- 1 mm diameter scintillating fibers, 0.5 mm thick lead foils.

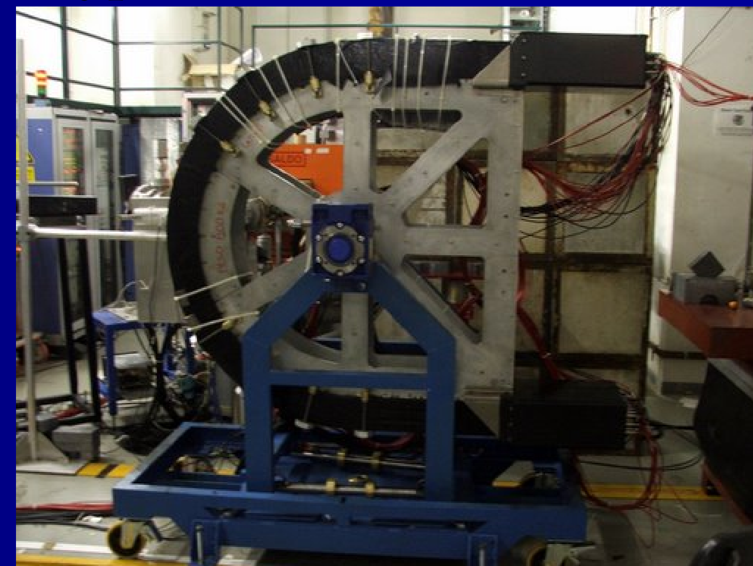
All fiber: 8 X_0

Fibers+lead wires: 9 X_0



16.8 cm

8.2 cm



- Readout granularity: 18 cells
  - Very well known and tested technology
  - Under test at the Frascati BTF

Lead scintillator tiles

- Studies of the efficiency of detectors built with this technology available
- Fermilab prototype under test at BTF
- Outgassing tests performed at CERN on detectors built with same technology: they can be placed in the vacuum of the decay region (10^{-6} mbar)

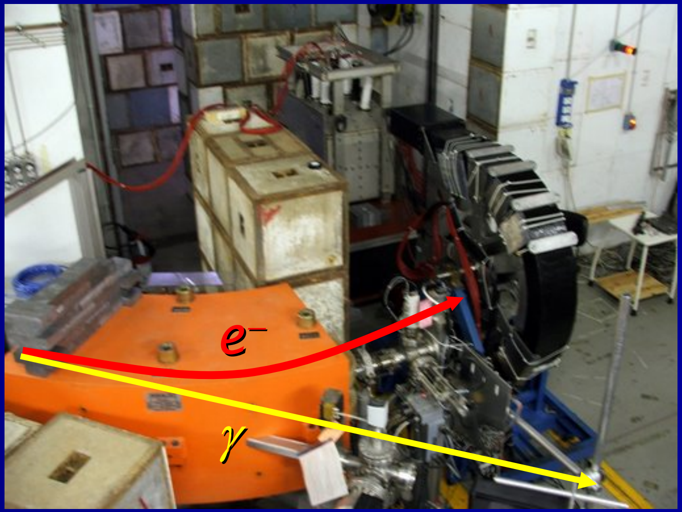
Large angle Photon Vetoes tests

- **Test beam activity at BTF in Frascati** (Frascati, Napoli, Pisa, Roma)

- e^- beam (300-500 MeV/c)
- Both calorimeter prototypes under test
- 1st step: test with electrons
- 2nd step: test with photons

- Test beam periods: March, April, June 2007
The main result: both prototypes show good characteristics: inefficiency ~ 10^{-5} for E=500, 200-350 MeV (10^{-4} for LG due to statistics). Good energy resolution is obtained for fiber calorimeter: $$\frac{\sigma(E)}{E} = \frac{5.88\%}{\sqrt{E(GeV)}} \oplus 4.63\%$$

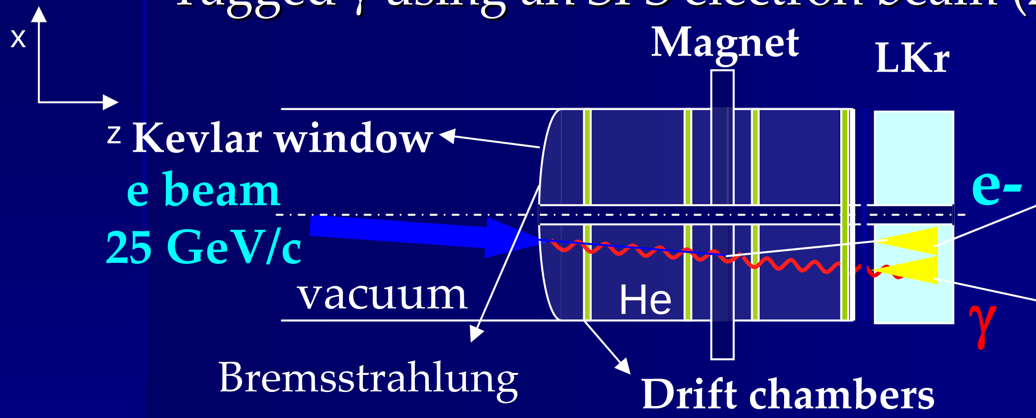
- It is necessary to understand the beam background and to make
- calibrations of the prototypes

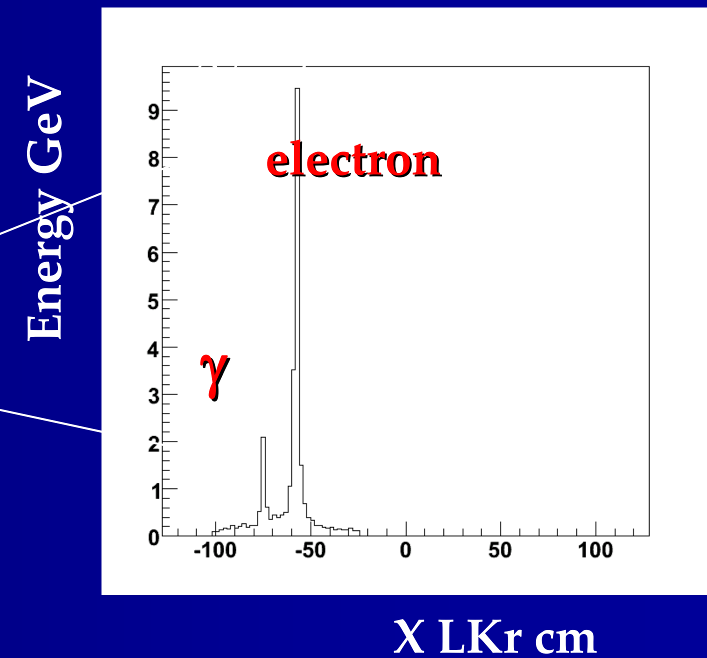


LKr calorimeter

- **Measurement of the inefficiency**
  - K^+ data taken in a dedicated NA48 test run in 2004 using $K^+ \to \pi^+\pi^0$

    ⇒ $\eta < 10^{-5}$ **(@90% C.L., E_γ>10 GeV)**
  - Tagged γ using an SPS electron beam (2006)





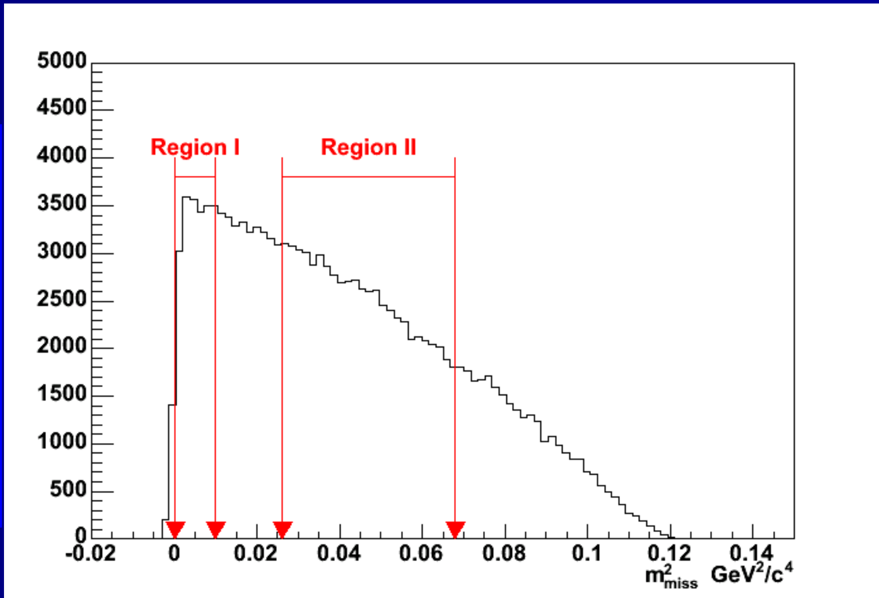
  - Inefficiency measured for E_γ > 2.5 GeV
  - **> 10 GeV, $\eta < 10^{-5}$ confirmed**
  - **< 10 GeV analysis in progress**

- **Consolidation of the readout**
  - Custom boards (FPGA based) sending data directly to PC Farm
  - Test of the new electronics in 2007 NA48 run

Preliminary sensitivity studies

Simulation of the P-326 apparatus

- Region I and II
- Momentum range: 15 < P_π < 35 GeV/c
  - Against muons
  - RICH operational reasons
  - Plenty of energy in photon vetoes



Acceptance (60 m fiducial volume):

- Region I: 4%
- Region II: 13%
- Total: 17%

To be reduced because of losses due dead time, reconstruction inefficiencies…

Acceptance ~ 10% is achievable

Analysis: background rejection

Events/year	Total	Region I	Region II
Signal *(acc=17%)*	65	16	49
$K^+ \to \pi^+\pi^0$	2.7	1.7	1.0
$K^+ \to \mu^+\nu$	1.2	1.1	<0.1
$K^+ \to e^+\pi^+\pi^-\nu$	~2	negligible	~2
Other 3 – track decays	~1	negligible	~1
$K^+ \to \pi^+\pi^0\gamma$	1.3	negligible	1.3
$K^+ \to \mu^+\nu\gamma$	0.5	0.2	0.2
$K^+ \to e^+(\mu^+)\ \pi^0\nu$, others	negligible	–	–
Total bckg.	<9	3.0	<6

➡ S/B ~ 8 (Region I ~5, Region II ~9)

Trigger

- **A possible scheme:**

Level	L0 "hardware"	L1-L2 "software"
Input	~10 MHz	1 MHz
Output	1 MHz	$\mathcal{O}$(KHz)
Implementation	Dedicated hardware	TDAQ farm
Actions	RICH minimum multiplicity, Muon vetoing, LKr vetoing	L1 = single sub-detectors L2 = whole event

- **Main work on possible solutions for the L0 hardware**
  - TELL-1 board (LHCb) based implementation for all non FADC sub detectors
  - Design of a new 100 ps TDC daughter-card (RICH, Straws, MAMUD,…)
    - Two prototypes under study (Mainz and Pisa)

Other physics opportunities

P-326 Kaon Flux ~100 times NA48/2 Kaon Flux

- Other physics opportunities can be addressed:
  - Lepton – flavor violation (started with a run 2007):
    - ✓ $K_{e2}/K_{\mu 2}$, $K^+ \to \pi^+ \mu^+ e^-$, $K^+ \to \pi^- \mu^+ e^+$
  - Search for new low mass particles:
    - ✓ $K^+ \to \mu^+ N$ *(light RH neutrinos)*
    - ✓ $K^+ \to \pi^+ \pi^0 P$ *(pseudoscalar sGoldstino)*
  - Hadron spetroscopy
  - …

Conclusions

- To search for new physics using rare Kaon decays P-326 experiment is proposed and prepared for measurement of the Br($K^+ \to \pi^+ \nu \bar{\nu}$) with a ~10% accuracy (& for other physics opportunities)

- General design is mostly defined. Overall simulation and performances are under review.

- The R&D program is well advanced: construction of detector prototypes and tests are in progress (in some cases - completed). Important results should be obtained by the end of 2007

- The new experiment should be able to reach a ~10^{-12} sensitivity per event at an existing machine and employing the infrastructures of an existing experiment.