NA62: New Opportunities In Rare Kaon Decays

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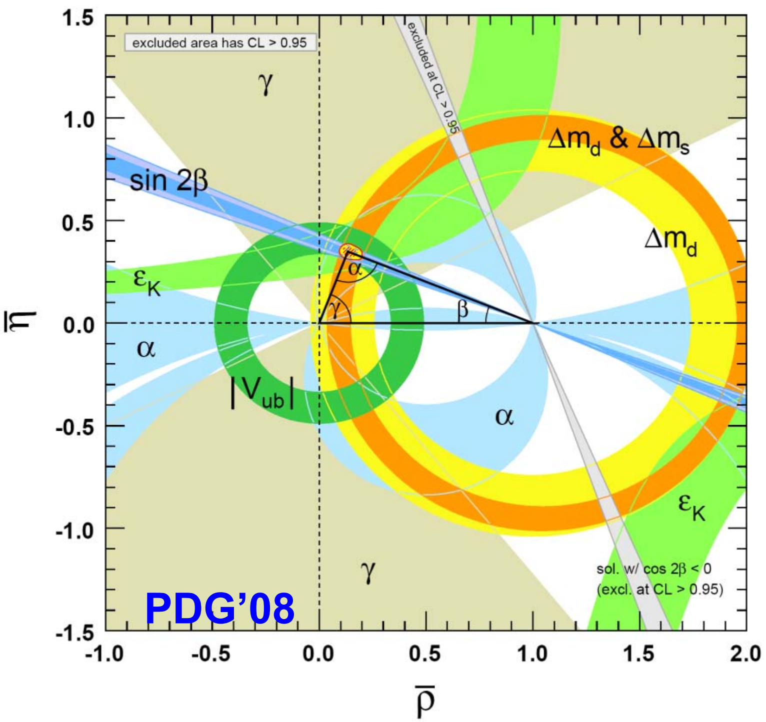
SPSC-M760

A. Ceccucci for the 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

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

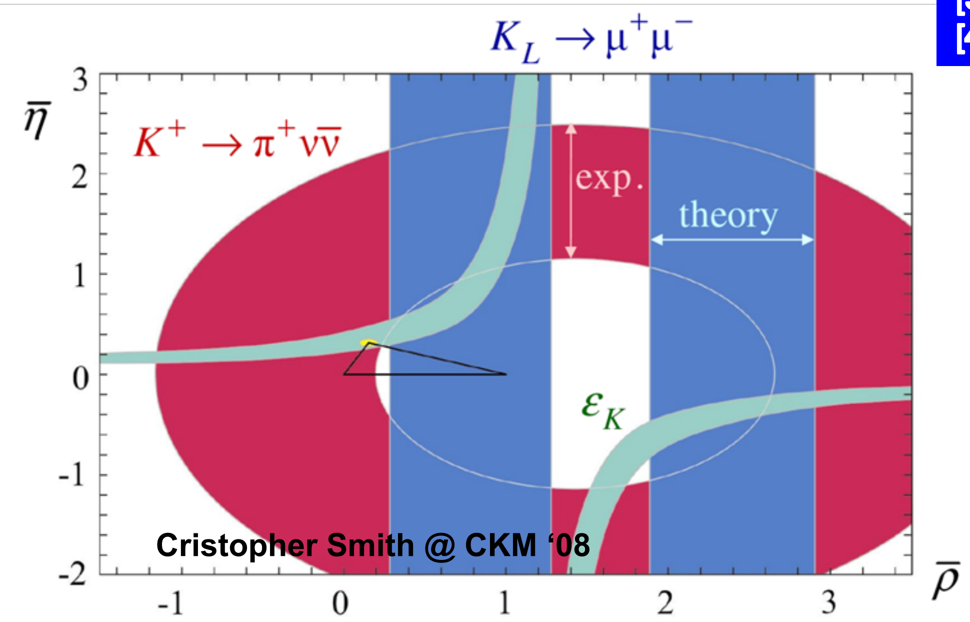
“[These articles] confirm that flavour physics is an essential ingredient in the future of high-energy physics”

- 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

$K \to \pi\nu\bar{\nu}$: Theoretically Pristine and Almost Unexplored

Decay	Branching Ratio ($\times 10^{10}$) Theory (SM)	Experiment
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	0.85 ± 0.07[1]	$1.73^{+1.15}_{-1.05}$[2]
$K_L^0 \to \pi^0 \nu\bar{\nu}$	0.28 ± 0.04[3]	< 670 (90% CL)[4]

[1] J.Brod, M.Gorbahn, PRD78, arXiv:0805.4119
[2] AGS-E787/E949 PRL101, arXiv:0808.2459
[3] c.f. CKM 08 procs.
[4] KEK-E391a PRL 100, arXiv:0712.4164



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

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

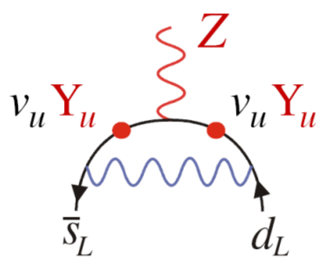
$K_L \to \pi^0 \mu^+\mu^-$: $\bar{\eta} < 5.4$

Proposed:
KOTO (E14) J-PARC

Kaon Rare Decays and NP

(courtesy by Christopher Smith)

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

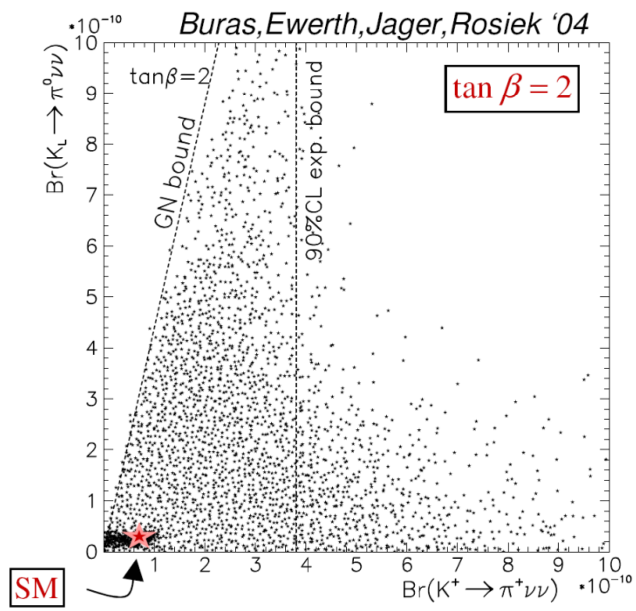


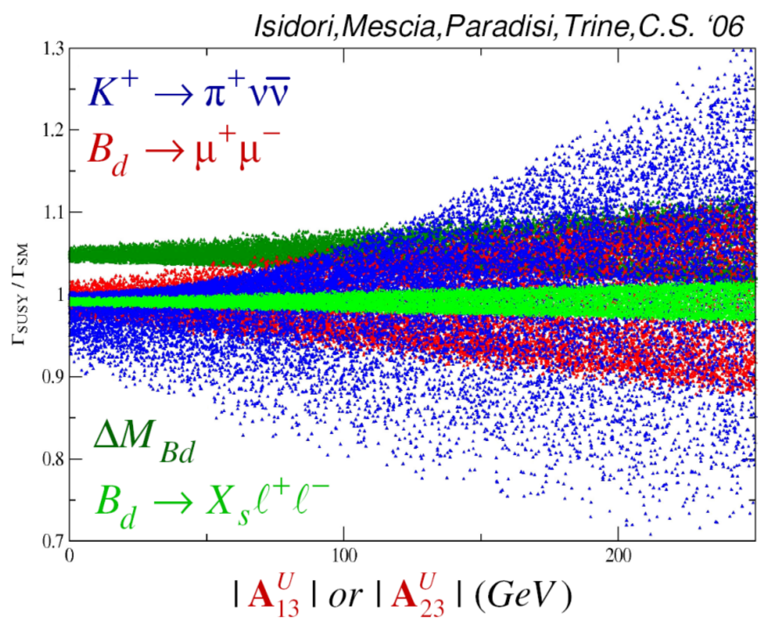
- $SU(2)_L$ breaking: $SM : v_u^2 Y_u^{*32} Y_u^{31} \sim m_t^2 V_{ts}^* V_{td}$

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

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

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

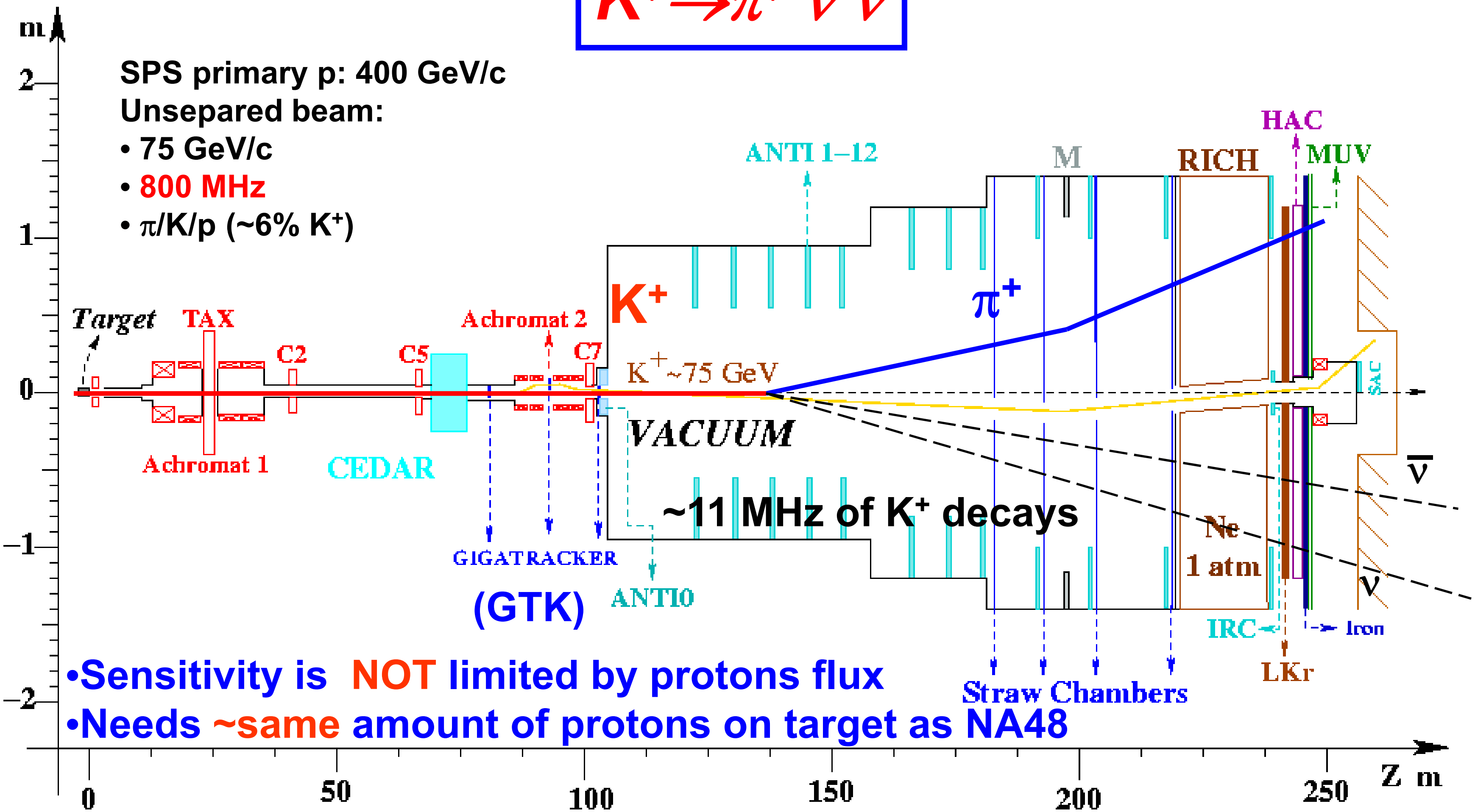




Proposed Detector Layout

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

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



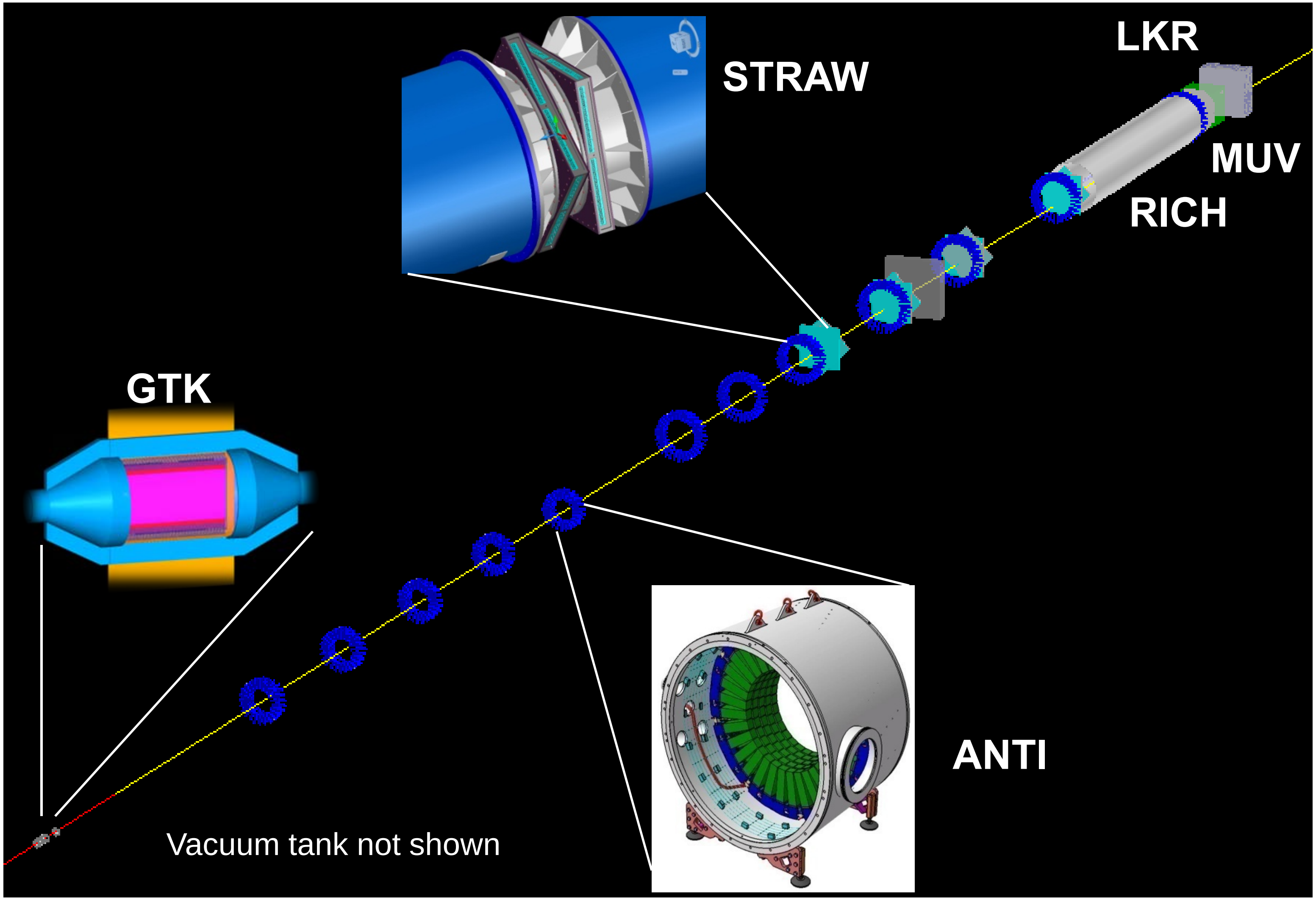
- Sensitivity is NOT limited by protons flux
- Needs ~same amount of protons on target as NA48

Principles of NA62

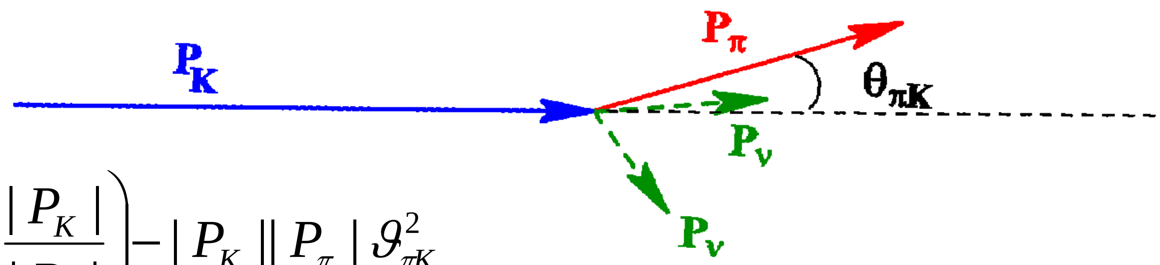
- K^+ Decay in-flight to avoid the scattering and the backgrounds introduced by the stopping target
  → long decay region
- High momentum to improve the background rejection
  → unseparated hadron beam

1. Precise timing to associate the decay to the correct incoming parent particle (K^+) in a ~800 MHz beam
   → Beam tracker with σ_t~100 (GTK)
2. Kinematical Rejection
   → low mass tracking (GTK + STRAW in vacuum tank)
3. Vetoes (γ and μ)
   → ANTI (OPAL lead glass) + NA48 LKR
   → MUV
4. Particle Identification
   → K/π (CEDAR)
   → π/μ (RICH)

NA62 Event Display

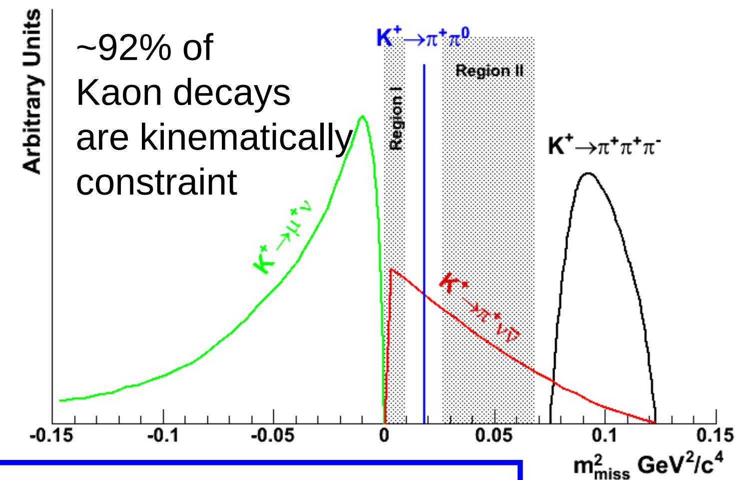


Background Rejection



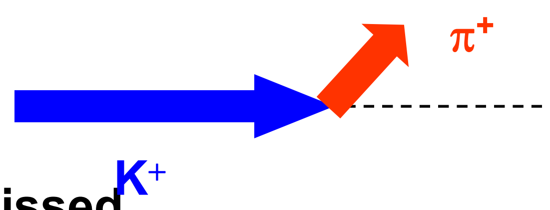
$$m_{miss}^2 \approx m_K^2\left(1-\frac{|P_\pi|}{|P_K|}\right)+m_\pi^2\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\vartheta_{\pi K}^2$$

Decay	BR
$K^+ \to \mu^+ \nu$ ($K_{\mu 2}$)	0.64
$K^+ \to \pi^+ \pi^0$ ($K_{\pi 2}$)	0.21
$K^+ \to \pi^+ \pi^+ \pi^-$ $K^+ \to \pi^+ \pi^0 \pi^0$	0.07



Signature:

- **Incoming high momentum (75 GeV/c) K^+**
- **Outgoing low momentum (< 35 GeV/c) π^+**
- **For $K_{\pi 2}$ P(π^0) > 40 GeV/c: it can hardly be missed**



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%)

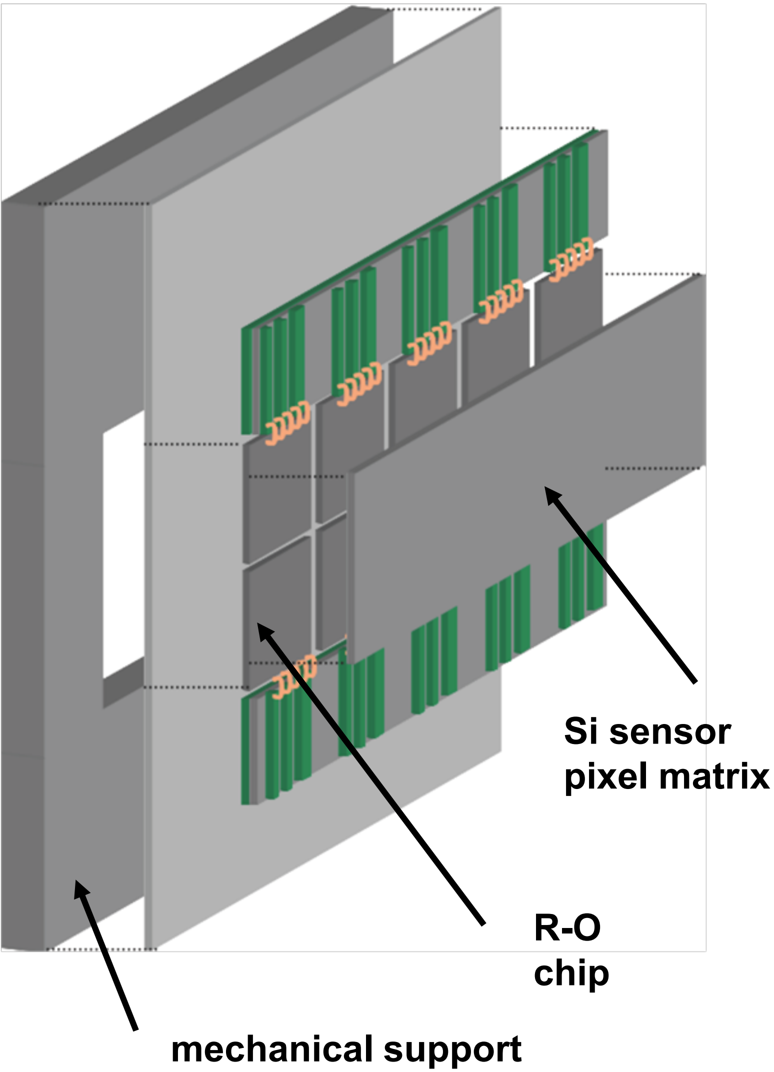
Definition of "year" and running efficiencies based on NA48 experience: ~100 days/year; 60% overall efficiency

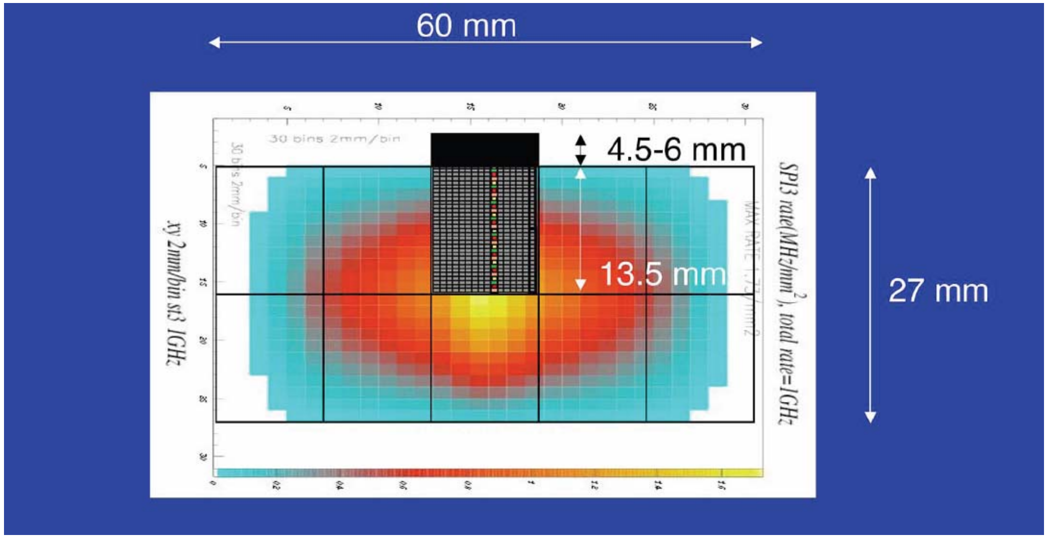
Key Points

- The physics case to study rare kaon decays at the SPS during the LHC era is very strong
- The experiment was approved by the CERN Research Board (December 5, 2008) "subject to the definition of resource sharing within the Collaboration”
- The MoU is under negotiation
- With ~50 times the kaon flux of NA48/2, the physics menu –in addition to the very rare decays- promises to be rich ranging from the precision-tests of lepton universality to the study of the strong interaction at low energy
- Excellent resolution, hermetic forward coverage and strong particle ID allow also to search for (e.g.):
  - Sgoldstinos (Gorbunov&Rubakov):
    $K^+ \rightarrow \pi^+\pi^0 P$, $P \rightarrow \gamma\gamma$, $P \rightarrow e^+e^-$ or P long-lived
  - νMSM Neutral Leptons (Gorbunov&Shaposhnikov)

Status of NA62

GTK Station





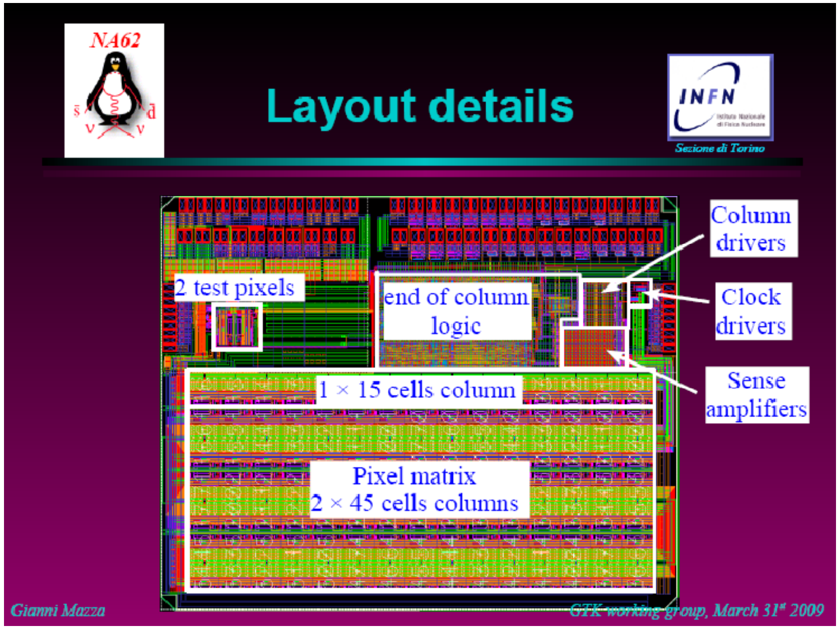
Requirements:

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:

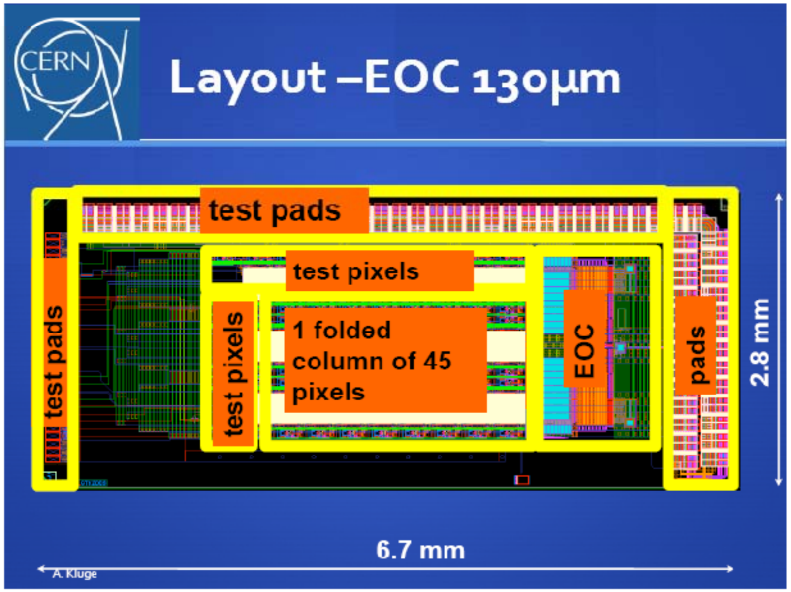
- **On-Pixel TDC**
- **End-of-Column TDC**

Gigatracker R/O Prototypes



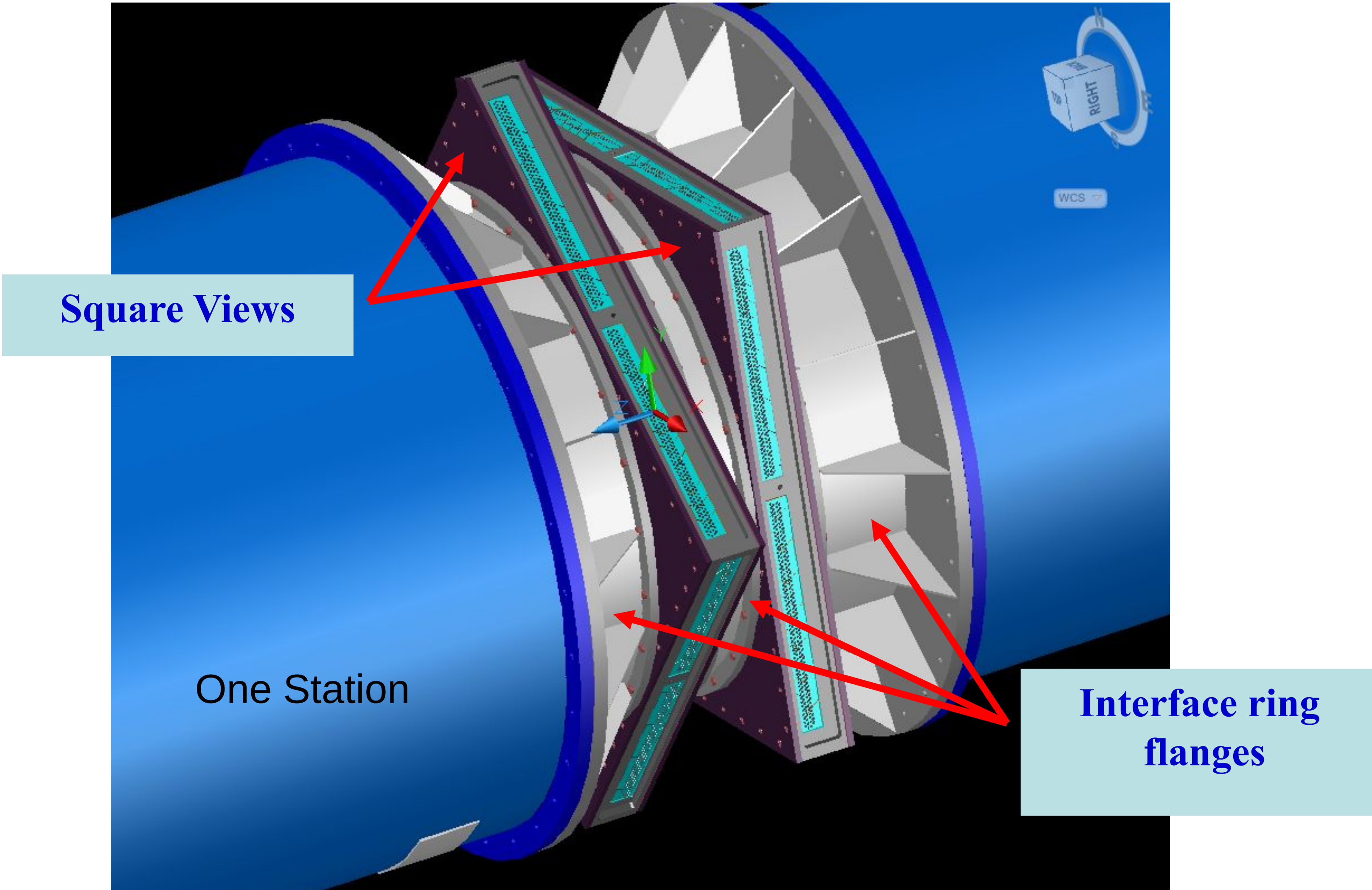
INFN Design: One TDC / pixel

CERN Design: End of Column TDC

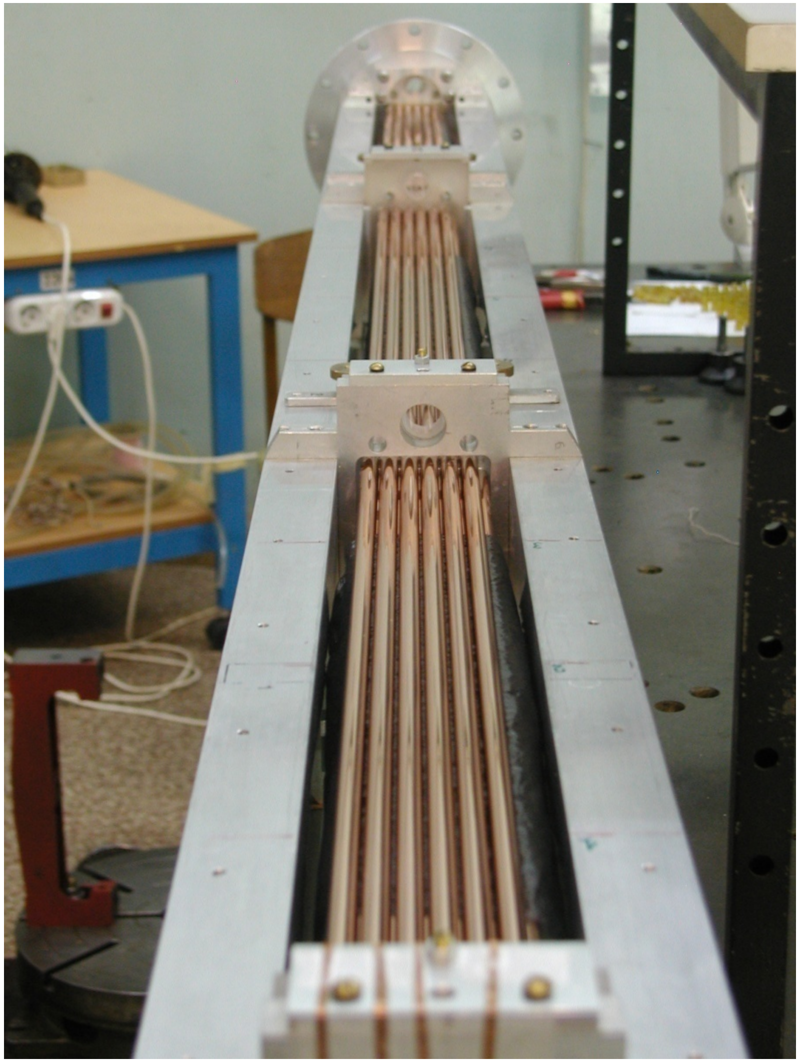


Both Designs in 130 nm IBM CMOS Technology (submitted in March 09)

STRAW Tracker

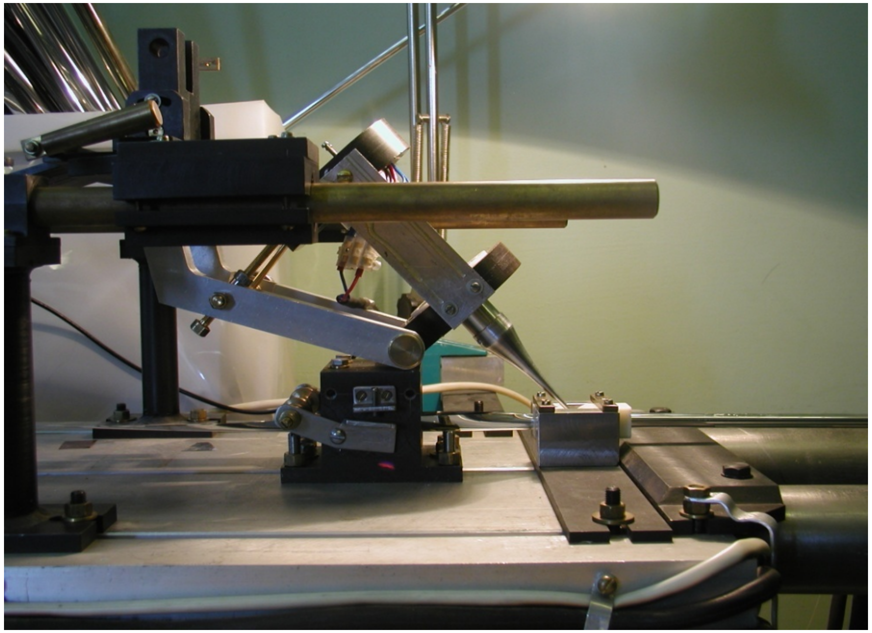


STRAW Prototype



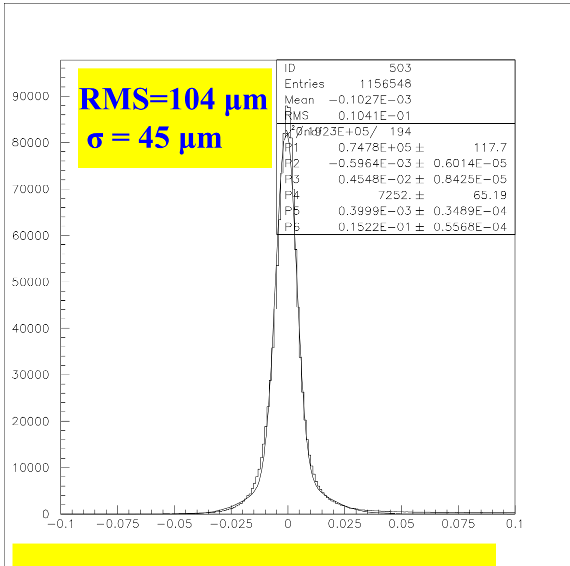
Ultrasound Welded mylar (linear weld, no glue!)

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

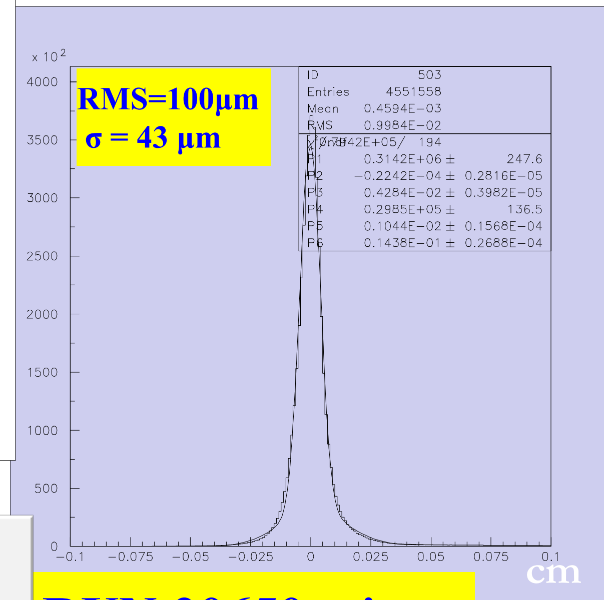


STRAW Prototype: Beam Test

Residuals

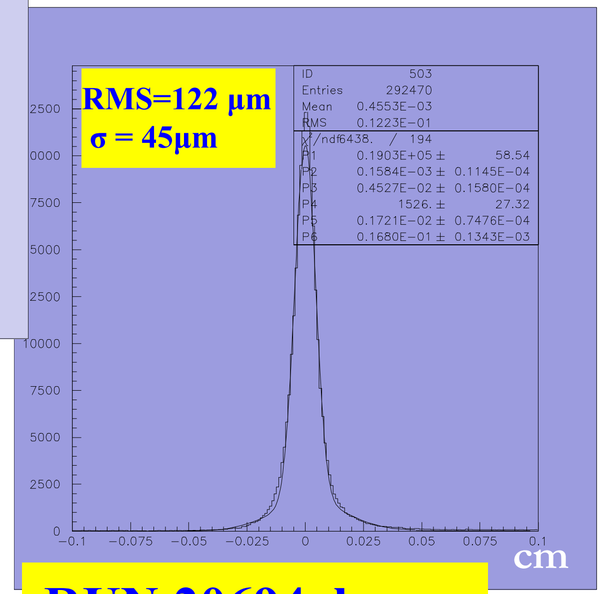


RUN 20629, muons

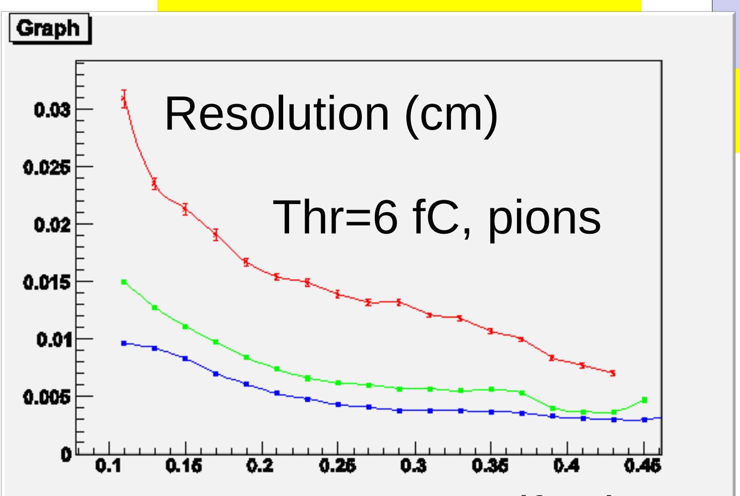


RUN 20650, pions

full length Straw Prototype: 2.1 m long Operated in Vacuum



RUN 20694, kaons

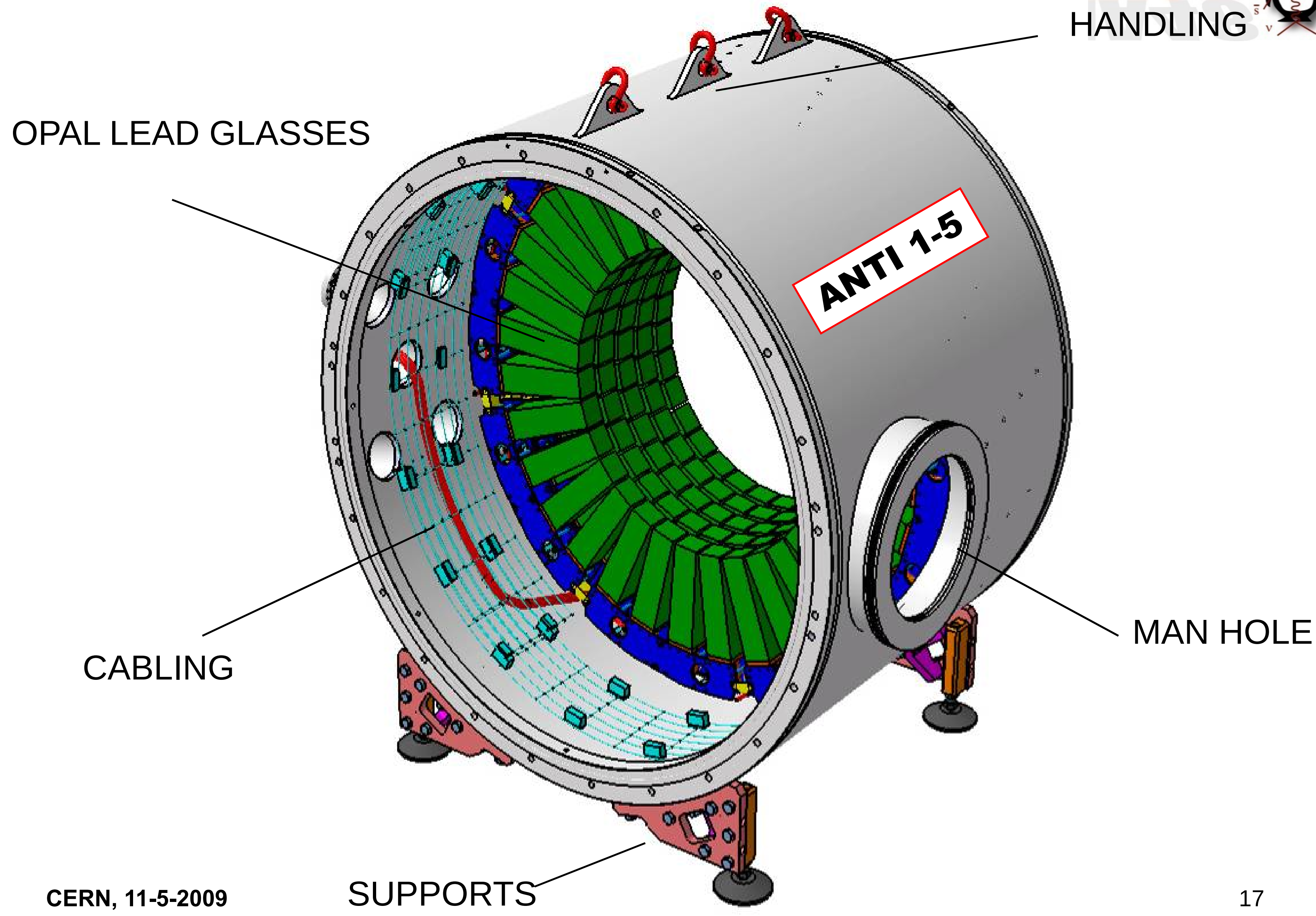


2200V
2300V
2400V

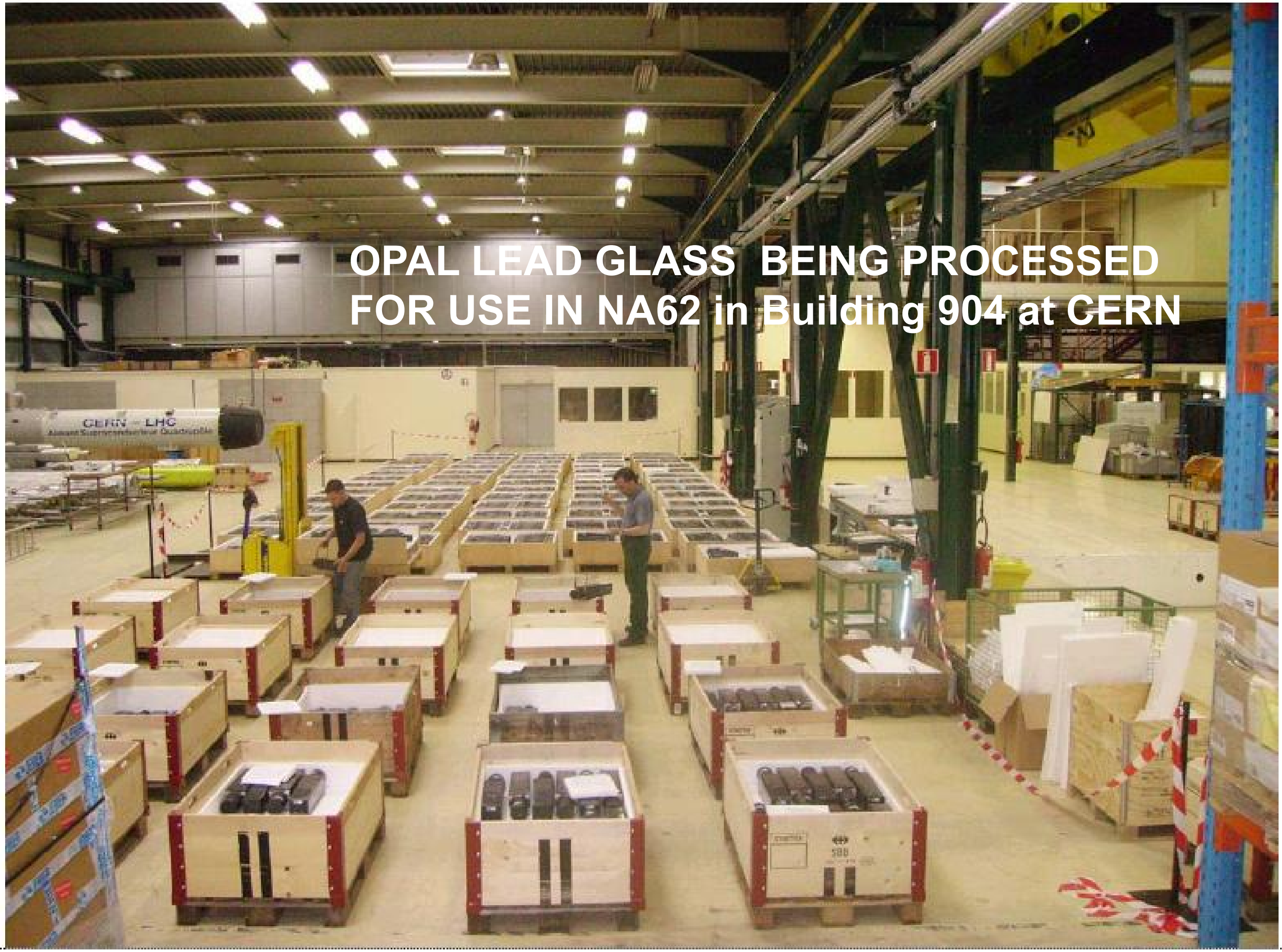
Drift Distance (cm)

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

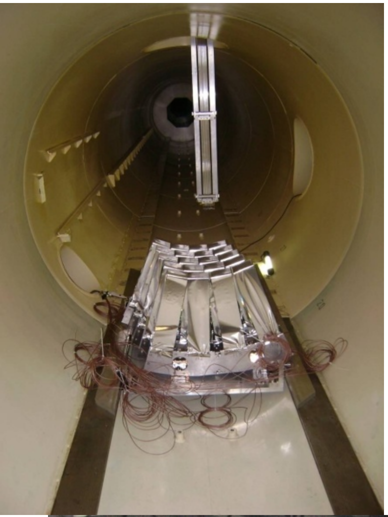
Photon ANTIcounters



Photon ANTIcounters



First ANTI Vessel complete

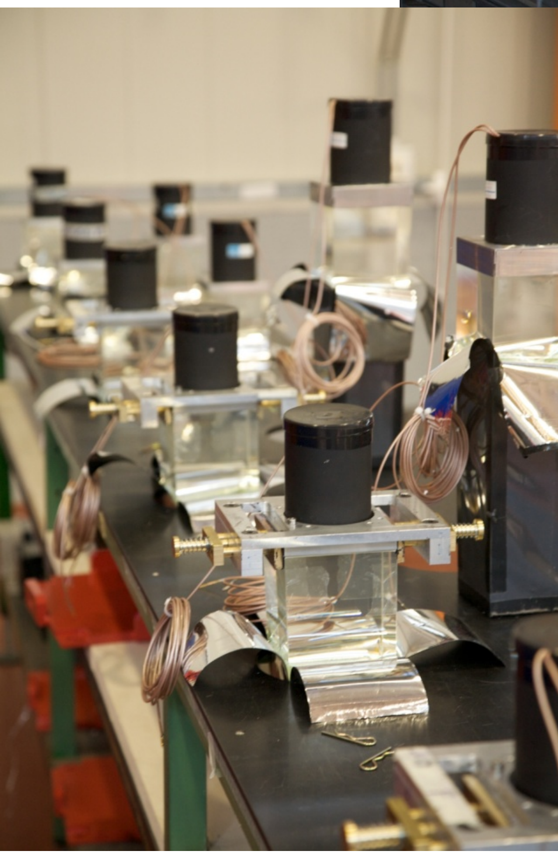


Prototype STRAW and ANTI
Tested in vacuum

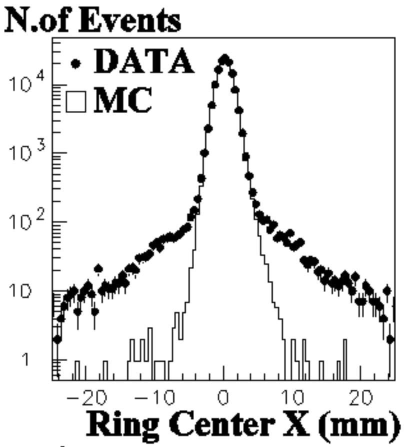
1st Complete vessel being
Prepared at LNF for installation
In the decay tank

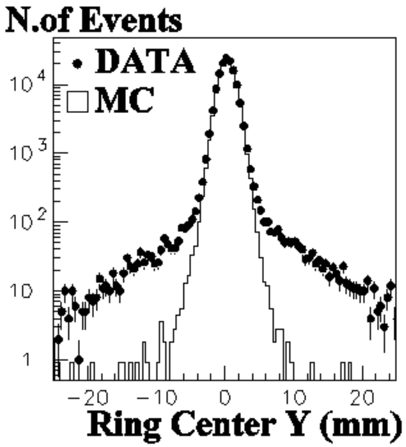
Space for Installation and Maintenance comes at a premium in ECN3

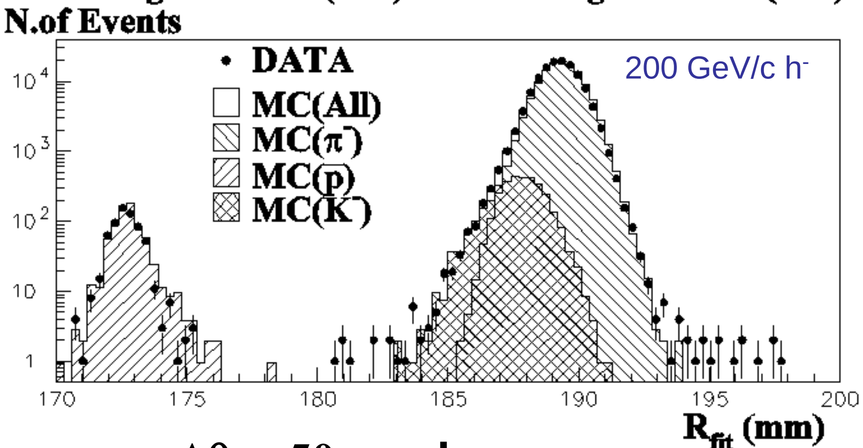
ANTI-A1 at LNF for Assembly



RICH-100: Test Beam Results



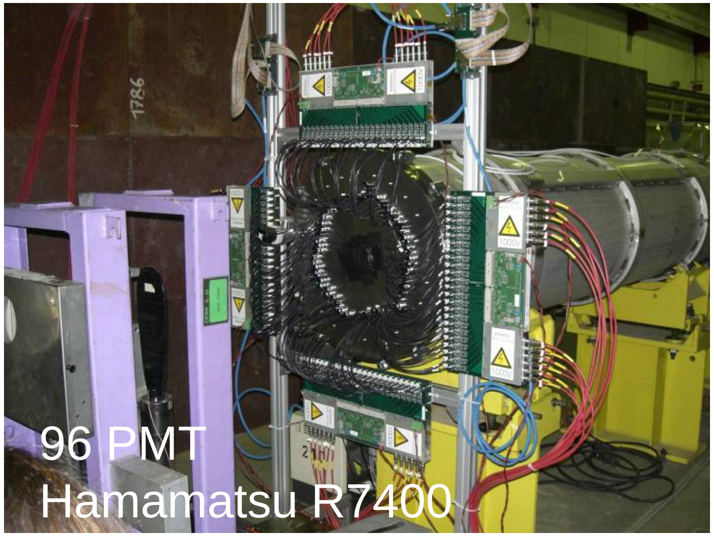




$\Delta\theta_c \approx 50\ \mu$rad
(biased by PM geometry)

$N_{Hits} \approx 17$

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

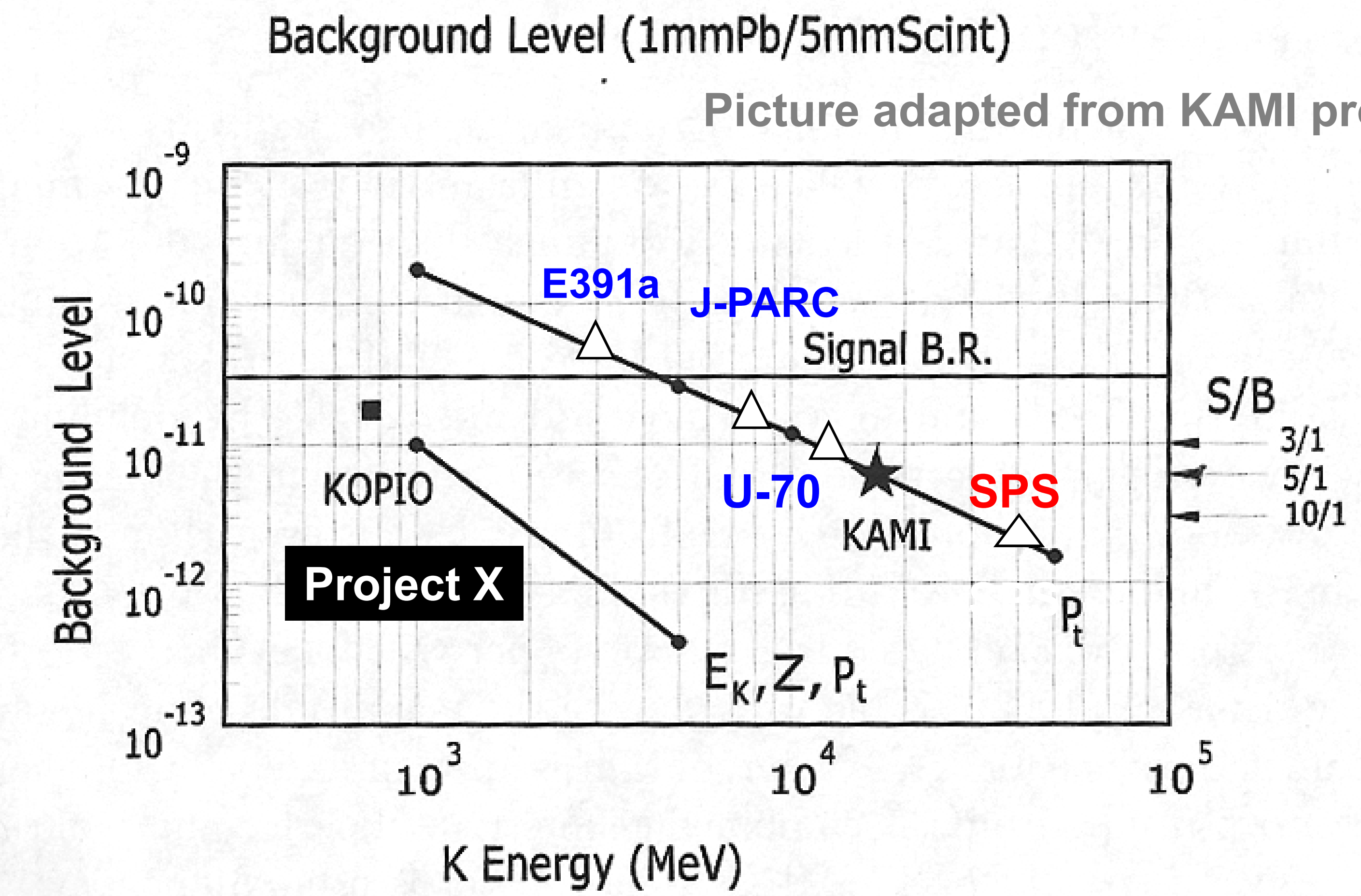


Summary

- With 2 (+1) years of data taking at the SPS, NA62 can make a ~10% test of the SM BR prediction
- This requires a SPS duty cycle of about 0.3 and 1.1×10^{12} protons on T10 / effective second
- A beam survey should be planned early (2011) to begin data taking with the full detector in 2012
- The construction schedule is mostly resource driven
- In the longer term, we look forward to SPS and Experimental Area upgrades as these could open the opportunity to study ultra-rare K^0_L decays

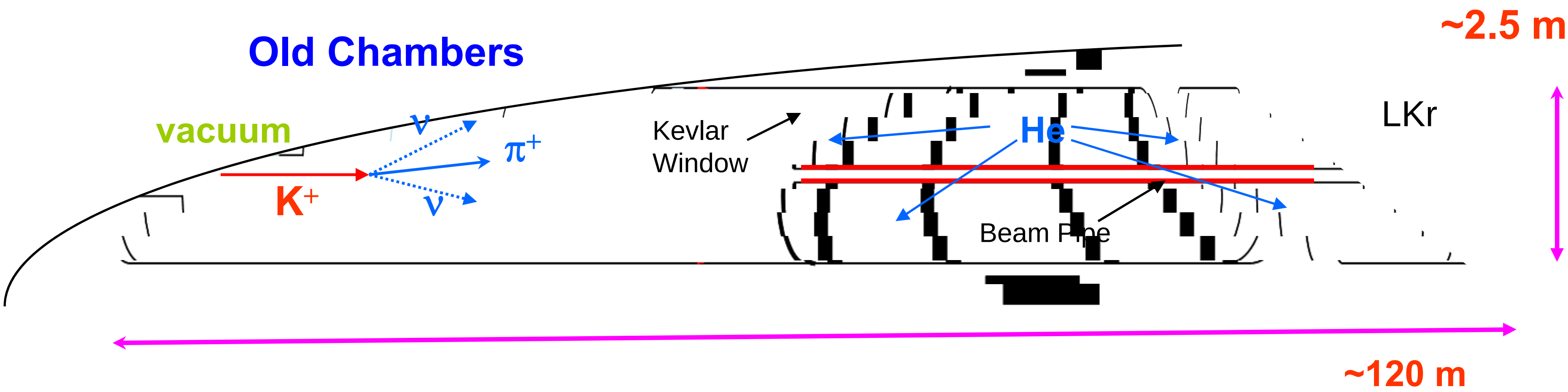
SPARES

$K_L \to \pi^0 \nu\nu$ Long Time Prospects

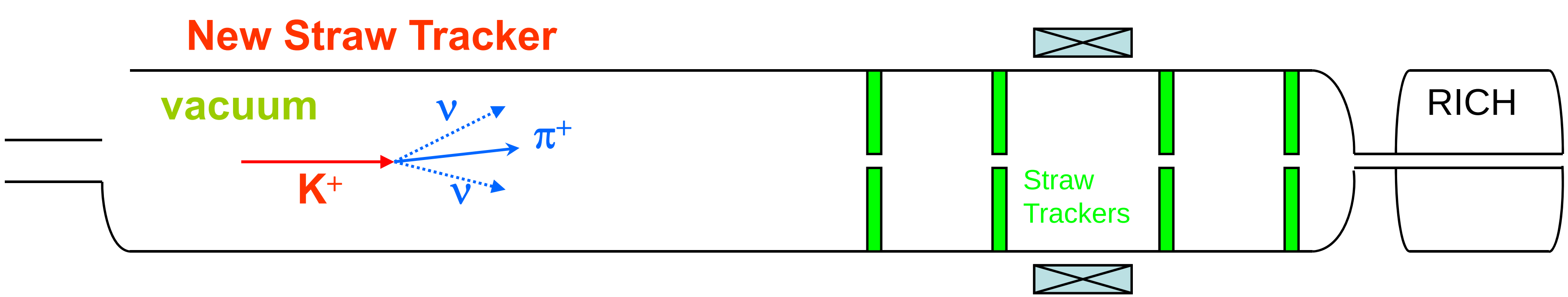


SPS is competitive if the KAMI/E391a technique is established

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**



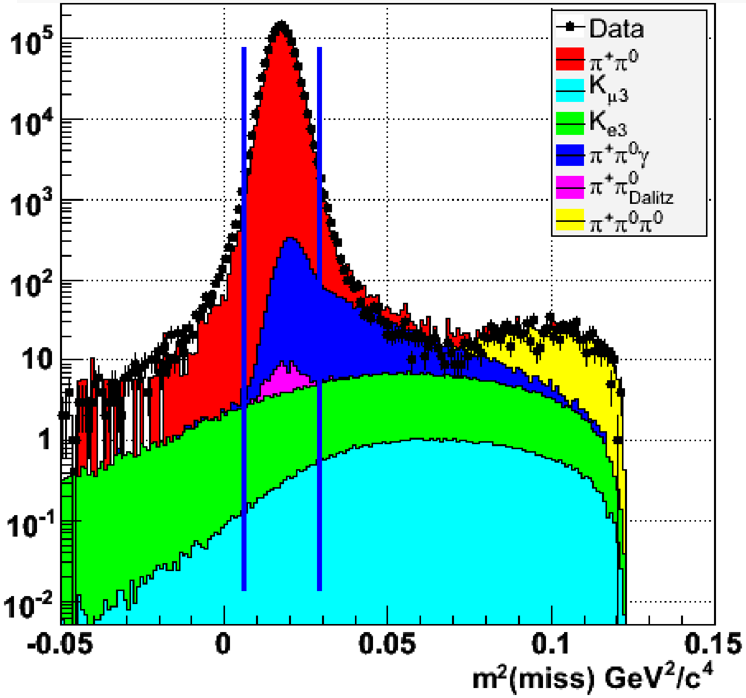
- **The Straw Tracker is essential to study ultra-rare-decays in flight**

LKr γ Detection Efficiency (Measured from data)

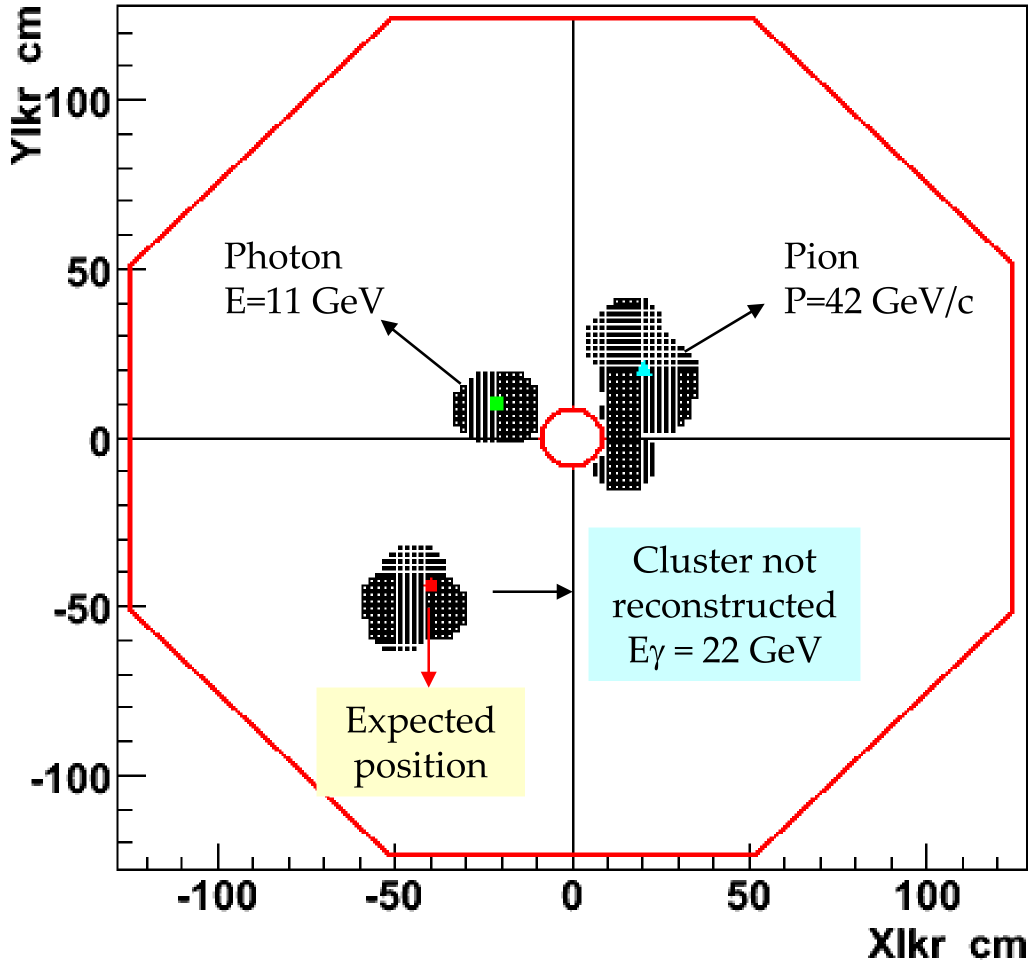
LKr ineff. per γ (E_γ > 10 GeV):

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

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

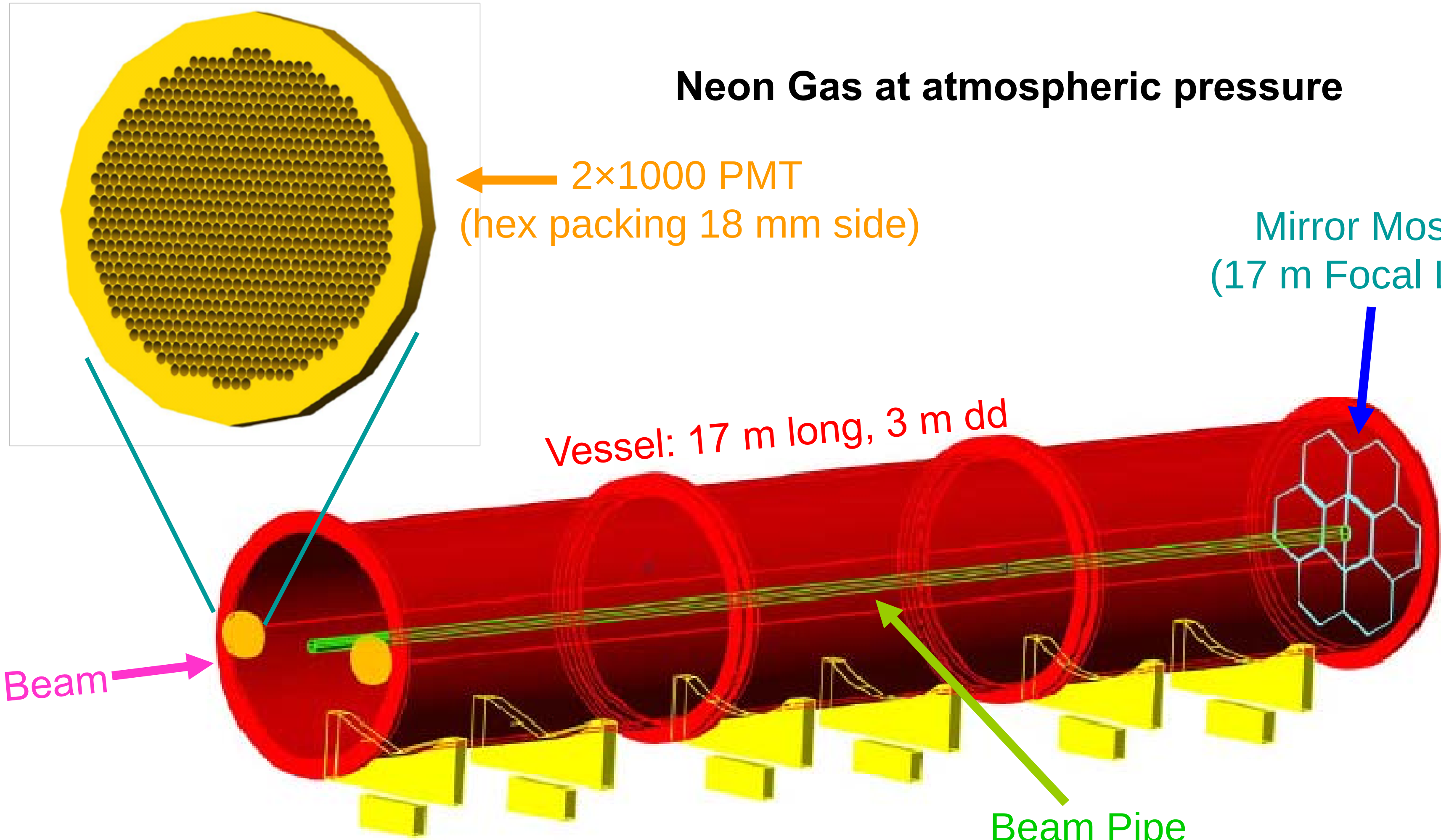


π^+ track and lower energy γ are use to predict the position of the other γ



The RICH Detector

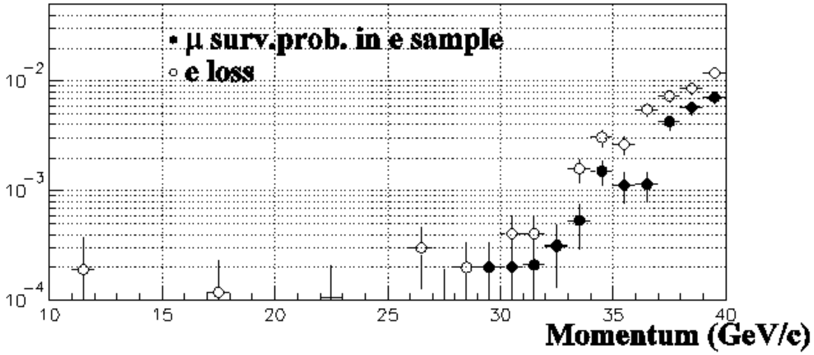
Neon Gas at atmospheric pressure

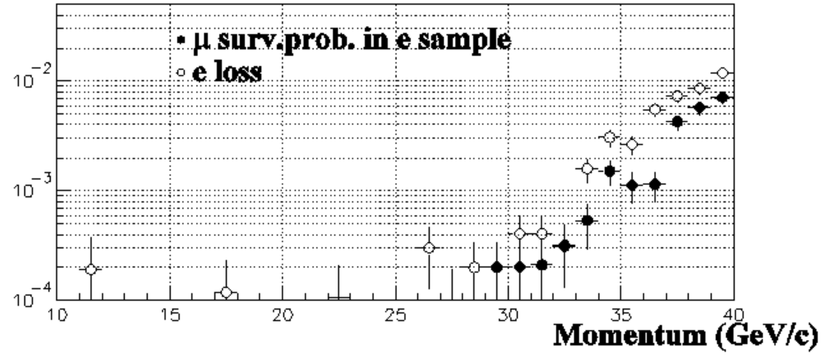


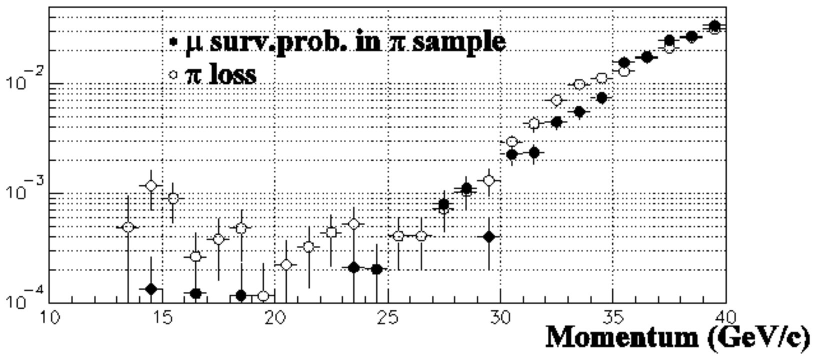
RICH Simulation: particles separation

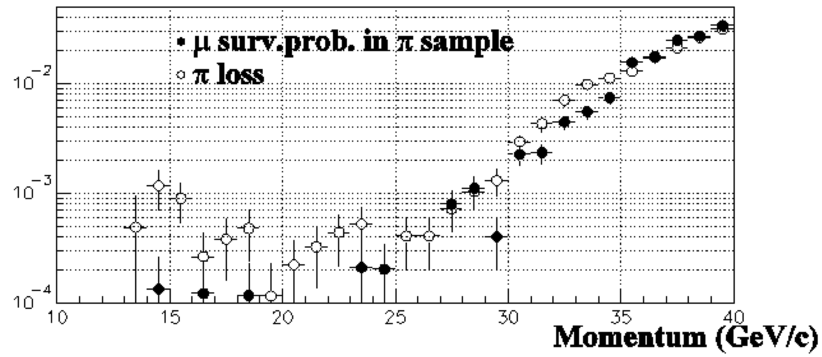
$$m_{rec}^2 = p^2\left(\vartheta_{max}^2 - \vartheta_c^2\right)$$

Momentum from the magnetic spectrometer









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

Kinematical Rejection

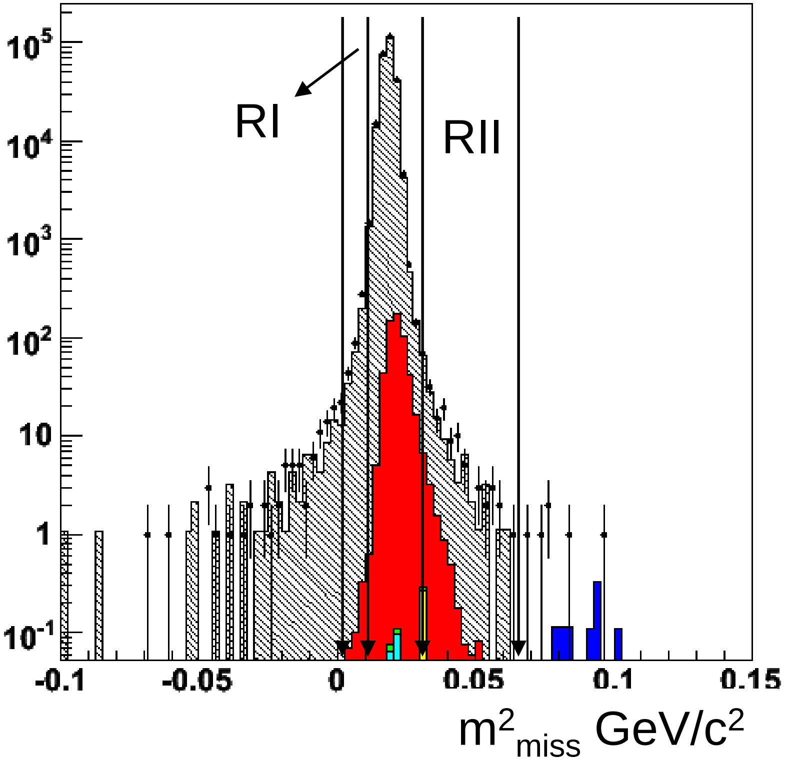
$K^+ \to \pi^+\pi^0$ selected on 2007 data using LKr information only

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

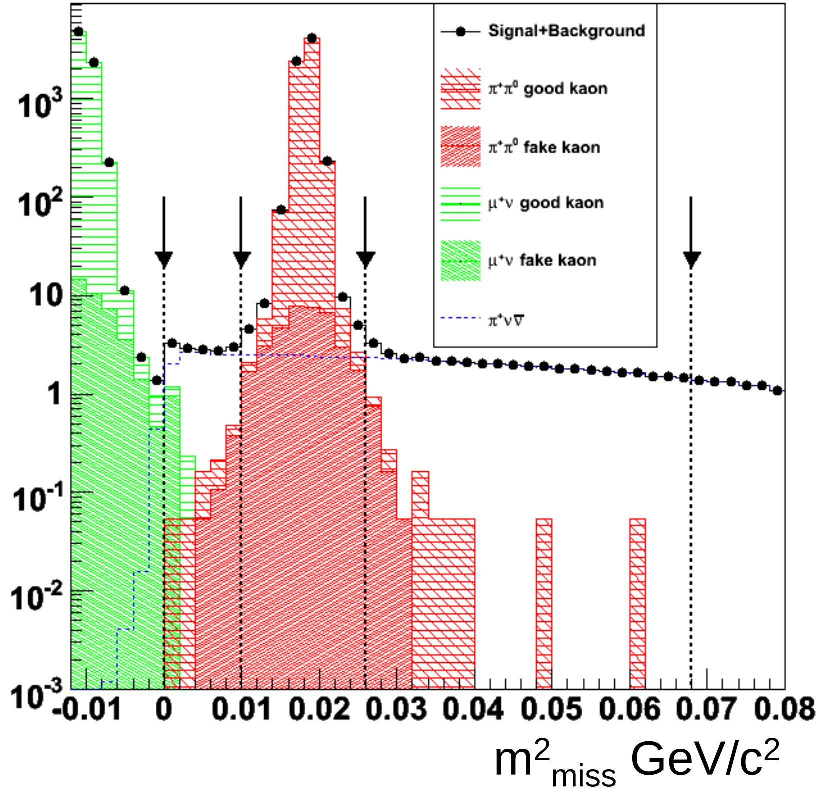
Data vs. NA48MC: reproducibility of non- gaussian tails within x2

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

OLD DCH: Data vs. MC



New Straw Tracker: MC

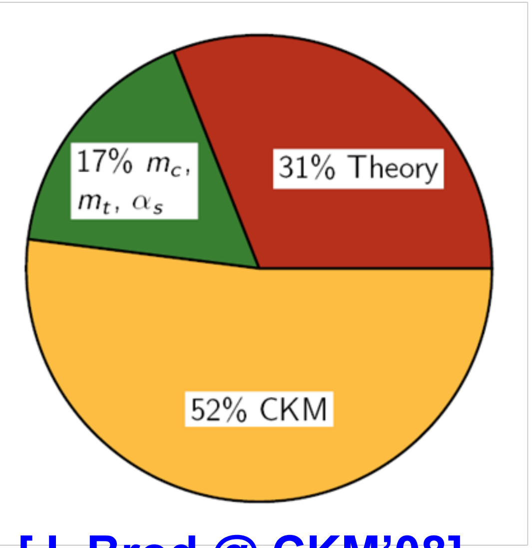


$K^+ \to \pi^+ \nu \bar{\nu}$: Physics Motivation

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]



[J. Brod @ CKM'08]

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

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]

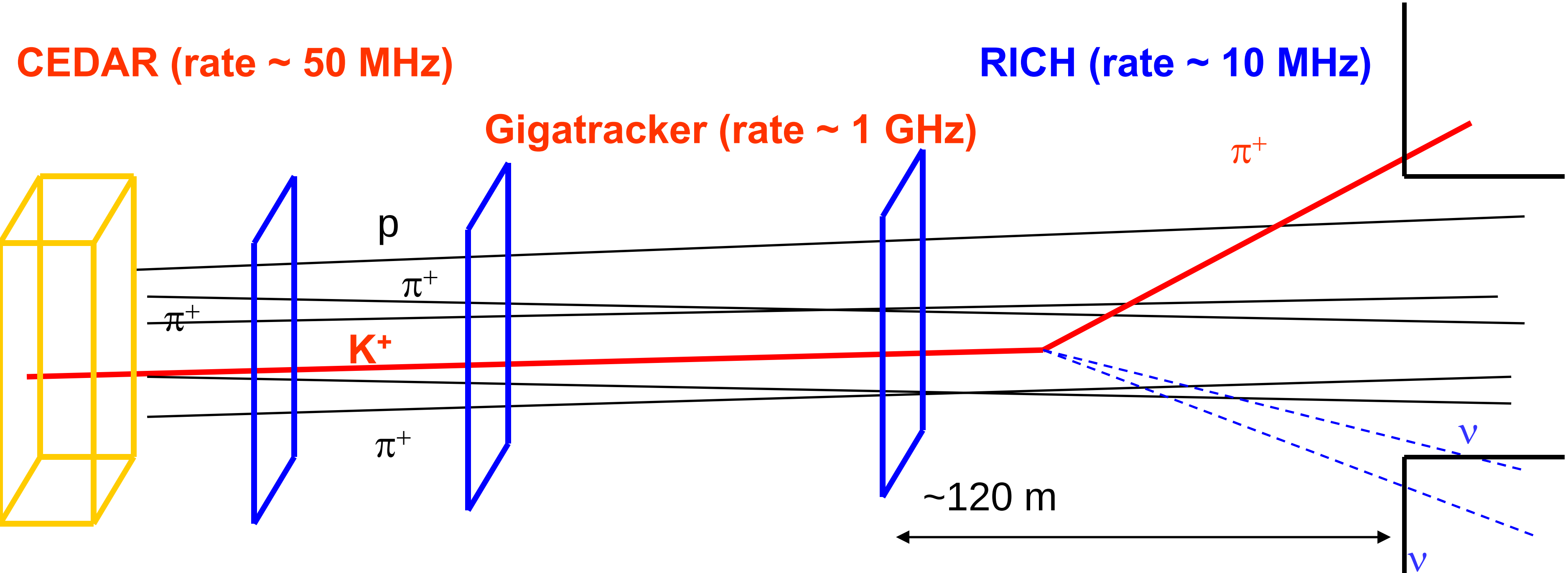
And, for comparison:

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

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

Future: E14 (KOTO) @ J-PARC

1. Precise Timing



Unseparated beam, in-flight decay:

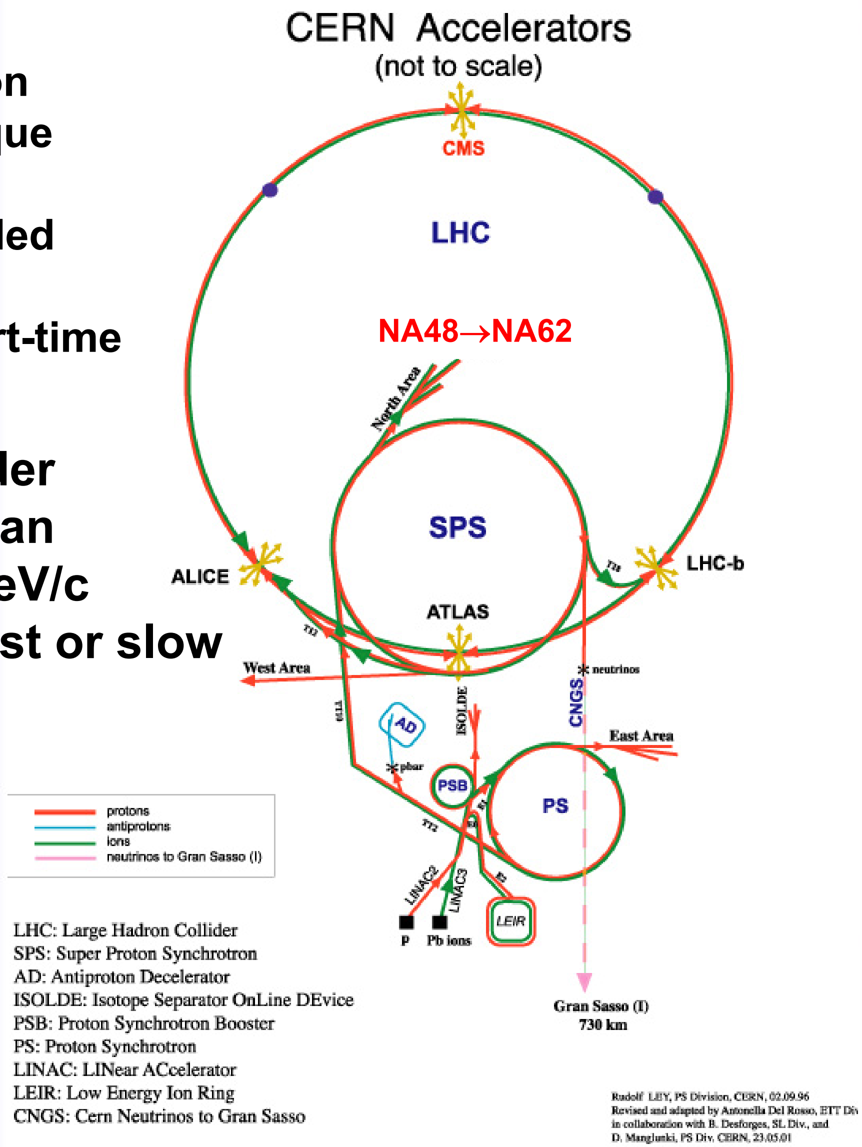
How do you associate the parent kaon to the daughter pion in a **~1 GHz beam** ?

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

The CERN proton Complex is unique

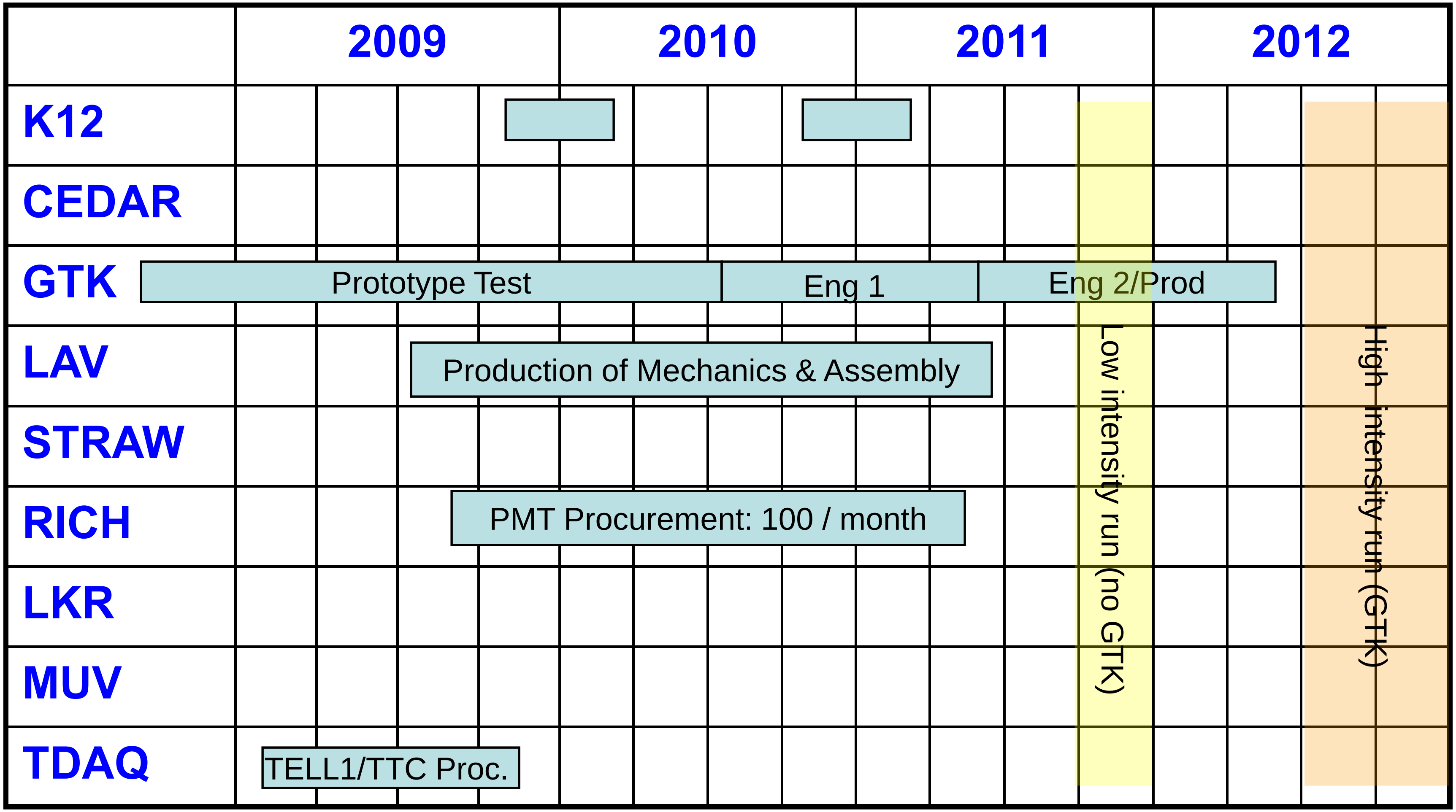
The SPS is needed as LHC proton injector only part-time

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

Timescale


2009
2010
2011
2012
K12
CEDAR
GTK
LAV
STRAW
RICH
LKR
MUV
TDAQ
Prototype Test
Eng 1
Eng 2/Prod
Production of Mechanics & Assembly
PMT Procurement: 100 / month
TELL1/TTC Proc.
Low intensity run (no GTK)
High intensity run (GTK)

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
$K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu3}$)	0.034
$K^+ \to \mu^+ \nu \gamma$ ($K_{\mu2\gamma}$)	6.2×10^{-3}
$K^+ \to \pi^+ \pi^- e^+ \nu$ (K_{e4})	4.1×10^{-5}
$K^+ \to \pi^+ \pi^- \mu^+ \nu$ ($K_{\mu4}$)	1.4×10^{-5}