NA62: Indirect Searches for New Physics in Rare Kaon Decays

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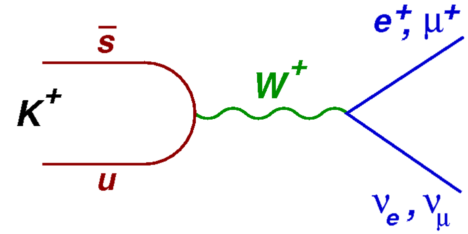
Introduction

- Precise measurement of FCNC processes in the B sector have severely restricted the parameter space of new-physics models
- Experiments at LHC have started a direct exploration of the physics in the TeV range
- In this scenario, which is the role of high-precision low-energy experiments on kaon physics in investigating the flavour structure of possible physics beyond the SM?

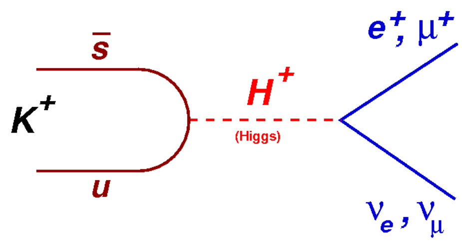
$K^+ \to l^+\nu$ (K_{l2}) and $K^+ \to l^+\pi^0\nu$ (K_{l3}) Decays

- Leptonic and semileptonic kaon decays are mediated by charged current at tree level

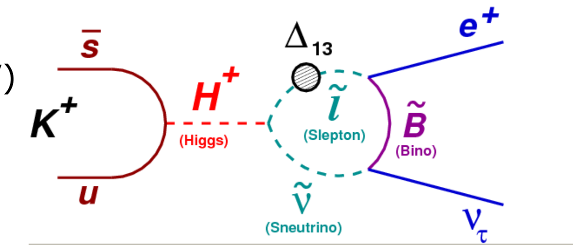


- The natural size of the non-standard contributions depends on the particular BSM scenario

SUSY
(LF conserving)



SUSY (LFV)

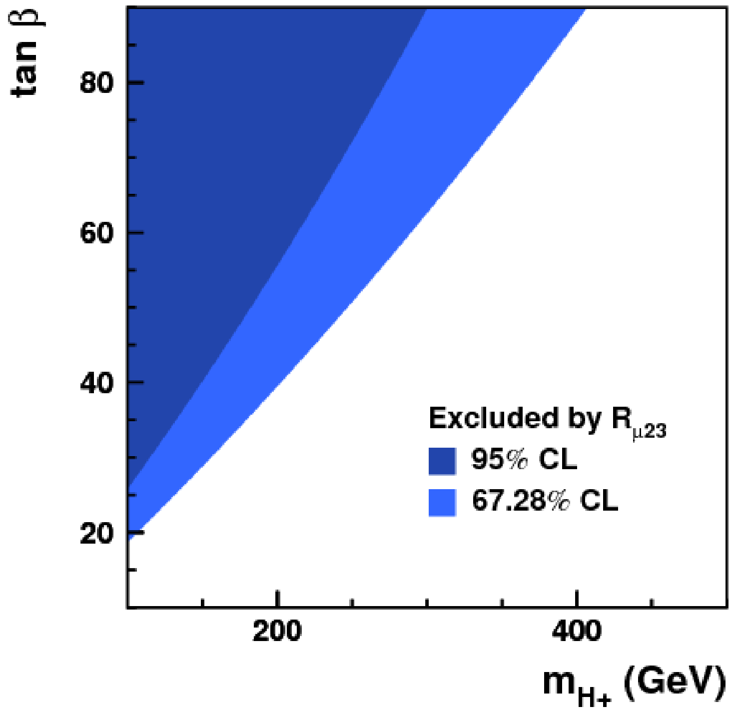


- In various consistent frameworks the effect is within the present experimental sensitivity
- In some cases ($R_K = K_{e2}/K_{\mu 2}$) SM theoretical predictions < 0.1%
  in others (V_{us}) errors larger but already < 1%
  (mainly thanks to Lattice progress)

Example of $K^+ \to \mu^+ \nu$ Sensitivity to NP

The effect of Higgs-mediated scalar currents is negligible in K_{l3}, while it could have a sizable impact in K_{l2}

$$R_{\mu 23} = \frac{K_{\mu 2}}{K_{\mu 3}} = \left(1 - \frac{m_K^2 \tan^2 \beta}{M_H^2 \left(1 + \varepsilon_0 \tan \beta\right)}\right)$$



Kaon data exclude the low-M_H and large tanβ region favoured by the 3σ discrepancy between the $B \to \tau \nu$ measured value and the preferred one from global CKM fit [M. Bona et al. arXiv:0908.3470]

[Eur. Phys. J. C 69 (2010) 399]

$R_K=\Gamma(K^+\to e^+\nu)/\Gamma(K^+\to\mu^+\nu)$

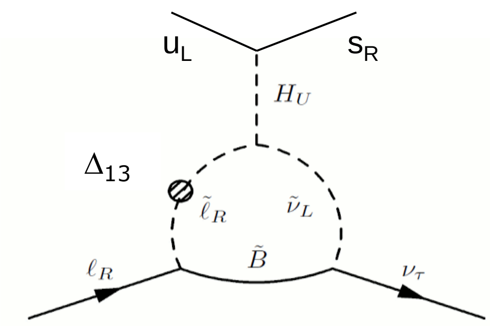
- In the ratio $R_K = \Gamma(K\to e\nu / K\to\mu\nu)$ hadronic uncertainties cancel
- The SM prediction of R_K has reached <0.1% precision

$$R_K^{SM} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1+\delta R_K^{rad.corr.}\right) = (2.477 \pm 0.001)\times 10^{-5}$$

[V. Cirigliano and I. Rosell Phys. Rev. Lett. 99 (2007) 231801]

- In MSSM with two Higgs doublets, LFV couplings, present at one loop level, can contribute to R_K^{SM} at the % level

$$R_K^{LFV} = R_K^{SM}\left[1+\left(\frac{m_K}{m_H}\right)^4\left(\frac{m_\tau}{m_e}\right)^2 |\Delta_{13}|^2 \tan^6\beta\right]$$

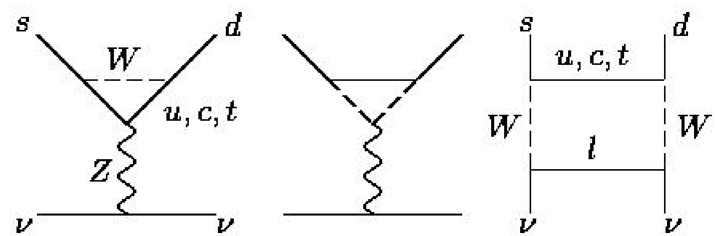


[A. Masiero, P.Paradisi, R. Petronzio Phys. Rev. D74 (2006) 0011701]

Larger effects foreseen in B decays due to $(m_B/m_K)^4 \sim 10^4$ but experimentally challenging

$K \to \pi \nu \bar{\nu}$ Decays

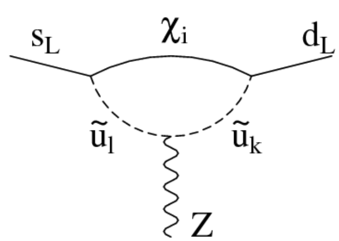
- FCNC decays mediated by Z penguins and box diagrams → strongly suppressed in the SM ($<10^{-10}$)

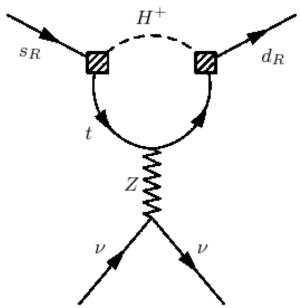


- Calculable with excellent precision [Phys.Rev. D83 (2011) 034030]

$$BR\left(K^{+} \to \pi^{+} \nu \bar{\nu}\right) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11} \qquad BR\left(K_{L} \to \pi^{0} \nu \bar{\nu}\right) = (2.43 \pm 0.39 \pm 0.06) \times 10^{-11}$$

- Sensitive to possible contributions from New Physics
  e.g. in MSSM with non-MFV:

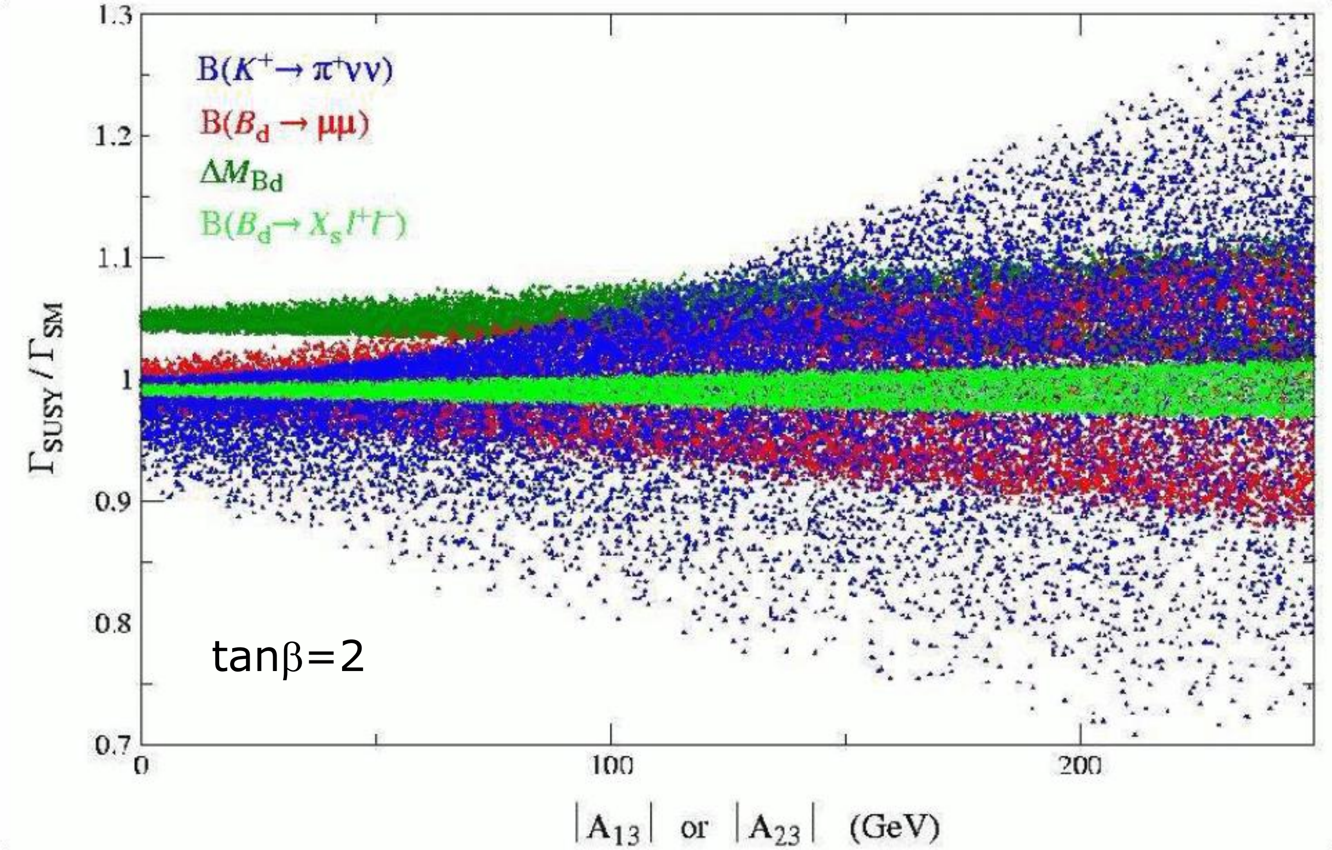




Example of $K^+ \to \pi^+ \nu\bar{\nu}$ Sensitivity to NP

- Non-standard effects induced by chargino-squarks amplitudes
- Small tanβ effects

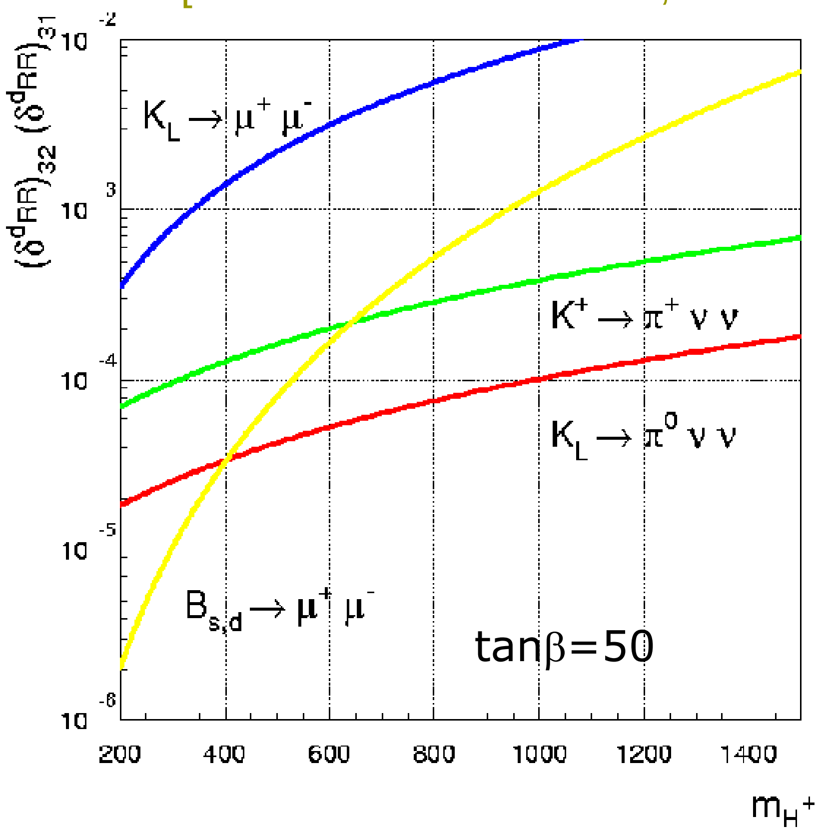
[G. Isidori et al. JHEP 0608:064 (2006)]



Example of $K^+ \to \pi^+ \nu\nu$ Sensitivity to NP

- Non-standard effects induced by charged Higgs top-quark loops
- Large $\tan\beta$ effects

[G. Isidori and P. Paradisi, PRD 73 (2006) 055017]

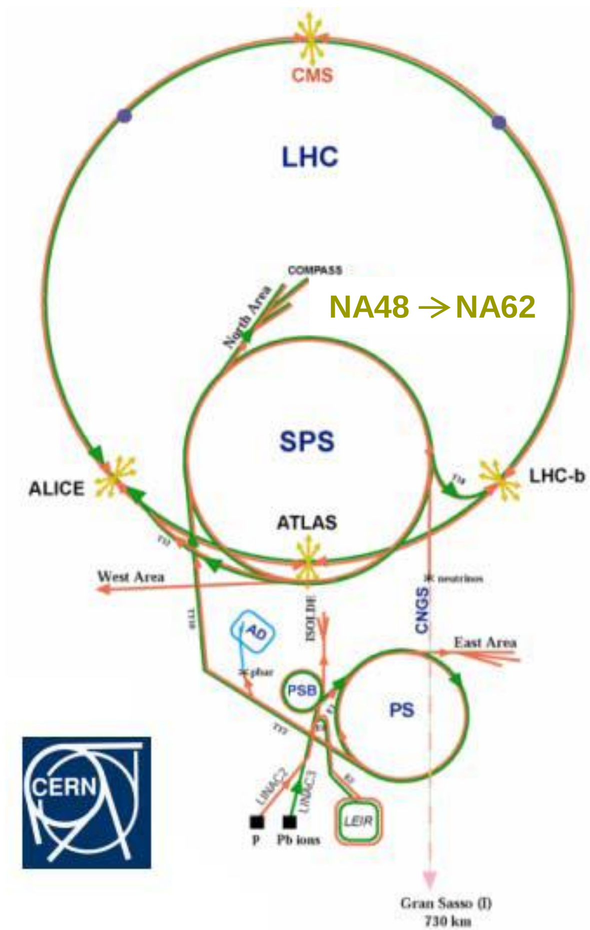


The NA62 experiment

A fixed target experiment at the CERN SPS

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

For the remainder of the time it can provide 400 GeV/c protons for fixed target and neutrino experiments



NA48-NA62 Experiments

Experience, infrastructures and (some) detectors from NA48 to NA62

NA48/2 Data taking:

- Six months in 2003 ($K^{\pm}$)
- Six months in 2004 ($K^{\pm}$)

NA62 phase I data taking (R_K measurement):

- Four months in 2007 (mostly K^{+} only)
- Two weeks in 2008

NA62 phase II data taking ($K^{+} \to \pi\nu\nu$ and R_K measurement):

- Two years of data taking

R_K: Measurement Strategy

- $K^+ \to e^+\nu$ (K_{e2}), $K^+ \to \mu^+\nu$ ($K_{\mu2}$) collected simultaneously:
  - No dependence on K flux
  - Cancellation of several effects at first order

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \cdot \frac{f_\mu \times A(K_{\mu2}) \times \varepsilon(K_{\mu2})}{f_e \times A(K_{e2}) \times \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKR}}$$

background events

signal events

acceptance

LKr trigger efficiency

measured PID efficiency

LKr readout

- Analysis performed in bins of the reconstructed lepton momentum

R_K: K_{e2} and $K_{\mu 2}$ Selection

Geometry

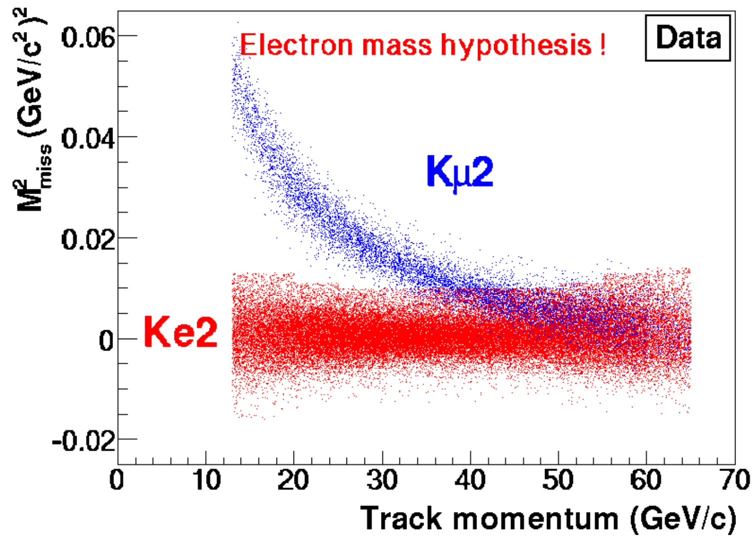
- One reconstructed charged track
- $13 < p < 65$ [GeV/c]
- Geometrical acceptance cut
- Decay vertex in the fiducial region upstream
- Photon veto using LKr

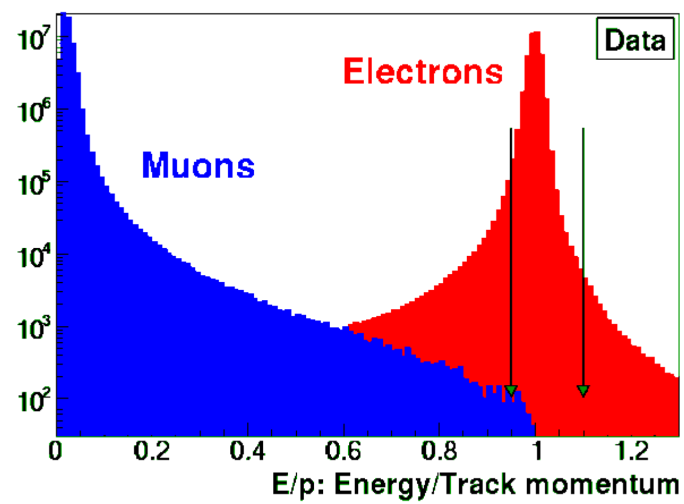
Kinematics

- Missing mass: $M_{miss}^2(l)=(p_K-p_l)^2$
- $-M_1^2<M_{miss}^2(l)< M_2^2$

Particle ID (E_{LKR}/p_{spectr})

- **e** ($(E/p)_{min} < E/p < 1.1$)
- μ ($E/p < 0.85$)

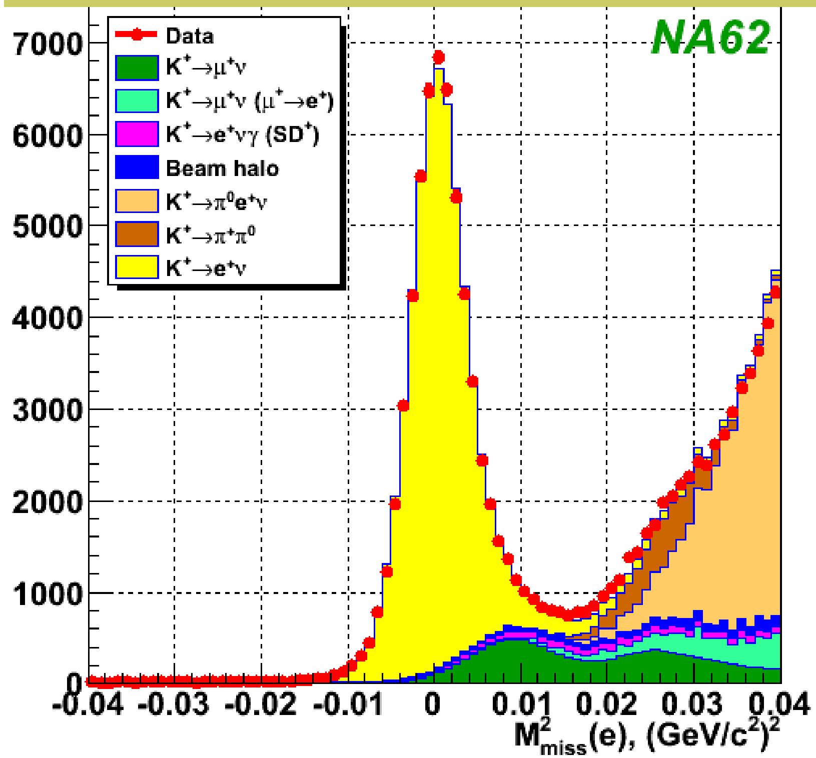




R_K: Signal and Background

40% of the total 2007 data analyzed

Missing invariant mass, K_{e2} candidates



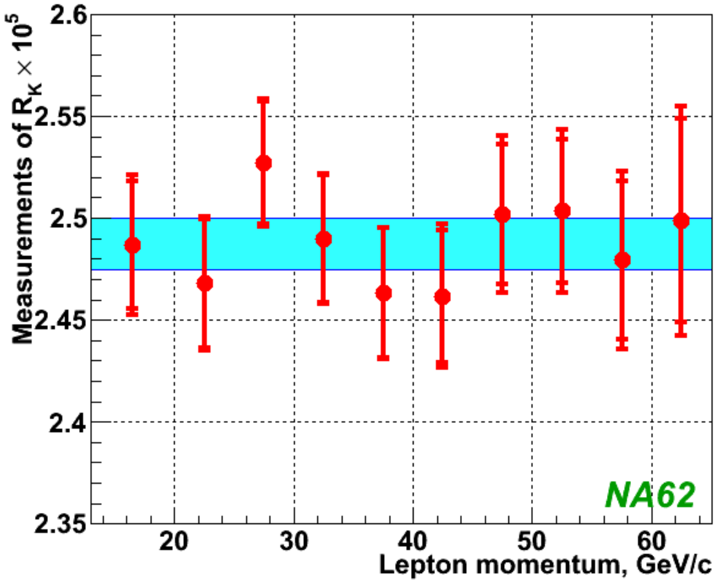
59,813 K_{e2}^+ candidates

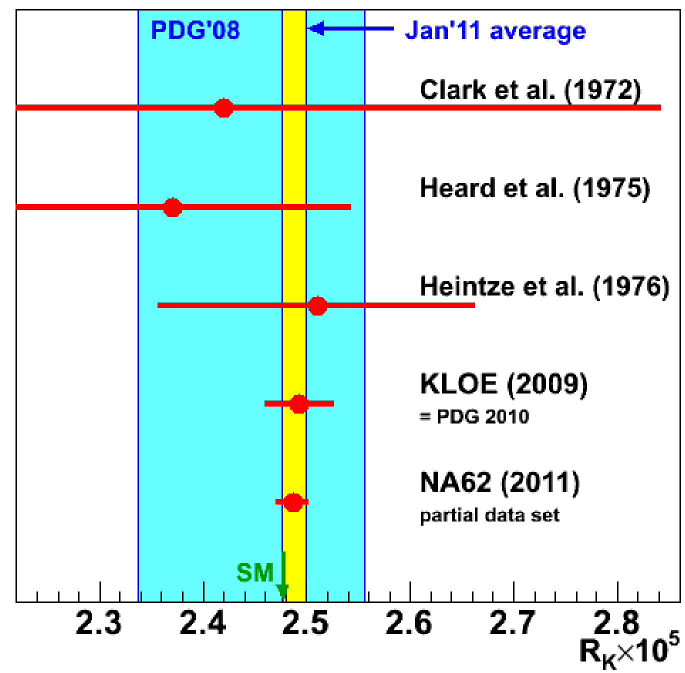
(99.27±0.05)% e^+ ID efficiency

Decay	B/(S+B)
$K^+ \to \mu^+\nu$	(6.11 ± 0.22)%
$K^+ \to \mu^+\nu$ ($\mu \to e$)	(0.27 ± 0.04)%
$K^+ \to e^+\nu\gamma$ (SD^+)	(1.07 ± 0.05)%
$K^+ \to \pi^0 e^+\nu$	(0.05 ± 0.03)%
$K^+ \to \pi^+\pi^0$	(0.05 ± 0.03)%
Beam halo	(1.16 ± 0.06)%

R_K: Final Result

[Phys. Lett. B 698 (2011) 105]





R_K = (2.487 ± 0.011 stat ±0.007 syst) x 10^{-5}
= (2.487 ± 0.013) x 10^{-5}

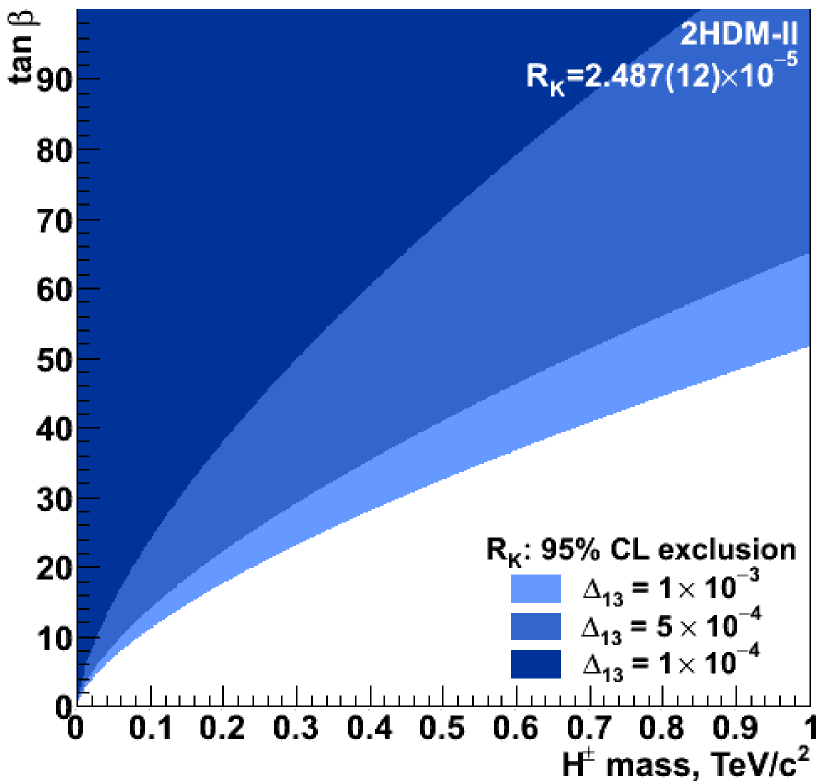
World average:

R_K = (2.487 ± 0.012) x 10^{-5}

The whole 2007 sample will allow stat uncertainty ~0.3%, total of ~0.4%

R_K: Sensitivity to NP

For non-tiny values of the LFV s-lepton mixing Δ_{13}
the sensitivity to $H^{\pm}$ in R_K is strong



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

Stopped

- Work in kaon frame
- High kaon purity
- Compact detectors

In-Flight

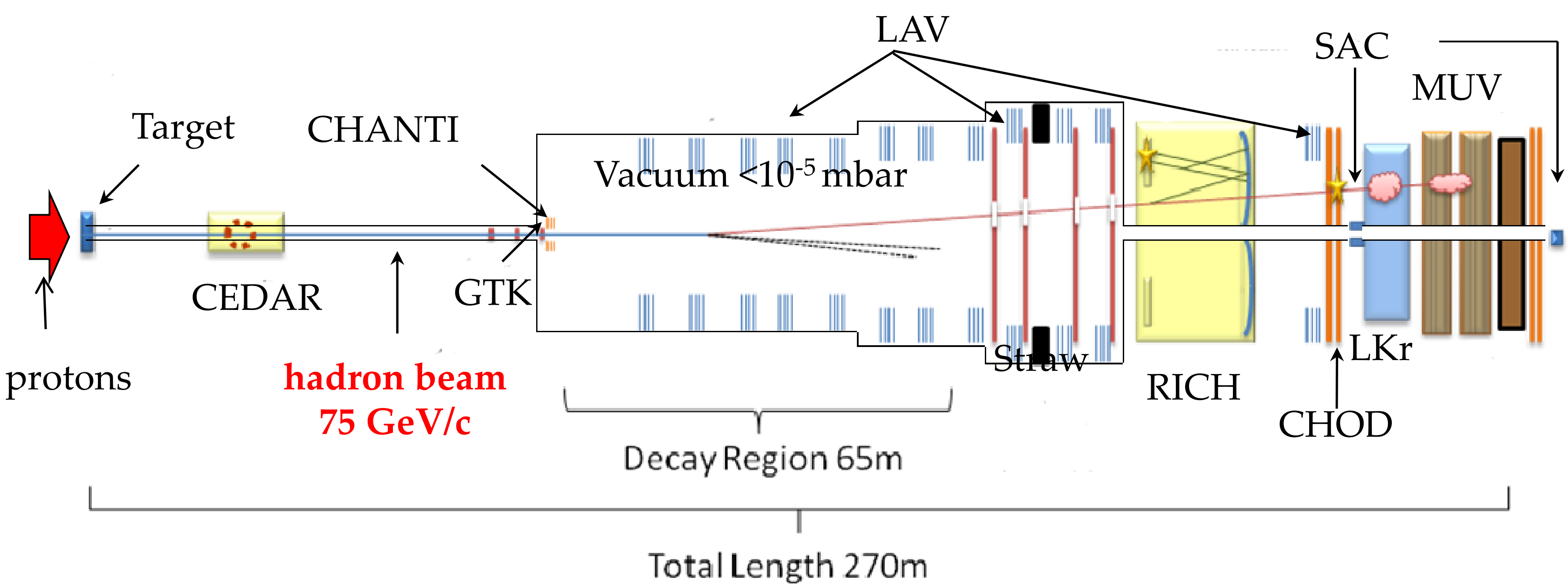
- Decays in vacuum
- RF separated or not separated beams
- Extended decay regions

Exp	Machine	Meas. or UL 90% CL	Notes
	Argonne	$<5.7\times10^{-5}$	Stopped; HL Bubble Chamber
	Bevatron	$<5.6\times10^{-7}$	Stopped; Spark Chambers
	KEK	$<1.4\times10^{-7}$	Stopped; $\pi^+ \to \mu^+ \to e^+$
E787/E949	AGS	$(1.73^{+1.15}_{-1.05})\times10^{-10}$	Stopped
NA62	SPS		In Flight; Unseparated
P996	FNAL		Stopped; Tevatron as strecher ring?

NA62 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Measurement

Branching ratio measurement of $K^+ \rightarrow \pi^+ \nu\nu$ with 10% accuracy

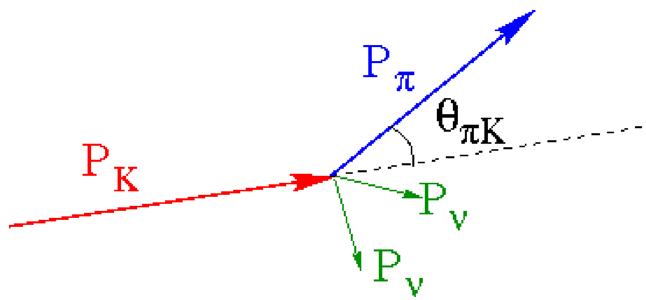
- O(100) $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events (2 years of data taking)
- 10/1 signal to background ratio



Background Rejection

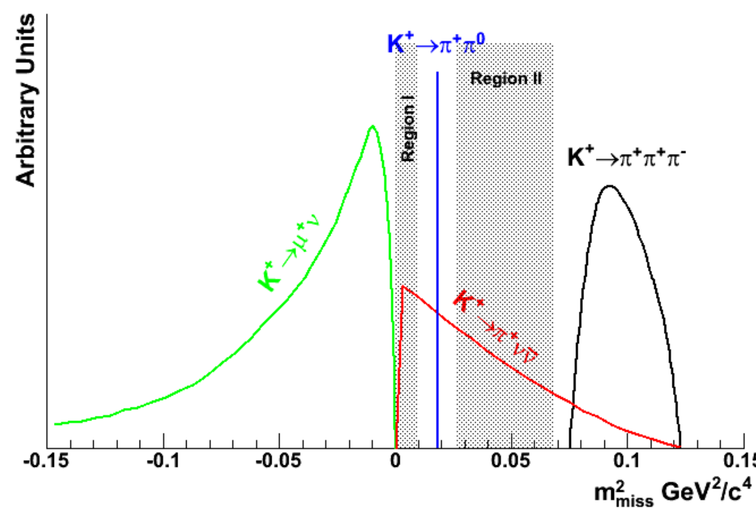
Signal signature:

- Incoming high momentum(75 GeV/c) K^+
- Outgoing low momentum(<35 GeV/c) π^+ in time with the incoming K^+



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

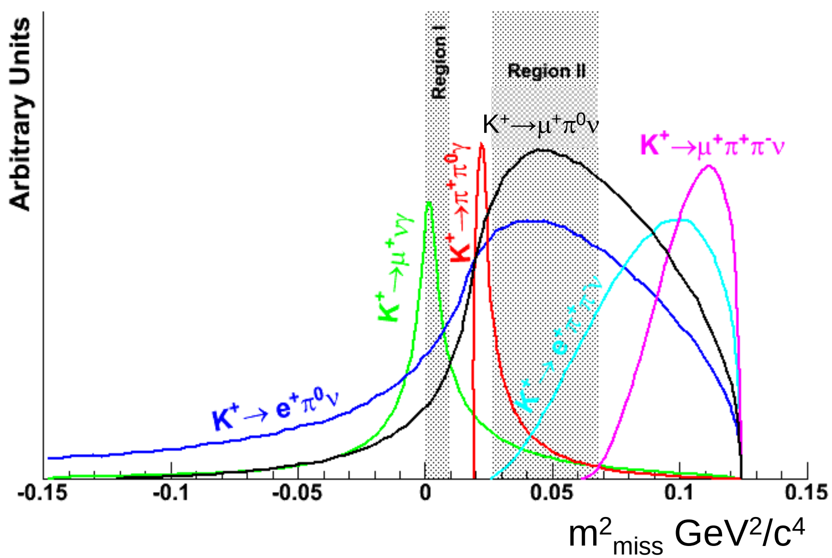
Decay	BR
$K^+ \to \mu^+ \nu (K_{\mu 2})$	0.64
$K^+ \to \pi^+ \pi^0 (K_{\pi 2})$	0.21
$K^+ \to \pi^+ \pi^+ \pi^-$ $K^+ \to \pi^+ \pi^0 \pi^0$	0.07



~92% of kaon decays kinematically constrained

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}

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 and 60% overall efficiency

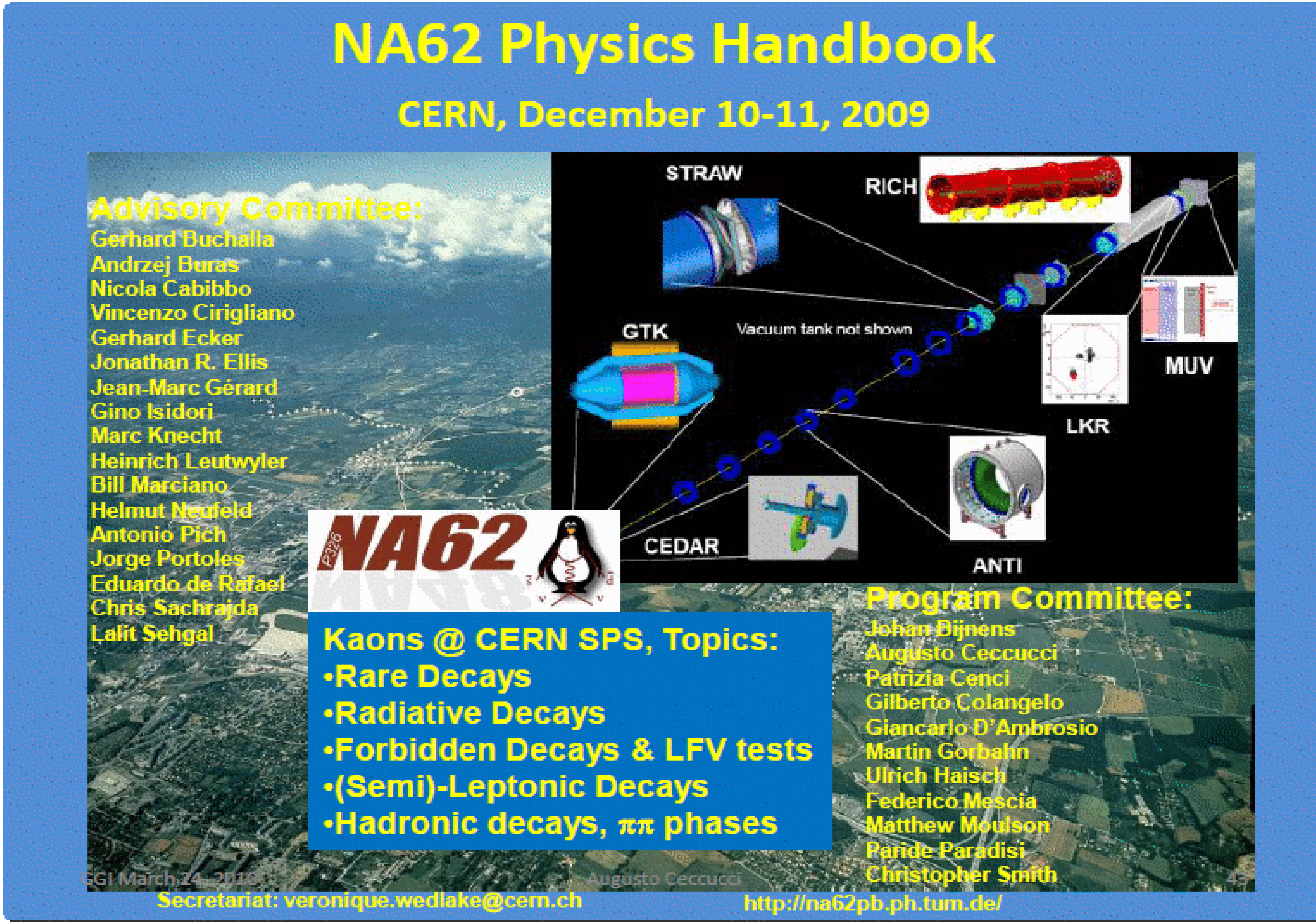
Detector Layout and Planning

- Beam tracker (10^9 part/s) based on Si micro pixel with ~200 ps time resolution and thickness ~0.5% X_0 per station
- Spectrometer (Straw Tubes) to be operated in the vacuum tank: total thickness for 16 views ~1%X_0
- PID (π/μ) with a μ rejection factor $>5\times10^3$ up to 35 GeV/c

  Employ a Neon RICH with 17 m focal length spherical mirrors
- Hermetic coverage with π^0 suppression factor $\sim10^8$

  Employ high performance calorimeters as photon vetoes: Liquid Krypton (NA48)+Lead Glass(OPAL)

- R&D finished in 2010
- 2010-2012: construction
- End 2012: first technical run
- Physics data taking driven by CERN accelerator schedule


NA62 Physics Handbook
CERN, December 10-11, 2009
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RICH
GTK
Vacuum tank not shown
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•Radiative Decays
•Forbidden Decays & LFV tests
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$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

The charm contribution can be fully neglected since it proceeds in the SM almost entirely through direct CP violation → determination of η

Exp	Machine	Meas. or UL 90% CL	Notes
KTeV	Tevatron	$<5.7\times10^{-7}(\pi^0\rightarrow ee\gamma)$	
E391a	KEK-PS	$<2.6\times10^{-8}$	
KOTO	J-PARC		Aim at 2.7 SM evts/3y
KOPIO			Opportunity at Project X ?

Need a huge number of K_L decays

NA48 K_L flux corresponding to 3×10^{10}/year

NA62 possible K_L flux 5-10 times NA48 one

After SPS upgrade 100 times more

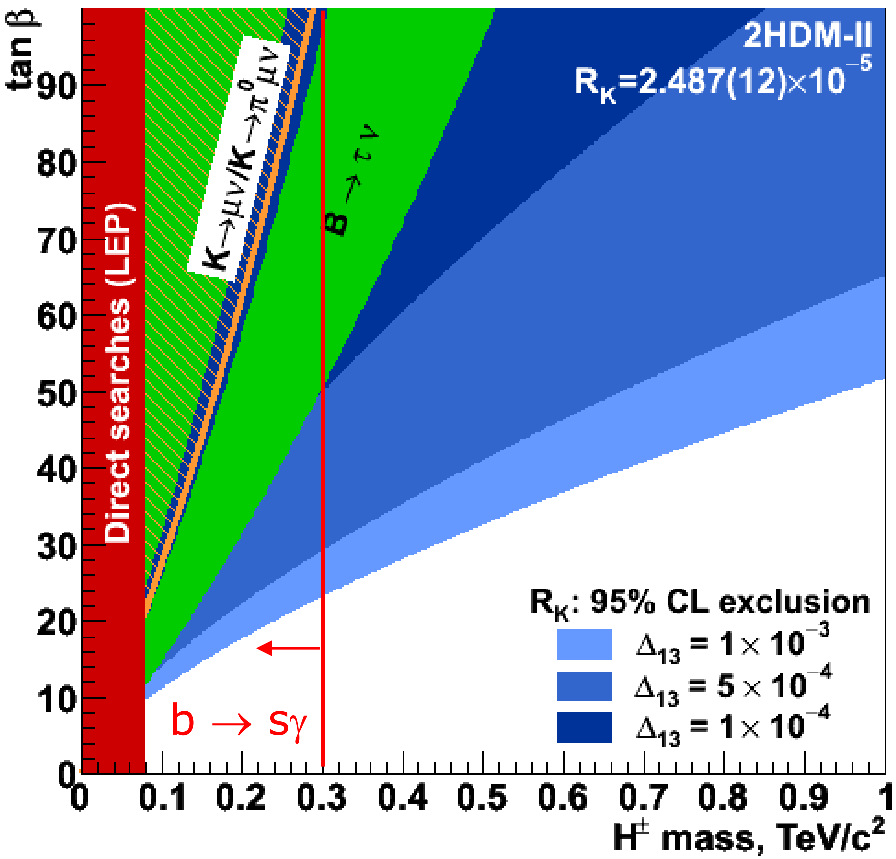
Conclusions

- R_K measurement:
  - The analysis of a partial data sample (40%) allows for 0.5% relative precision, combined with the other world measurements
  - The complete data set will allow a total uncertainty of 0.4%
  - The NA62 phase-II could improve the precision down to 0.2%
- $B(K^+ \rightarrow \pi^+ \nu\nu)$ measurement:
  - High sensitivity to New Physics
  - 10% precision BR measurement in two years of data taking planned
  - **Experiment under construction**

Rare kaon decays are an outstanding opportunity to search for NP effects complementary to the high energy frontier and to the precision B physics

Spares

R_K: Sensitivity to NP



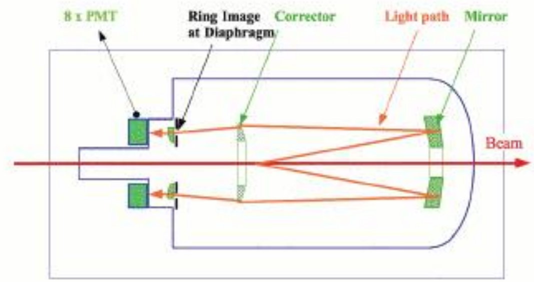
$B\to\tau\nu$ [HFAG 2010]

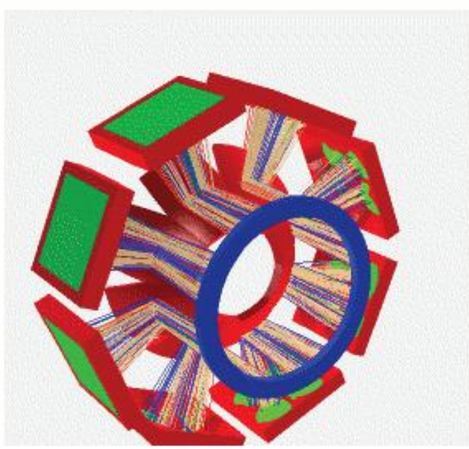
$R_{\mu 23}$ [Eur. Phys. J. C 69 (2010) 399]

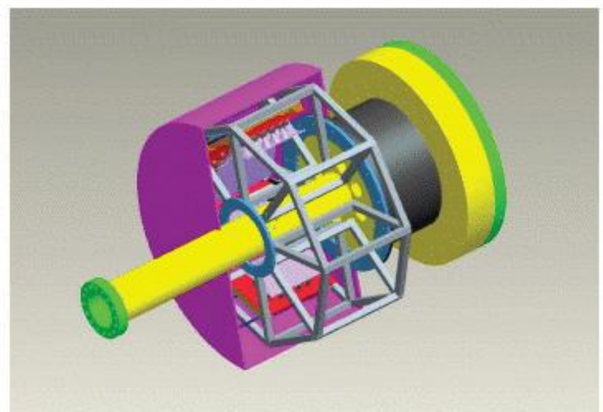
$b\to s\gamma$ [HFAG 2010]

Cedar

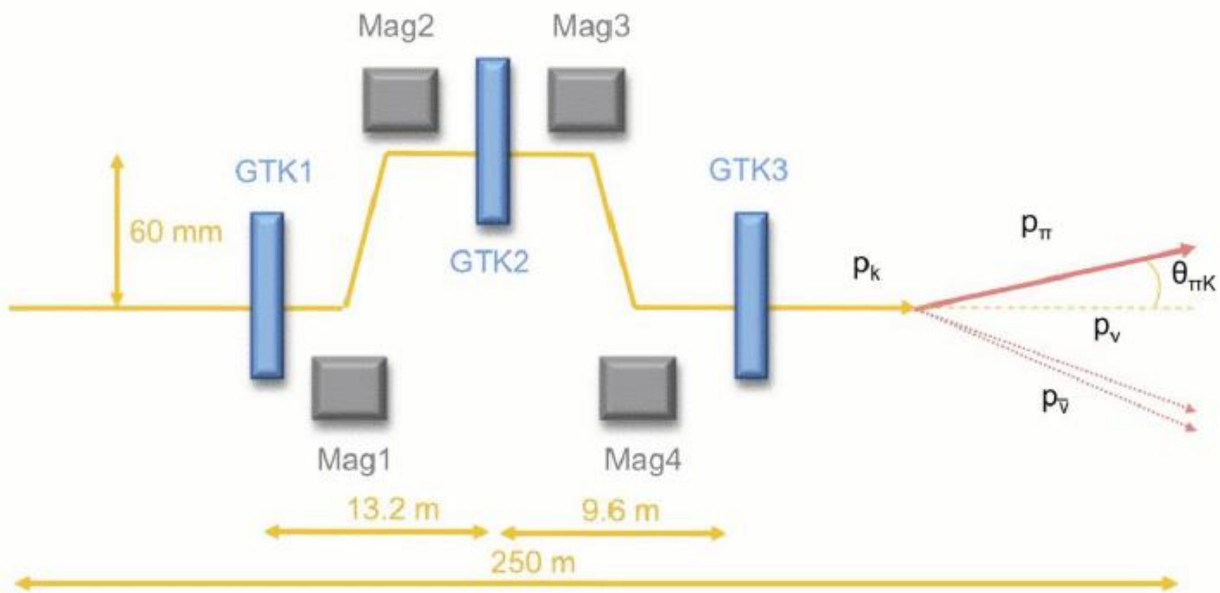
- H_2 @ 3.86 bar
- 100 photons/K
- K @ 50MHz
- $\approx$ 250 PMs
- 3MHz/PM
- $\sigma_t < 100$ps







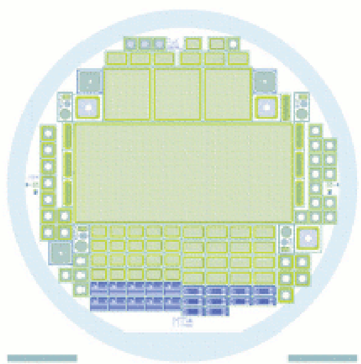
GigaTracker

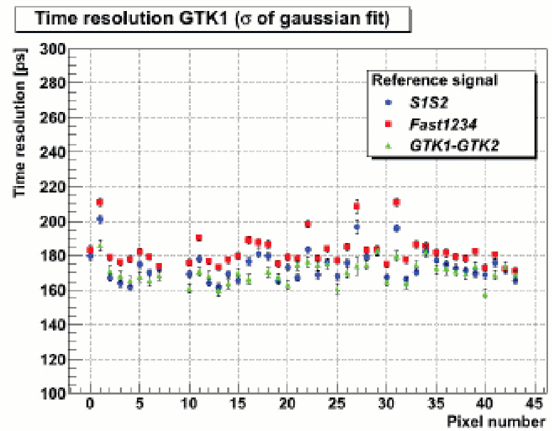


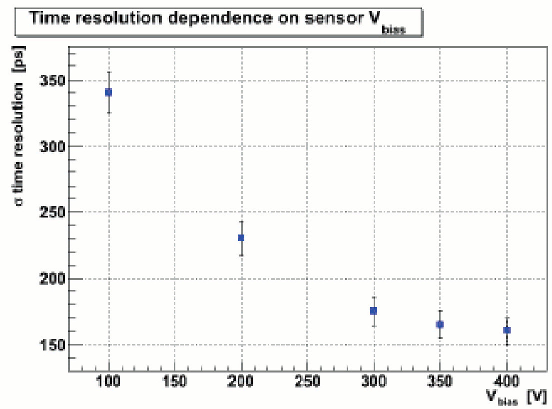
- Si μ-pixel (300μm$\times$300μm)
- $< 3 \times 0.5\% X_0$ ($< 1mm$)
- $> 99\%$ efficiency
- $\sigma_p/p \approx 0.2\%$
- $\sigma_\theta \approx 16\mu$rad
- $\sigma_t < 200$ps/station

GigaTracker: Test Beam

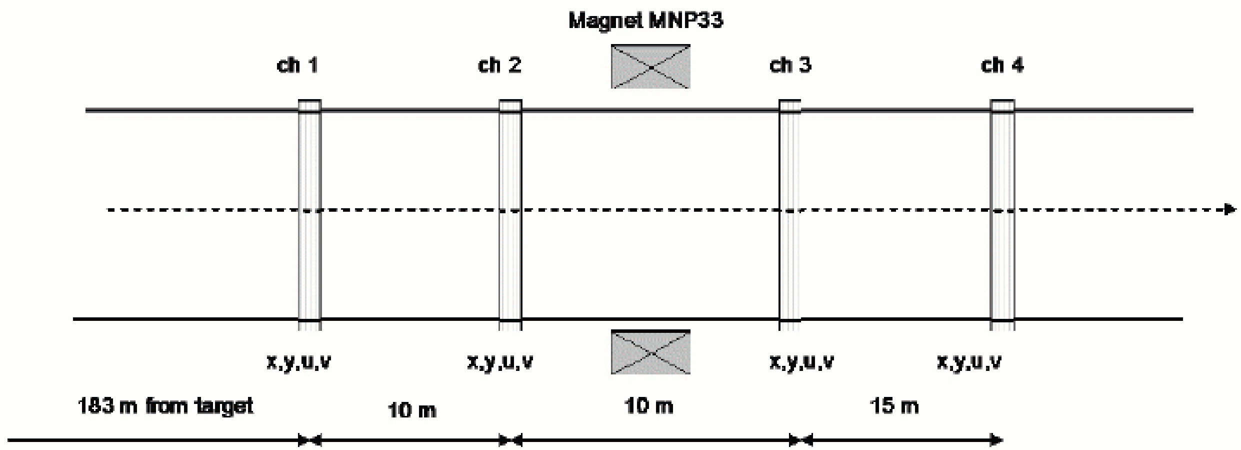
- Wafer with
  - Full final sensor
  - Single chip sensors
  - Prototype ASICs (EOC, p-TDC)
- 10GeV π beam
- 4 stations/ASIC prototype







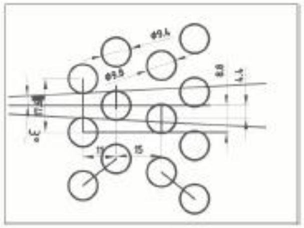
Spectrometer

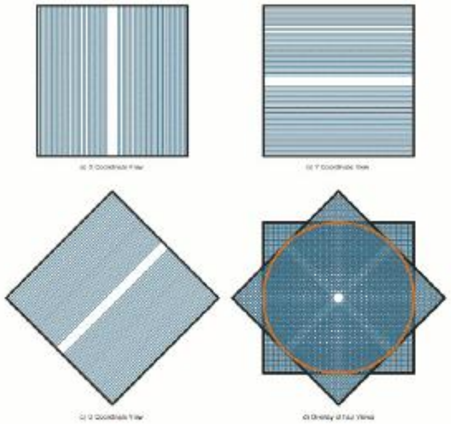


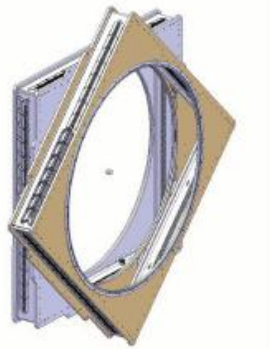
- Dipole magnet 0.36T (270MeV/c p_T kick)
- In vacuum ($< 10^{-6}$mbar)
- 7168 mylar straws
- $ArCO_2$ 70%:30%
- $< 4 \times 0.5\% X_0$
- $\sigma_p/p < 1\%$
- $\sigma_\theta < 60\mu$rad
- $\geq 99\%$ hit efficiency
- leakrate $< 10^{-1}$mbar l/s

Straw Chambers

- 4 views (u,v,x,y)
- $\oslash = 2.1$m acceptance
- $\oslash \approx$12cm beam hole
- Track angle coverage $\pm 3^o$
- 30μm gold-plated W wire
- 100μm straw straightness
- 200μm| wire position acccuracy
- $\sigma < 130\mu$m single view

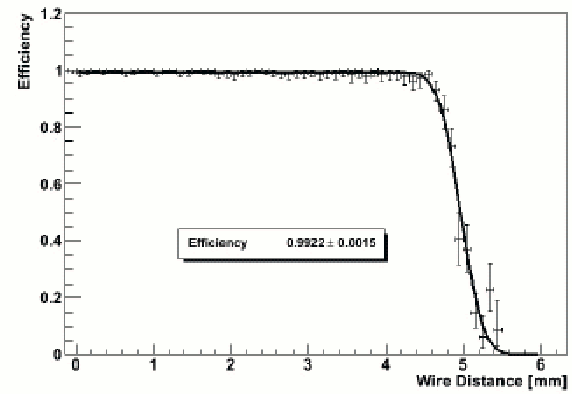


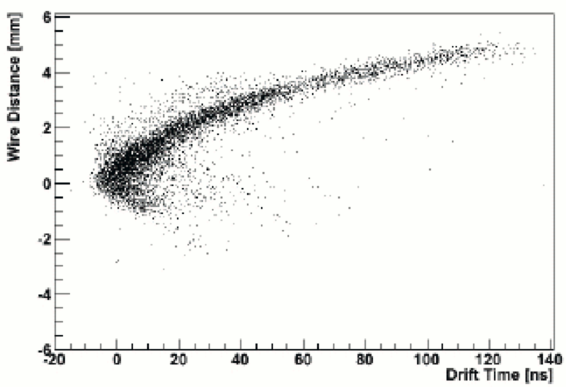


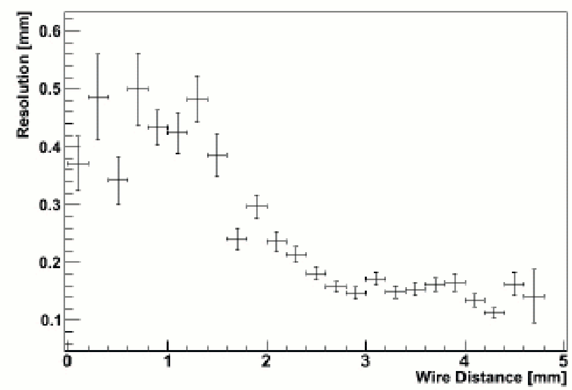


Straw : Test Beam

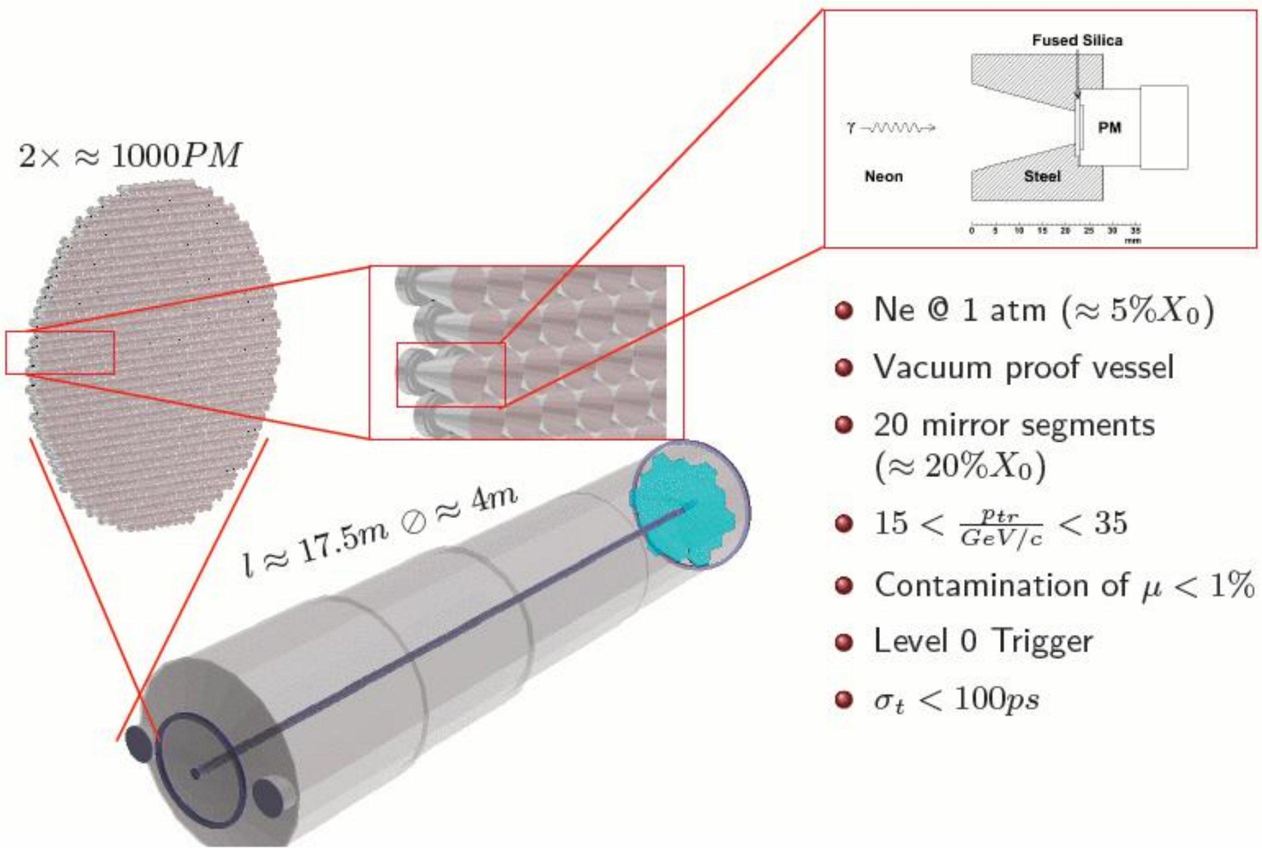
- 64 straws prototype
- Final mechanics
- Vacuum proof vessel
- CARIOCA based FE
- 120GeV π beam





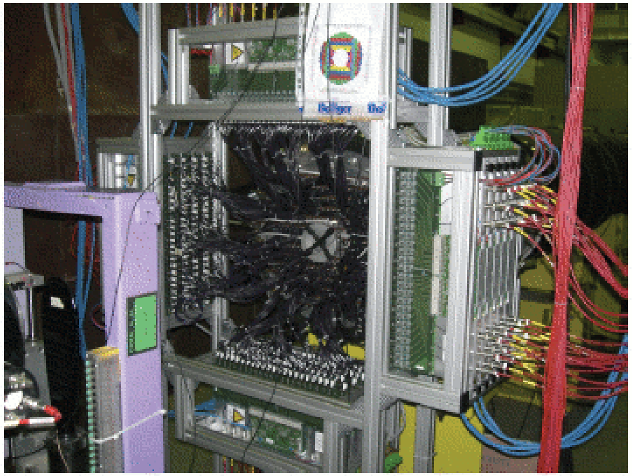


RICH

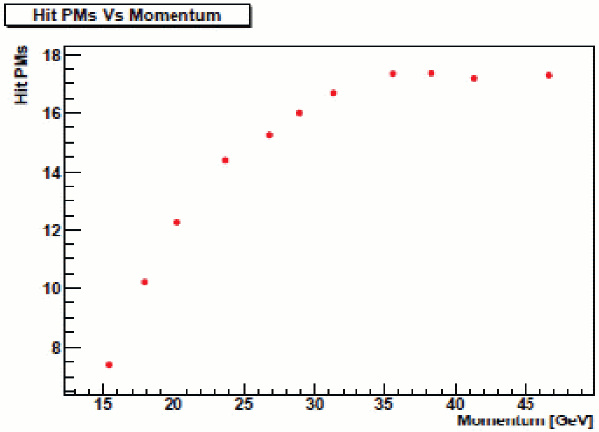


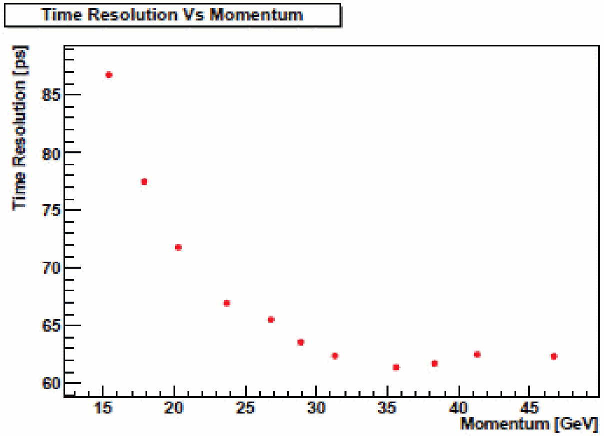
- Ne @ 1 atm ($\approx 5\% X_0$)
- Vacuum proof vessel
- 20 mirror segments ($\approx 20\% X_0$)
- $15 < \frac{ptr}{GeV/c} < 35$
- Contamination of $\mu < 1\%$
- Level 0 Trigger
- $\sigma_t < 100ps$

RICH: Test Beam

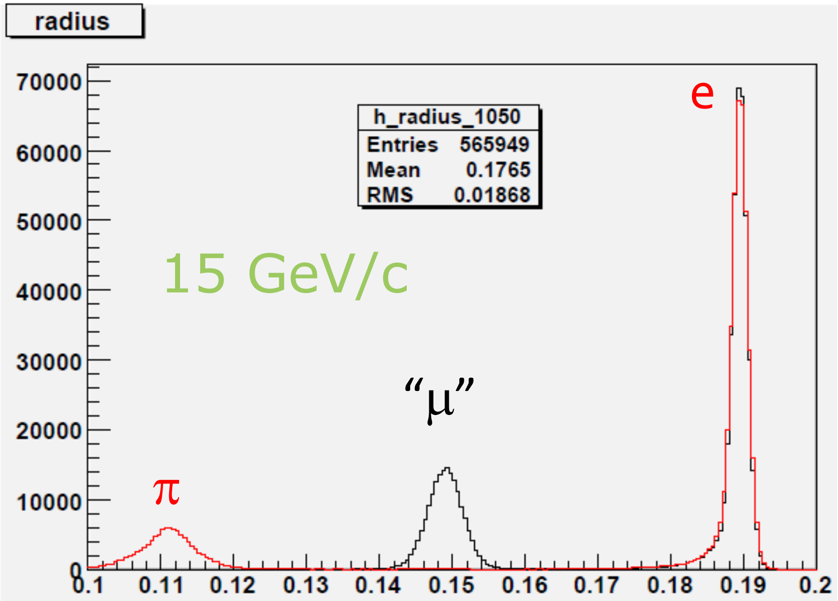


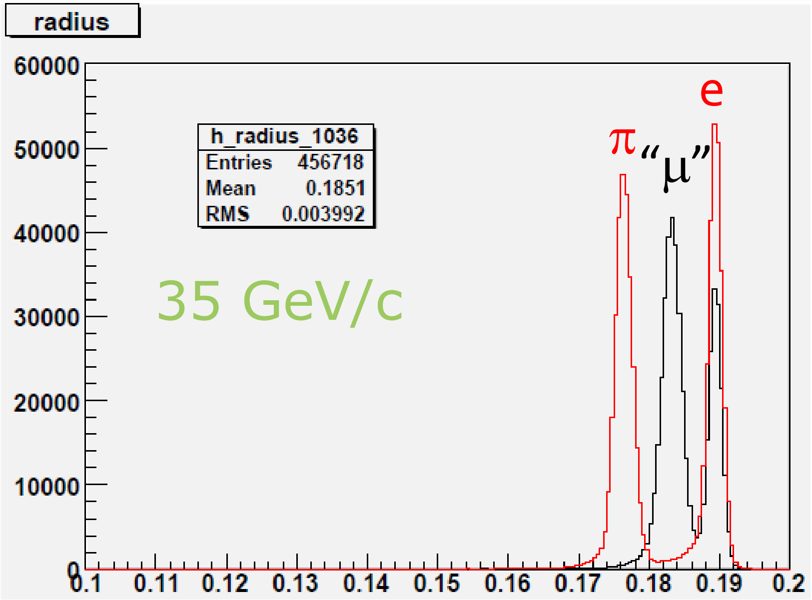
- 414 PMs (full acceptance covered)
- Same mirror (2 aluminizations)
- Beam $\pi^+/e^+/p$ @ 10-46 GeV/c
- Cooling





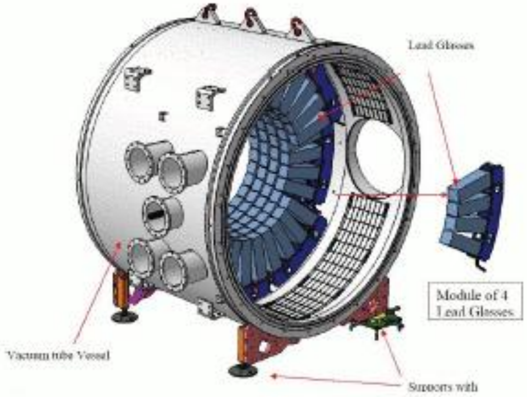
RICH: Test Beam





LAV

- 12 stations
- 2500 lead glass blocks (part of OPAL e.m calorimeter)
- Able to operate in a vacuum of 10^{-6}mbar
- $\approx$8 to 50 mrad
- Inefficiency $< 10^{-4}$ for $E_\gamma > 200\text{MeV}$



LAV: Test Beam

- 1 full station
- Beam:
  - e^- @ 0.3-2GeV
  - μ @ 8GeV
- FE validated
- Charge from ToT technique validated