The NA62 Project at CERN: $K^+ \to \pi^+ \nu \bar{\nu}$ at the SPS

CERN-SPSC-2005-013
SPSC-P-326
CERN-SPSC-2007-035
SPSC-M760

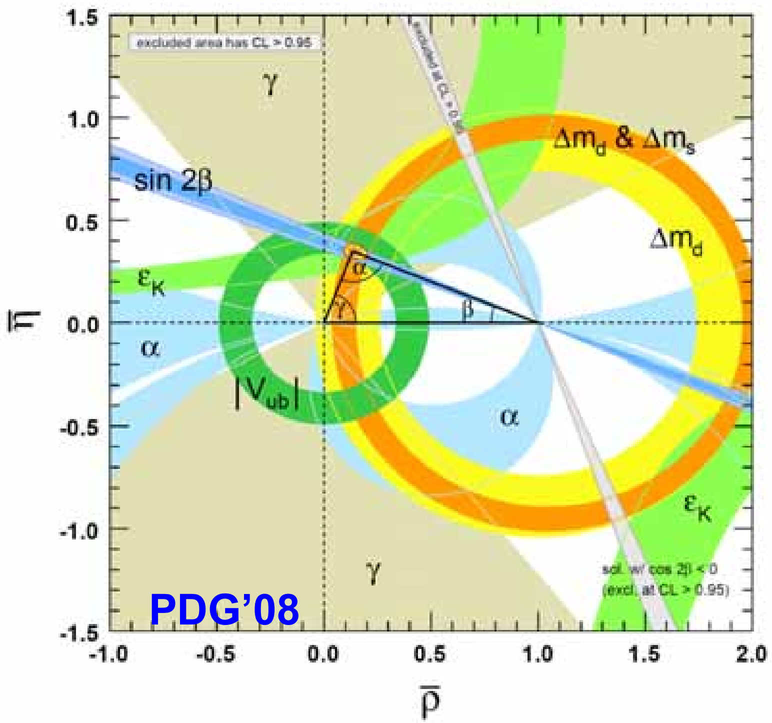
Rencontres de Moriond EW,
March, 7-14, 2009

A. Ceccucci for the NA62 Collaboration:

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

Flavor in the Era of the LHC*

- The current experimental manifestations of CP-Violation (K and B decays and mixing) are consistent with just one complex phase in the CKM matrix ("Standard Model")



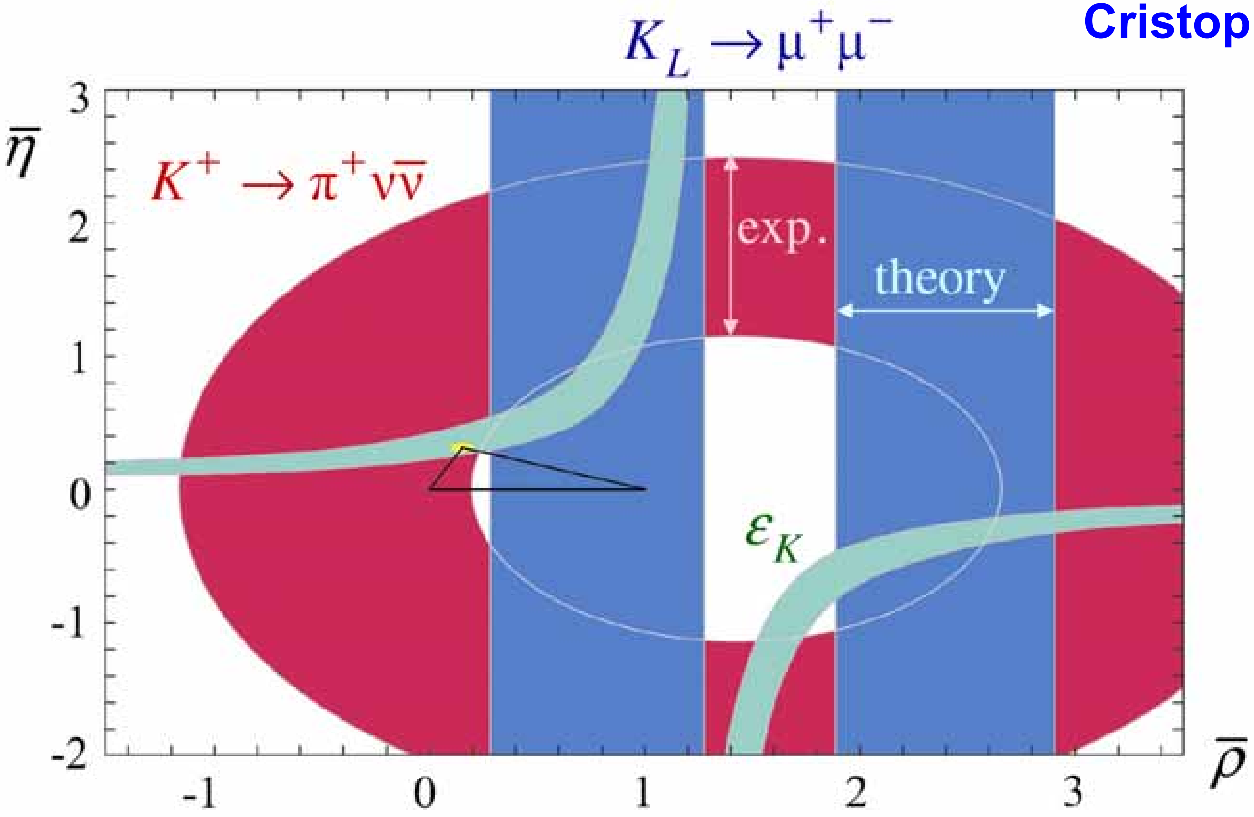
*CERN Extended workshop, Nov 2005, March 2007, Edited by R. Fleischer, T. Hurth and M.L. Mangano
EPJ C, 57, Vol 1-2, Sept 2008

"[These articles] confirm that flavour physics is an essential ingredient in the future of high-energy physics"

- Paradigm shift: we should determine the "true" CKM parameters from observables not affected by New Physics (e.g. B tree decays) and measure loop-induced, precisely predictable (SM), FCNC to detect patterns of deviation

Rare Kaon Decays

Cristopher Smith @ CKM '08



$K_L \to \pi^0 \nu\bar{\nu}$: $\bar{\eta} < 17$

$K_L \to \pi^0 e^+ e^-$: $\bar{\eta} < 3.3$

$K_L \to \pi^0 \mu^+ \mu^-$: $\bar{\eta} < 5.4$

$K \to \pi\nu\bar{\nu}$: A theoretically pristine and experimentally almost unexplored opportunity

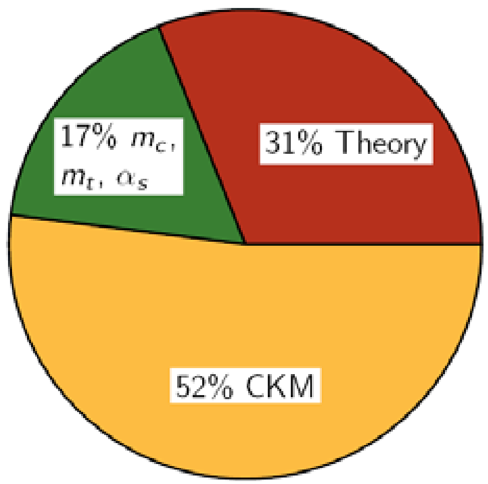
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Physics Motivation

In the Standard Model:

$$B(K^+ \to \pi^+ \nu \bar{\nu}(\gamma)) = k_+ (1 + \Delta_{EM}) \times \frac{|V_{ts}^* V_{td} X_t(m_t^2) + \lambda^4 \, \mathrm{Re} V_{cs}^* V_{cd} (P_c(m_c^2) + \delta P_{c,u})|^2}{\lambda^5}$$

- **NLO QCD [Buchalla, Buras '94], [Misiak, Urban '99], [Buchalla, Buras '99]**
- **Charm**
  - **NNLO QCD [Buras, Gorbahn, Haisch, Nierste '06]**
  - **EW Corrections to P_c [Brod, Gorbahn '08]**
- **Long Distance**
  - **$|\Delta E| <$ 1% [Mescia, Smith '07]**
  - **$\delta P_{c,u}$ +6% [Isidori, Mescia, Smith '05]**

•The SM Branching Ratio prediction is precise (~8%) and the intrinsic theory error is small
•The parametric error will be further reduced



[J. Brod @ CKM'08]

SM Prediction vs. Experiment

As reported by J. Brod, CKM '08

$$B^{TH}(K^+ \to \pi^+ \nu \bar{\nu}(\gamma)) = (0.85 \pm 0.07) \times 10^{-10}$$

For m_c=(1286 ± 13) MeV   [Kühn et al. '07]

$$B^{EXP}(K^+ \to \pi^+ \nu \bar{\nu}(\gamma)) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

[E787, E949 '08]

And, for comparison:

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

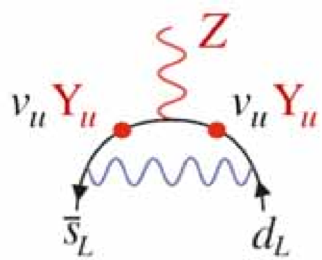
$$B^{EXP}(K_L^0 \to \pi^0 \nu \bar{\nu}) \leq 6.8 \times 10^{-8} \quad 90\% \text{ CL}$$ [E391a '08]

Future: E14 (KOTO) @ J-PARC

Kaon Rare Decays and NP

(courtesy by Christopher Smith)

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

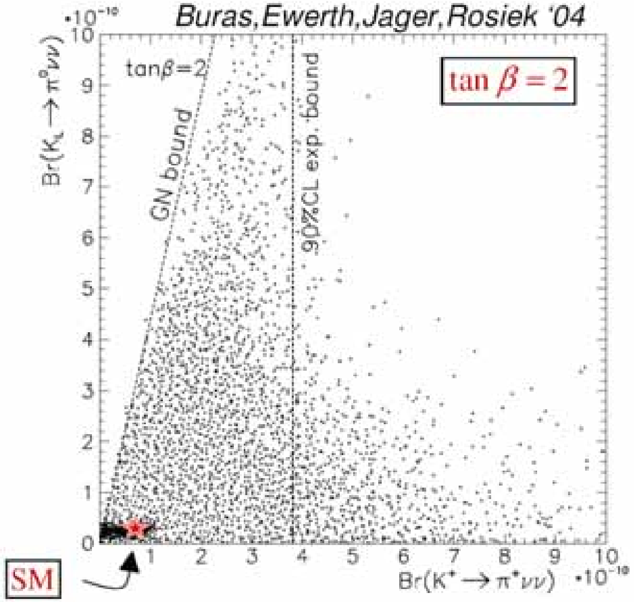


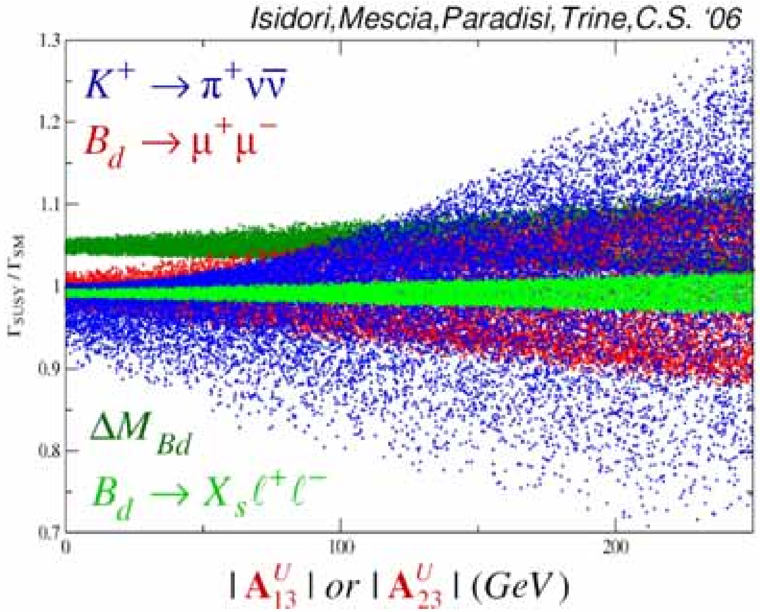
- $SU(2)_L$ breaking: $SM : v_u^2 Y_u^{*32} Y_u^{31} \sim m_t^2 V_{ts}^* V_{td}$

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

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

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

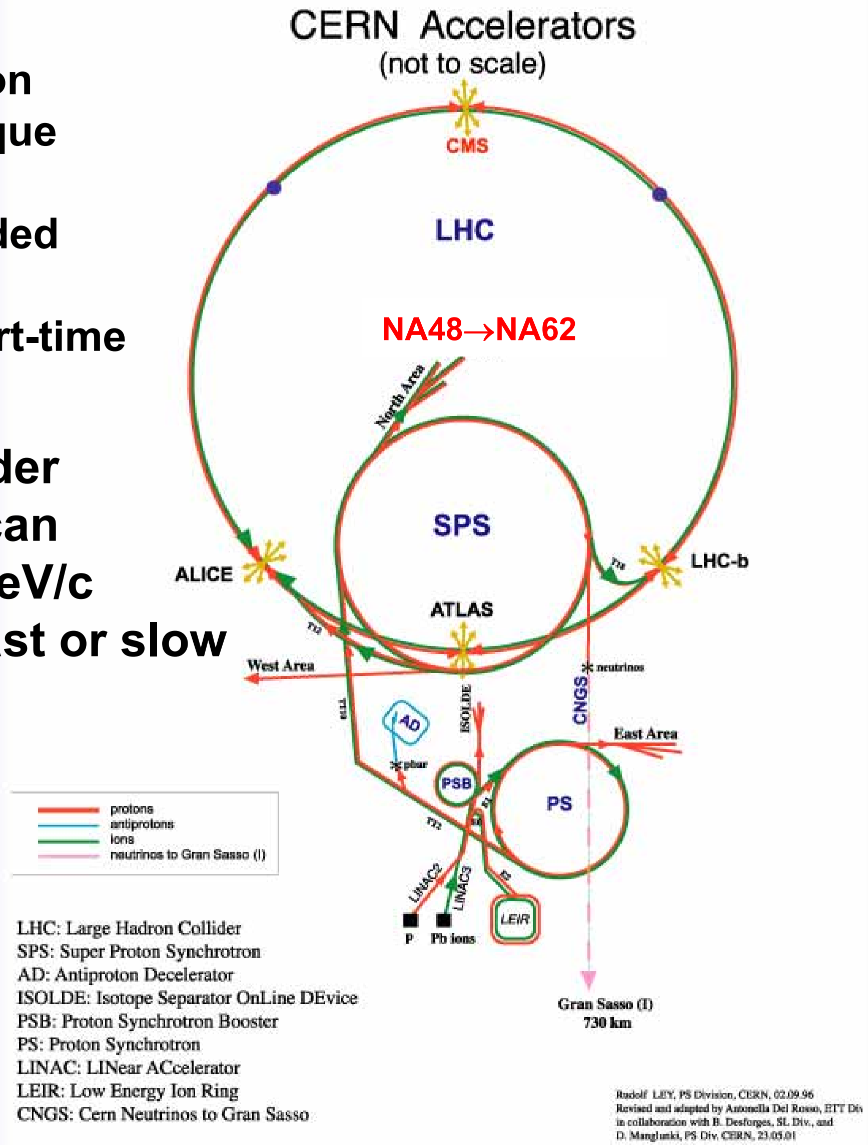




The CERN proton Complex is unique

The SPS is needed as LHC proton injector only part-time

For the reminder of the time it can provide 400 GeV/c protons for fast or slow extraction

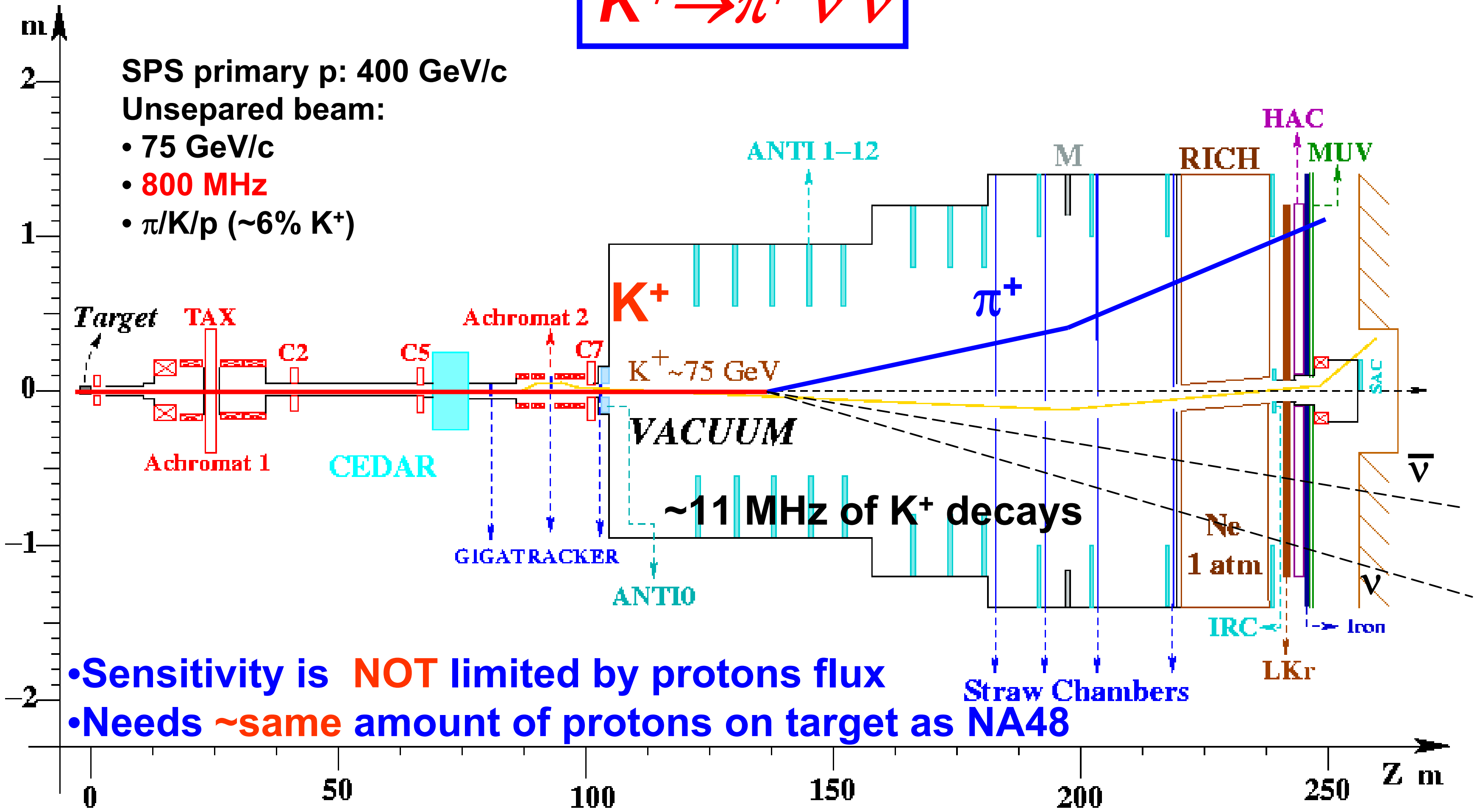


Nota Bene:
NAYY ≡ YYth Experiment Performed at the North Area SPS Extraction site

Proposed Detector Layout

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

SPS primary p: 400 GeV/c
Unsepared beam:
- 75 GeV/c
- 800 MHz
- π/K/p (~6% K⁺)



•Sensitivity is NOT limited by protons flux
•Needs ~same amount of protons on target as NA48

Principles of NA62

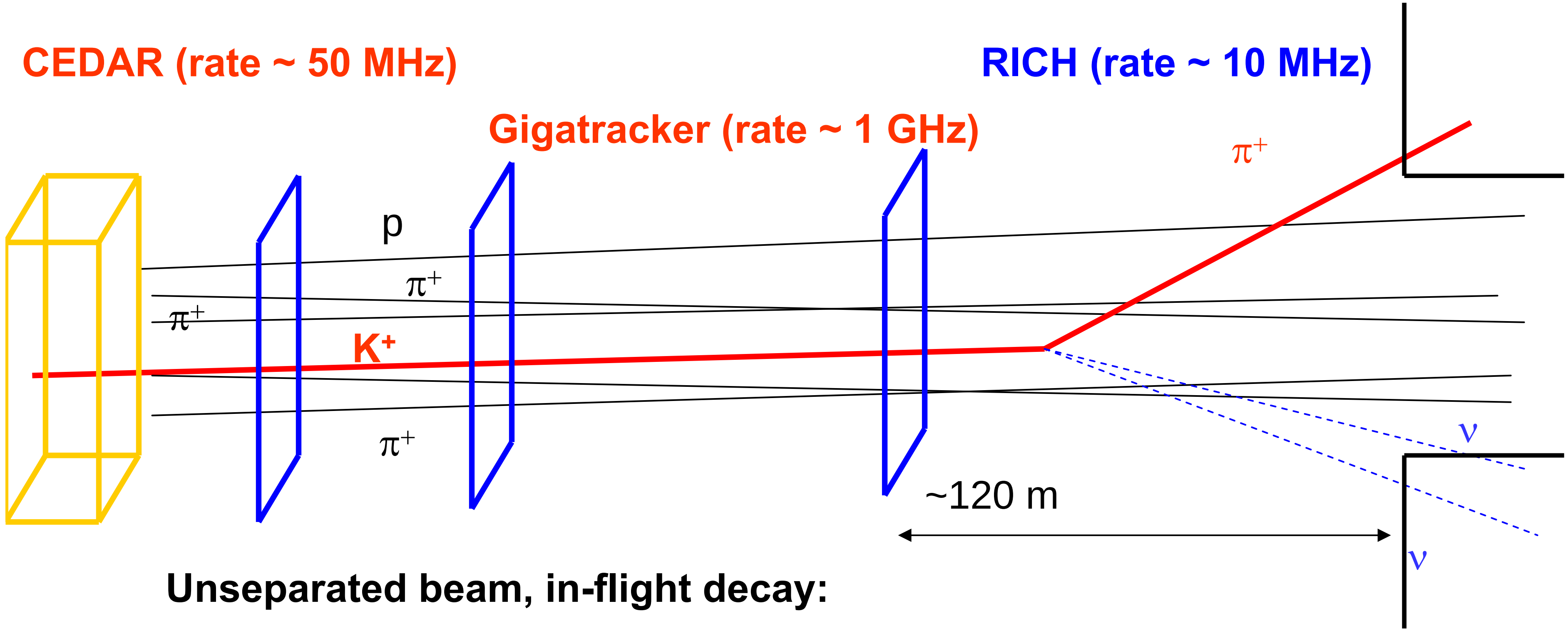
- **High momentum kaon beam to improve the rejection of the π^0 induced backgrounds**
- **Decay in-flight to avoid the scattering and the backgrounds introduced by the stopping target**

The experimental technique exploits:

1. **Precise timing to associate the outgoing π^+ to the correct incoming parent particle (K^+)**
2. **Kinematical Rejection of two- and three-body backgrounds**
3. **Vetoes (γ and μ)**
4. **Particle Identification (K/π, π/μ)**

To achieve the required background suppression, these techniques have to be combined together and possible correlations have to be measured

1. Precise Timing

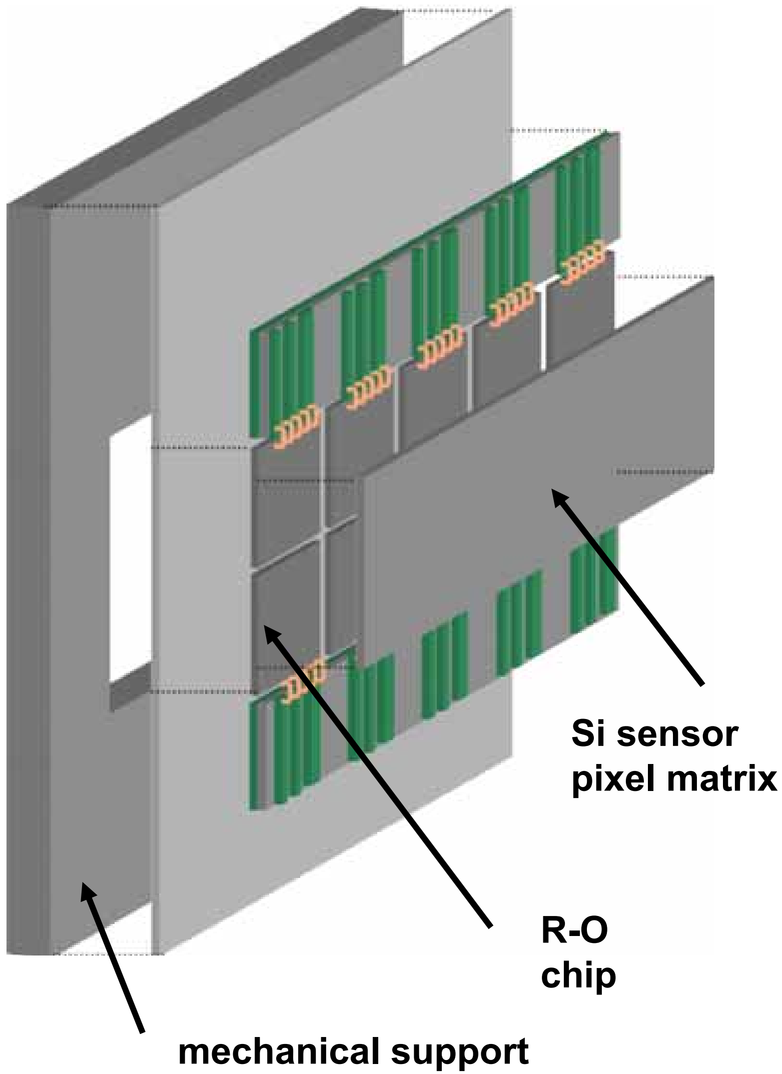


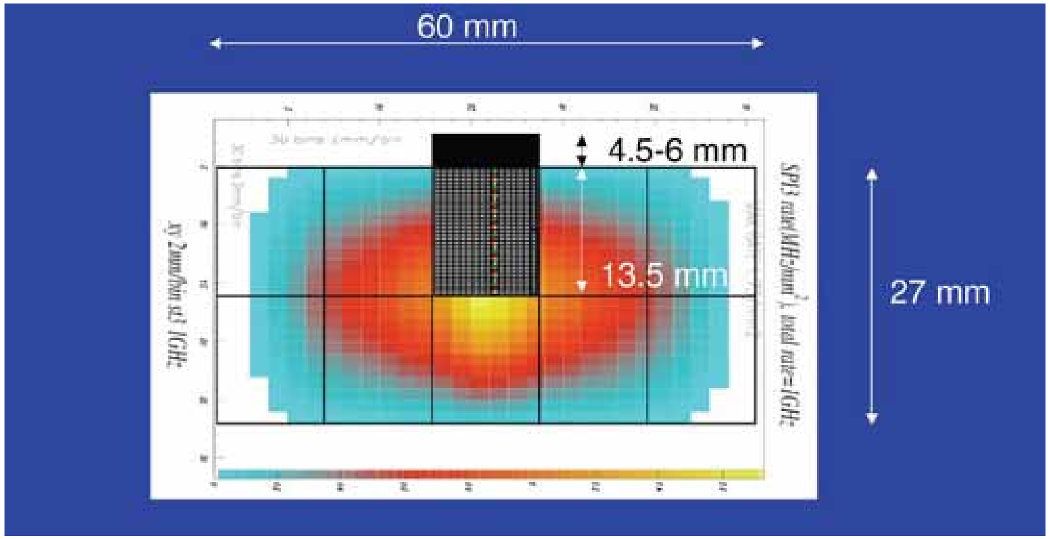
Unseparated beam, in-flight decay:

How do you associate the parent kaon to the daughter pion in a **~1 GHz beam** ?

K^+ : Gigatracker (pixel detector) with very good time resolution **(~ 100 ps)**
π^+ : **RICH** (Neon, 1 atm) read out by Photomultipliers

GTK Station





Requirements:

Track and time each beam particle

Time resolution: 200 ps / station

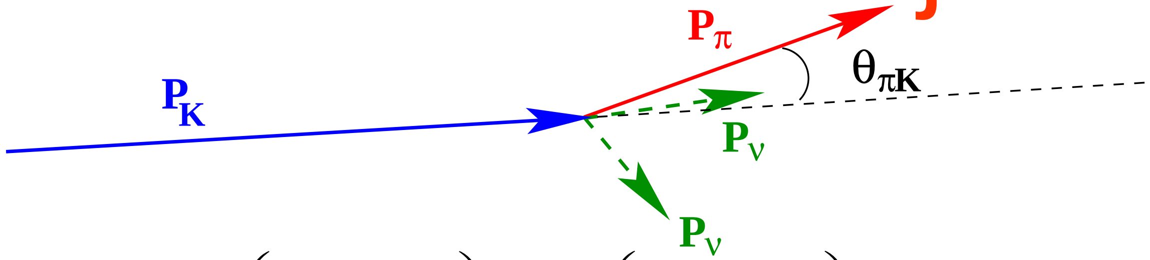
Material Budget: < 0.5 % X_0 / station

Pattern: 300 x 300 μm^2

Two options for the Read-Out:

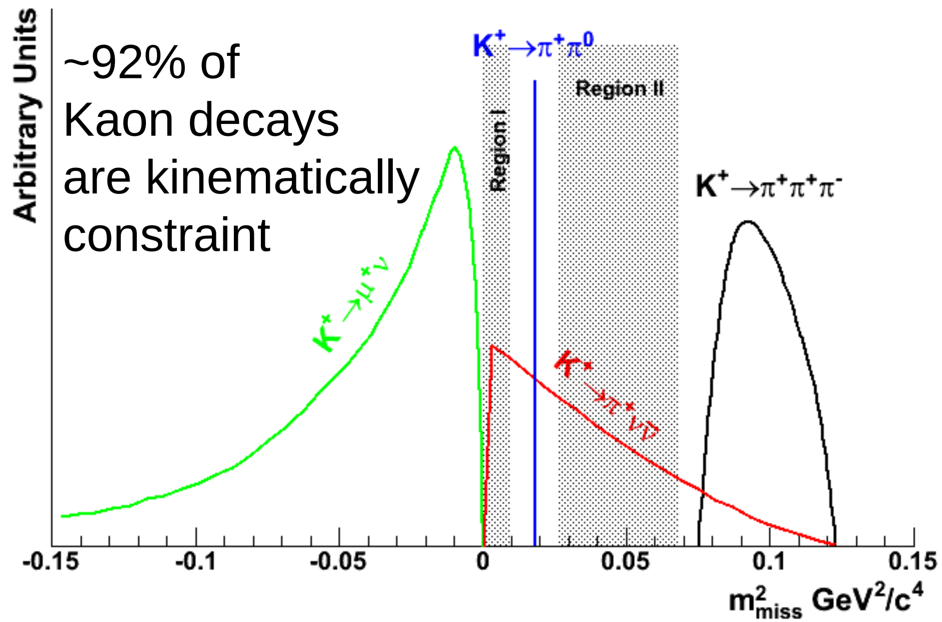
- **On-Pixel TDC**
- **End-of-Column TDC**

2. Kinematic Rejection



$$m^2_{miss} \approx m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right)+m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\vartheta^2_{\pi K}$$

Decay	BR
$K^+\to\mu^+\nu$ ($K_{\mu2}$)	0.64
$K^+\to\pi^+\pi^0$ ($K_{\pi2}$)	0.21
$K^+\to\pi^+\pi^+\pi^-$ $K^+\to\pi^+\pi^0\pi^0$	0.07



Kinematical Rejection

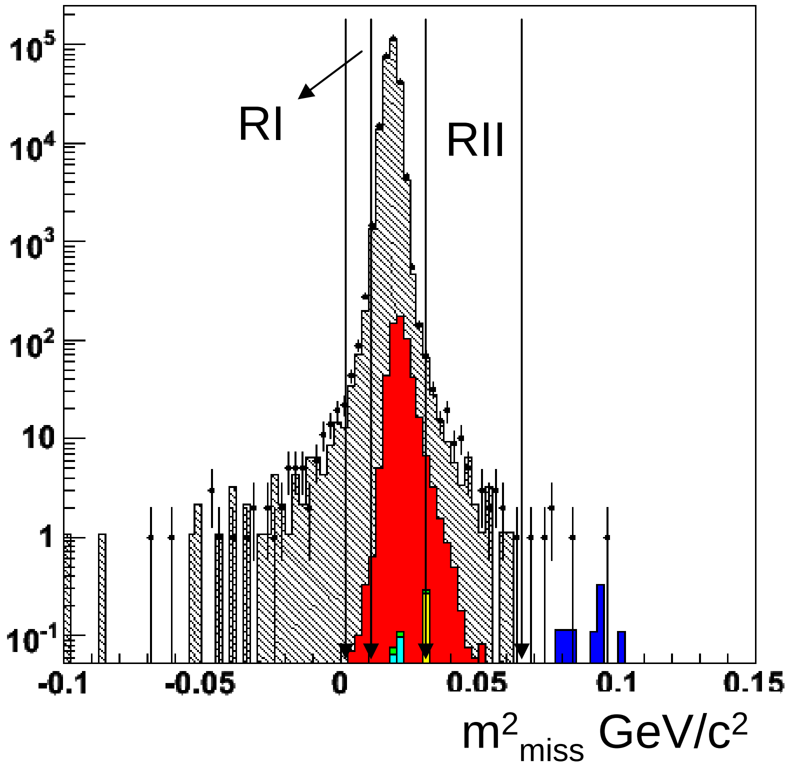
$K^+ \to \pi^+\pi^0$ selected on 2007 data using LKr information only

Look at the tails in the m^2_{miss} reconstructed with the NA48 DCH

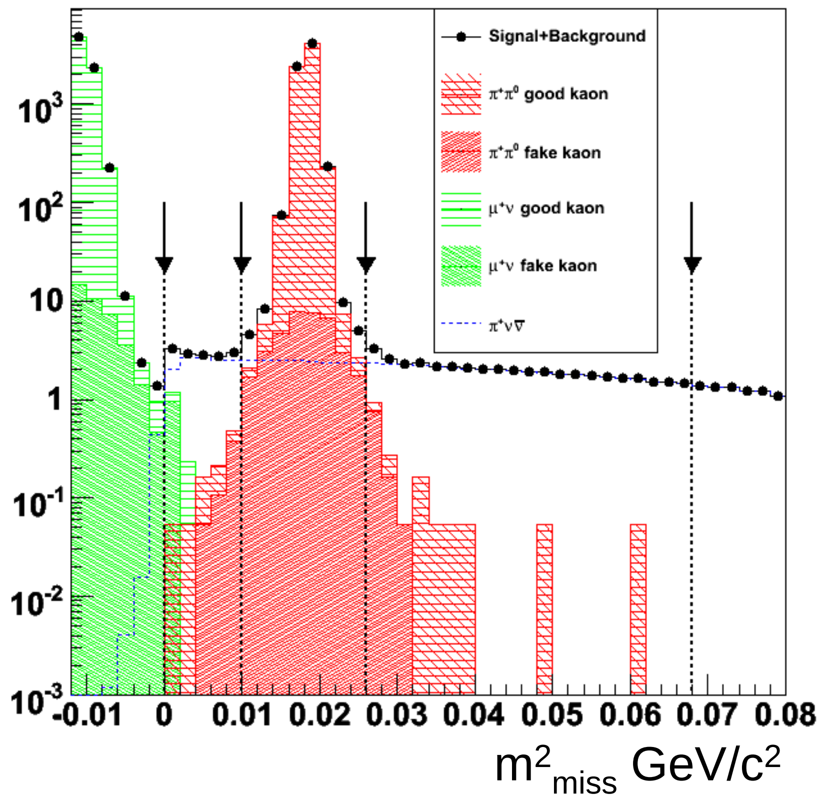
Data vs. NA48MC: reproducibility of non- gaussian tails within x2

$K^+ \to \pi^+\nu\nu$ regions: background ~2×10^{-3}

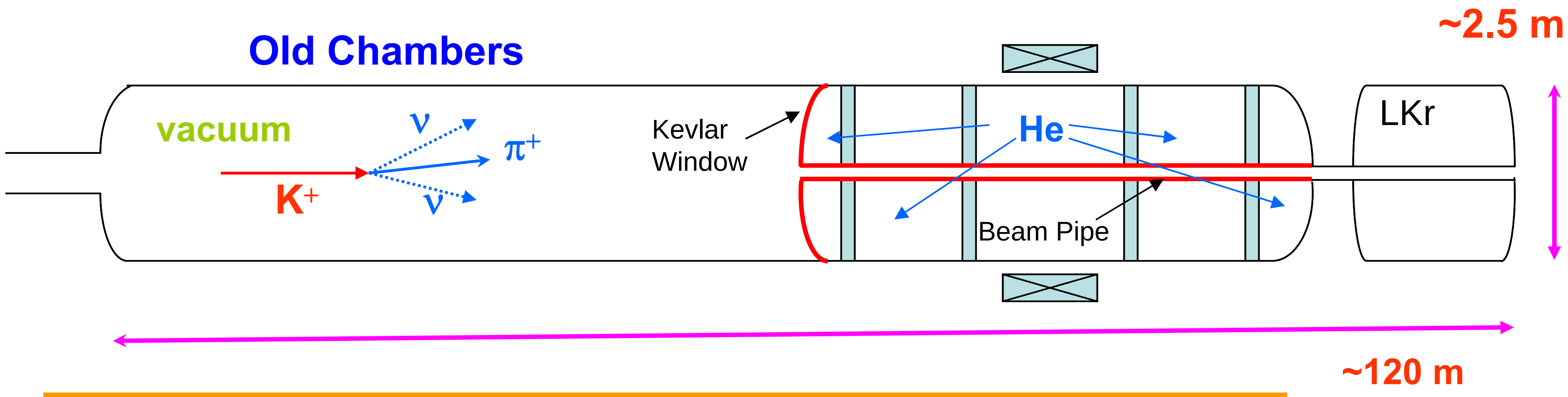
OLD DCH: Data vs. MC



New Straw Tracker: MC

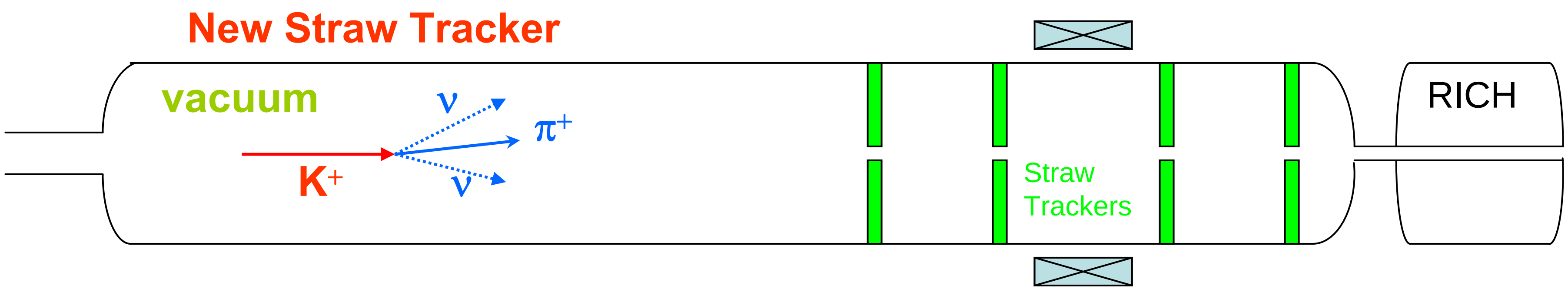


New Spectrometer



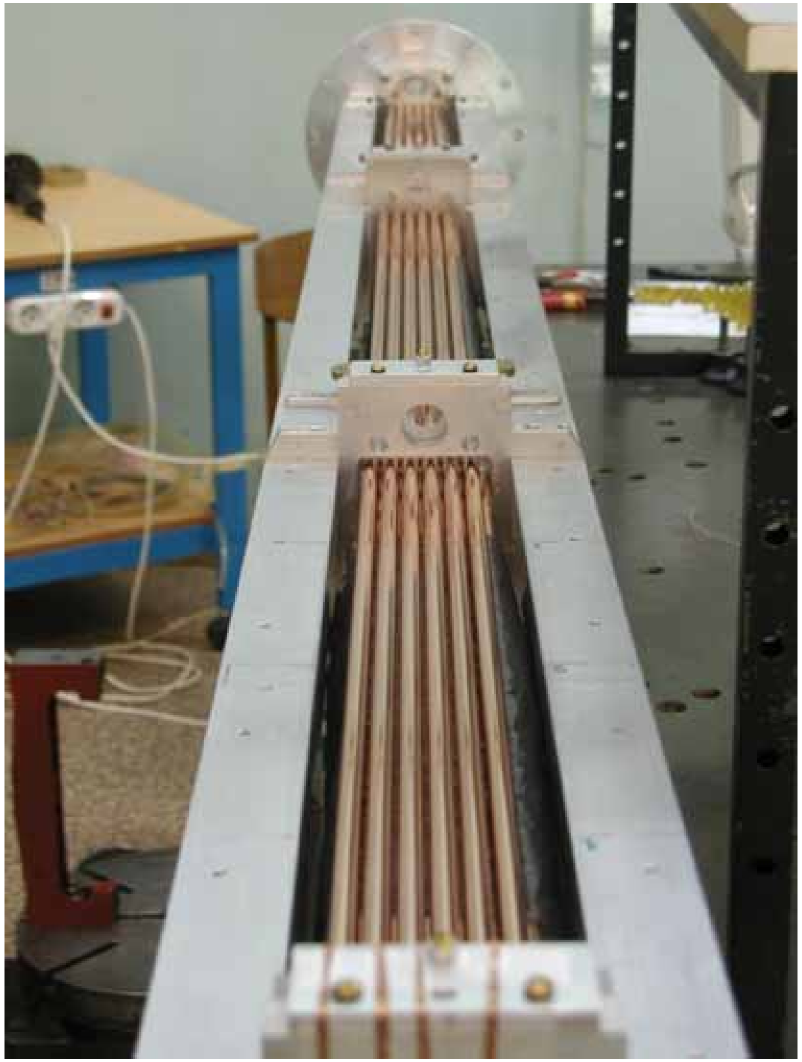
The Straw Trackers operated in vacuum will enable us to:

- **Remove the multiple scattering due to the Kevlar Window**
- **Remove the acceptance limitations due to the beam-pipe**
- **Remove the helium between the chambers**



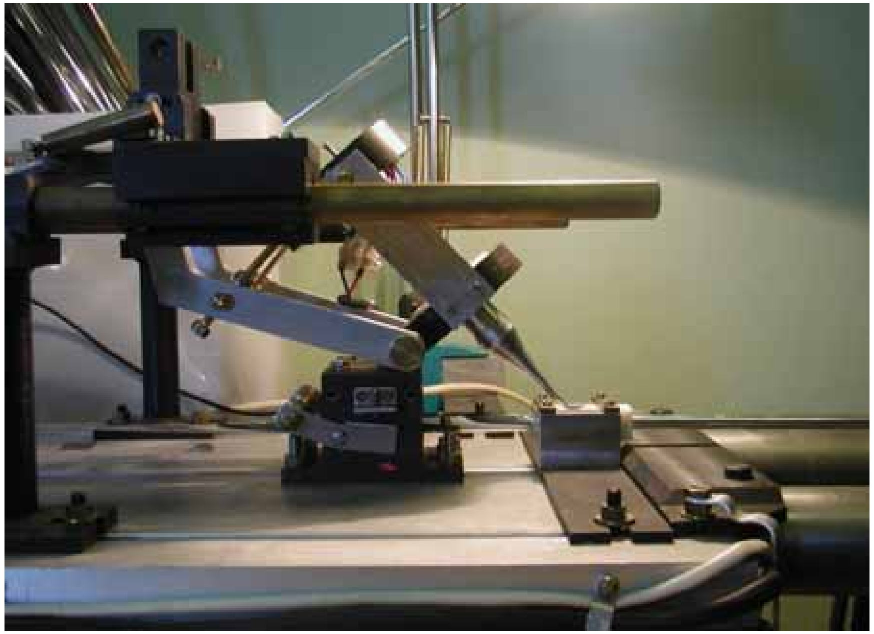
- **The Straw Tracker is essential to study ultra-rare-decays in flight**

STRAW Prototype built in 2007



Ultrasound Welded mylar (linear weld, no glue!)

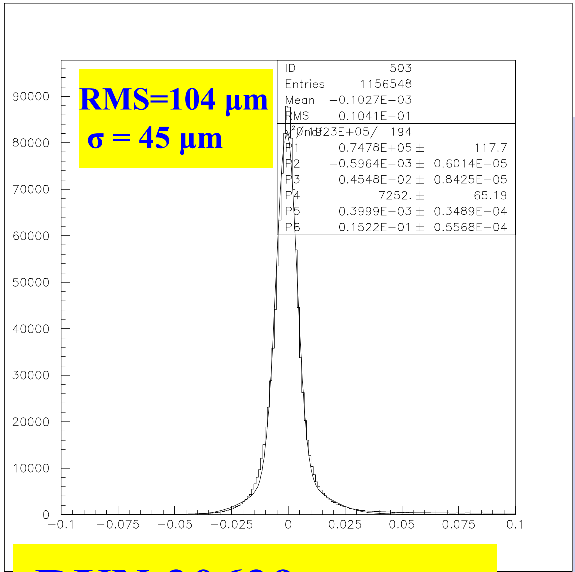
- 36 Al
- 12 (Cu+Au) mylar straws



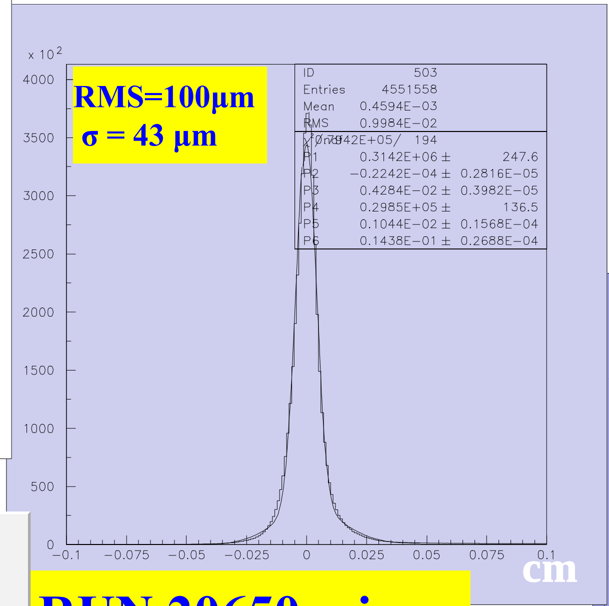
Straw Prototype: Beam Test 2007

Residuals

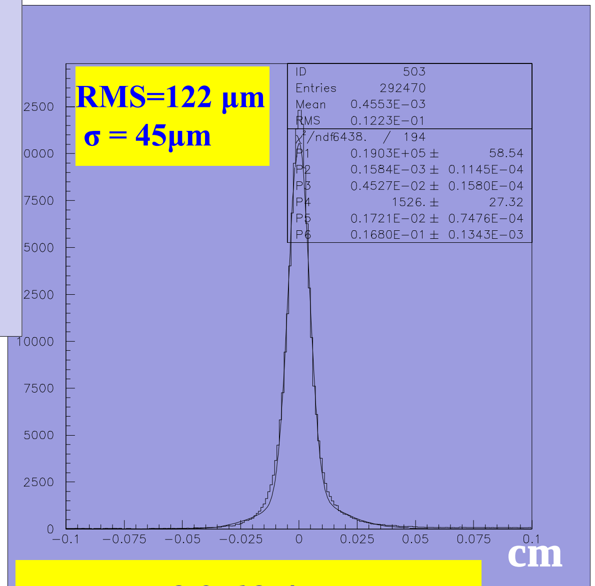
full length Straw Prototype: 2.1 m



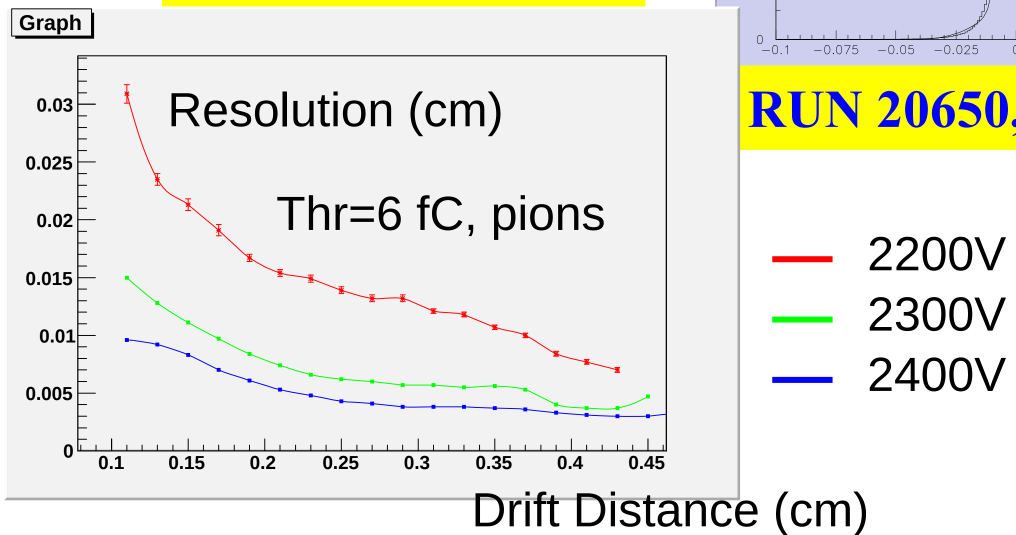
RUN 20629, muons



RUN 20650, pions



RUN 20694, kaons



CO_2 (80%) CF_4 (10%) Isob. (10%)

3. Vetoes

- **Photon vetoes to reject $K^+ \rightarrow \pi^+ \pi^0$**

  P(K^+) = 75 GeV/c

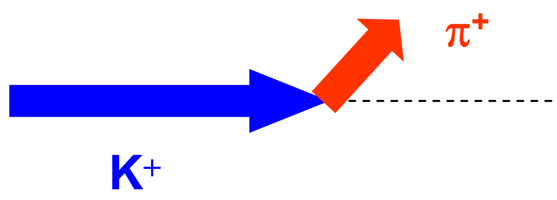
  Requiring P(π^+) < 35 GeV/c

  P(π^0) > 40 GeV/c ➡ It can hardly be missed in the calorimeters

Signature:

•Incoming high momentum K^+

•Outgoing low momentum π^+



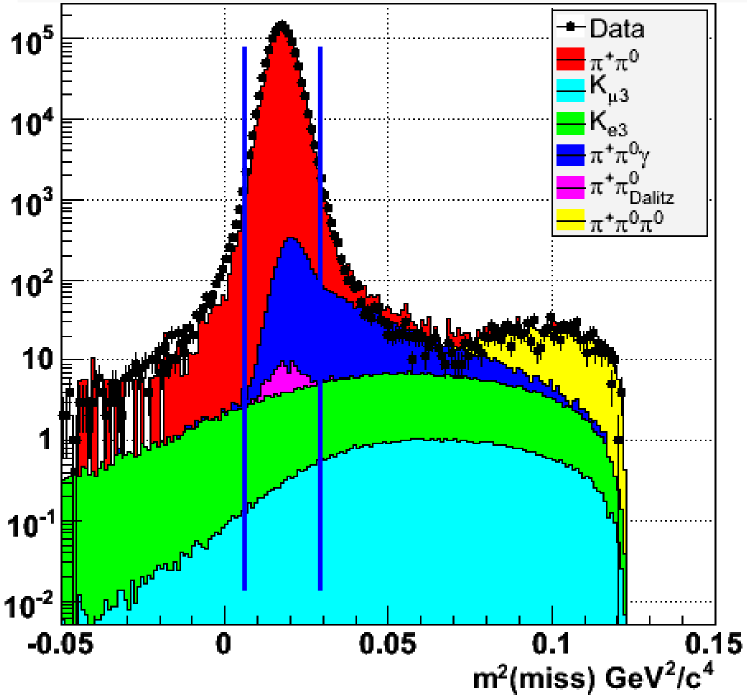
- **Muon Veto to reject $K^+ \rightarrow \mu^+ \nu$**

LKr γ Detection Efficiency (Measured from data)

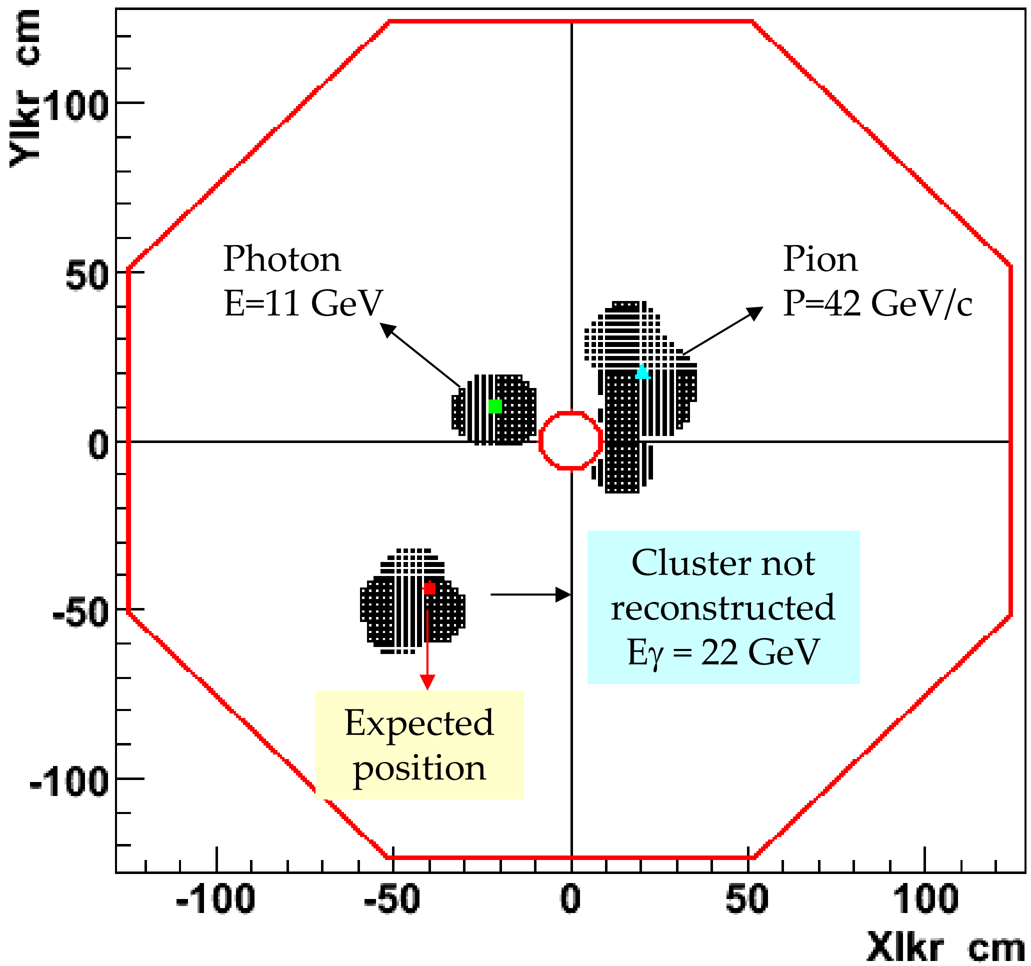
LKr ineff. per γ (E_γ > 10 GeV):

$\eta \sim 7 \times 10^{-6}$ (preliminary)

$K^+ \to \pi^+ \pi^0$ **selected kinematically**

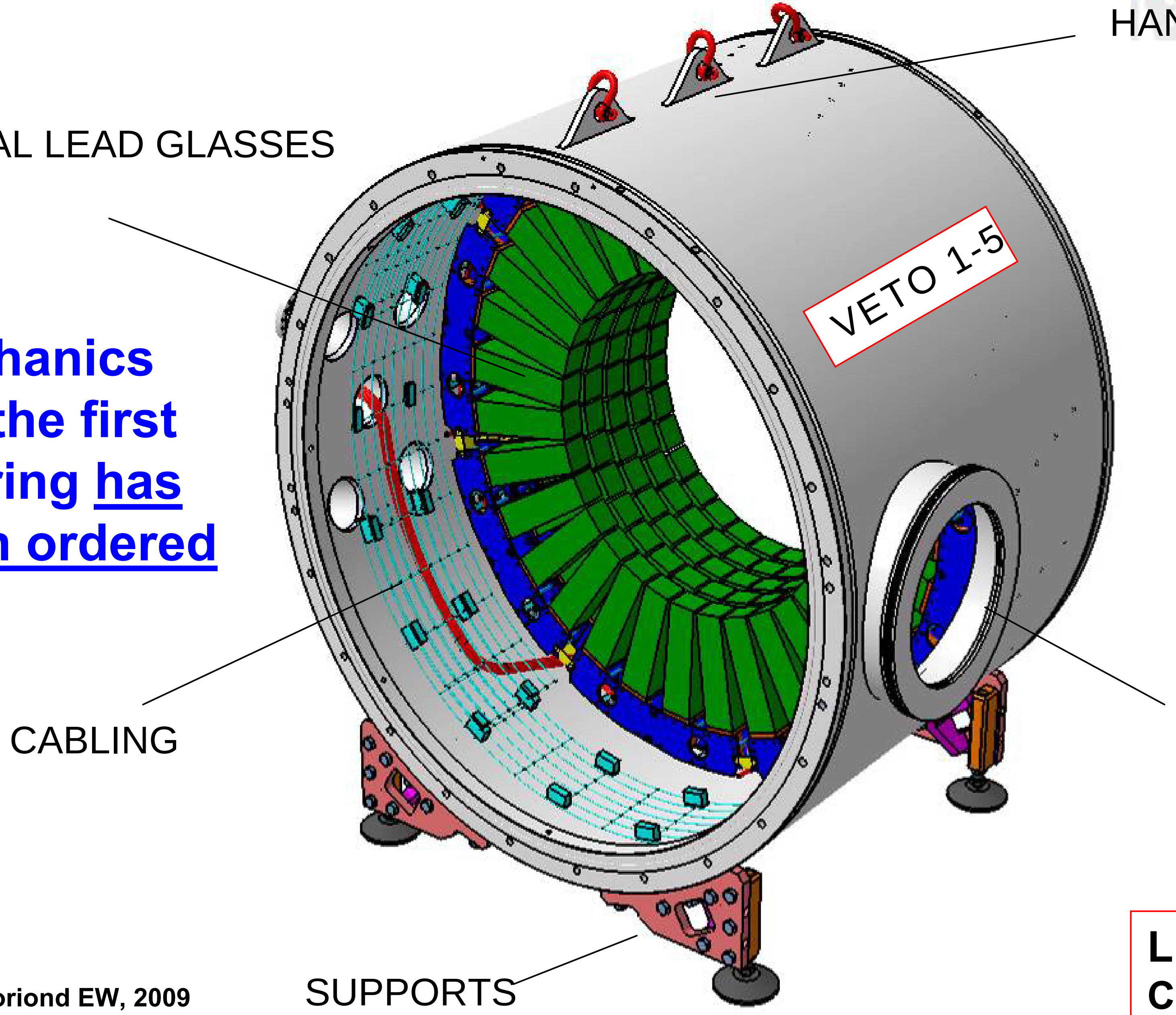


π^+ **track and lower energy γ are use to predict the position of the other γ**



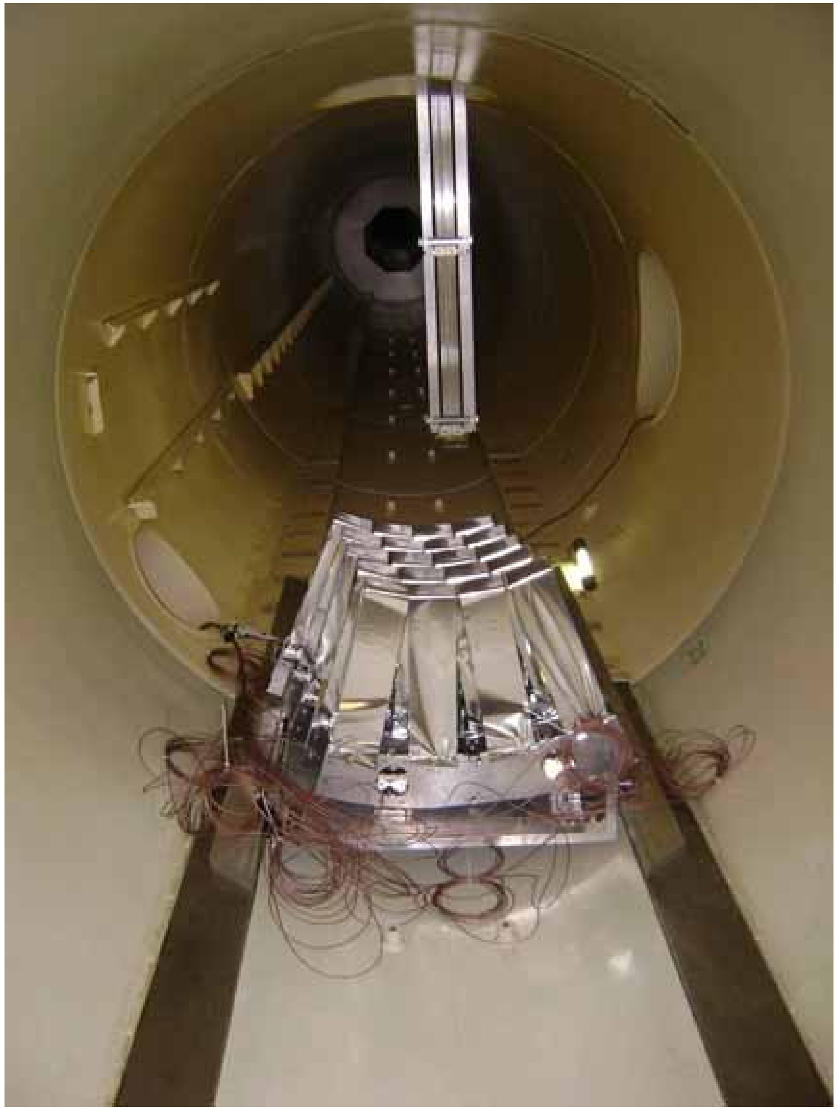
Photon Anticounters

Mechanics
For the first full ring <u>has been ordered</u>



LNF-SPAS
C.Capoccia

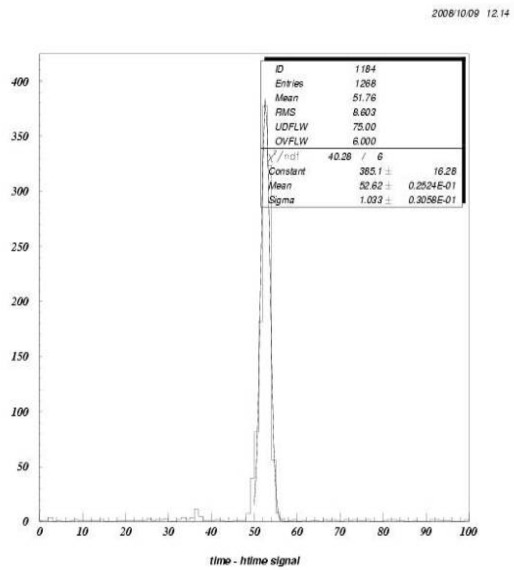
LAV prototype tested at CERN



20 blocks installed in the NA62 vacuum tube

Muons and kaons from 2/10 to 6/10

Validation of the operation in vacuum, cabling and support mechanics



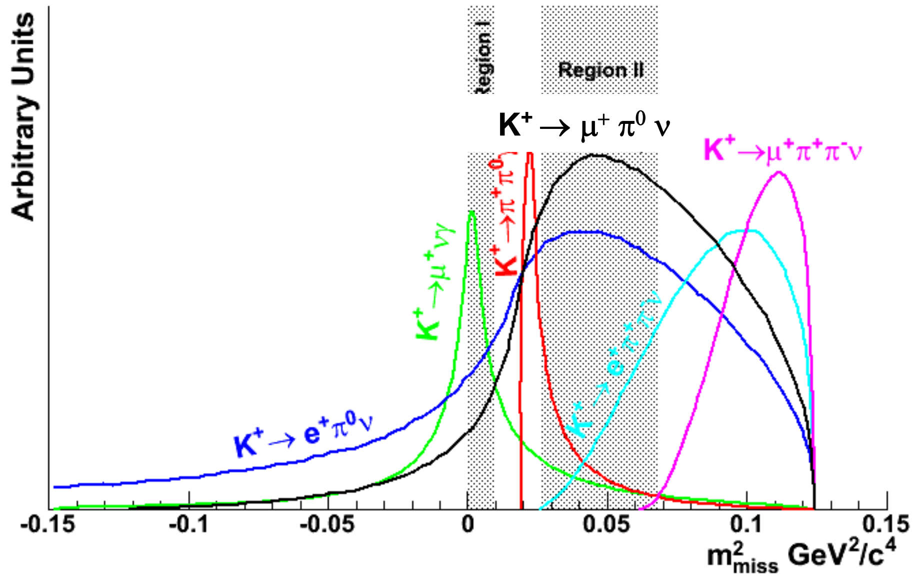
Preliminary time resolution with kaons

σ_t = 1.02 ns

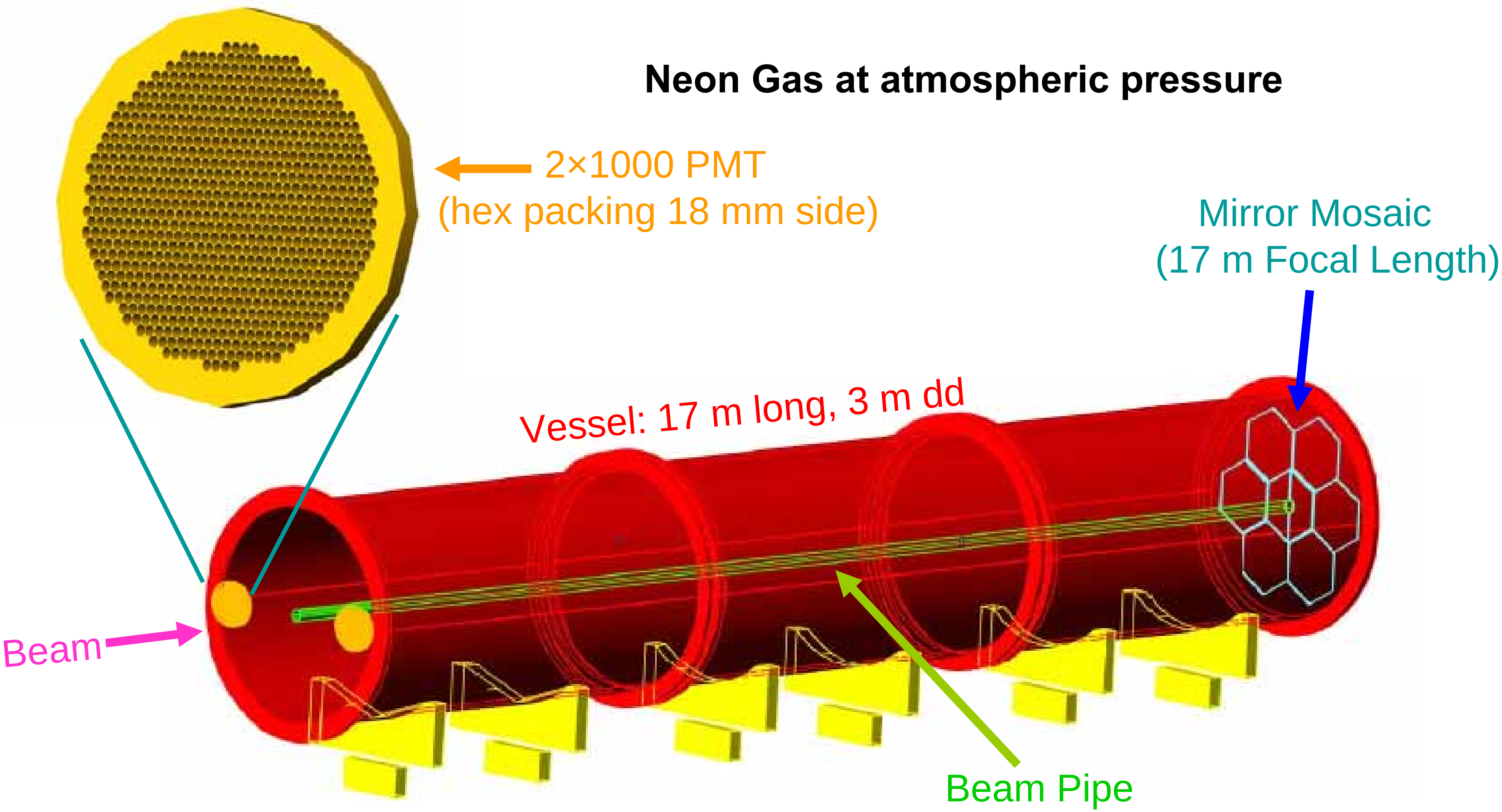
4. Particle Identification

- K^+ Positive identification (CEDAR)
- π/μ separation (RICH)
- π/e separation (E/P)

Decay	BR
$K^+ \to \pi^0 e^+ \nu$ (K_{e3})	0.051
$K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu 3}$)	0.034
$K^+ \to \mu^+ \nu \gamma$ ($K_{\mu 2\gamma}$)	6.2×10^{-3}
$K^+ \to \pi^+ \pi^- e^+ \nu$ (K_{e4})	4.1×10^{-5}
$K^+ \to \pi^+ \pi^- \mu^+ \nu$ ($K_{\mu 4}$)	1.4×10^{-5}

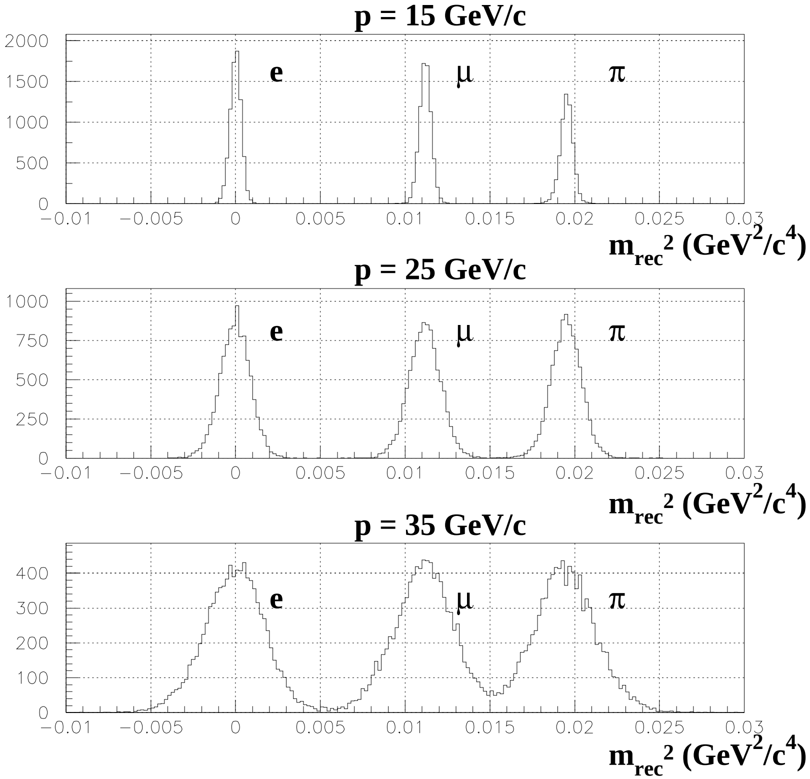


The RICH Detector

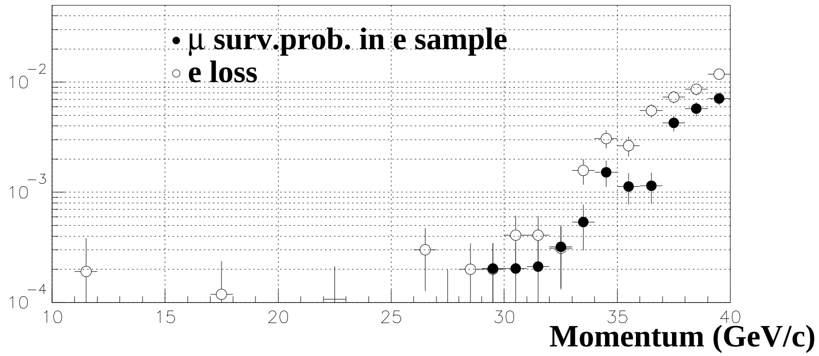


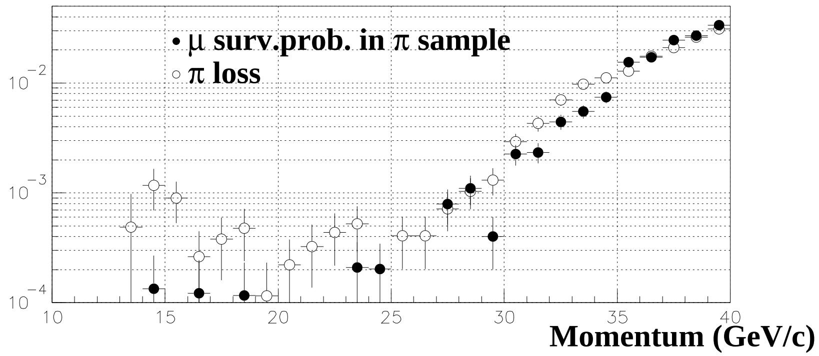
RICH Simulation: particles separation

$$m_{rec}^2 = p^2 \left(\vartheta_{\max}^2 - \vartheta_c^2 \right)$$



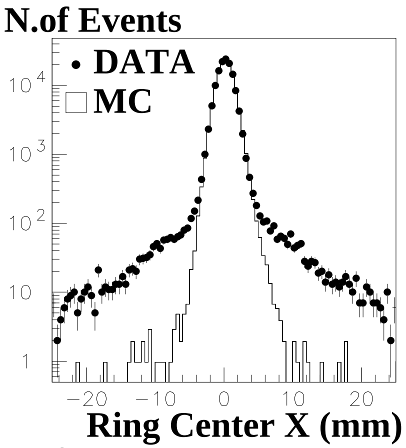
Momentum from
the magnetic spectrometer

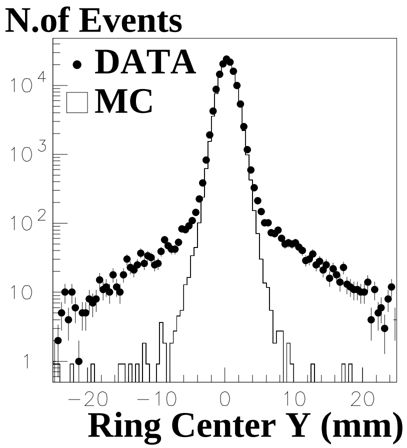


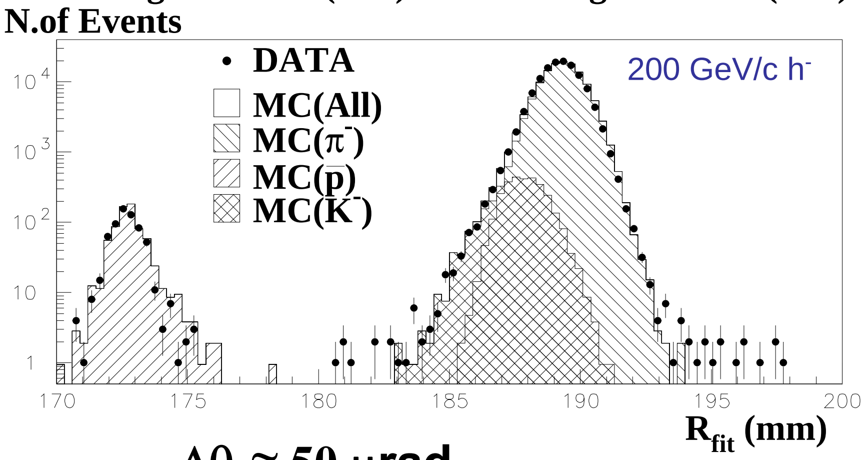


Muon suppression in π sample (15<p<35 GeV/c): 1.3×10^{-3}

RICH-100: 2007 Test Beam results



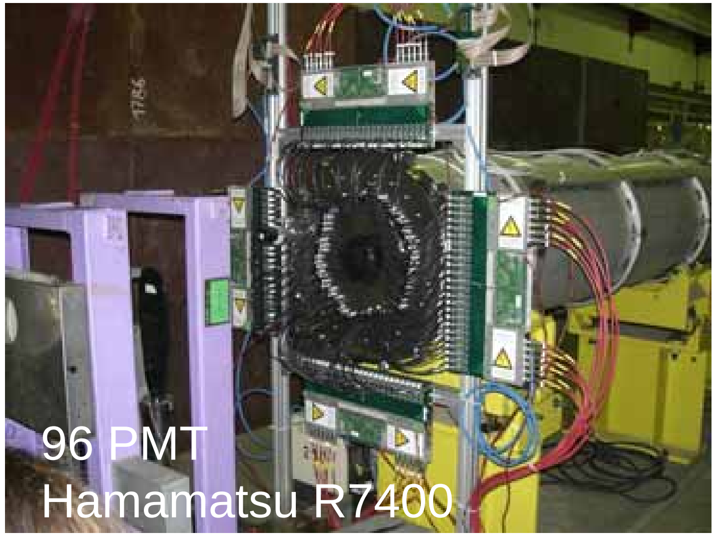




$\Delta\theta_c \approx 50\ \mu$rad
(biased by PM geometry)

$N_{Hits} \approx 17$

$\Delta t_{Event} \approx 70$ ps



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%)

Definition of "year" and running efficiencies based on NA48 experience

Summary

- The physics case to study rare kaon decays at the SPS during the LHC era is very strong
- The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ proposal has received recommendation for approval by the CERN SPS Committee.
- The experiment was approved by the CERN Research Board (December 5, 2008) "subject to the definition of resource sharing within the Collaboration. The experiment will continue to be known as NA62"
- The MoU is under discussion
- With ~50 times the kaon flux of NA48/2, the physics menu –in addition to the very rare decays- promises to be very rich ranging from the precision-tests of lepton universality to the study of the strong interaction at low energy (there should be good material for both EW and QCD Moriond sessions in 201X!)

SPARES

NA62 Seen from the CERN Management

Excerpt from the interview to Sergio Bertolucci
(Director of Research and Scientific Computing)

CERN Bulletin, Issue No. 05-06/2009 Monday 26, January 2009

…favouring the birth of smaller experiments is also important in maintaining a dynamic physics community. 'Smaller' does not mean 'less challenging'. One good example is the NA62 experiment, which will look for rare kaon decays and which is in a very advanced stage of approval: it is extremely challenging, both in terms of the detector requirements and physics studies. In Spring 2009 we will hold a workshop to assess the situation and to encourage the submission of more proposals of this sort.