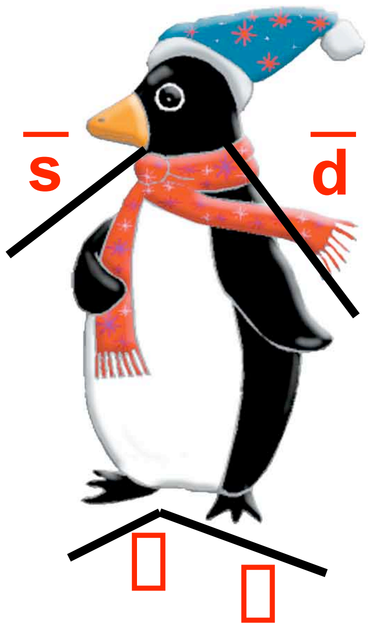
Rare Kaon Decays: Opportunities at CERN

Augusto Ceccucci/CERN



Laboratori Nazionali di Frascati
March 23, 2005

Abstract

- We have studied the possibility to measure the very rare $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay at the **CERN SPS**

- The experiment will employ a high energy, un-separated kaon beam to better control backgrounds originating from $K^+ \rightarrow \pi^+ \pi^0$ decays

- The data taking may start before the end of this decade aiming to a **~10 % measurement of the CKM parameter $|V_{td}|$.**

Physics Introduction: CKM matrix and CP-Violation

Quark mixing is described by the
Cabibbo-Kobayashi-Maskawa (CKM) matrix

KM mechanism:

$N_g=2 \quad N_{phase}=0 \Rightarrow$ No CP-Violation

$N_g=3 \quad N_{phase}=1 \Rightarrow$ CP-Violation Possible

$$\boxed{e.g.\ Im\ \lambda_t = Im\ V_{ts}^{*}V_{td} \neq 0 \rightarrow \cancel{CP}}$$

KM mechanism appears to be the main source of CP-violation in quarks:

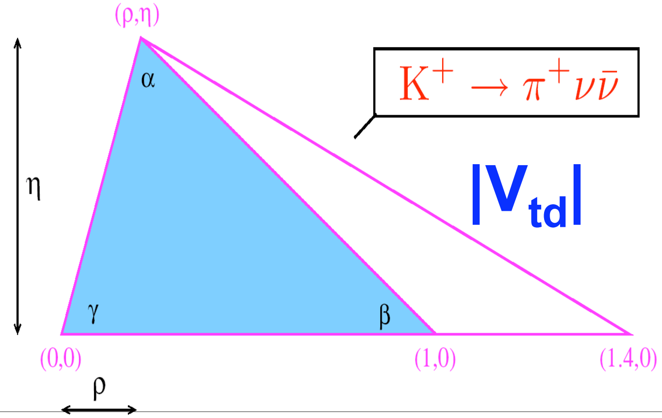
- Direct-CP Violation exists: $\varepsilon'/\varepsilon \neq 0$ NA48, KTeV
- CP violation in the B meson sector: $A_{CP}(J/\psi\ K_s)$, BaBar, Belle

Now look for inconsistencies in SM using independent observables affected by small theoretical uncertainties and different sensitivity to new physics

Kaon Rare Decays and the SM

$K_L \to \pi^0 \nu\bar{\nu}$ **(holy grail)**

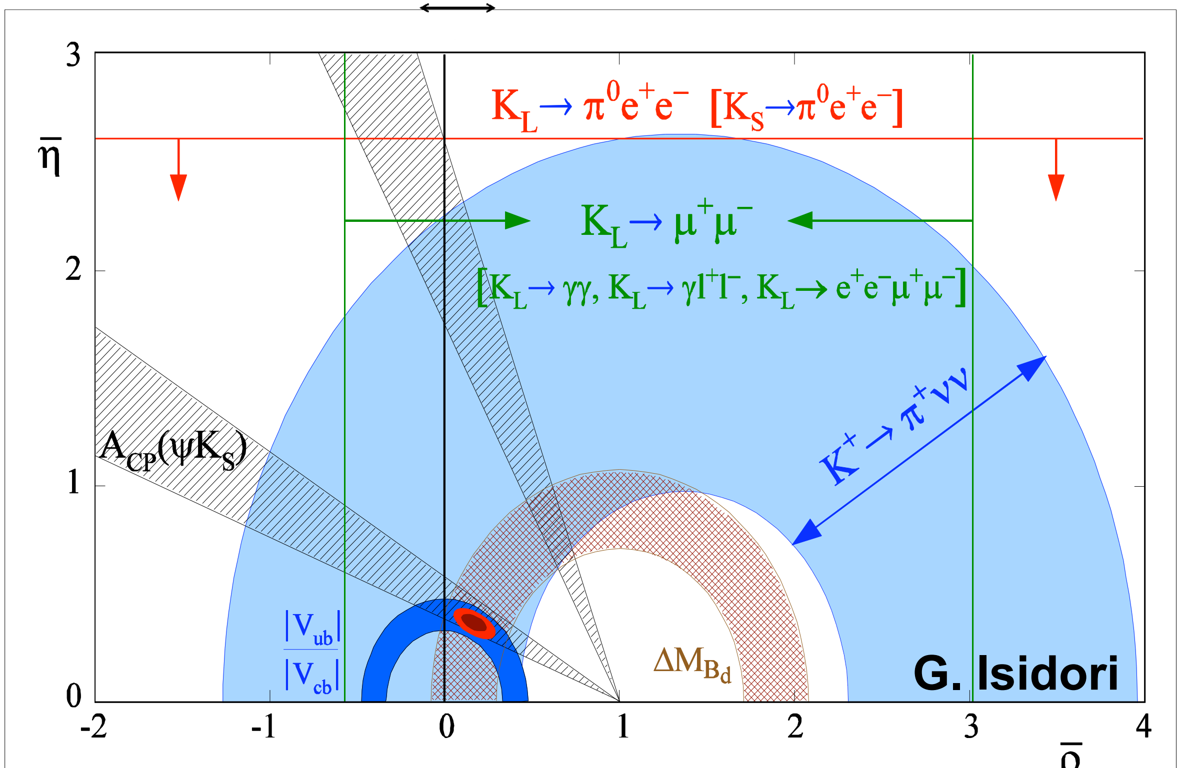
$$K_L \to \pi^0 e^+ e^- \left\{ \begin{array}{l} K_S \to \pi^0 e^+ e^- \\ K_L \to \pi^0 \gamma\gamma \\ K_L \to ee\gamma\gamma \end{array} \right.$$



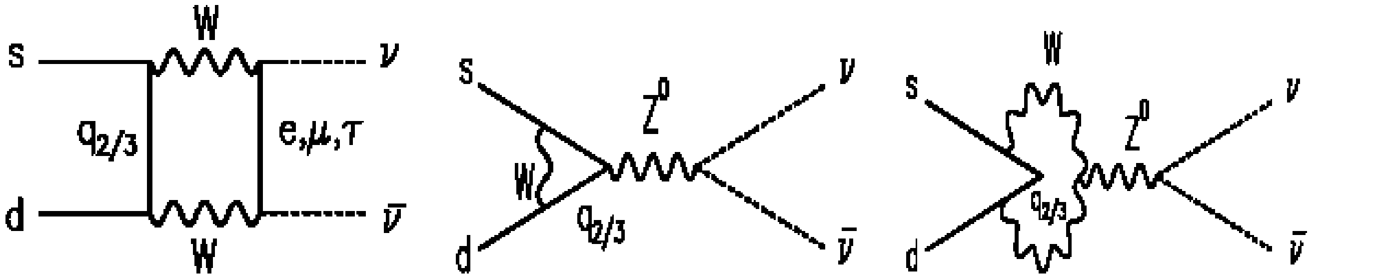
Kaons provide quantitative tests of SM independent from B mesons…

…and a large window of opportunity exists!

$$\boxed{\begin{array}{l} Im\ □_t = A^2\ □^5\ □ \\ Re\ □_t = A^2\ □^5\ □ \end{array}}$$



K→□ □□: Theory in Standard Model



charm contribution

top contributions

The Hadronic Matrix Element is measured and isospin rotated (~10% correction)

Predictions in SM

Error ~ 14% Mainly parametric
Theory error due to charm (Buras04):

For long distance contribution
see:"LIGHT-QUARK LOOPS IN K->PI NU NU"
By G. Isidori, C.Smith, F.Mescia.
e-Print Archive: hep-ph/0503107

Largest contribution from scale error. To be reduced by NNLO calculation

The error is almost purely parametric

Possibly the Cleanest SM test

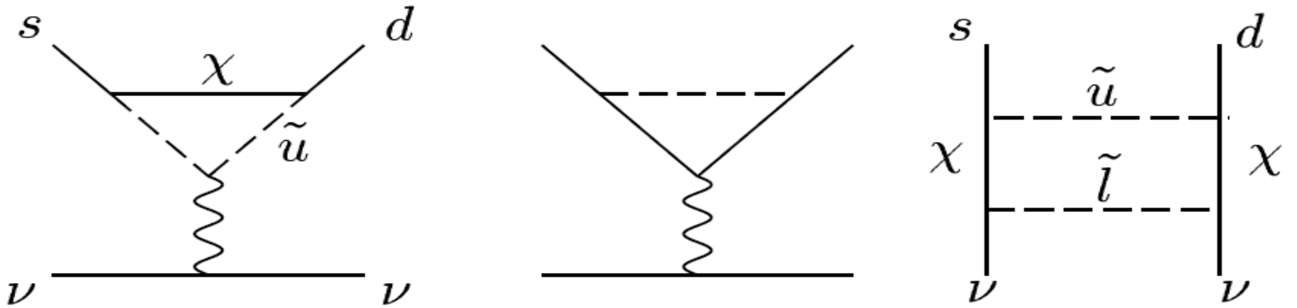
- In The phase □ derives from Z^0 diagrams (□S=1) whereas in A(J/□ K_S) originates in the box diagram (□B=2)
- Any non-minimal contribution to Z^0 diagrams would be signalled by a violation of the relation:

- A deviation from the predicted rates of SM would be a clear indication of new physics
- Complementary programme to the high energy frontier:
  - When new physics will appear at the LHC, the rare decays may help to understand the nature of it

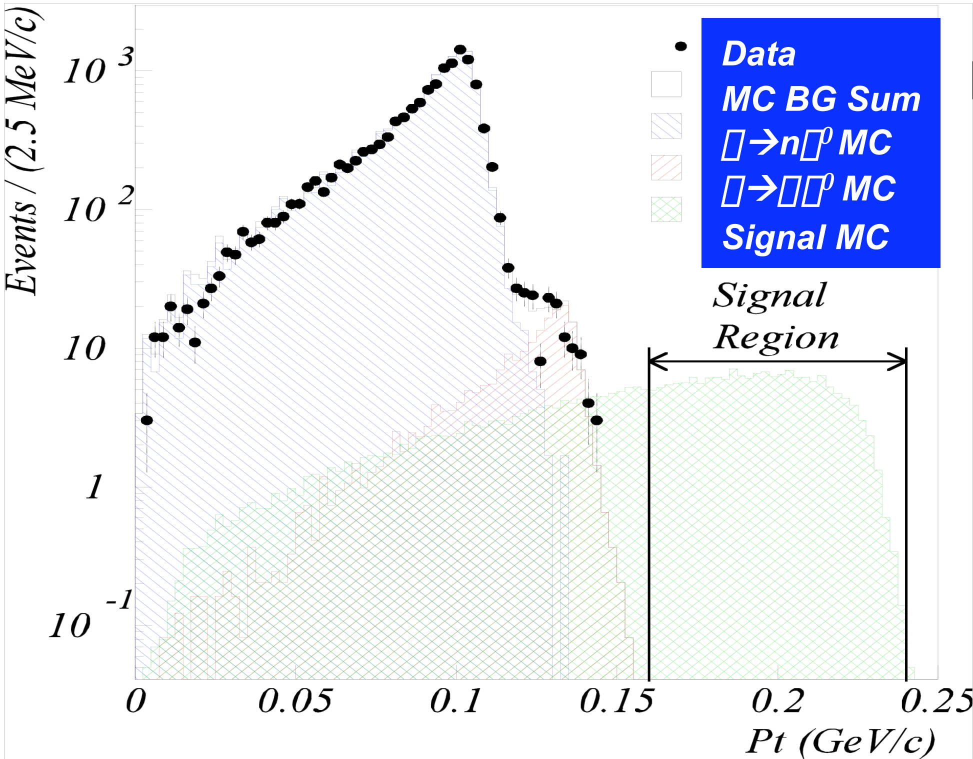
Some BSM Predictions

Compiled by S. Kettel

SM	8.0 ± 1.1	3.0 ± 0.6
MFV hep-ph/0310208	19.1	9.9
EEWP NP B697 133	7.5 ± 2.1	31 ± 10
EDSQ hep-ph/0407021	15	10
MSSM hep-ph/0408142	40	50



$K^0_L \to \pi^0\nu\bar{\nu}$:State of the Art



KTeV 1997 Data
Dalitz Analysis

Still far from the model independent limit:

$BR(K^0 \to \pi^0\nu\bar{\nu}) < 4.4 \times BR(K^+\pi^+\nu\bar{\nu}) \sim 1.4 \times 10^{-9}$

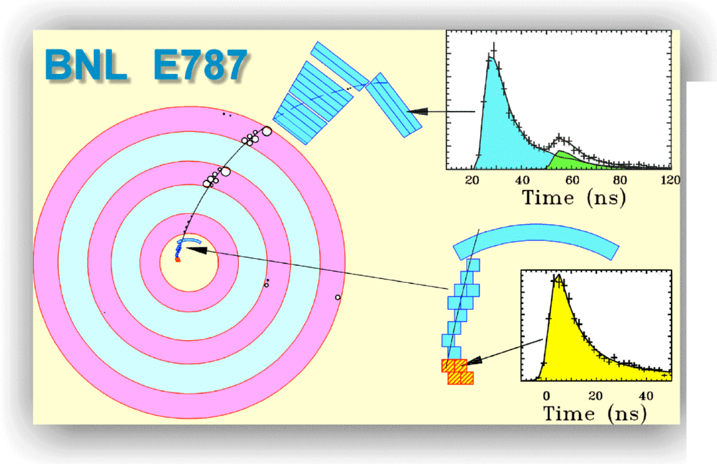
Grossman & Nir, PL B407 (1997)

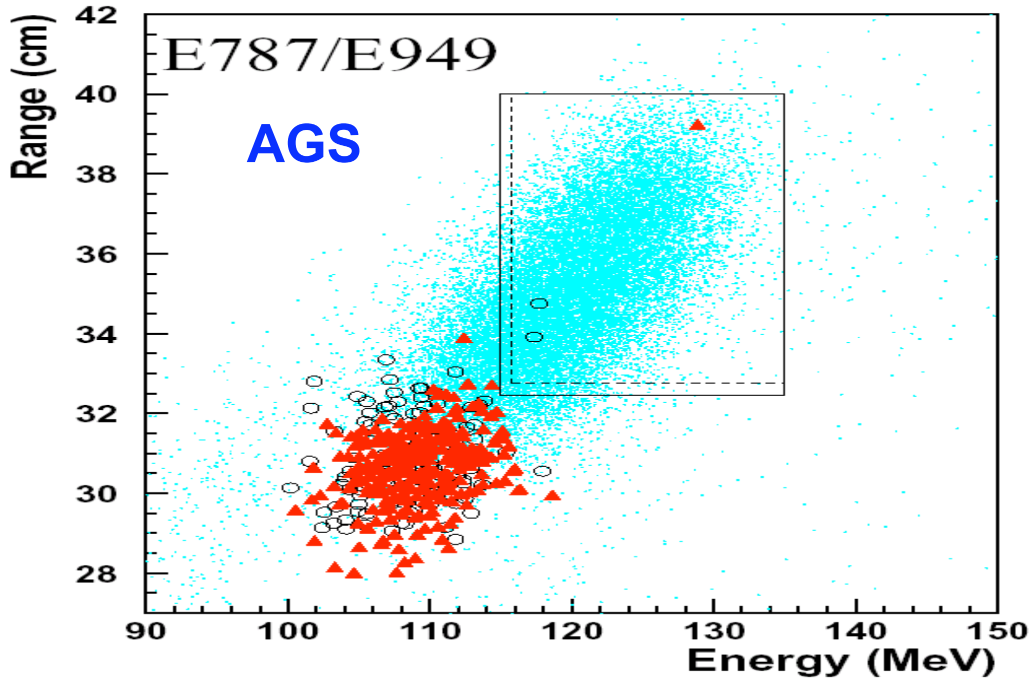
$BR(K_L \to \pi^0\nu\bar{\nu}) < 5.9 \times 10^{-7}$ ($\pi^0 \to ee\gamma$, 1997 Data) [PRD 61,072006 (2000)]

$BR(K_L \to \pi^0\nu\bar{\nu}) < 1.6 \times 10^{-6}$ ($\pi^0 \to \gamma\gamma$, 1997 1 Day) [PLB 447, 240 (1999)]

$K^+ \to \square^+ \, \square\square$: State of the art

hep-ex/0403036 PRL93 (2004)





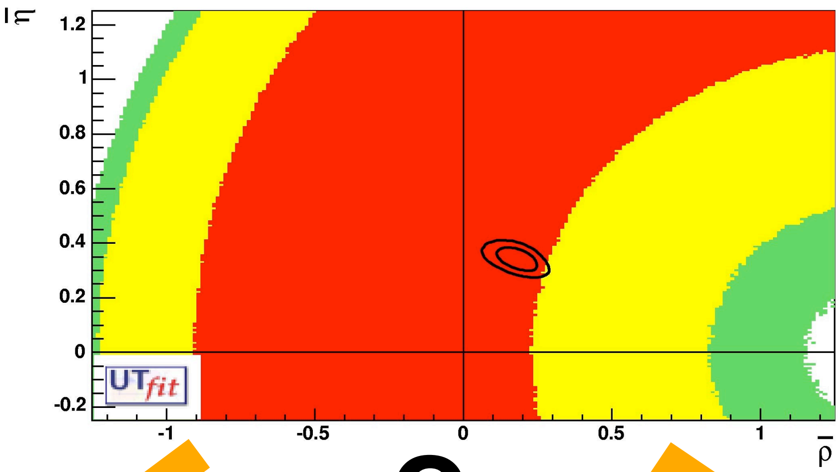
Stopped K
~0.1 % acceptance

$$BR(K^+ \to \square^+ \, \square\square) = 1.47^{+1.30}_{-0.89} \_ \; 10^{-10}$$

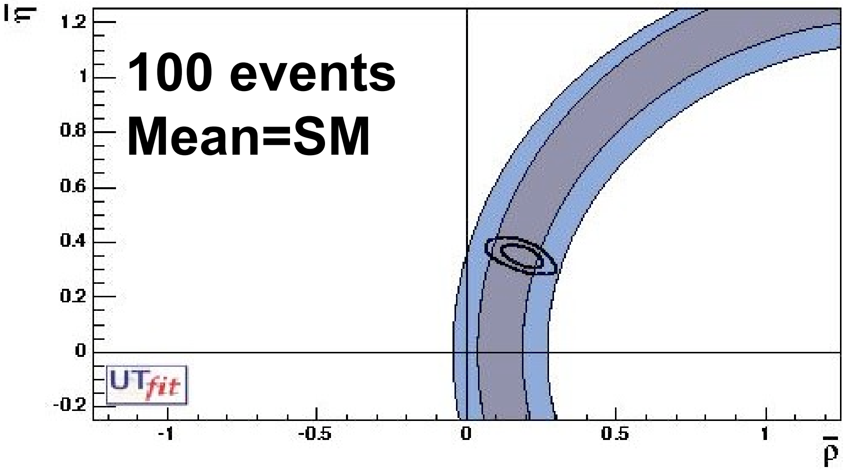
- **Compatible with SM within errors**

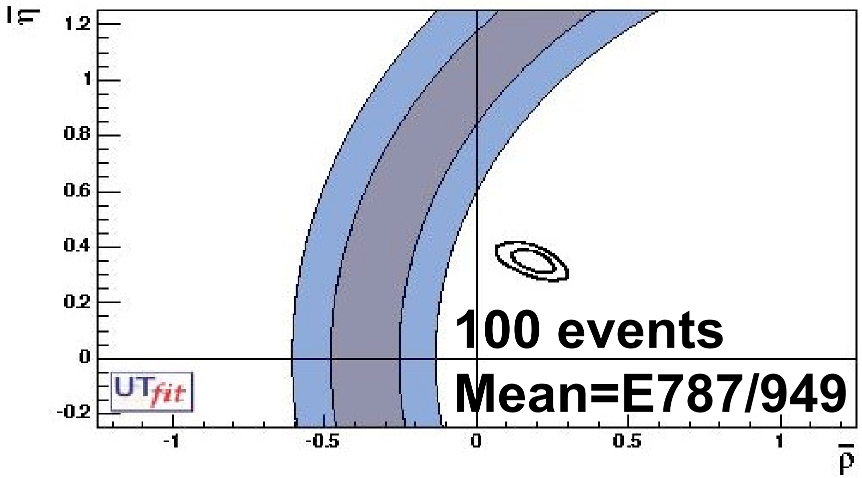
Setting the bar for the next generation of $K^+\to\pi^+\nu\bar{\nu}$ experiments

Current constraint on ρ,η plane



?





Prospects

- $K^0_L \to \pi^0 \nu\bar{\nu}$
  - Large window of opportunity exists.
  - Upper limit is 4 order of magnitude from the SM prediction
  - Expect results from data collected by E391a (proposed SES~3 10^{-10})
  - Next experiment KOPIO@ BNL
- $K^0_L \to \pi^0 ee(\mu\mu)$
  - Long distance contributions under better control
  - Measurement of K_S modes by NA48/1 has allowed SM prediction
  - K_S rates to be better measured (KLOE?)
  - Background limited (study time dep. Interference?)
  - 100-fold increase in kaon flux to be envisaged
- $K^+ \to \pi^+ \nu\bar{\nu}$
  - The situation is different: 3 clean events are published
  - Experiment in agreement with SM
  - Next round of exp. need to collect O(100) events to be useful
  - Move from stopped to in flight experiments

Prospects on $K^{+}\rightarrow\pi^{+}\nu\bar{\nu}$

- **Decays at rest:**
  - **Window of opportunity to accumulate more data at BNL until 2010 (before KOPIO data taking starts)**
  - **Ideas to pursue stopped kaon decays in Japan**
  - **Established technique…**
  - **…but hard to extrapolate to O(100) events**
- **Decays in flight**
  - **Large acceptances, good photon rejection**
  - **Separated beam: FNAL CKM (Approved but Not Ratified)**
    - **Limited to about P_K<30 GeV/c**
  - **Un-separated beam: CERN-NA48/3, FNAL-P940**
    - **Limited by rate in beam trackers**

Opportunity: NA48/3
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at the CERN-SPS

SPSC-2004-029
SPSC-I229

Cambridge, CERN, Dubna, Ferrara, Firenze, Mainz, UC Merced, Perugia, Pisa, Saclay, Sofia, Torino, + ??

Work inspired by:

- **High Quality NA48/2 charged Kaon beams and Beam Spectrometers**
- **Outstanding Progress by BNL E787/E949**
- **In flight technique with separated beam proposed at FNAL**

Since LOI:

- **Cambridge dropped off**
- **Roma I, Naples and Protvino joined the working groups**

Message from the CERN Director General to the staff (Jan 05)

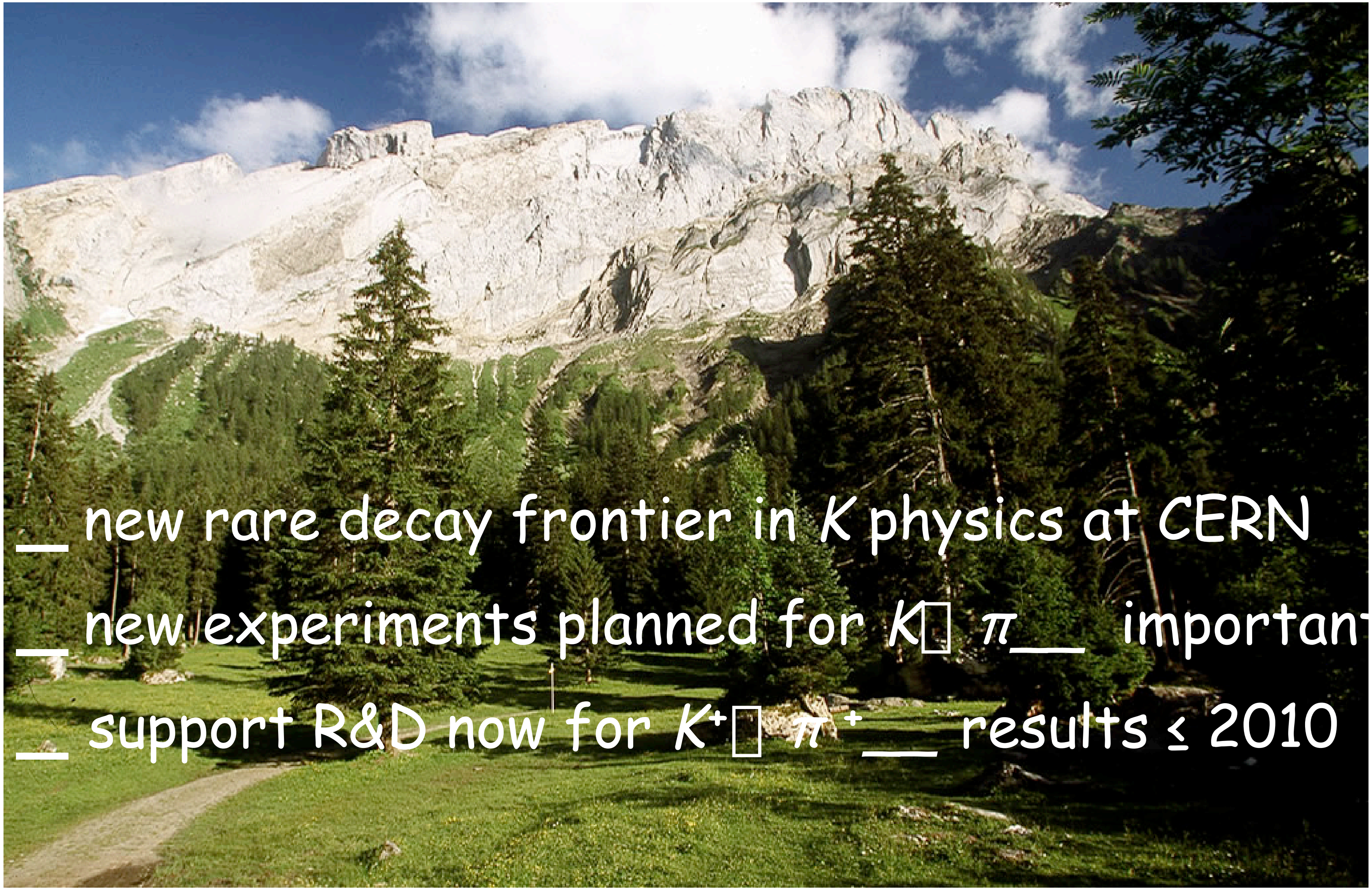
- The top priority is to maintain the goal of starting up the Large Hadron Collider (LHC) in 2007

- "…Meanwhile, the natural break we have in the fixed-target programme in 2005 is already allowing the community to develop a well-focused programme for the future"

The possible Non-LHC Future Programme was reviewed by the SPSC in Villars (September 22-27, 2004)

John Dainton
Villars 2004
October 7th 2004
CERN seminar

SPSC@Villars



From the Villars Report…

CERN-SPSC-2005-010
SPSC-M-730
Febbruary 28, 2005

3.3 Flavour Physics

There is a strong physics case for pursuing an ambitious program of kaon physics at CERN, exploiting the high-energy proton beams available at the SPS for rare *K*-decay in-flight measurements. Building on its expertise in high-intensity neutral and charged kaon beams and on the outstanding physics achievements of the NA48, NA48/1 and NA48/2 experiments in the last decade, CERN should remain in the future a major laboratory for kaon physics at the sensitivity frontier.

The possibility of a precise measurement of the $K^+ \to \pi^+ \nu\nu$ transition is exciting. The goal is to detect more than 100 signal events over two years starting in 2009. The challenge is for experimental sensitivity to a *K*-decay BR of order 10^{-11}. A major upgrade of the present NA48/2 set-up would be necessary and the required R&D and detector developments should be supported. According to present studies this measurement appears globally competitive.

NA48/3: SPSC-I229

- Collect 80 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events in about two years of data taking for:
  - 4×10^{12} Kaon decays/SPS year
  - BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)~10^{-10}
  - Acceptance ~ 10%

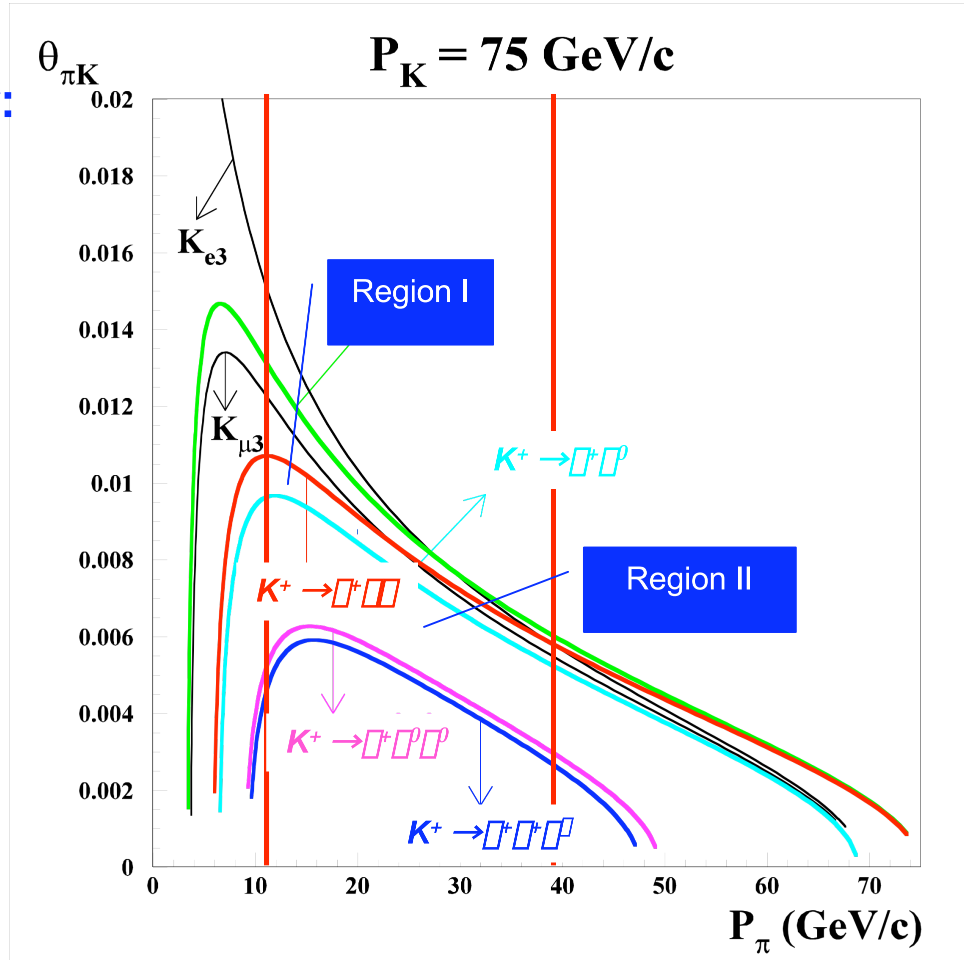
LOI numbers

  - Absolute advantage:

    High energy kaon beam: >35 GeV of EM energy deposited in the vetoes very difficult to miss π^0 !!

  - Disadvantage:

    ~1 GHz particle rate in beam tracker

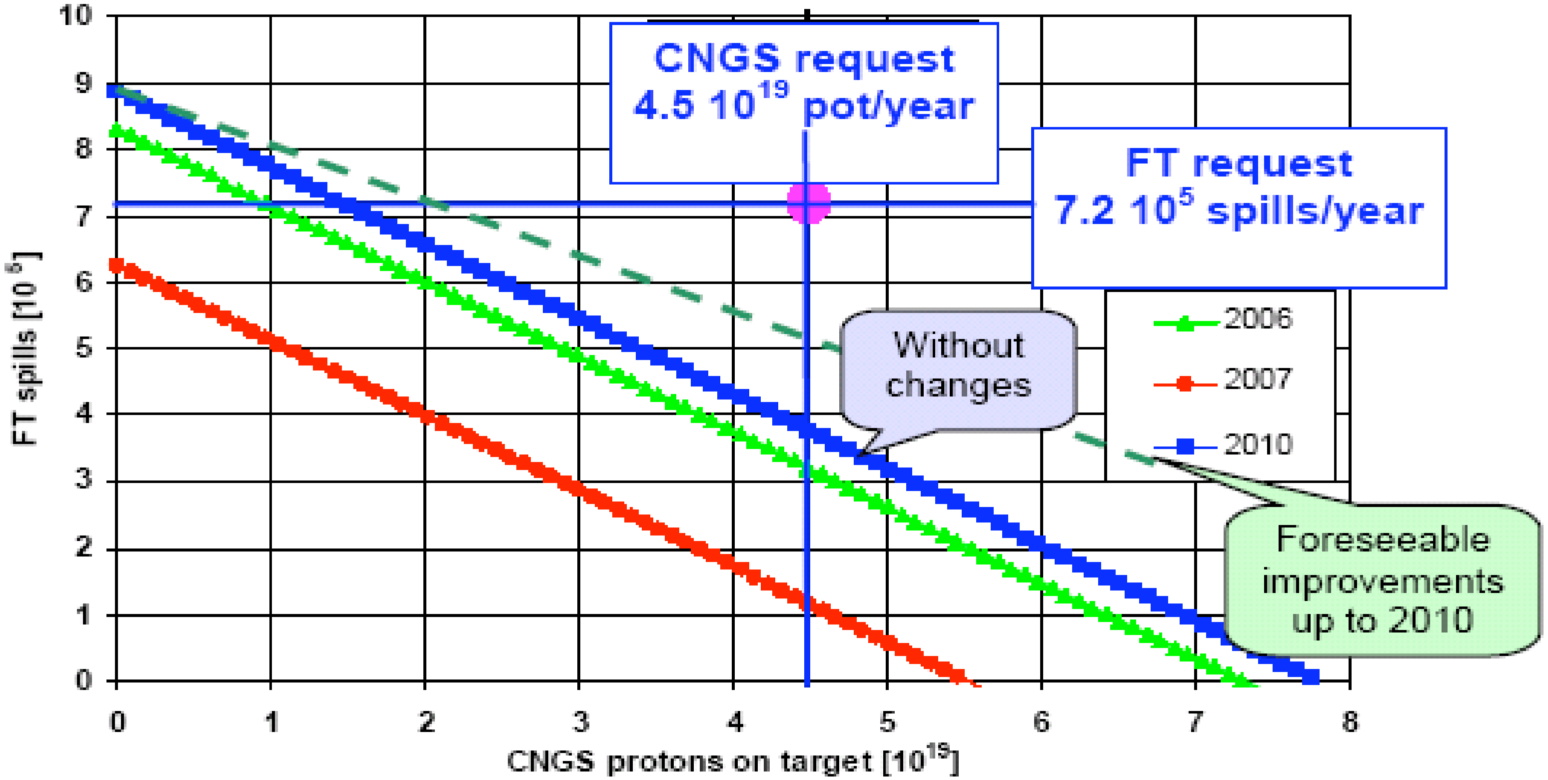


New high-intensity K^+ beam for NA48/3

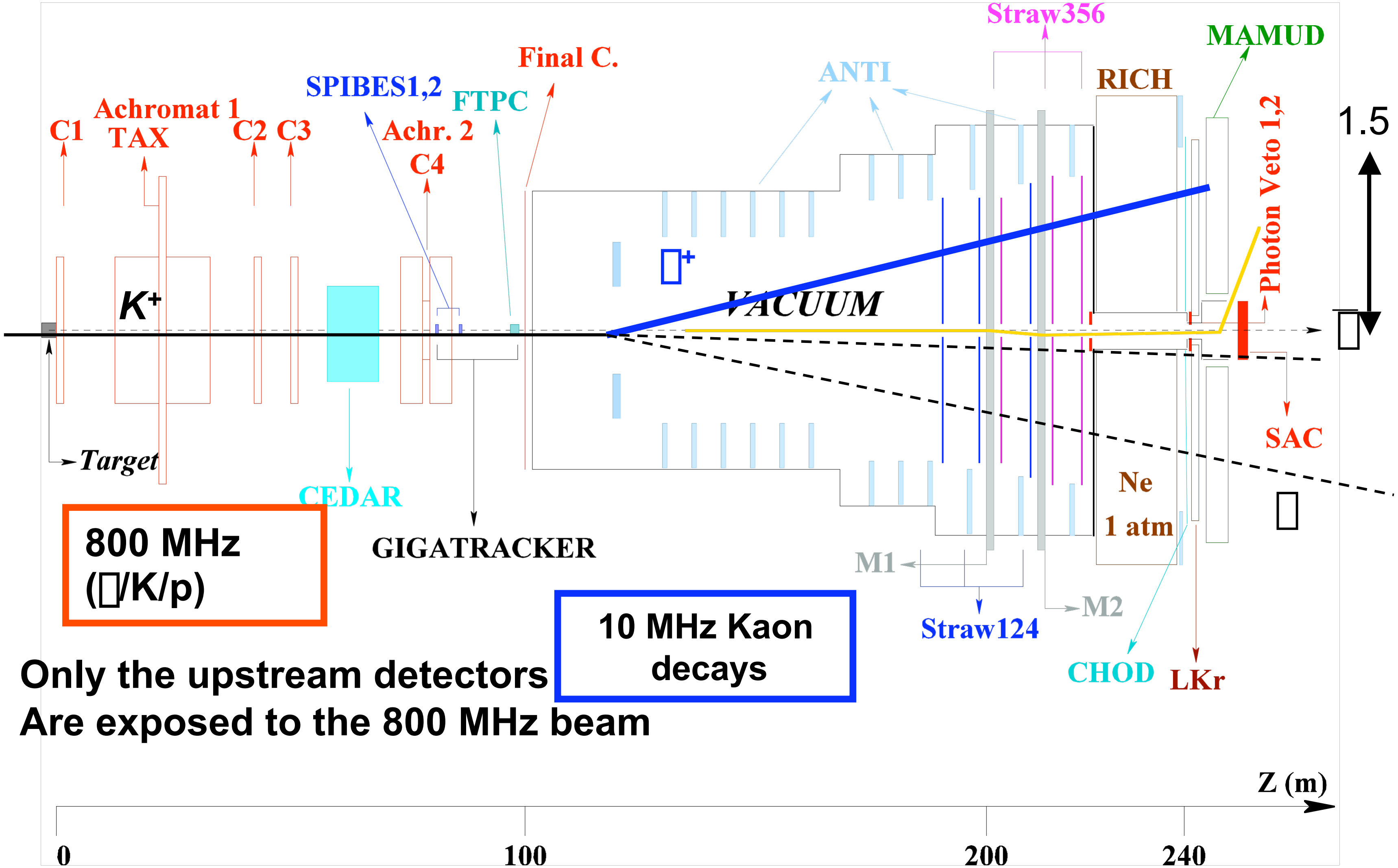
Already Available

Beam:	Present K12 (NA48/2)	New HI K^+ > 2006	Factor wrt 2004
SPS protons per pulse on T10	1×10^{12}	3×10^{12}	3.0
Duty cycle (s./s.)	4.8 / 16.8		1.0
Solid angle (μsterad)	$\approx$ 0.40	$\approx$ 16	40
Av. K^+ momentum $\langle p_K \rangle$ (GeV/c)	60	75	Total : 1.35
Mom. band RMS: ($\Delta p/p$ in %)	$\approx$ 4	$\approx$ 1	~0.25
Area at Gigatracker (cm^2)	$\approx$ 7.0	$\approx$ 20	$\approx$ 2.8
Total beam per pulse ($\times 10^7$)	5.5	250	~45 (~27)
per Effective spill length MHz	18	800	~45 (~27)
MHz/cm^2 (gigatracker)	2.5	40	~16 (~10)
Eff. running time / yr (pulses)	$3^* \times 10^5$	$3.1 * 10^5$	1.0
K^+ decays per year	1.0×10^{11}	4.0×10^{12}	$\approx$ 40

SPS Protonomics



(Latest) NA48/3 Detector Layout



800 MHz (π/K/p)

10 MHz Kaon decays

Only the upstream detectors Are exposed to the 800 MHz beam

Acceptance

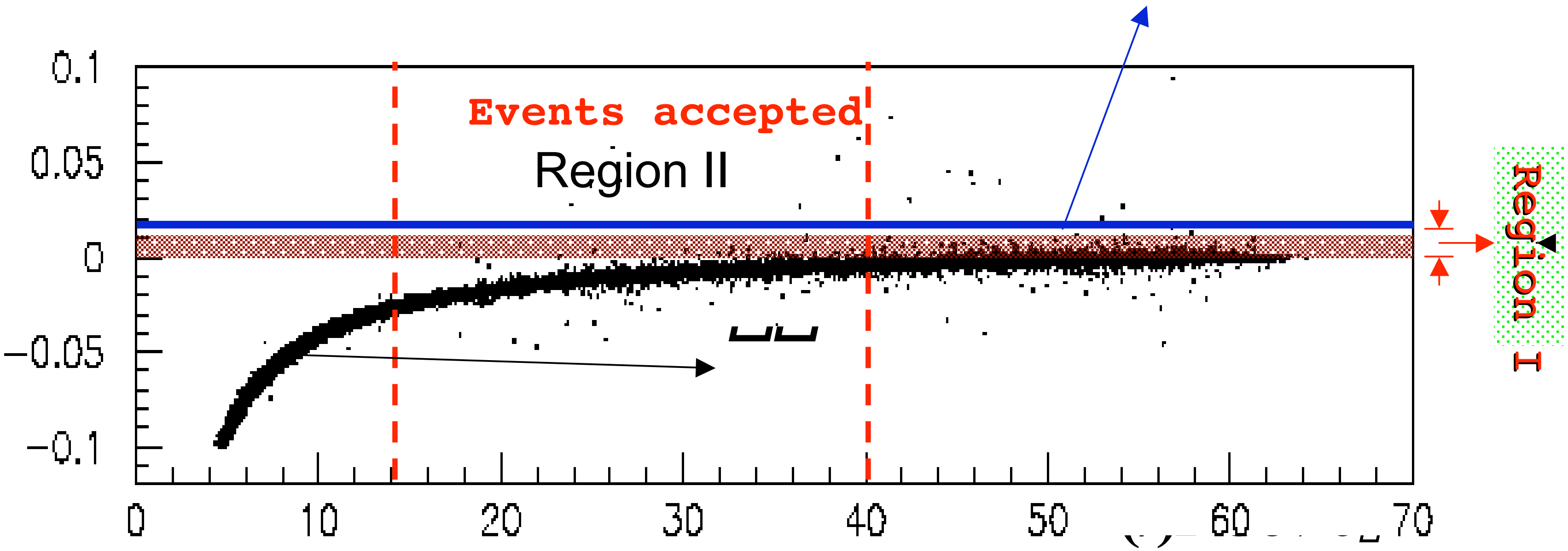
K^+ momentum: (75.0 ± 0.8) GeV/c

	Region I	Region II
P = [15- 35] GeV/c (RICH)	2.8 _ 10^{-2}	14.8 _ 10^{-2}
P = [10 – 40] GeV/c	3.9 _ 10^{-2}	21.7 _ 10^{-2}

4_10^{12} decays/year
@ BR = 10^{-10}

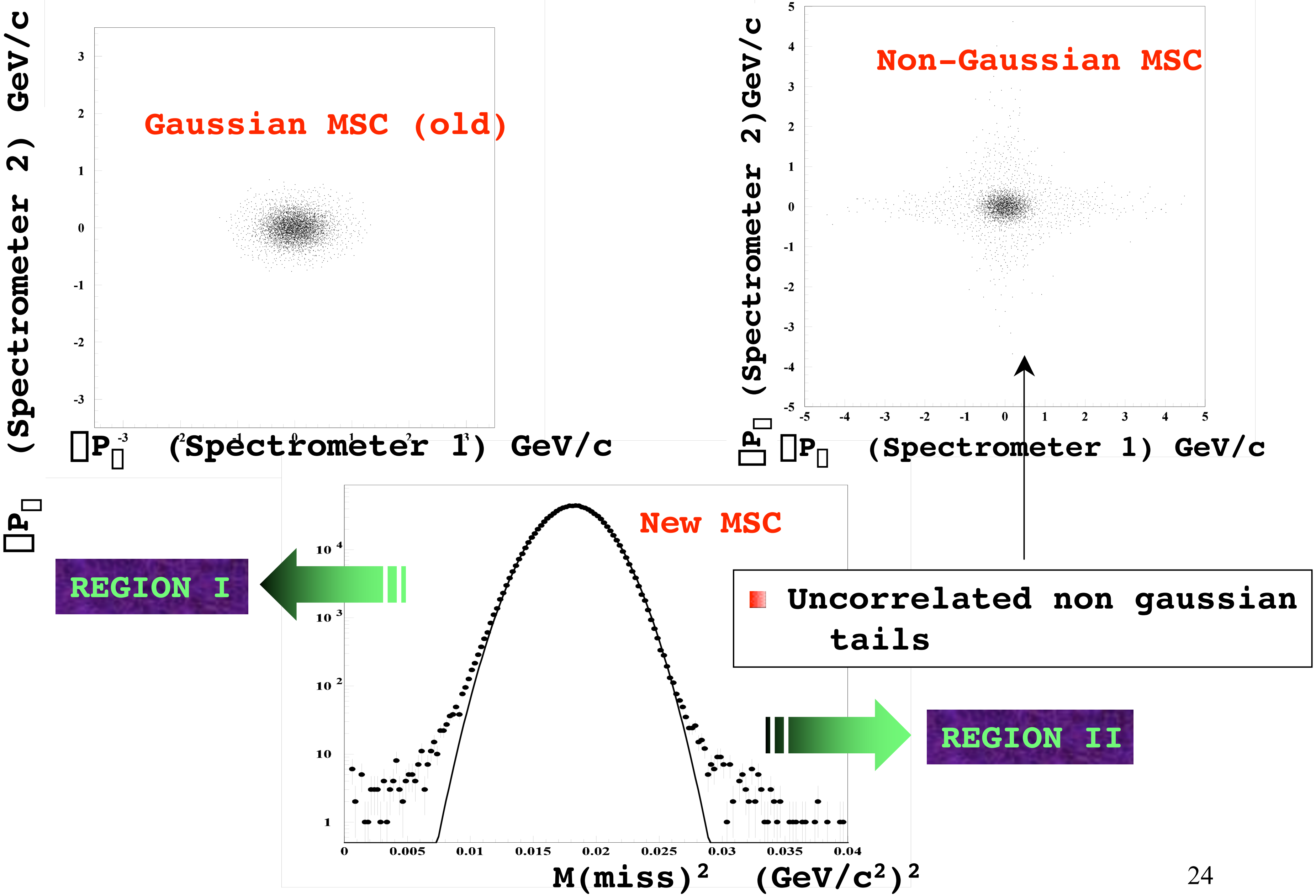
I+II (RICH)
70 events/year

Kinematical rejection



Measured quantities

NA48/3 simulation



Backgrounds to $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

		Veto	kinem.	acc.%	bck.
$\mu^+\nu$	63 %	5.10^{-6}	2.10^{-6}	30	8(<1*)
$\pi^+\pi^0$	21 %	3.10^{-7}	2.10^{-5}	20	~1
$\pi^+\pi^+\pi^-$	6 %	10^{-6}	2.10^{-5}	20	~1
$\pi^+\pi^0\pi^0$	2 %	$<10^{-8}$	2.10^{-5}	15	<<1
$\pi^0\mu^+\nu$	3 %	No problem			<<1
$\pi^0e^+\nu$	5 %	$e/\pi < 10^{-3}$			<<1

* RICH

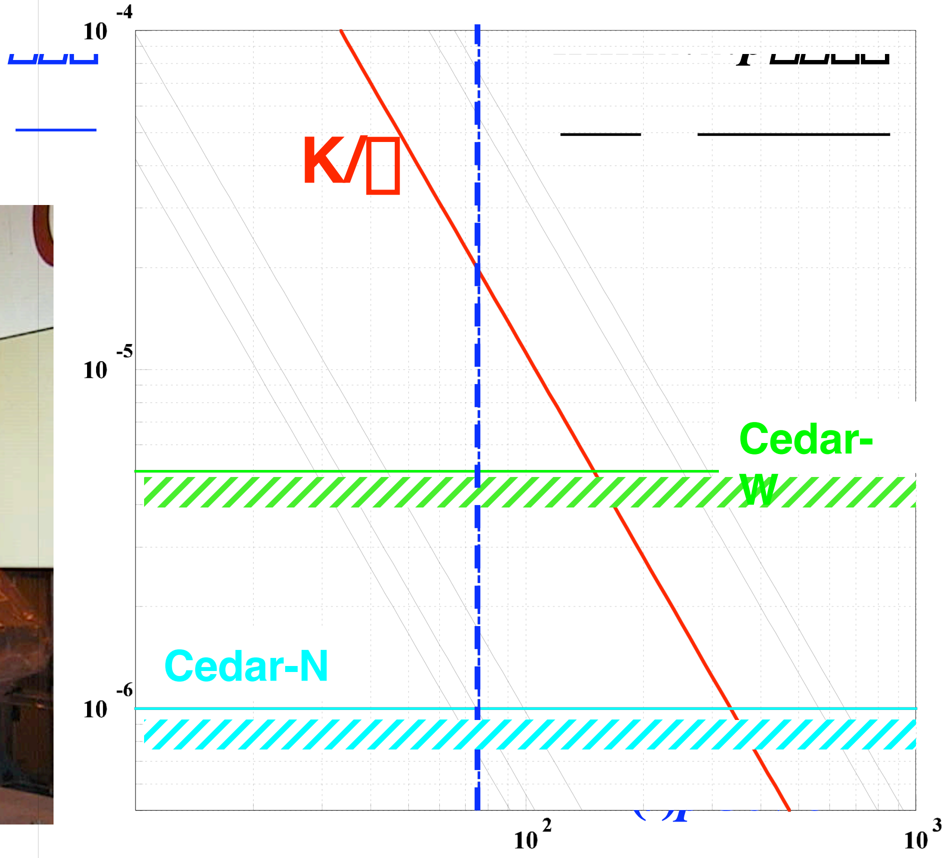
- Hermetic photon vetoes

… Design simplified by high energy K …

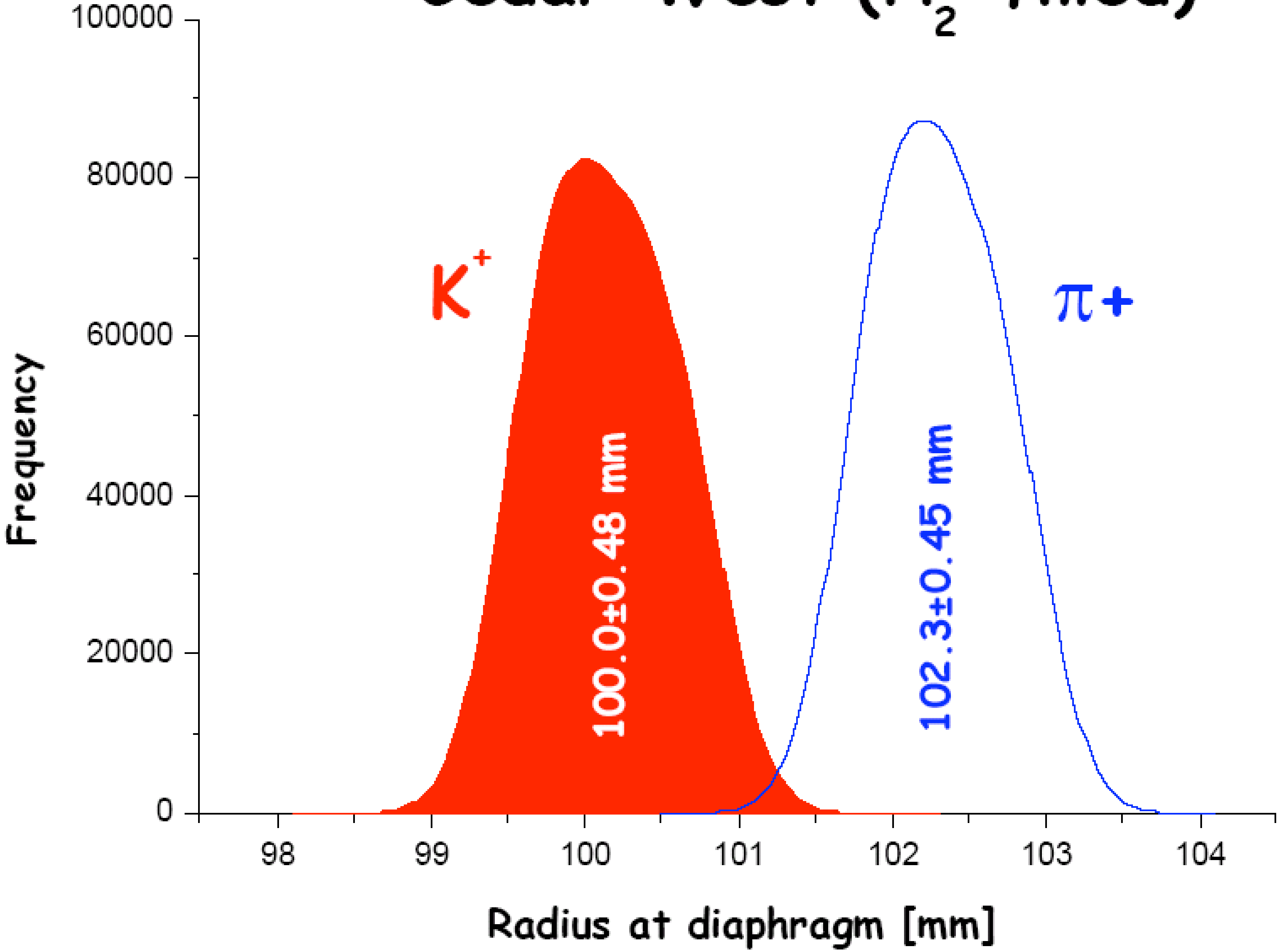
Detectors

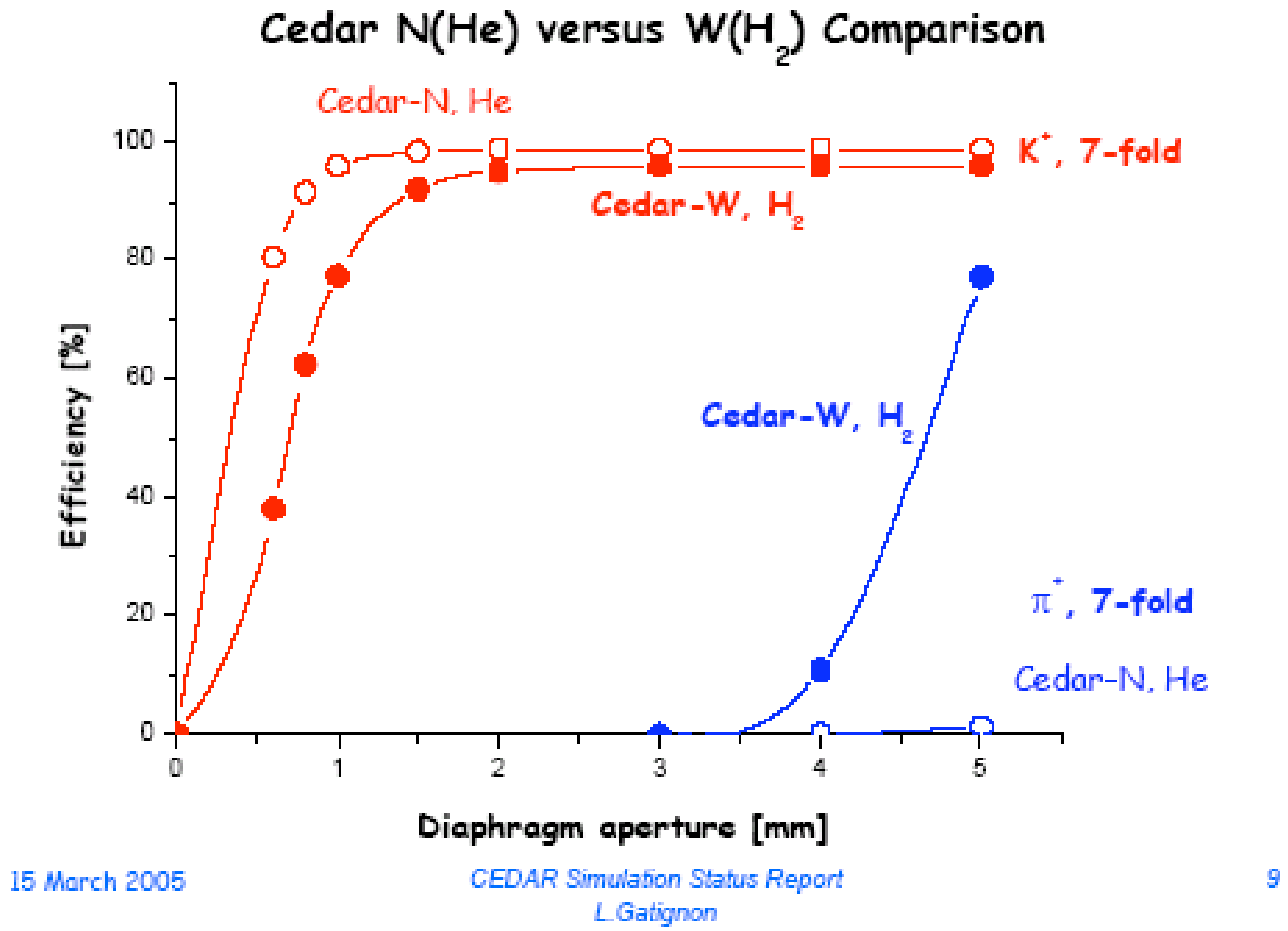
- CEDAR
  - Differential Cherenkov counter for positive kaon identification
- GIGATRACKER
  - To Track the beam before it enters the decay region
- ANTI
  - Photon vetoes surrounding the decay tank
- WC
  - Straw chambers to track the kaon decay products
- RICH
  - For redundant muon/pion separation
- CHOD
  - Fast hodoscope to make a tight kaon-pion time coincidence
- LKR
  - Forward photon veto and e.m. calorimeter
- MAMUD
  - Hadron calorimeter, muon veto and sweeping magnet
- SAC and CHV
  - Small angle photon and charged particle vetoes

CEDAR



Cedar-West (H_2-filled)



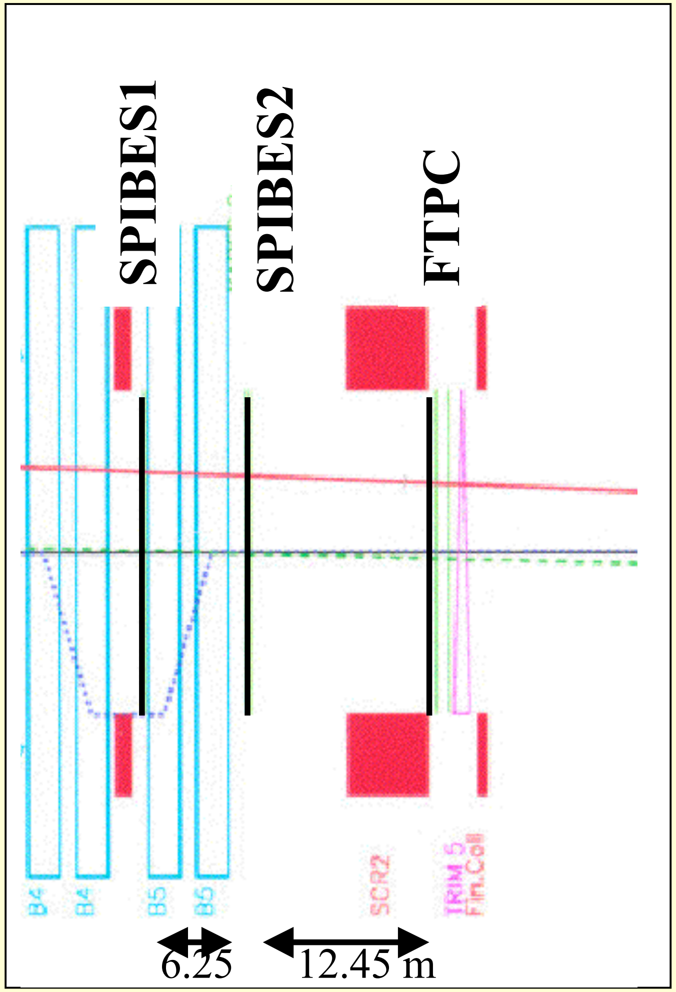


Cedar N(He) versus W(H2) Comparison
Cedar-N, He
K+, 7-fold
Cedar-W, H2
Cedar-W, H2
π+, 7-fold
Cedar-N, He
Efficiency [%]
Diaphragm aperture [mm]
0
20
40
60
80
100
0
1
2
3
4
5
15 March 2005
CEDAR Simulation Status Report
L.Gatignon
9

GIGATRACKER

- Specifications:
  - Momentum resolution to ~ 0.5 %
  - Angular resolution ~ 10 μrad
  - Time resolution ~ 100 ps
  - Minimal material budget
  - Perform all of the above in
    - 800 MHz hadron beam, 40 MHz / cm^2
- Hybrid Detector:
  - SPIBES (Fast Si micro-pixels)
    - Momentum measurement
    - Facilitate pattern recognition in subsequent FTPC
    - Time coincidence with CHOD
  - FTPC (NA48/2 KABES technology with FADC r/o)
    - Track direction

GIGATRACKER



_ momentum: use SP1 and SP2 to measure y = 40 mm displacement. Assuming _$_p$~50µm from pixel and 350µm thick Si (0.37% X_0)

✓ _ = (_$_p$√2 ‡ _$_{MS}$)/ 40 mm = 0.25%

_ direction: use SP2 and FTPC. Assuming _$_p$~100µm from pixel and similar from FTPC and no MS from FTPC (from SP2 no influence)

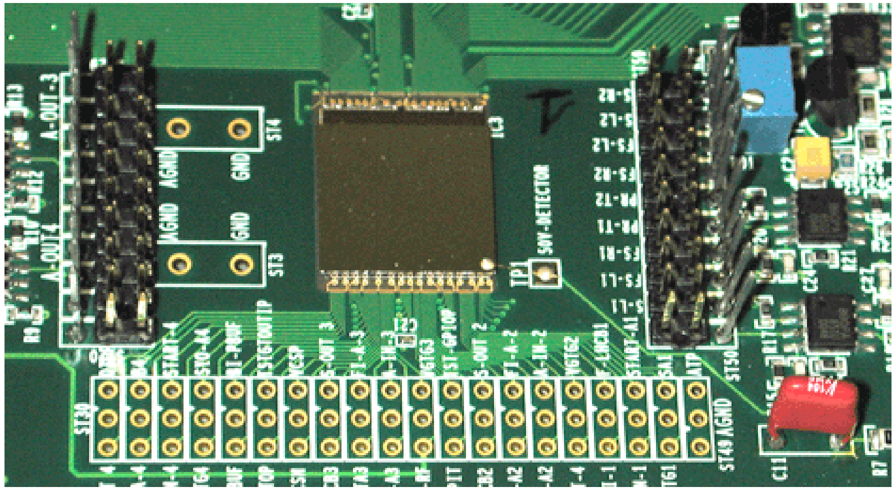
✓ Δ_$__$ = _$_p$√2 / 12.4m = 11µrad

_ time resolution: essential to obtain a low background due to accidental hits and to allow the pattern recognition (see result from test beam) . For a pixel C≈ 100 fF a risetime ~ 2 ns should be achievable for 130 nm technology and a good S/N.

Single Chip Alice Assembly tested in NA48/2

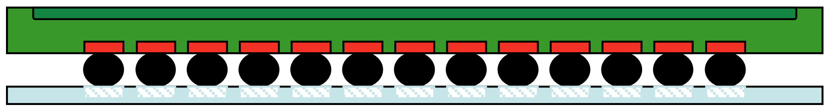
<u>Assembly 7:</u>

- 150µm thick ALICE chip
- 200µm thick sensor
- 1.1 % X_0 all together



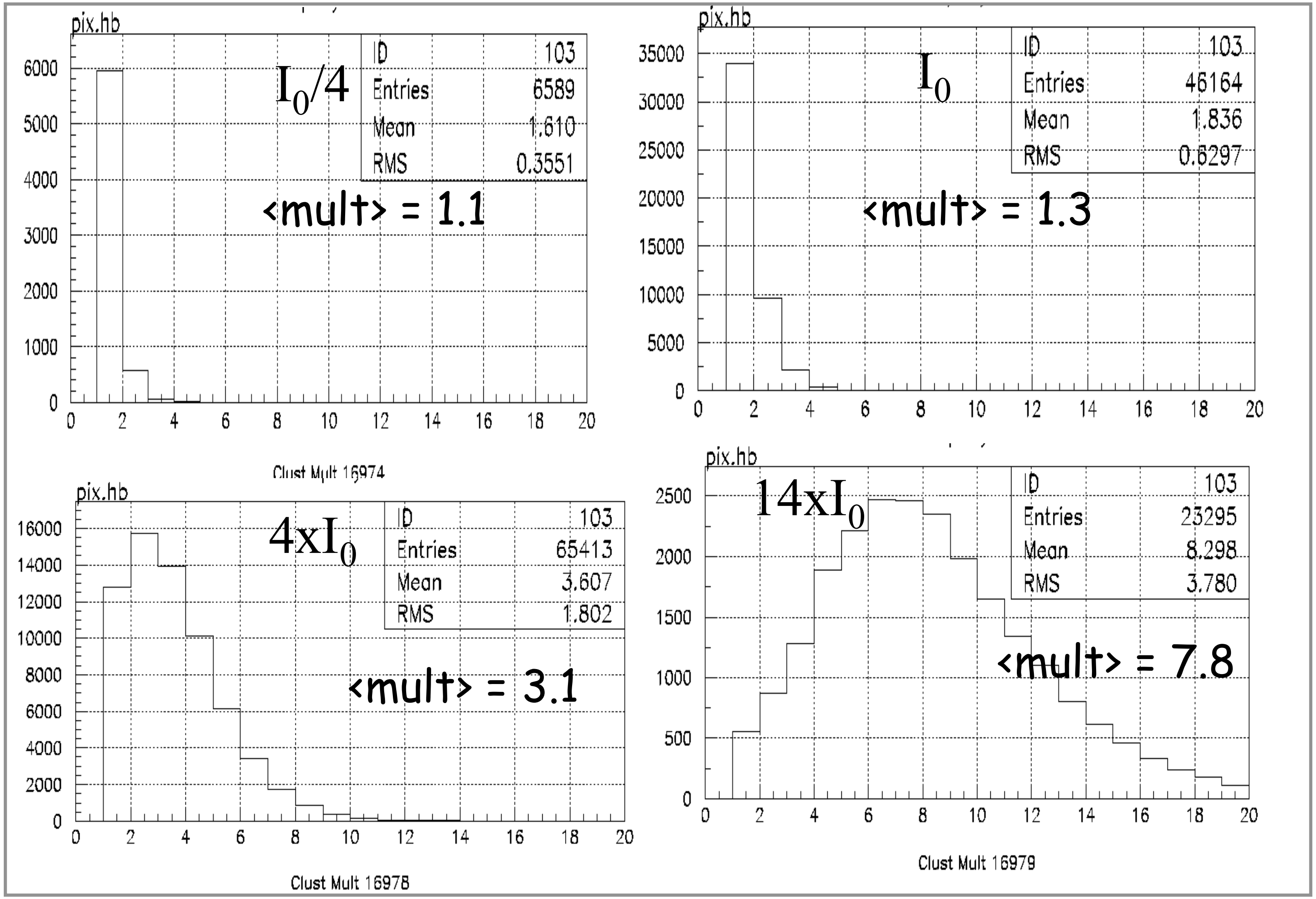
Mounted on a thin test-PCB

V_{fd}=15V
V_{op}=50V

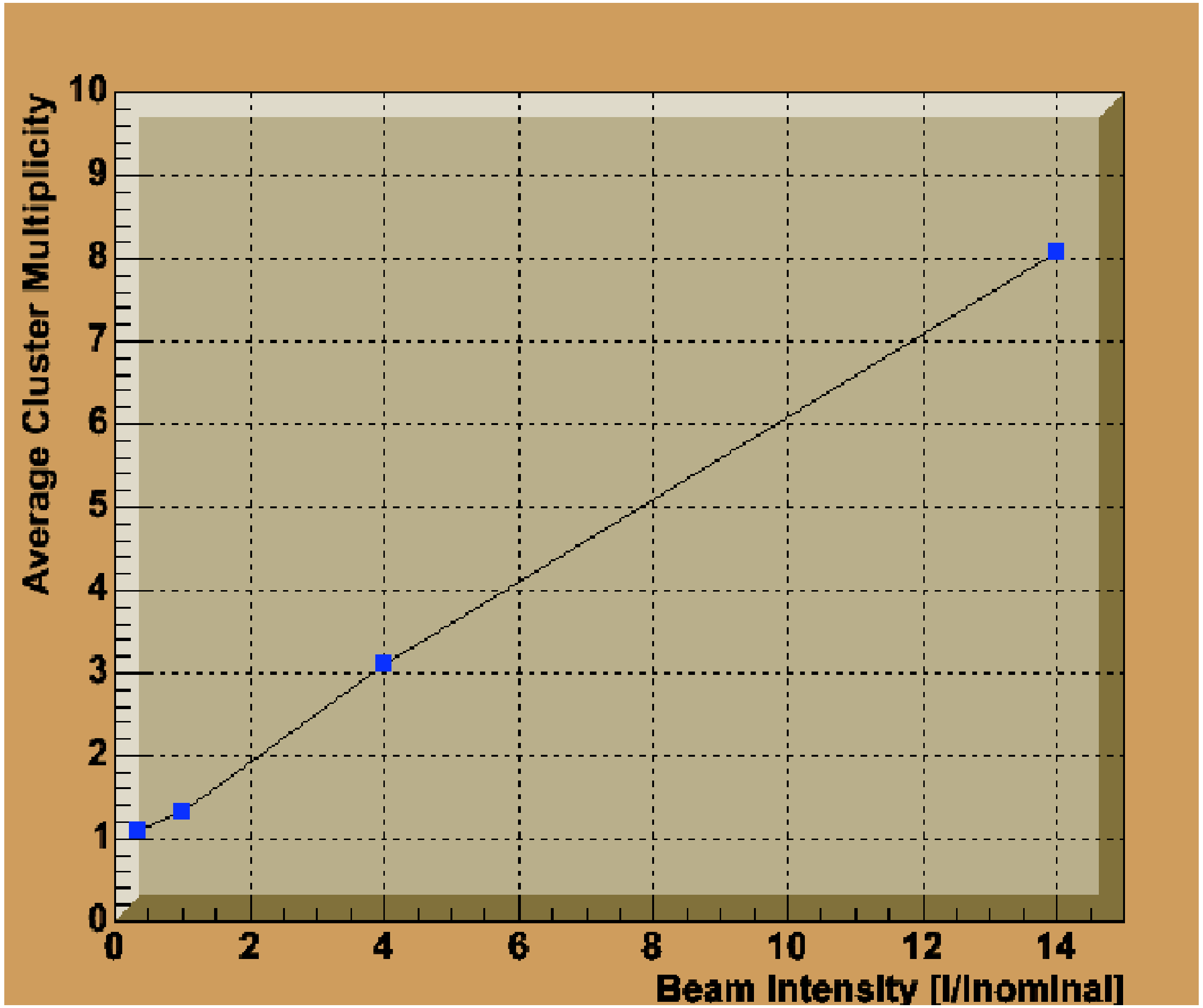


8192 pixels
Produced 2003, tested in ALICE p-TB 2003

MULTIPLICITY (200 ns gate)



MULTIPLICITY (200 nsec gate)

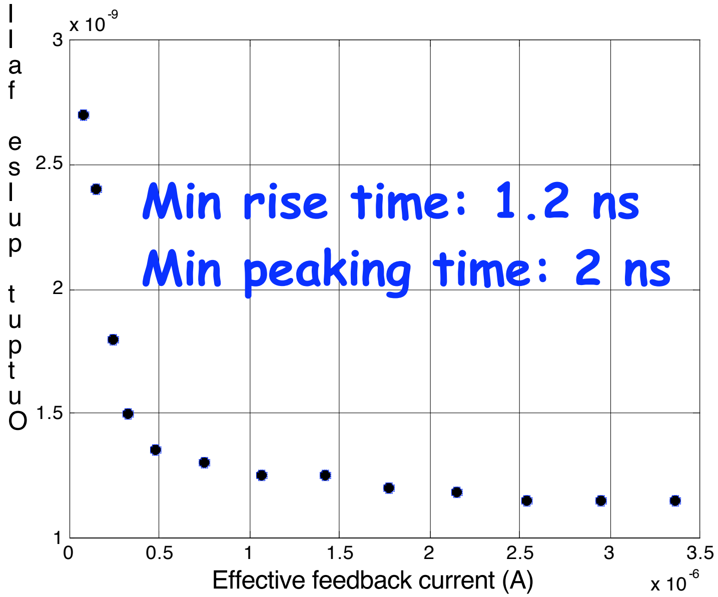


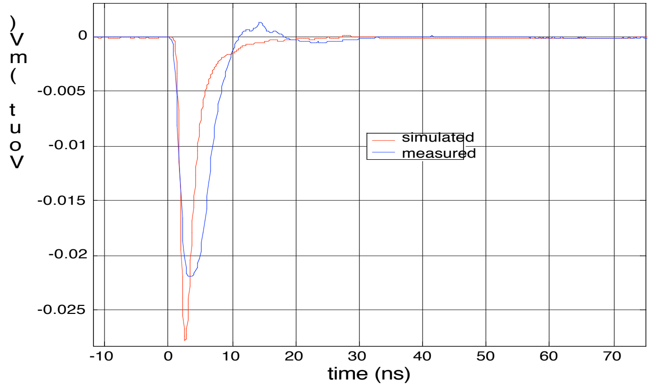
for r/o window
of 10 ns:

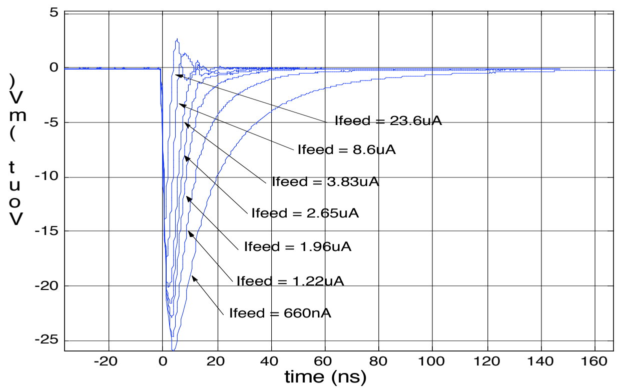
1GHz x 10 ns x 1.1 ~
10 hits/ trig

for _ = 100ps we
expect in a ±2.5_:
0.5 accident hits/trig

Active Feedback Preamp in 0.13μm CMOS







Good noise and speed performance, but again power > 1 mW

M. Despeisse – G. Anelli

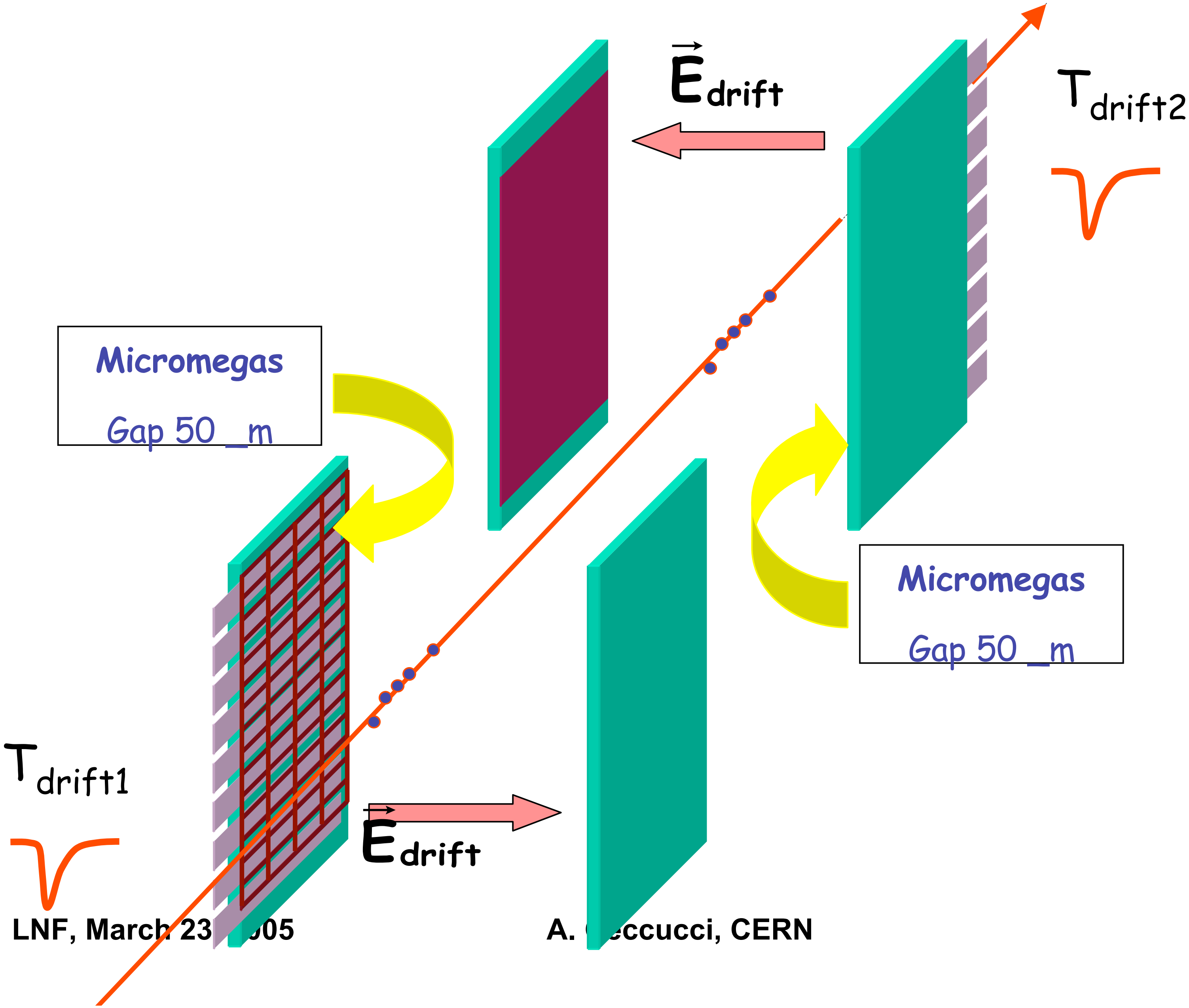
SPIBES ASIC

- Two options have been considered:
  - Minimum pixel-level processing with global time-stamp generator
  - Pixel level timing (e.g. 1 TDC/pixel)
- In option 1 the clock is not distributed to the pixels.
- Option 1 requires more area at the chip periphery.
- Option 2 increases the dead time of the pixel and may require high precision analogue components.
- Option 2 requires more area at the pixel level

FTPC (KABES+FADC)

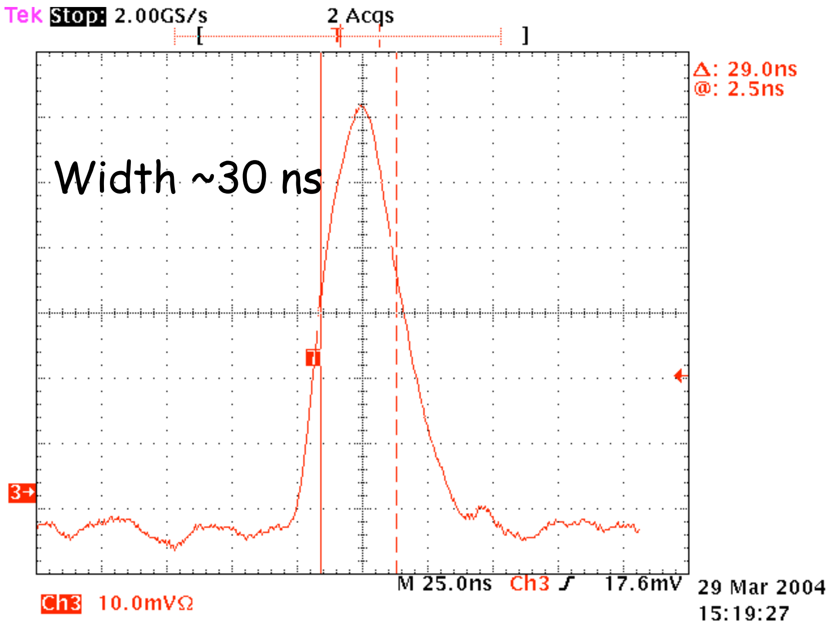
- NA48/2
  - KABES has achieved very good performance
  - Position resolution ~ 70 micron
  - Time resolution ~ 0.6 ns
  - Rate per micro-strip ~ 2 MHz
- NA48/3
  - Intensity ~ 10 higher per unit area
  - 600 ns drift
  - The long drift (600 ns) makes a standalone pattern recognition very difficult or just impossible (That's why we plan to have SPIBES in front)
  - To reduce double pulse resolution and improve the time resolution one has to reduce the pulse duration and possibly read-out every micro-strip with 1 GHz FADC

KABES principle: TPC + micromegas

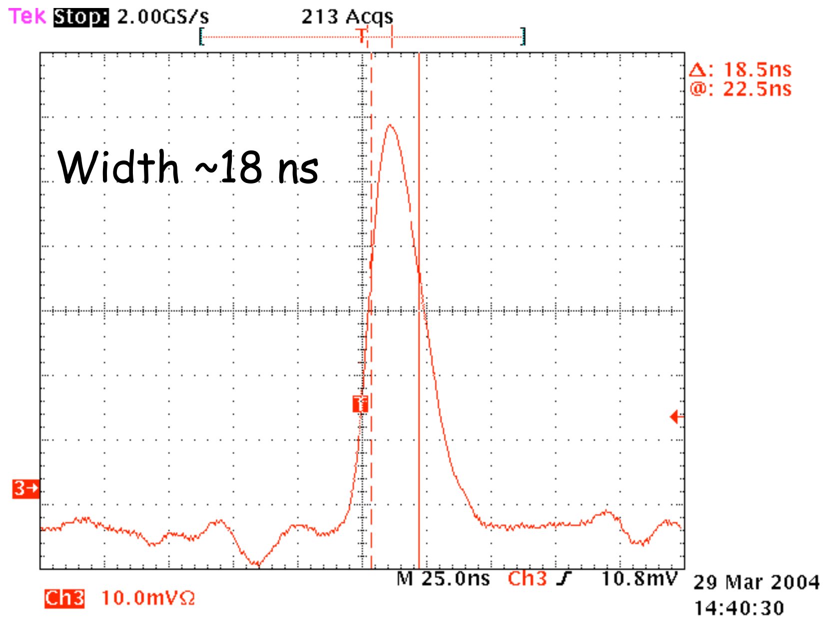


KABES 25 micron amplification gap

Recent lab test with 25 μm gap



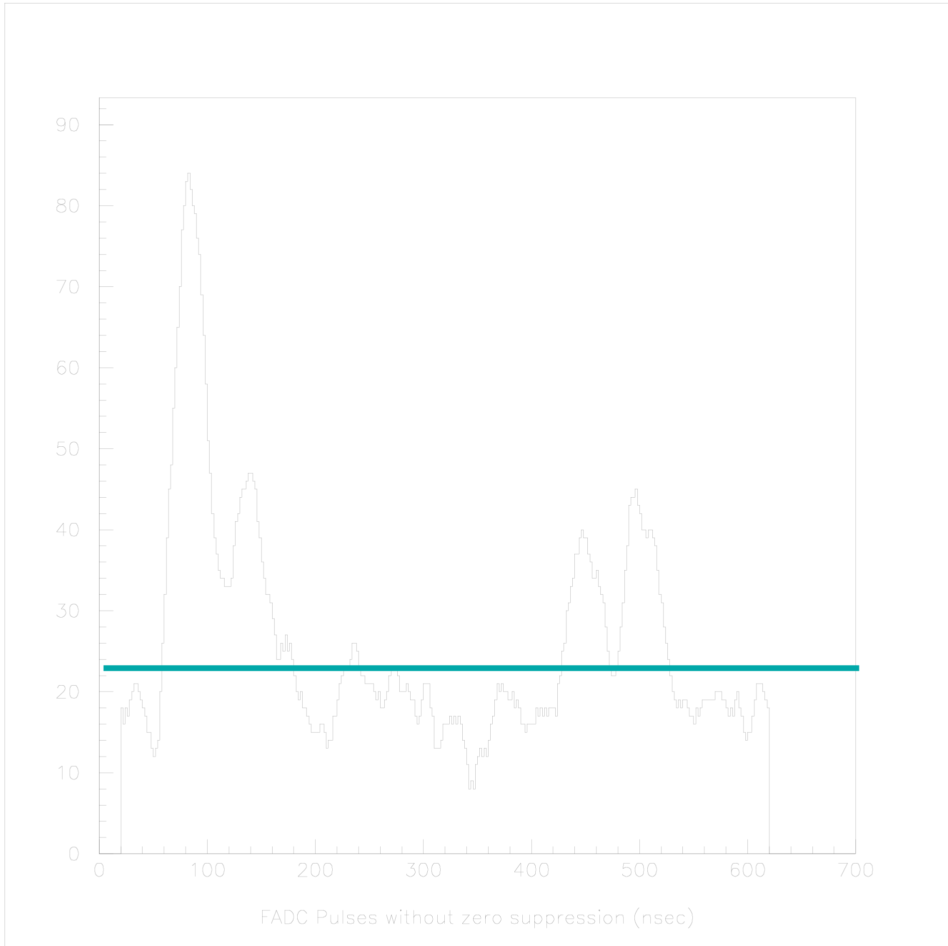
50 μm gap



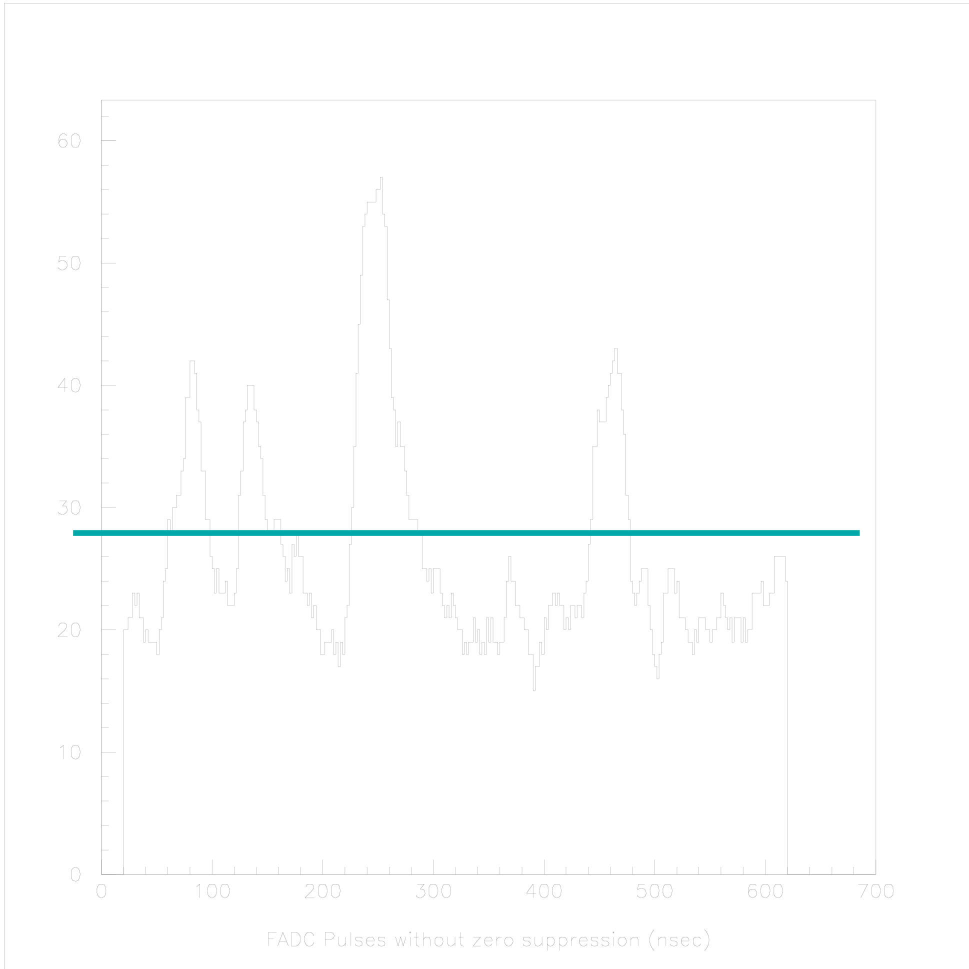
25 μm gap

improvement of occupancy observed with 25μm amplification gap

480 MHz FADC



90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
FADC Pulses without zero suppression (nsec)



60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
FADC Pulses without zero suppression (nsec)

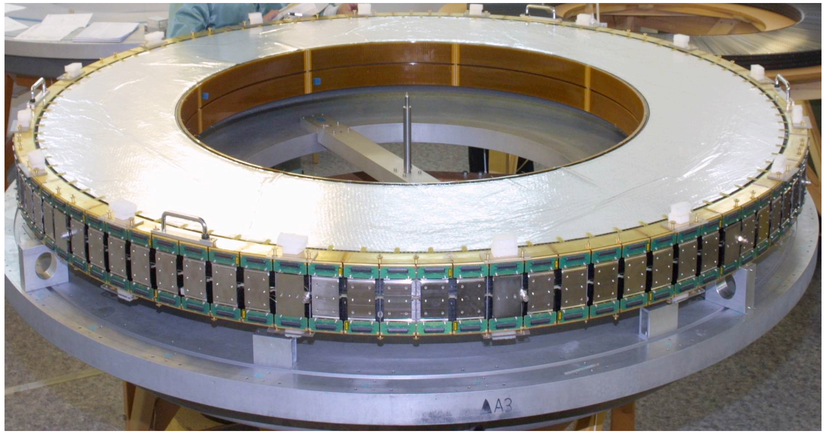
Straw Tracker

COMPASS TRACKER

Straw diameter – 6 and 10 mm, length up to 3.8 m

TRT ATLAS

Straw diameter – 4 mm, length – 40 and 150 cm



15 chambers were built in JINR

Straw tracker operated in vacuum:

COSY-TOF, Juelich,IKP

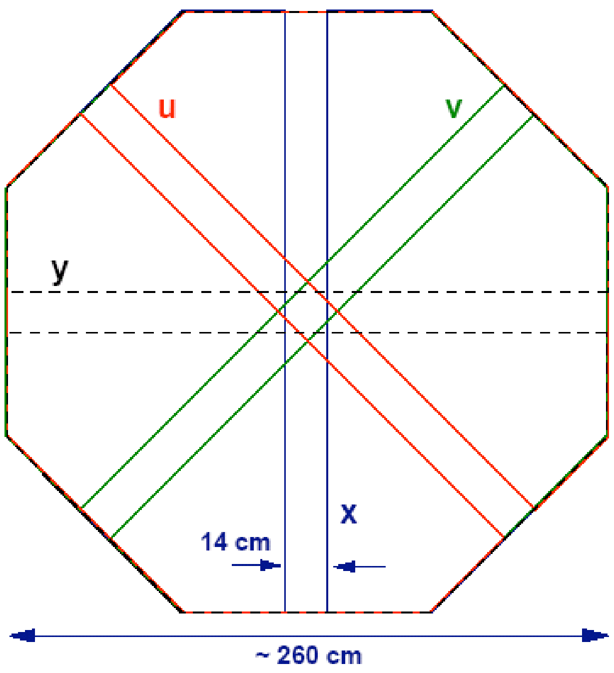
Straw tracker, 3100 straws, evacuated –

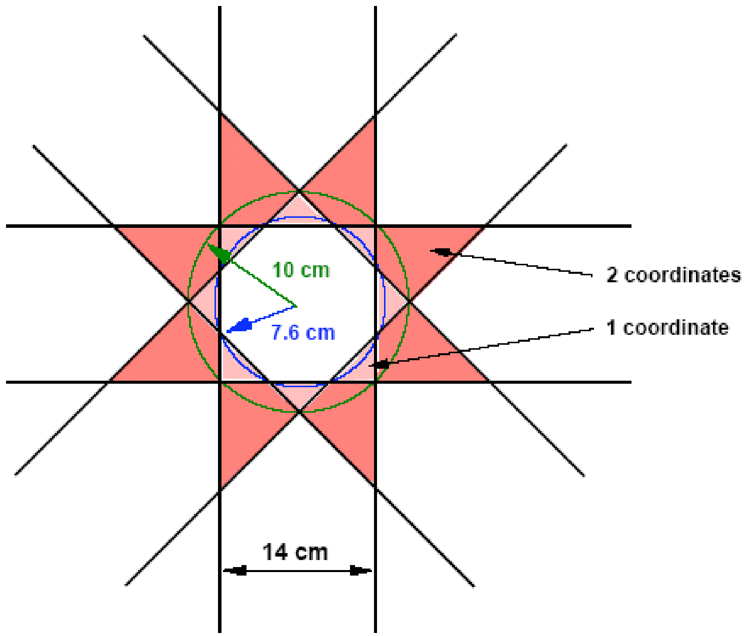
10^{-3} mbar (P.Wintz)

MECO, BNL (W.Molzon)

Etc.

Octagonal Configuration



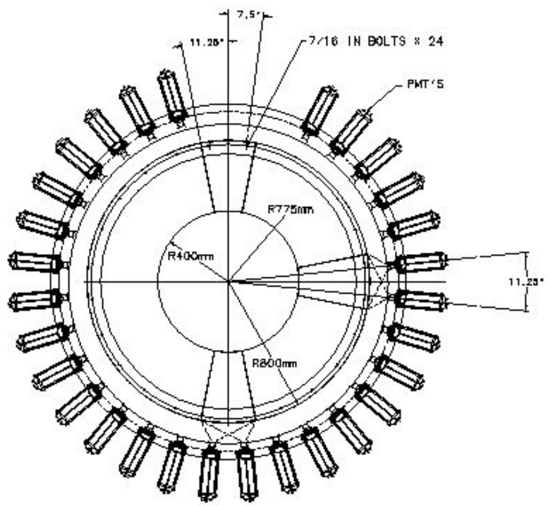


- Similar design as current drift chambers.
- Small regions with only 1 or 2 views.
- **But:** 4 double layers $\Longrightarrow$ $\sim 0.8\% \ X_0$ per station.

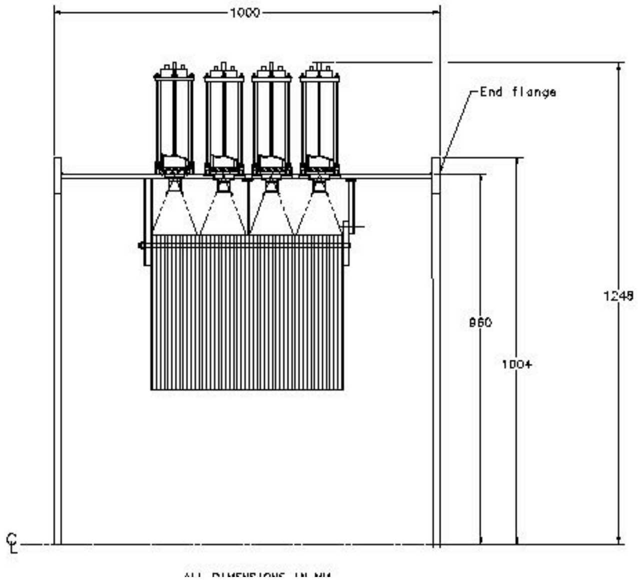
Rainer Wanke, NA48 Analysis Meeting, CERN, February 11, 2005 – p.9/17

ANTI

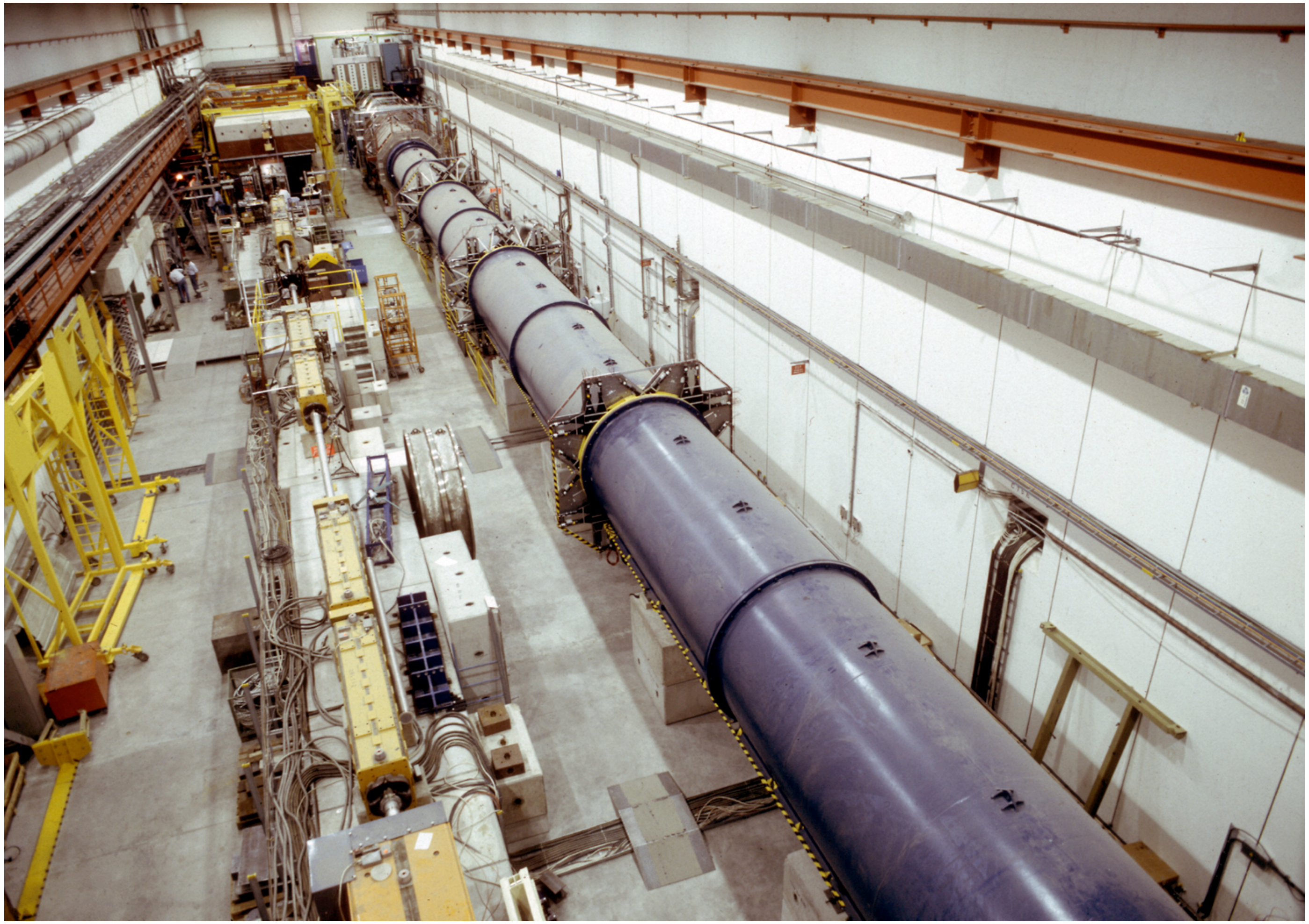
- Set of ring-shaped photon vetoes surrounding the decay tank
- Specification: inefficiency to detect photons above 100 MeV $< 10^{-4}$
- The NA48 ANTI's (AKL) need to be replaced
- Extensive R&D performed by American and Japanese groups
- Claims that inefficiency as low as 10^{-5} can be achieved
- Baseline solution: Lead/ Plastic scintillator sandwich (1-2 mm lead / 5 mm plastic scintillator)
- SPACAL and TILECAL options also being studied



CKM design

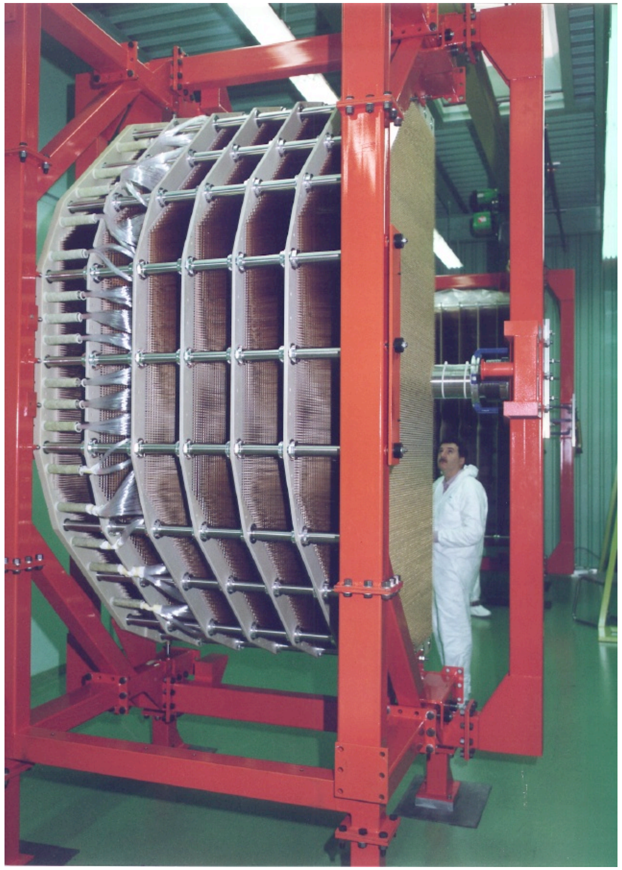


NA48 Vacuum Tank



LKR

- The NA48 Liquid Krypton Calorimeter
- Must achieve inefficiency < 10^{-5} to detect photons above 1 GeV
- Advantages:
  - It exists
  - Homogeneous (not sampling) ionization calorimeter
  - Very good granularity (~2 $\times$ 2 cm^2)
  - Fast read-out (Initial current, FWHM~70 ns)
  - Very good energy (~1%, time ~ 300ps and position (~1 mm) resolution
- Disadvantages
  - 0.5 X_0 of passive material in front of active LKR
  - The cryogenic control system needs to be updated



LKr Geant4 simulation

Two samples of $\pi^+\pi^0$ events (F. Marchetto):

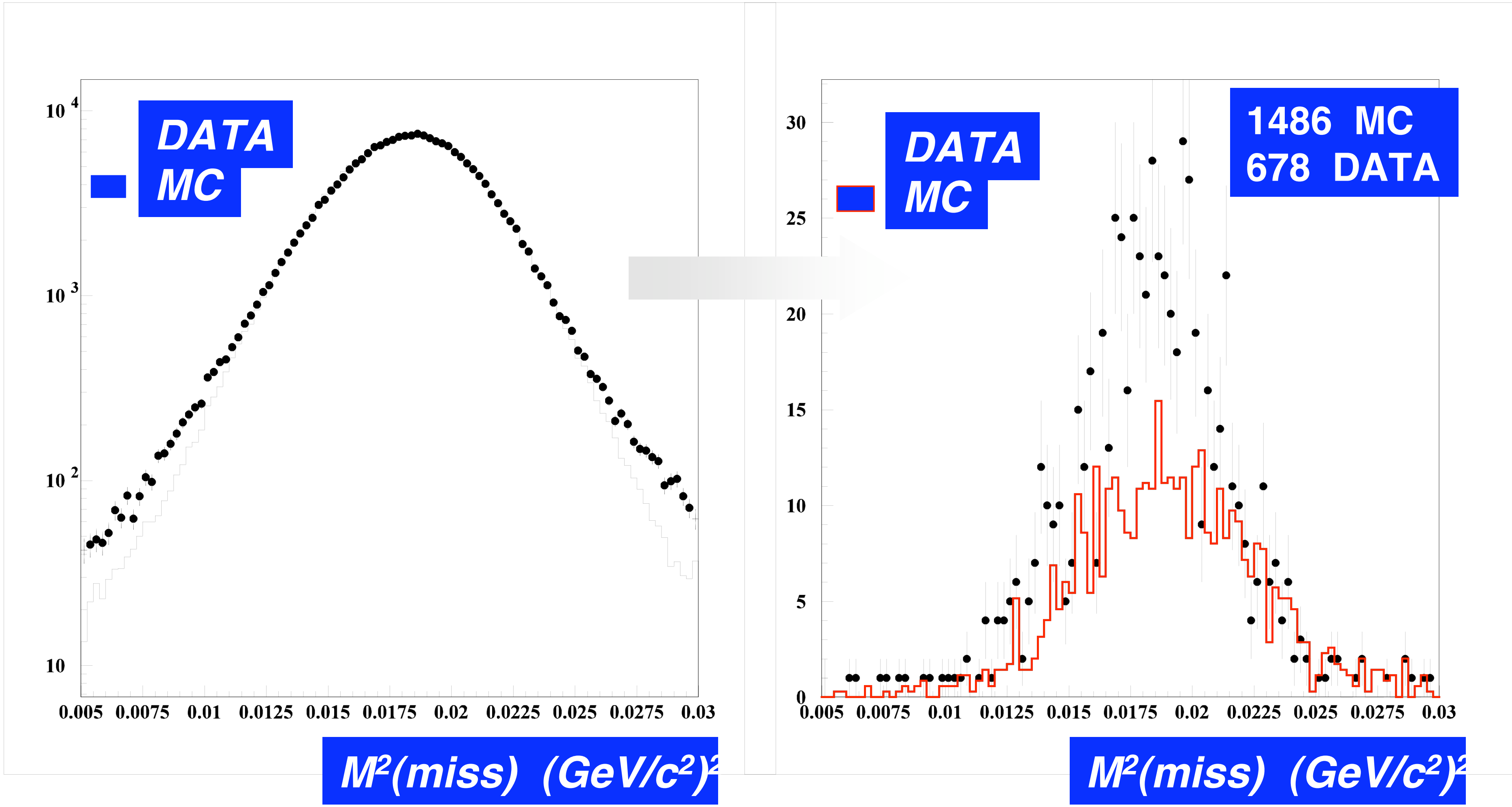
- single photon in LKR → deposited energy below 400 MeV :

  $< 1.4 \times 10^{-6}$ ($0/1.75\times10^{6}$ events generated)

- pairs of photon in LKR → deposited energy below 400 MeV :

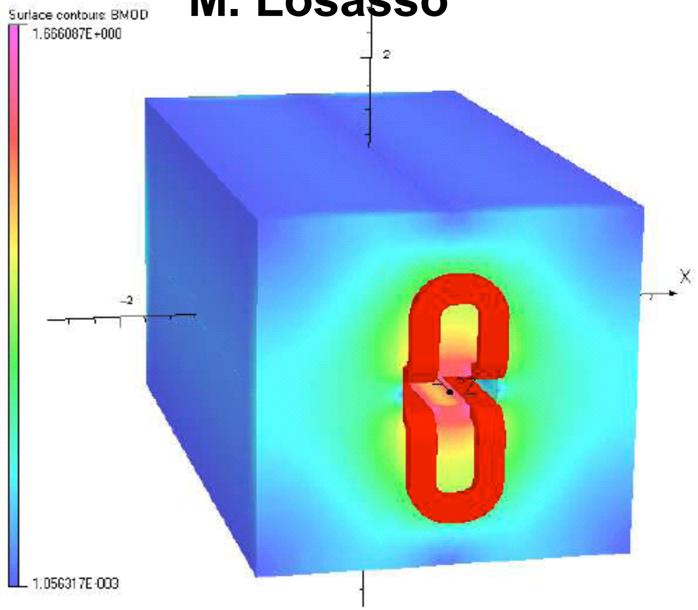
low energy photon	1.1×10^{-6} ($2/1.75\times10^{6}$ events)
high energy photon	$< 3.4\times 10^{-6}$ ($0/0.7\times10^{6}$ events)

How to measure $\pi^+\pi^0$ Rejection



MAMUD

M. Losasso



Magnetic field on iron surface

Pole gap is 2 x 11 cm V x 30 cm H

Coils cross section 10 cm x 20cm

- **To provide pion/muon separation and beam sweeping.**
  - **Iron is subdivided in 150 2 cm thick plates (260 × 260 cm^2)**
- **Four coils magnetise the iron plates to provide a**
  0.9 T dipole field in the beam region
- **Active detector:**
  - **Strips of extruded polystyrene scintillator**
    (1 x 4 x130 cm^3)
  - **Light is collected by WLS fibres with 1.2 mm diameter**

Time Schedule

- 2005
  - Launch R&D
  - Vacuum tests
  - Evaluate straw tracker
  - Start realistic cost estimation
  - Complete analysis of beam-test data
  - Submit proposal to SPSC
- 2006-2008
  - Costruction, Installation and beam-tests
- 2009-2010
  - Data Taking

Conclusions

- We have found a fortunate combination where a compelling physics case can be addressed with an existing accelerator, employing the infrastructure (i.e. civil engineering, hardware, some sub-systems) of an existing experiment
- We stress that this initiative in not a mere continuation of NA48
- We are seeking new Collaborators!