Towards a future experiment to measure BR($K^+ \rightarrow \pi^+ \nu\nu$)

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for P326 collaboration

New Trends in High Energy Physics Conference

Yalta-2005

OVERVIEW

- Why ?
- Where ?
- Who ?
- How ?
- When ?

Conclusion

Why do we want to measure BR($K^+ \rightarrow \pi^+ \nu\nu$) ?

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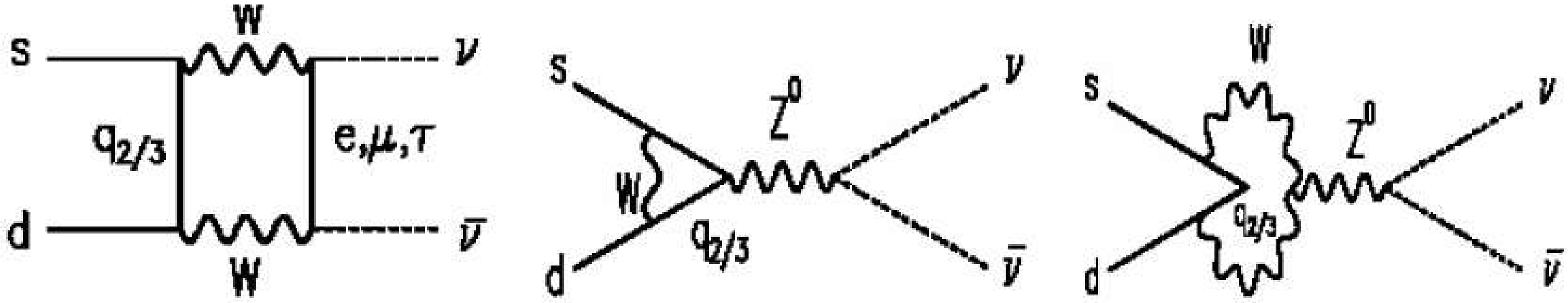
$K\rightarrow\pi\nu\nu$ in the SM



$$B(K^+\rightarrow\pi^+\nu\bar{\nu})=\kappa_+\cdot\left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2+\left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5}X(x_t)+\frac{\mathrm{Re}\,\lambda_c}{\lambda}P_c(X)\right)^2\right]$$

$$B(K_L^0\rightarrow\pi^0\nu\bar{\nu})=\kappa_L\cdot\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2$$

charm quark contribution

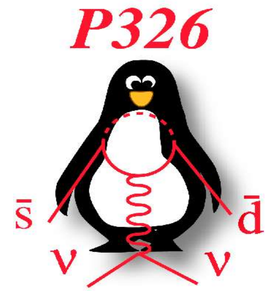
$$\lambda=V_{us}$$
$$\lambda_c=V_{cs}^*V_{cd}$$
$$\lambda_t=V_{ts}^*V_{td}$$

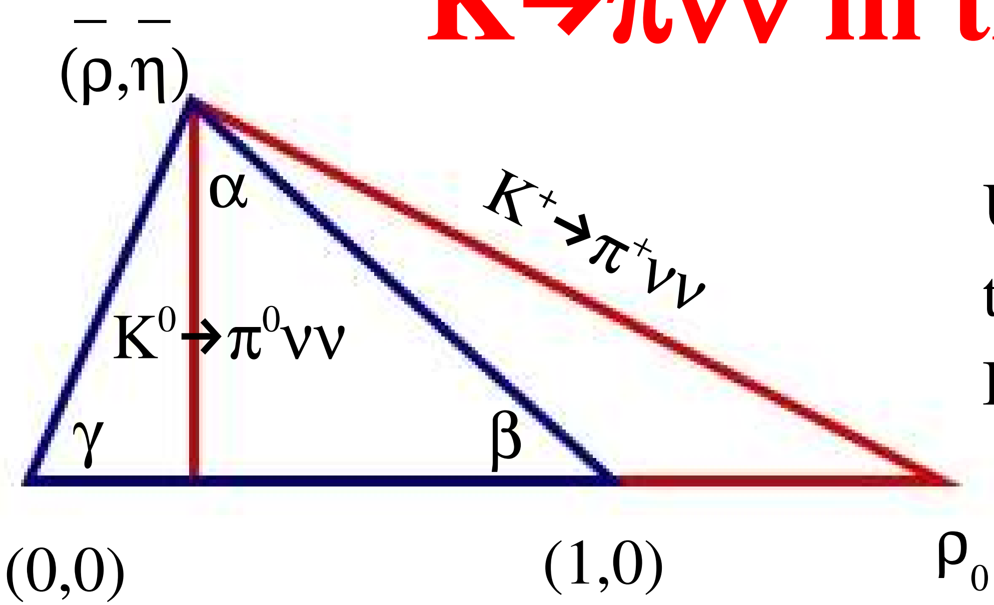
top quark contributions

$$\kappa_+=r_{K^+}\cdot\frac{3\alpha^2Br(K^+\rightarrow\pi^0e^+\nu)}{2\pi^2\sin^4\theta_W}\cdot\lambda^8$$

- **Hadronic matrix element measured**
- r_{K+} =0.901 – isospin breaking correction, arising in relating $K^+\rightarrow\pi^+\nu\nu$ to $K^+\rightarrow\pi^0e^+\nu$

K→πνν in the SM





Using the current CKM parameters the SM prediction is:

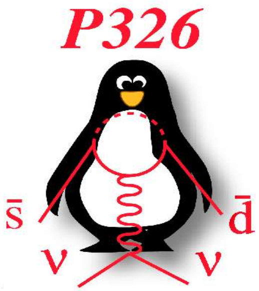
$BR(K^+ \to \pi^+ \nu\nu) = (8.0 \pm 1.1) \times 10^{-11}$

NLO calculations

- K→πνν decays provide alternative method for determination of the apex of the unitarity triangle.
- The phase β derives from Z^0-penguin diagrams (ΔS=1) wheres in B in A(J/y K_S) originates in the $B_d^0 - \bar{B}_d^0$ mixing box diagram (ΔB=2)

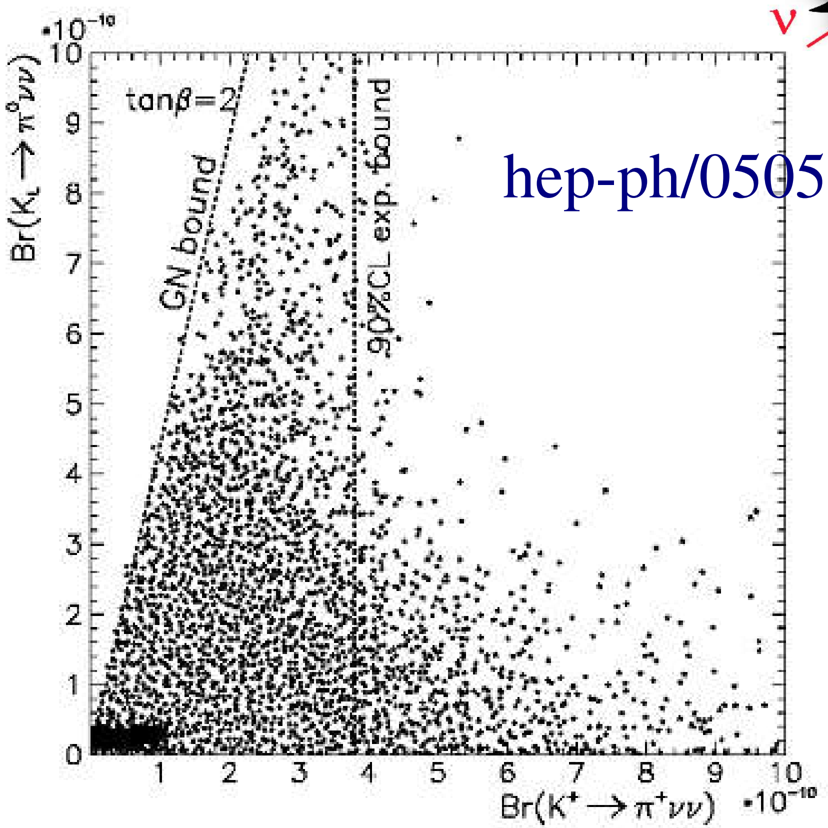
$$\sin(2\beta)_{K\to\pi\nu\nu} = \sin(2\beta)_{B\to J/\Psi\, Ks}$$

- A deviation from the upper equation will be a clear indication of new physics

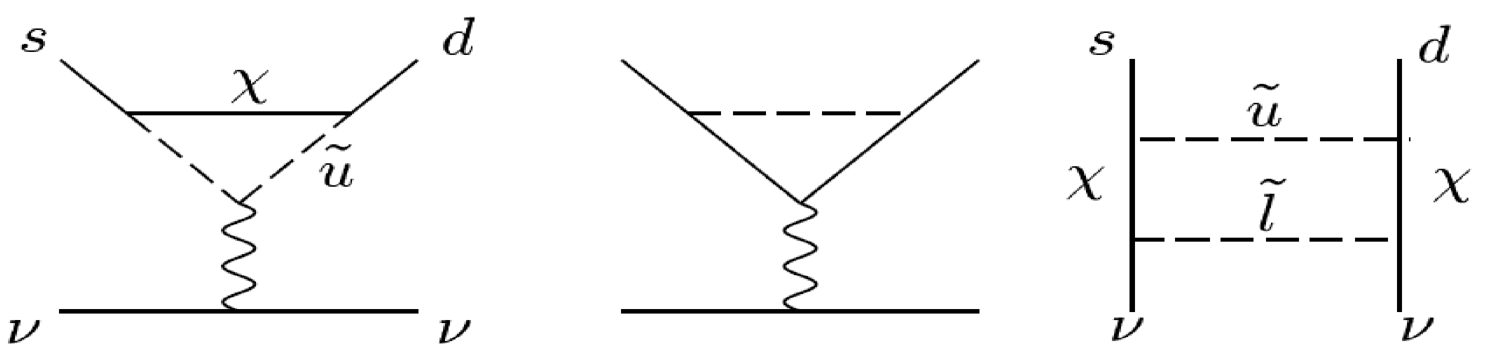


Theory predictions

Model	Prediction - x10^{-10}
SM	8.0 ± 1.1
MFV hep-ph/0310208	19.1
EEWP NP B697 133	7.5 ± 2.1
EDSQ hep-ph/0407021	15
MSSM hep-ph/0408142	40



hep-ph/0505171



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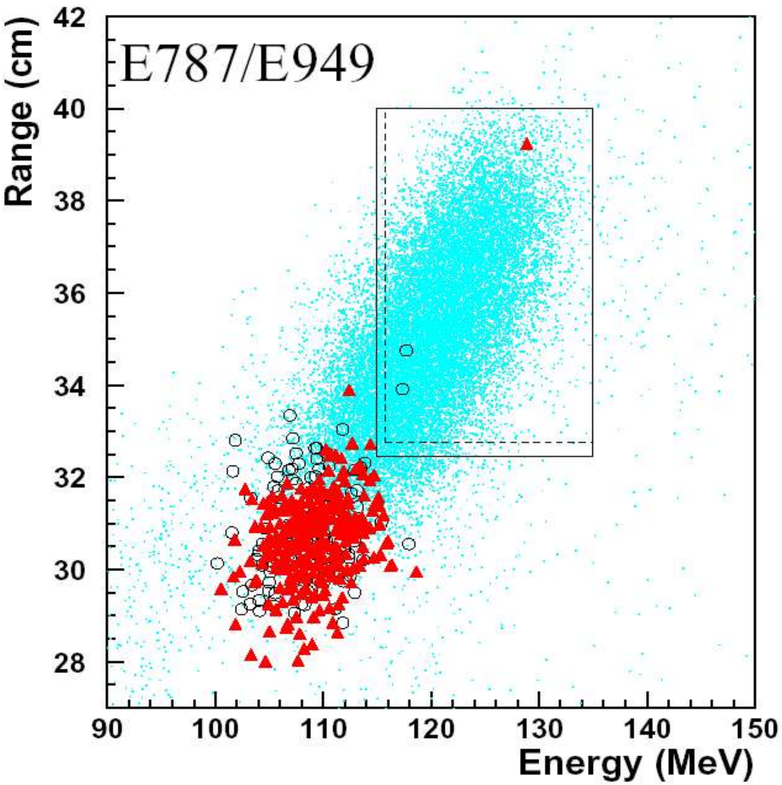
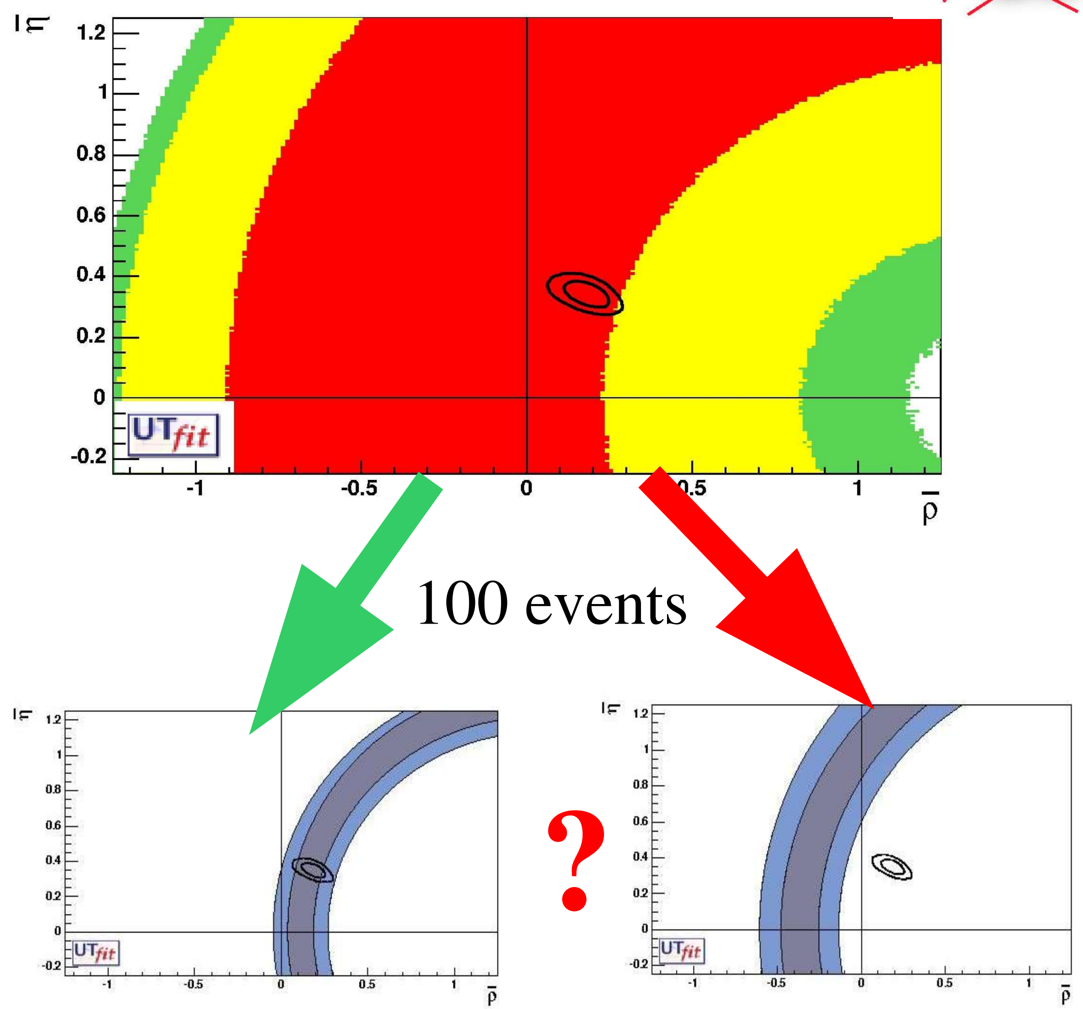
Current situation

hep-ex/0403036 PRL93 (2004)





- Experiment with stopped Kaons
- ***$BR(K^+ \rightarrow \pi^+ \nu\nu) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$***
- Compatible with the SM

Where ?

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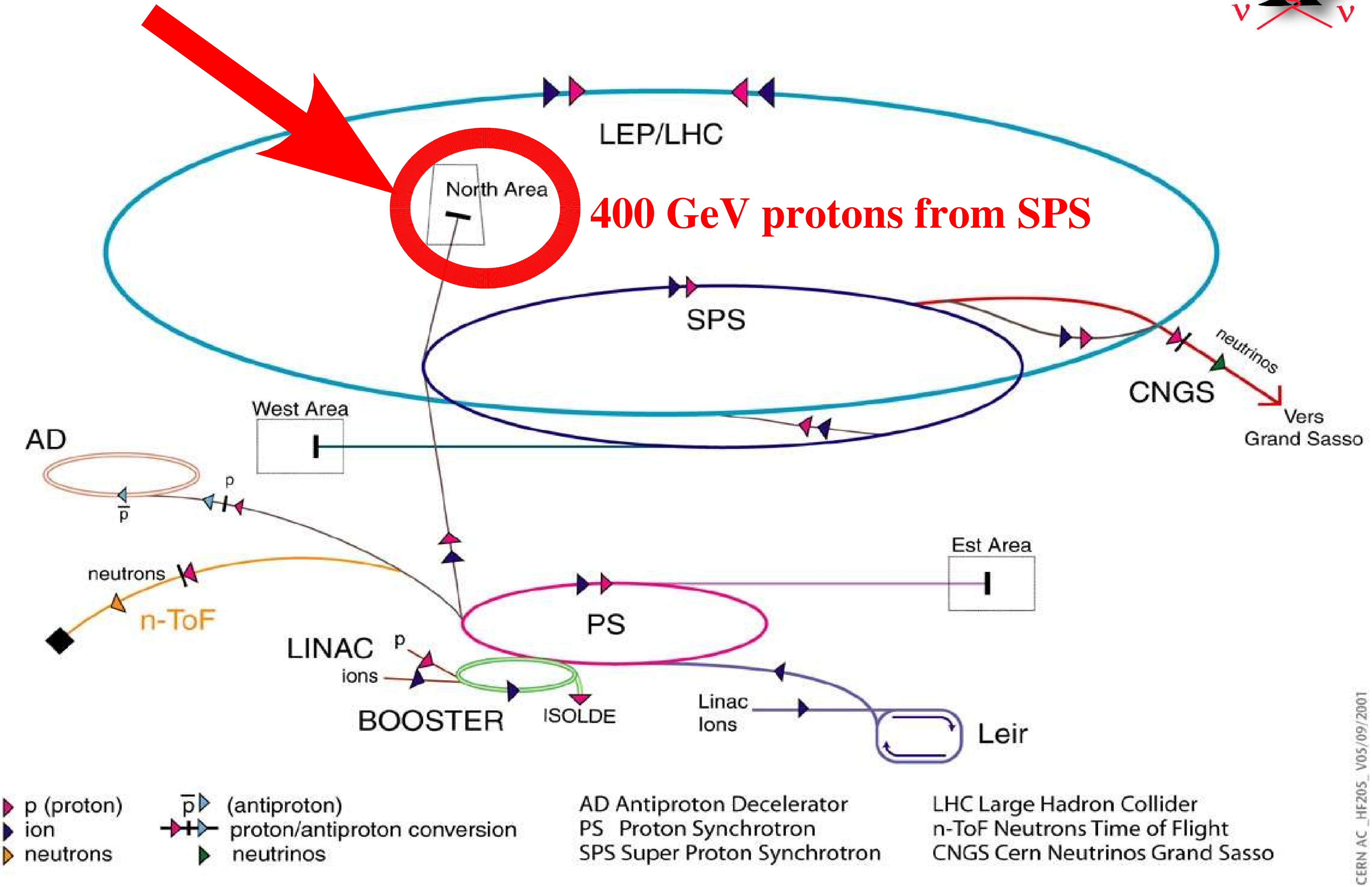
CERN


LEP/LHC
North Area
400 GeV protons from SPS
SPS
neutrinos
CNGS
Vers
Grand Sasso
West Area
AD
p
p̄
neutrons
n-ToF
Est Area
PS
LINAC
p
ions
BOOSTER
ISOLDE
Linac
Ions
Leir
p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos
AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron
LHC Large Hadron Collider
n-ToF Neutrons Time of Flight
CNGS Cern Neutrinos Grand Sasso
CERN AC _HF205_ V05/09/2001

Who will make the experiment ?

P326 collaboration

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CERN-SPSC-2005-013

SPSC-P-326

11.6.2005

Proposal to Measure

the Rare Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at the CERN SPS

Signed by 94 physicists, 16 institutes

Submitted to SPSC

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

How do we plan to measure $K^+ \rightarrow \pi^+ \nu\nu$ decay

Beam + **Detector**

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AIM

- **Collect ~80 $K^+ \rightarrow \pi^+ \nu\nu$ events with background ≈ 10%**
  - ✗ 2 years of data taking
  - ✗ 10% acceptance
  - ✗ BR≈1×10^{-10}
  - ✗ Losses (Dead time) ≈ 20%
- **We need ≈5×10^{12} K^+ decays per year**

Experiment strategy

- Kaon decays in flight
- Unseparated K^+ beam
- High Kaon momentum
  - High acceptance
- Reuse the NA48 underground hall, part of the beam setup and part of the detectors
  - P326 is not a continuation of NA48/2. It is a new experiment which will get its name ones it is approved.

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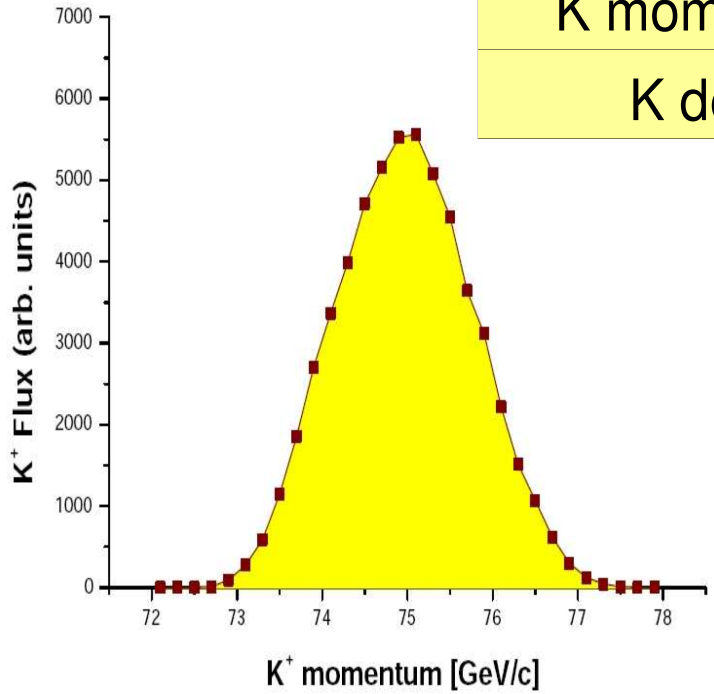
Beam

- Unseparated beam
  not proton limited
- 60m decay volume
- Beam size:
  - 3.2 x 4.4 cm
  - 14 cm^2

	Current Beam	Beam – P326
Duty cycle (s/s)	4.8/16.8	4.8/16.8
Pulses per year	$3x10^5$	$3x10^5$
Protons/pulse	$1x10^{12}$	$3x10^{12}$
Beam acceptance (μsr)	0.4	16
Beam flux /pulse	$5.5x10^7$	$250x10^7$
K momentum (GeV/c)	60	75
K decays / year	$1x10^{11}$	$48x10^{11}$



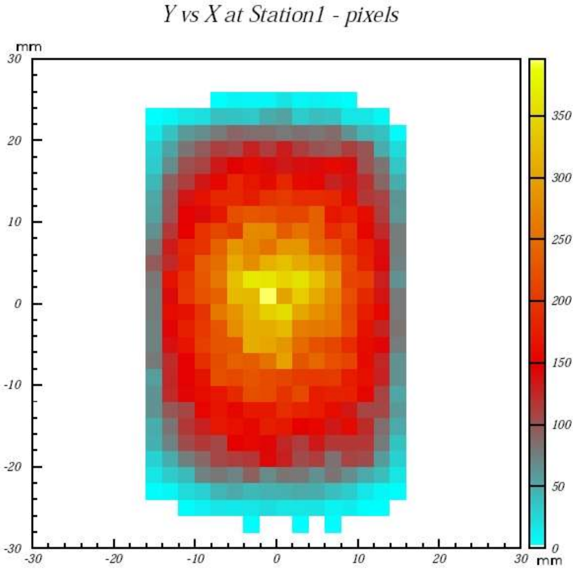
- Beam momentum – 75GeV/c. Chosen after investigation and optimizing π/K ratio, K decay flux and acceptance
- RMS: $\Delta p/p = 1\%$

Beam spectrometer

- Assuming 3s effective spill length

  ~1 GHz hadron beam

  60MHz / cm^2

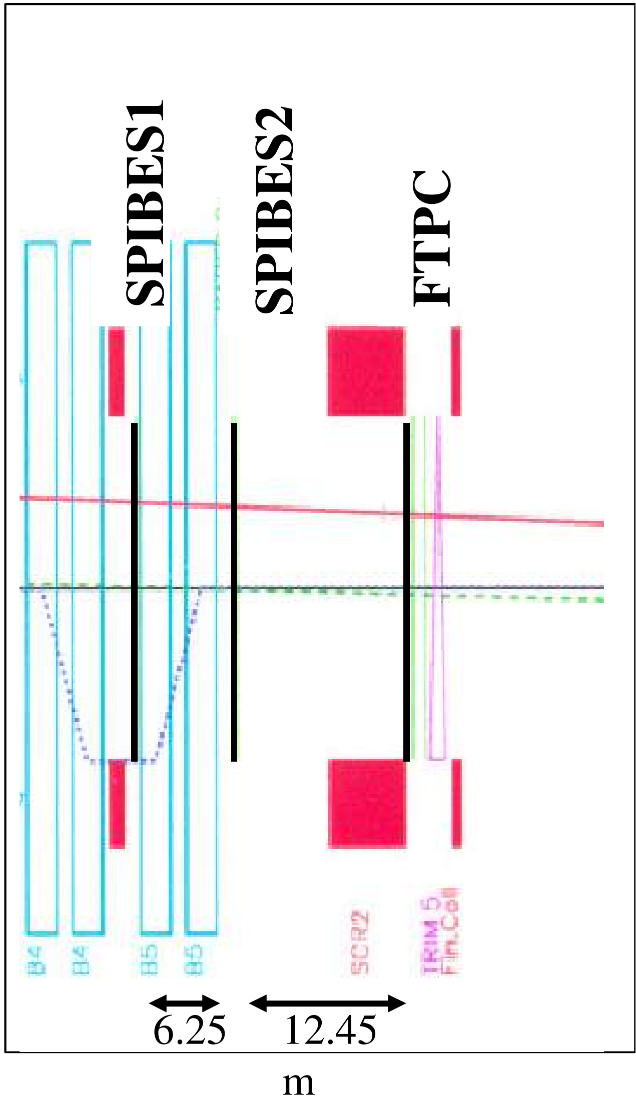


Beam spot

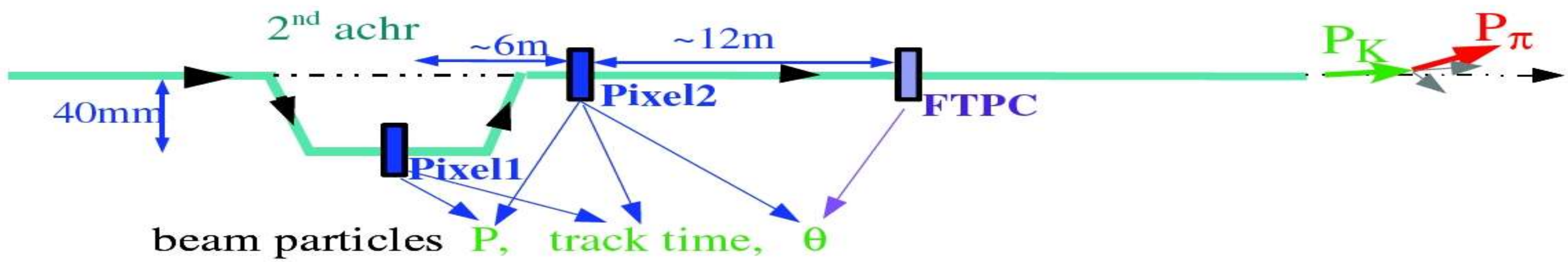
Requirements

- Momentum resolution: <0.5%
- Angular resolution - <17μrad
- Time resolution ~150ps per station
- Material budget <<1%X_0 per station
- Should survive 1GHz hadron beam

Design: Hybrid detector



Gigatracker: SPiBeS

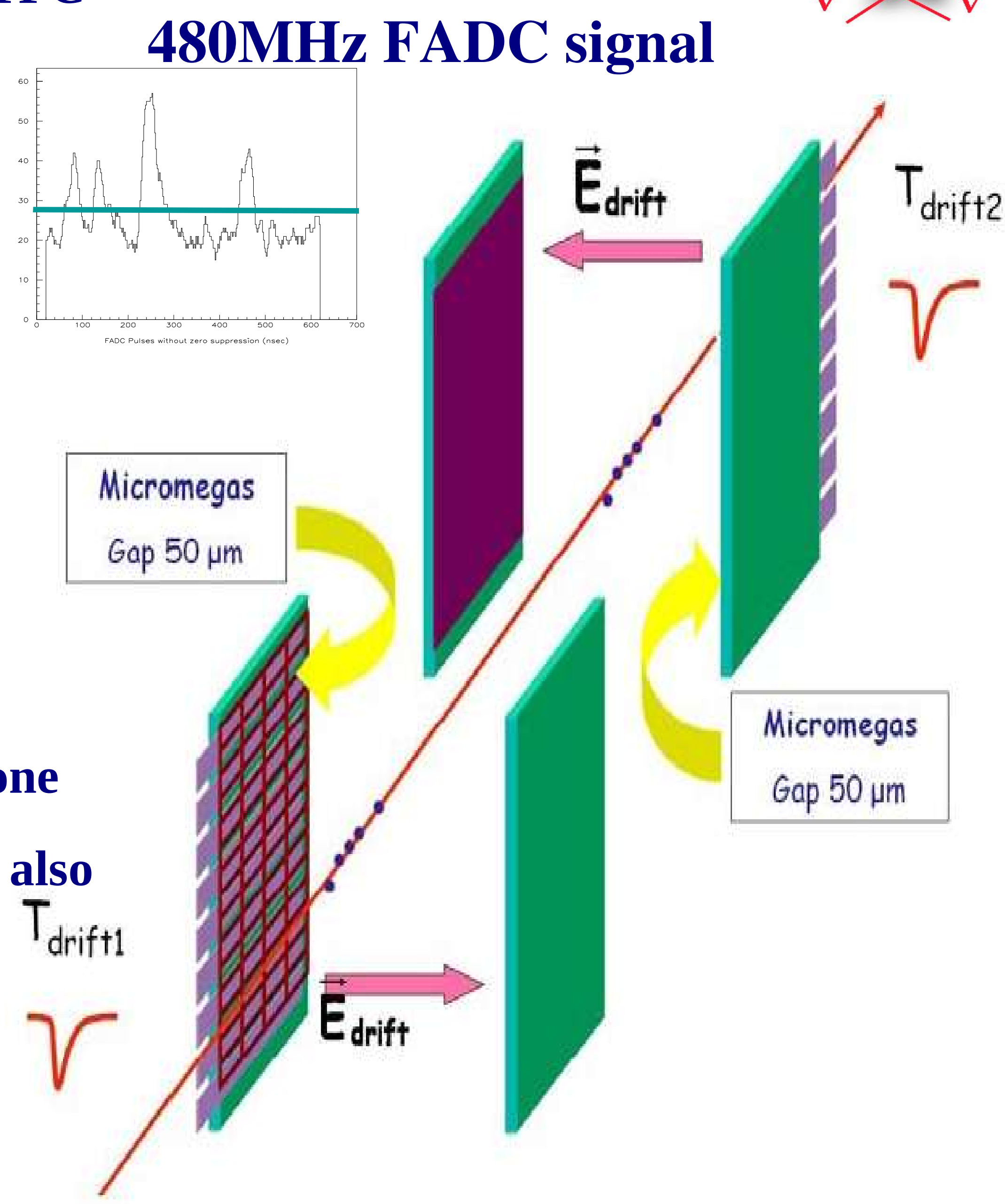


- 2 stations of hybrid silicon micropixels, measuring deflection inside achromatic magnet ensemble
- Minimal thickness is 0.4%X_0 per station
- Provides momentum and time measurement

- Very challenging analog+digital chip
- Solutions under investigation
  - *300μm thick detector+electronics*
  - *300x300μm sensors*
  - *Custom high performance TDC ASIC*
  - *Evaluating 0.25* ***against*** *0.13μm technology*

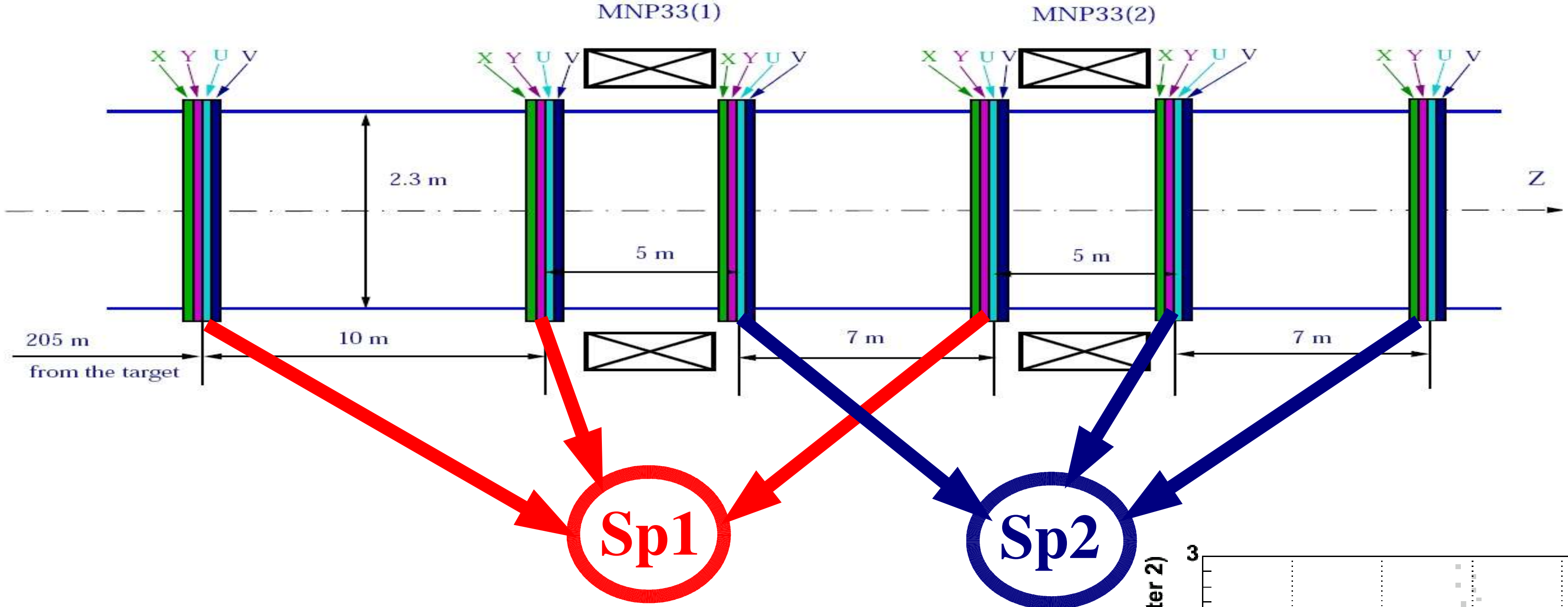
Gigatracker: FTPC

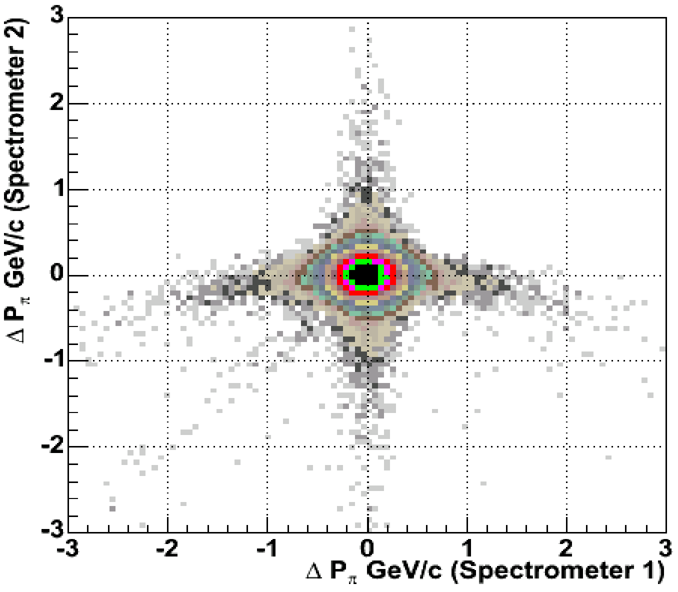
- Micromegas gas chambers operated in TPC mode
- Used in NA48/2
  - Rate per micro-strip ~ 2 Mhz
  - Time resolution ~ 0.6 ns
  - Position resolution – 70mm
- 20Mhz rate per strip in P326
- The long drift (600 ns) makes a standalone pattern recognition very difficult – use also SPiBeS2
- Read-out with 1 GHz FADC



Downstream spectrometer

- Double spectrometer – measure momentum twice





- Minimum material – minimal multiple scatering
- Reconstruction tails uncorrelated – redundancy
- Design: **Straw Chambers**

Straw tracker

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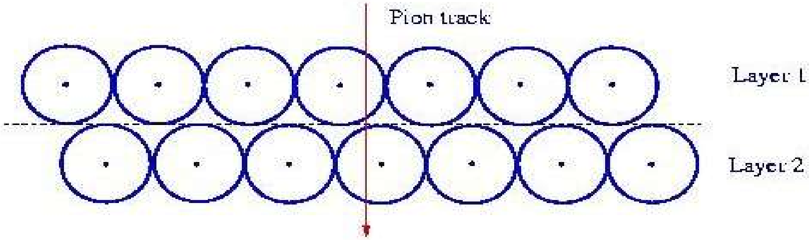
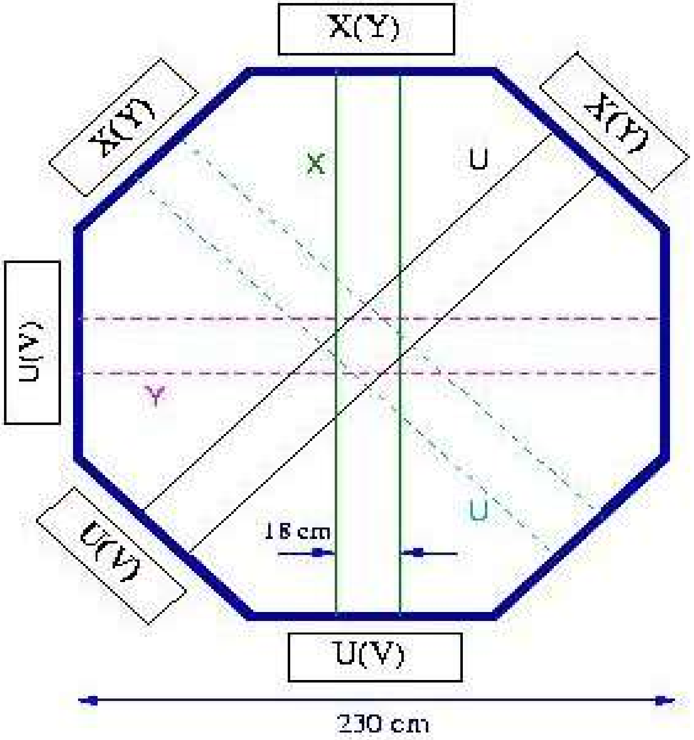
- Straw can operate in vacuum
- Well known technology (ATLAS, COMPASS)
- Experience (JINR, Dubna)
- Double layers per view



- 4 views to construct a chambre
- Each half/layer consists of 112x9.8mm + 16x4.8mm diameter straws
- Small regions with only 1 or 2 coordinates



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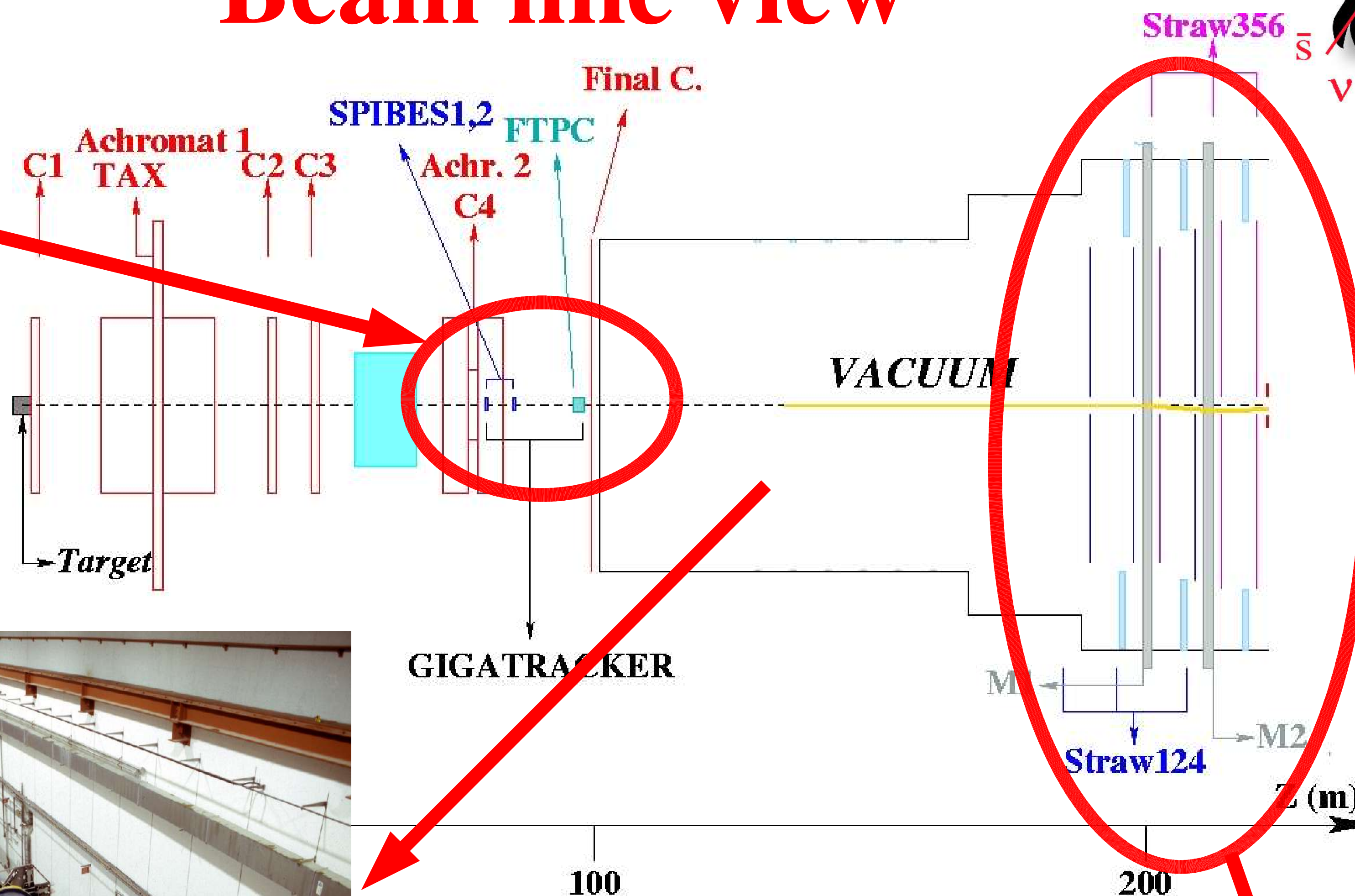
Beam line view

Beam Spectrometer



NA48 vacuum tank

Downstream Spectrometer

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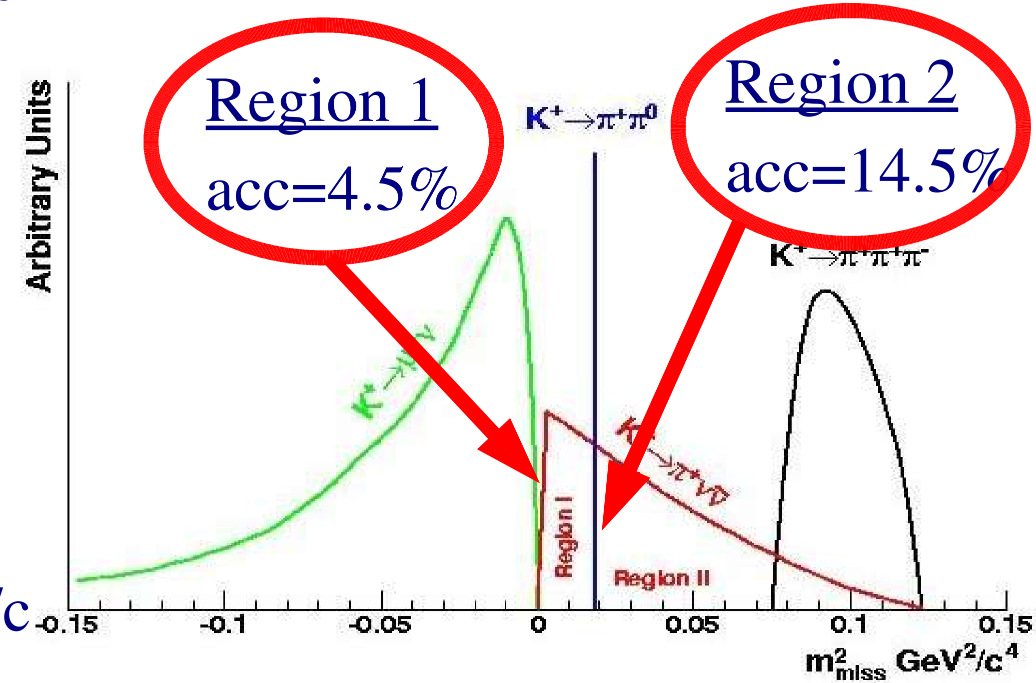
Kinematics

Now we can start looking at the decay

Measured quantities

$$m^2_{miss} = m^2_K + m^2_\pi - 2(E_K E_\pi - p_K p_\pi \cos\theta_{K\pi})$$

- Define 2 regions in missing mass distribution
  - Region 1: **$0 < m^2_{miss} < 0.01$ GeV^2/c^4**
  - Region 2: **$0.026 < m^2_{miss} < 0.068$ GeV^2/c^4**



- Both regions with $15 < P_\pi < 35$ GeV/c

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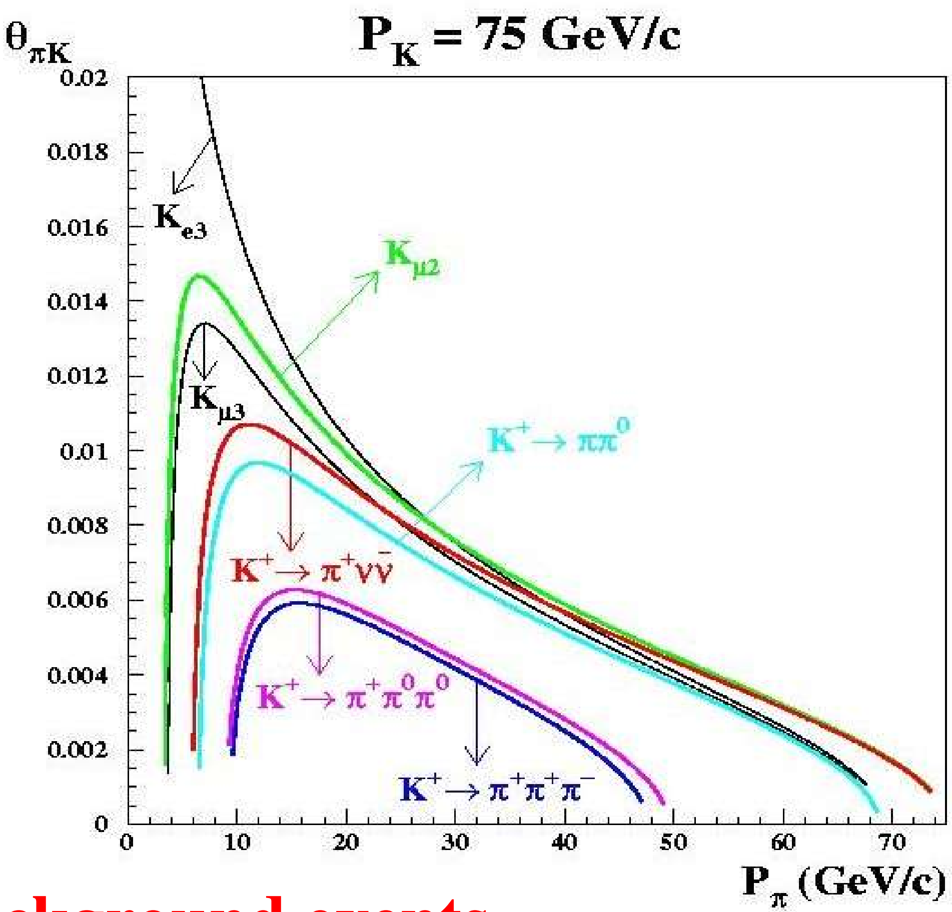
Background

Decay	B.R. [%]
$K^+ \rightarrow \mu^+\nu \ (K_{\mu 2})$	~63
$K^+ \rightarrow \mu^+\nu\gamma \ (K_{\mu 2\gamma})$	~0.55
$K^+ \rightarrow \pi^+\pi^0$	~21
$K^+ \rightarrow \pi^+\pi^+\pi^-$	~6
$K^+ \rightarrow \pi^0\pi^0\pi^+$	~2
$K^+ \rightarrow \pi^0\mu^+\nu \ (K_{\mu 3})$	~3
$K^+ \rightarrow \pi^0 e^+\nu \ (K_{e3})$	~5



For 1 signal event we have to reject:

- 6.3×10^9 $K^+ \to \mu^+\nu$ events
- 2.1×10^9 $K^+ \to \pi^+\pi^0$ events
- 0.6×10^9 $K^+ \to \pi^+\pi^+\pi^-$ events
- 0.2×10^9 $K^+ \to \pi^+\pi^0\pi^0$ events
- 0.5×10^9 Ke3 events
- 0.3×10^9 Kmu3 events, ...

10^{10} background events

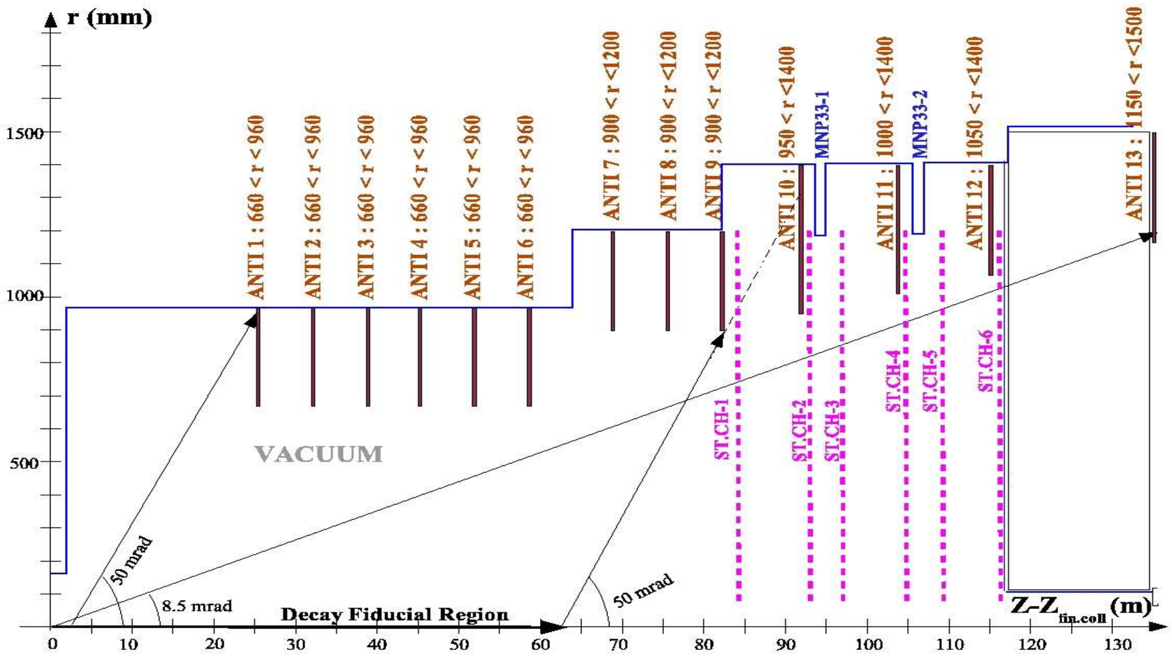
Solution:

Vetoes + Particle Identification

Photon vetoes

- **Requirements**
  - Suppresion of $K^+ \to \pi^+\pi^0$, $K\mu 3$, $K^+ \to \pi^+\gamma\gamma$, ...
  - Inefficiency $<10^{-4}$ for $E_\gamma > 100$MeV (and $<10^{-5}$ for $E_\gamma > 1$GeV)
- **Large Angle vetoes**
  - **Lead-scintillator sandwich calorimeter around the decay region**
- **Liquid-Krypton Calorimeter (LKR)**
  - **Use existing NA48 calorimeter as a photon veto**
- **Small Angle vetoes**
  - **Covering of the beam pipe**

Large Angle Vetoes



- 13 annular rings in vacuum
- Hermeticity 8.5 - 50mrad
- **Inefficiency budget:**

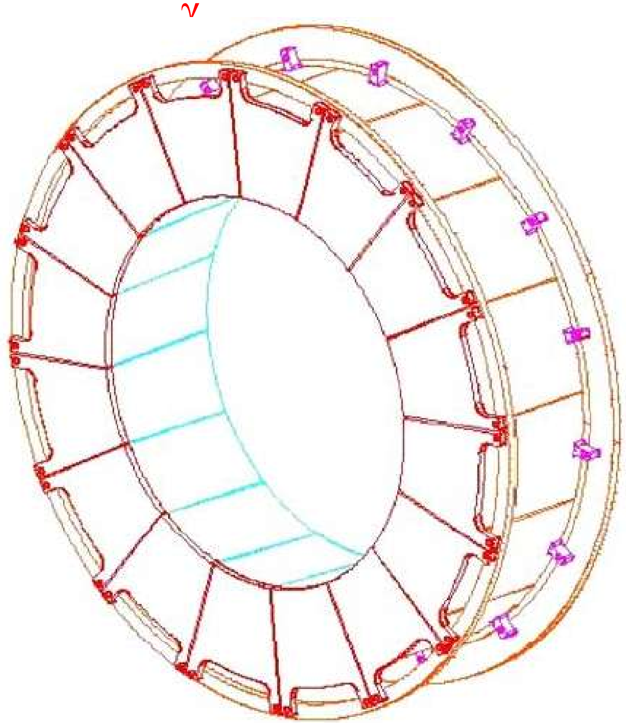
10^{-4} for E_γ >100MeV

10^{-5} for E_γ >1GeV

- **2 solutions under considered**

  - Pb/Sci 1mm/5mm > 80 layers (16 X_0), WLS readout, 20 p.e. per MIP

  - Pb+Sci fibres modules with two-side readout ("spaghetti calorimeter").



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LKR

- Main detector element for NA48/0/1/2
- 13212 cells of 2x2 cm^2 in liquid krypton
- High resolution
  - 250ps time resolution
  - 1mm spacial resolution
  - (3.2%/√E [GeV]) energy resolution
- Noise about 90MeV per cluster

Inefficiency budget:

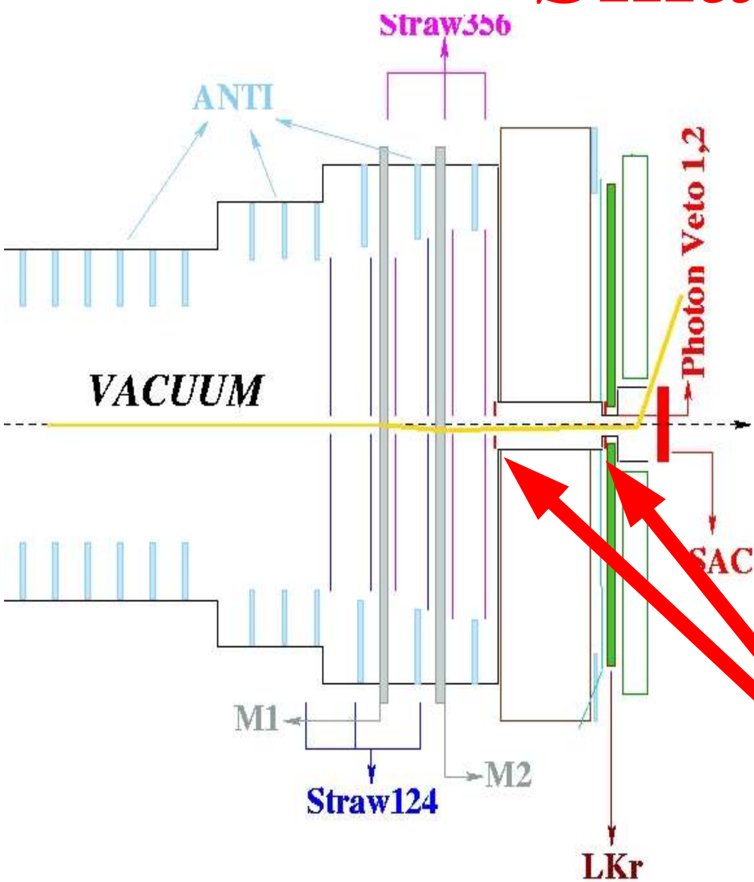
$<10^{-5}$ for $E_\gamma > 1$GeV

$<10^{-5}$ electron ID inefficiency

being tested with data

Read-out and cryogenics system upgrades needed

Small Angles Vetoes

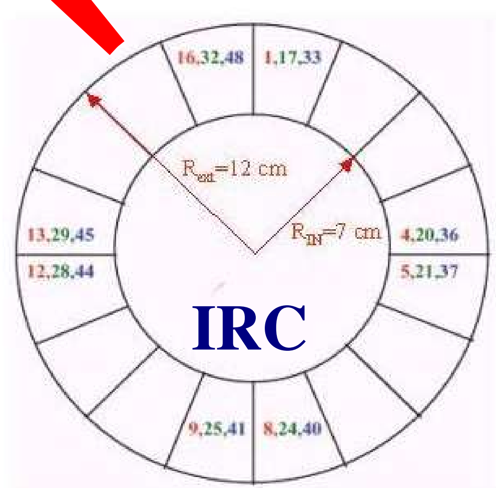


- IRC – Inner ring callorimeter
- SAC – Coverage down to $\theta = 0^o$

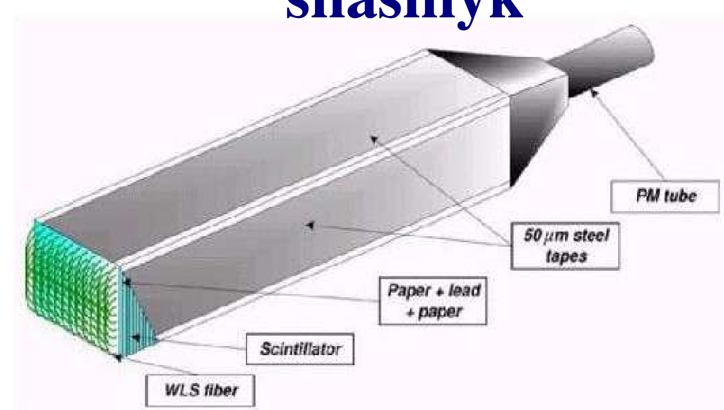
2 solutions in consideration:

Shashlyk: Layers of Pb + scintillator (total 17 X_0)

$PbWO_4$ crystals



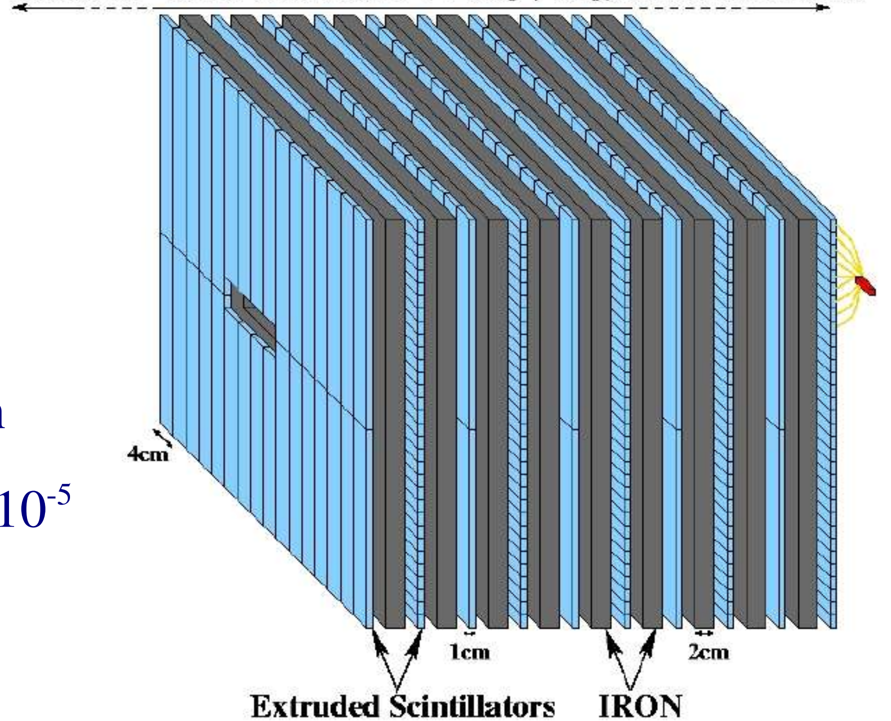
shashlyk

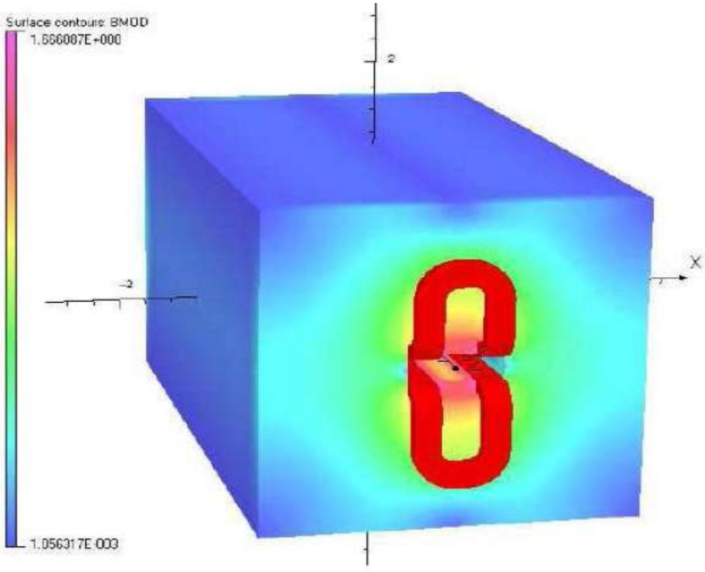


In order SAC to work we need to deflect the beam from the z-axis !!!

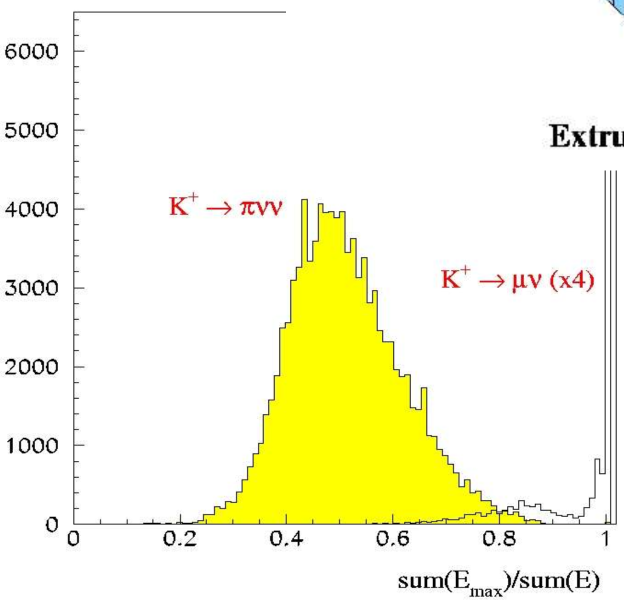
MAMUD

- **Magnetized muon and hadron detector**
  - **- π/μ separation for $K_{\mu2}$ suppression**
  - **- beam sweeping for SAC**
- Design
  - - Magnetized iron => 0.9 T field in the beam region
  - - Instrumented by scintillators => muon rejection ~10^{-5}



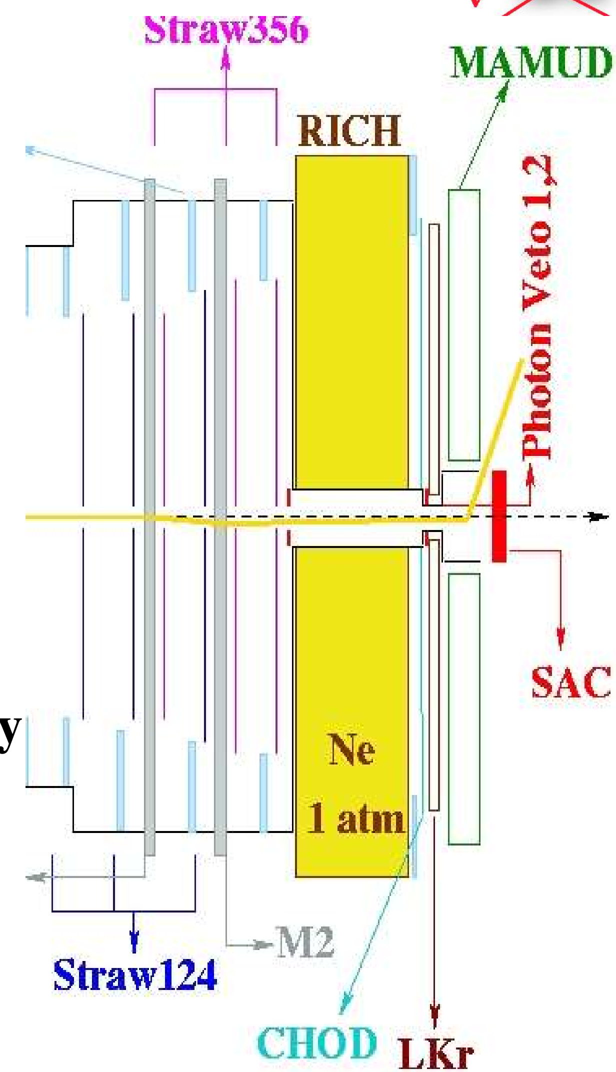


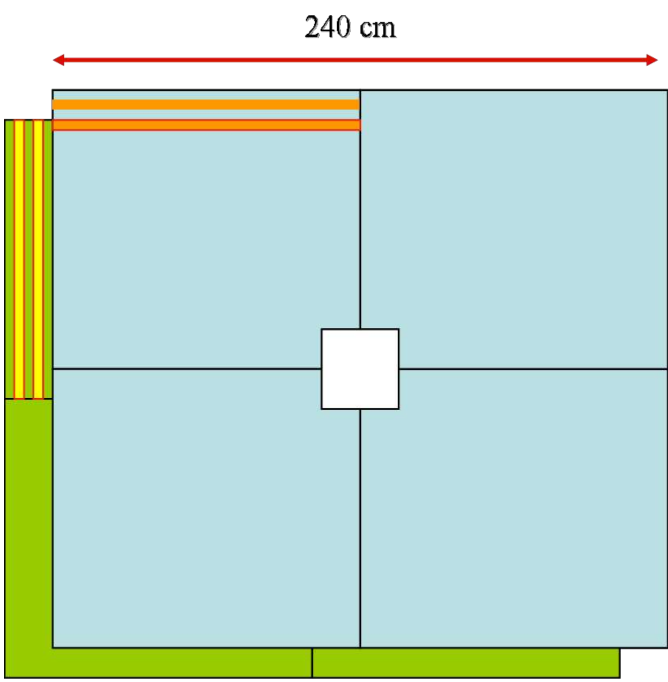
Magnetic field on iron surface



RICH and CHOD

- **RICH**
  - Needed for additional π/μ separation
  - Design under study (Kplus-like)





Charged Hodoscope

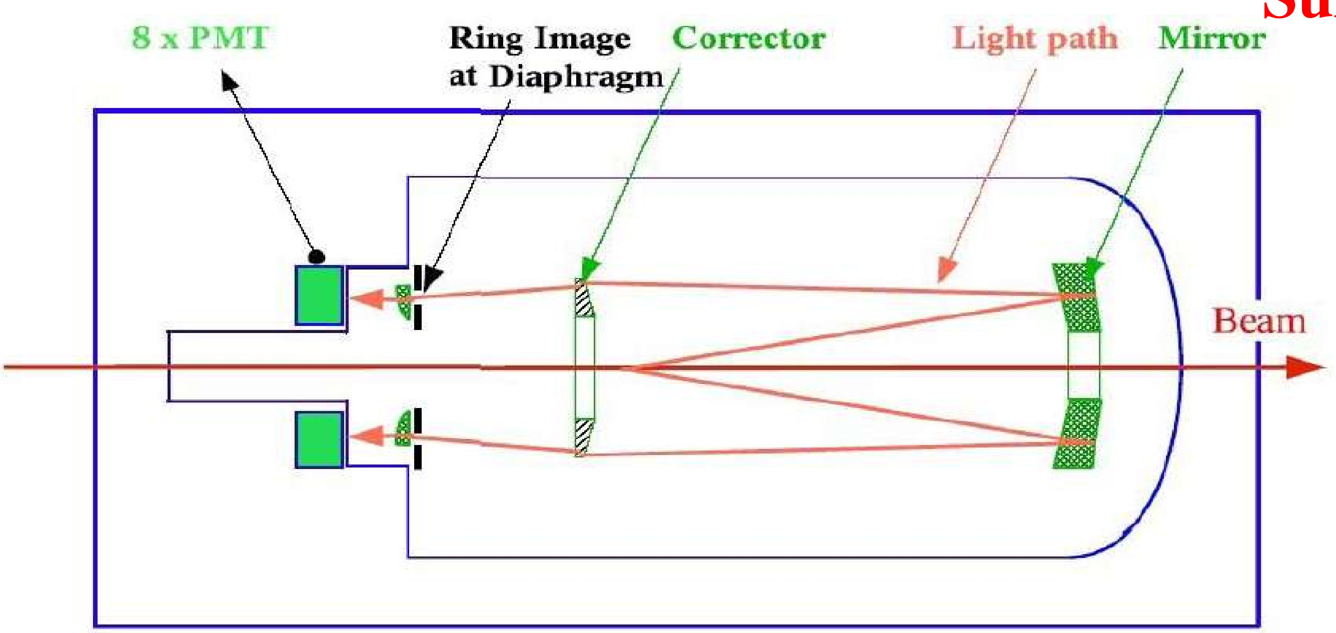
- Excellent time resolution <100ps
- Rejection of high multiplicity events
- Design: Multigap glass RPC (a la ALICE TOF)

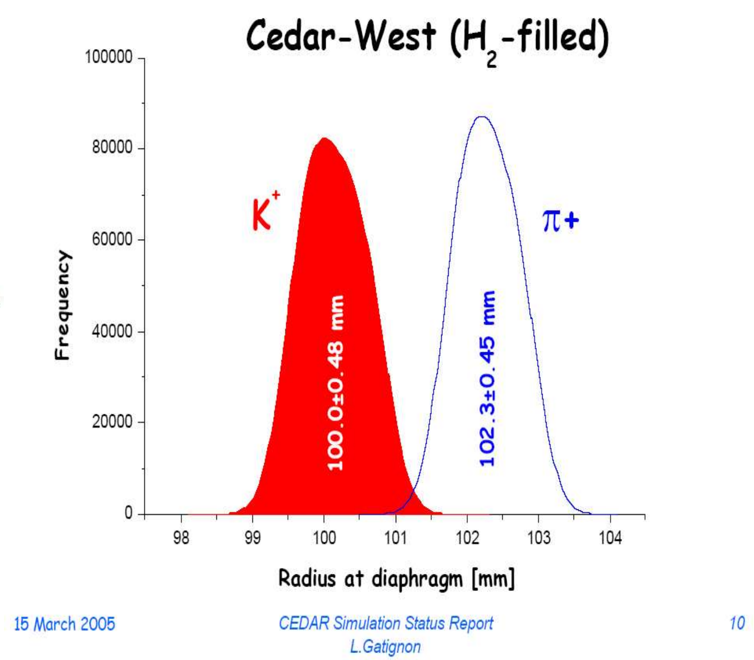
CEDAR

- Differential Cerenkov counter with achromatic focus
- Requirement: **K^+ tagging together with CHOD** – allow to diminish the decay volume vacuum requirement by **1 order** of magnitude
- Two versions have been used in SPS
  - He-filled "North CEDAR"
  - N_2-filled "West CEDAR"

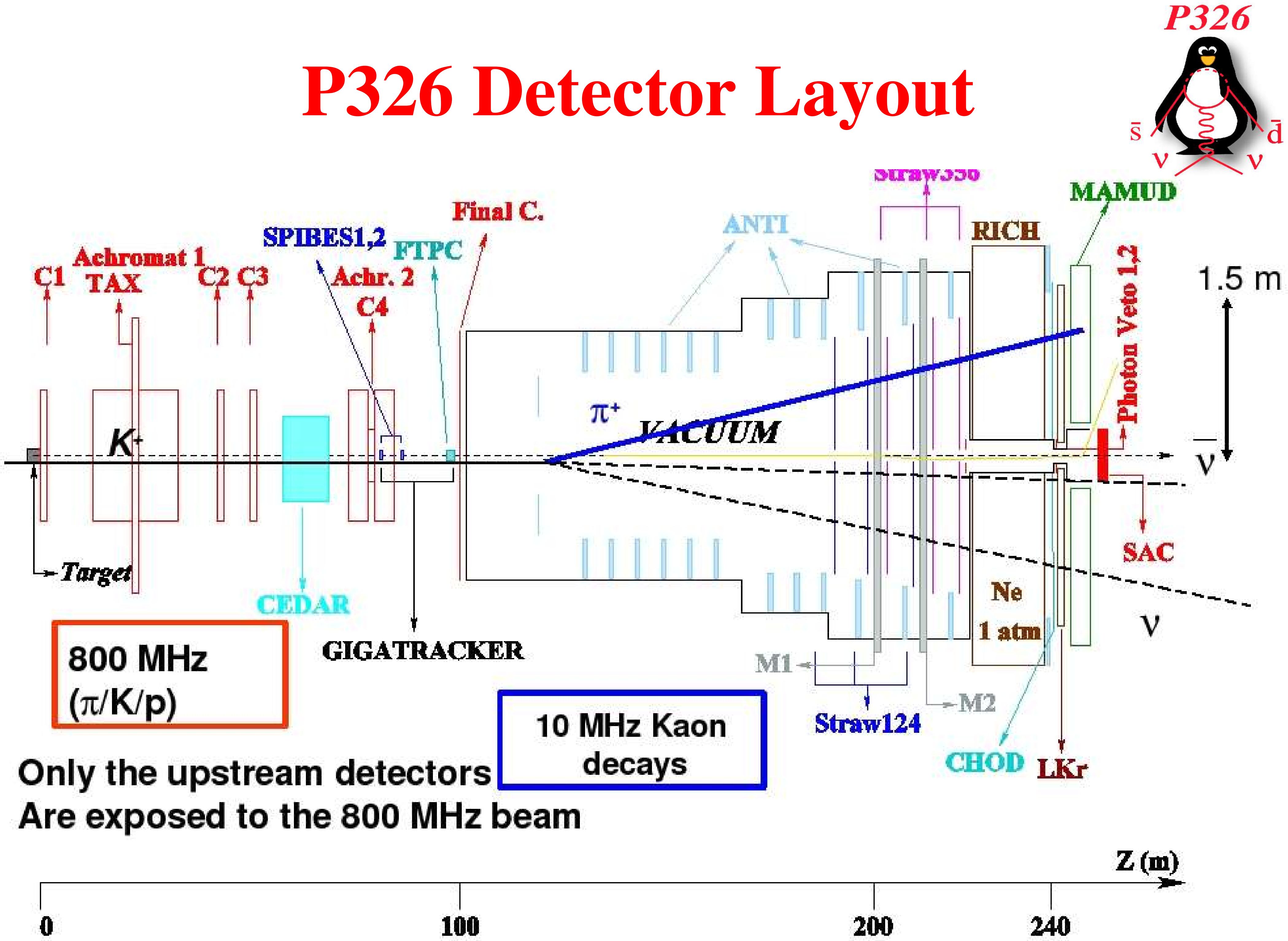
CEDAR West filled with H_2

Suitable for P326





P326 Detector Layout



800 MHz
(π/K/p)

10 MHz Kaon decays

Only the upstream detectors
Are exposed to the 800 MHz beam

$K^+ \rightarrow \pi^+ \nu\nu$ decay in P326 layout

PRELIMINARY

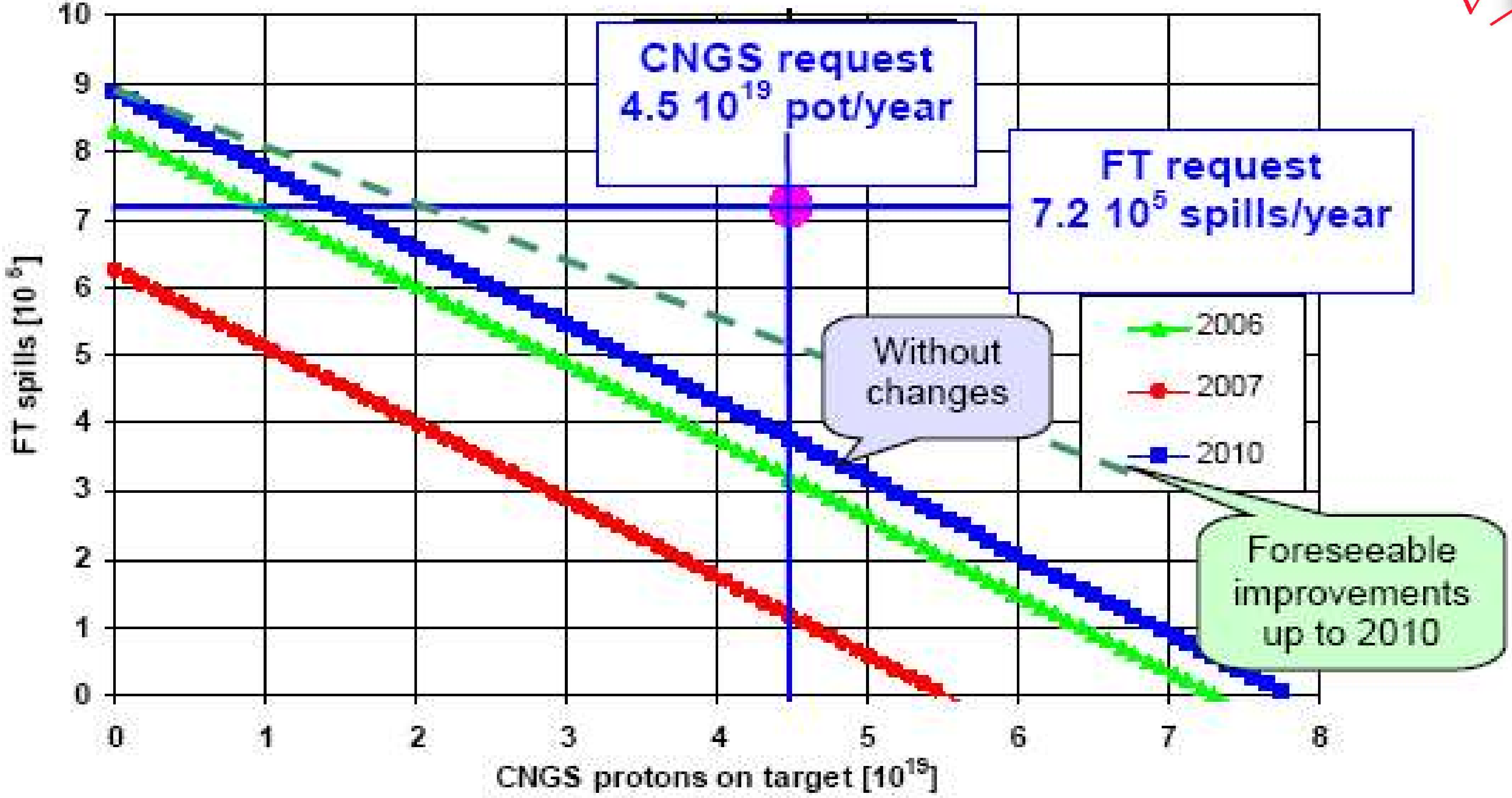
Decay	Type of rejection	Background/Signal
$K_{2\pi}$	photon veto, kinematics	4.1 %
$K_{\mu 2}$	μ particle ID, kinematics	1.9 %
K_{e4}	photon veto, kinematics, PID	3.1 %
3-tracks	charged veto, kinematics	1.5 %
$\pi^+\pi^-\gamma$	photon veto, kinematics	2.0 %
$K_{\mu 2}$	μ particle ID, photon veto	0.6 %
K_{e3}, $K_{\mu 3}$, others	photon veto, particle ID	negligible

Total: 13.2 %

assuming SM branching

WHEN ?

Proton availability at SPS



- **≥3x10^5 proton spills per year for fixed target experiments**
- **Fully compatible with approved COMPASS running, LHC filling and CNGS**

Time schedule

- 2003: Working groups started
- 2004: Parasitic tests in NA48/2 beam
  Letter of Intent submitted
- 2005: Design and development of main detectors
  Proposal P326 submitted to SPSC
  Beam tests outside CERN (Frascati)
- 2006-2008: Construction, Installation, Tests
- 2009-2010: Data-taking

P326

From Villars report

CERN-SPSC-2005-010

SPSC-M-730

February 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.

Conclusion

- **We have found a lucky 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**
- **P326: impressive opportunity to measure $\geq 80\ K^+ \rightarrow \pi^+ \nu\nu$ events in two years of data taking at CERN SPS**
- **Backgrounds are challenging, but under control**
- **Proposal submitted**

SPARE SLIDES

Detector

- 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
- SPECTROMETER
  - 2 magnets + 6 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 (~100 ps)
- LKR
  - Forward photon veto and e.m. calorimeter
- MAMUD
  - Hadron calorimeter, muon veto and sweeping magnet
- SAC
  - Small angle photon vetoes

P326

CKM matrix

$V_{CKM}=$

V(ud)	V(us)	V(ub)
V(cd)	V(cs)	V(cb)
V(td)	V(ts)	V(tb)

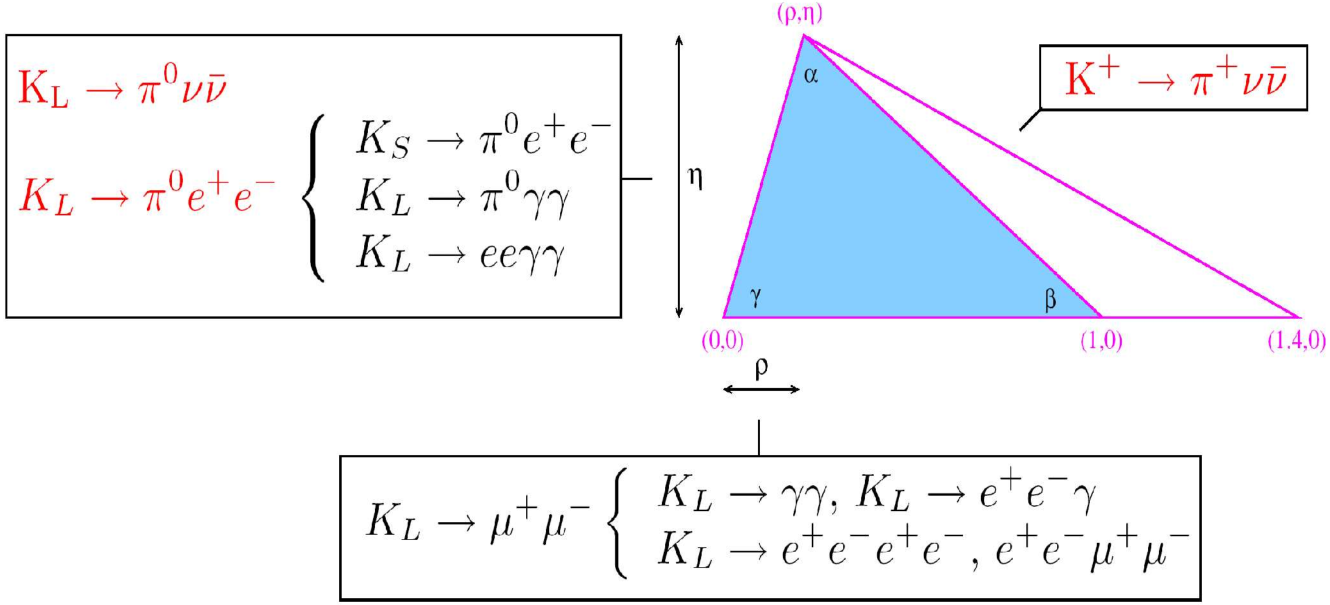
=

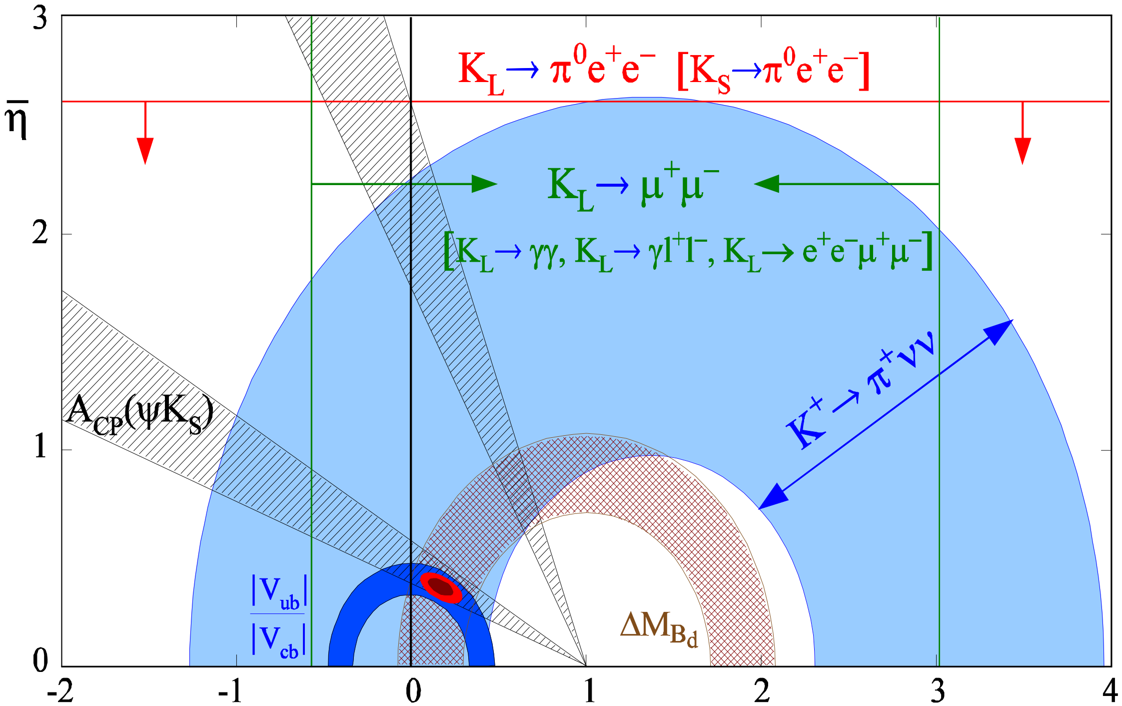
$c_{12}c_{13}$	$s_{12}c_{13}$	$s_{13}e^{-i\delta}$
$-s_{12}c_{23}-c_{12}s_{23}s_{13}\,e^{-i\delta}$	$c_{12}c_{23}-s_{12}s_{23}s_{13}\,e^{-i\delta}$	$s_{23}c_{13}$
$s_{12}s_{23}-c_{12}c_{23}s_{13}\,e^{-i\delta}$	$-c_{12}s_{23}-s_{12}c_{23}s_{13}\,e^{-i\delta}$	$c_{23}c_{13}$

Wolfenstein representation

$$V_{CKM}=\begin{pmatrix} 1-\lambda^2 & \lambda & A\lambda^3(\rho-i\eta+\eta\lambda^2/2) \\ -\lambda & 1-\lambda^2/2-i\eta A^2\lambda^4 & A\lambda^2(1+\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Kaon Rare Decays in the SM

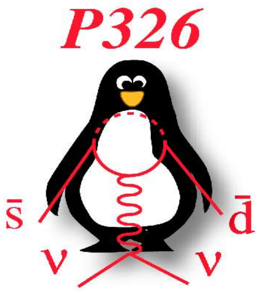


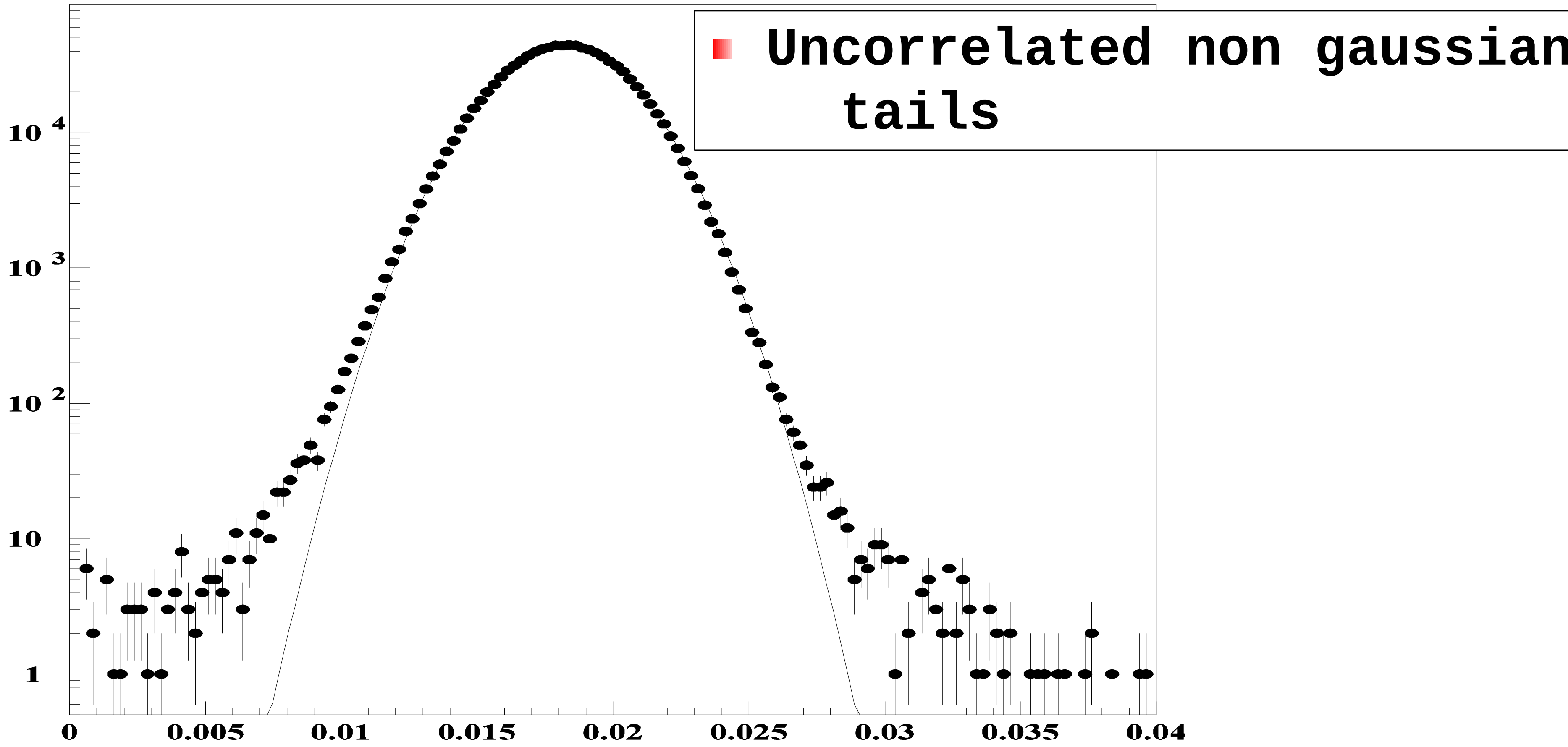


Im $\boldsymbol{\lambda_t = A^2 \lambda^5 \eta}$

Re $\boldsymbol{\lambda_t = A^2 \lambda^5 \rho}$

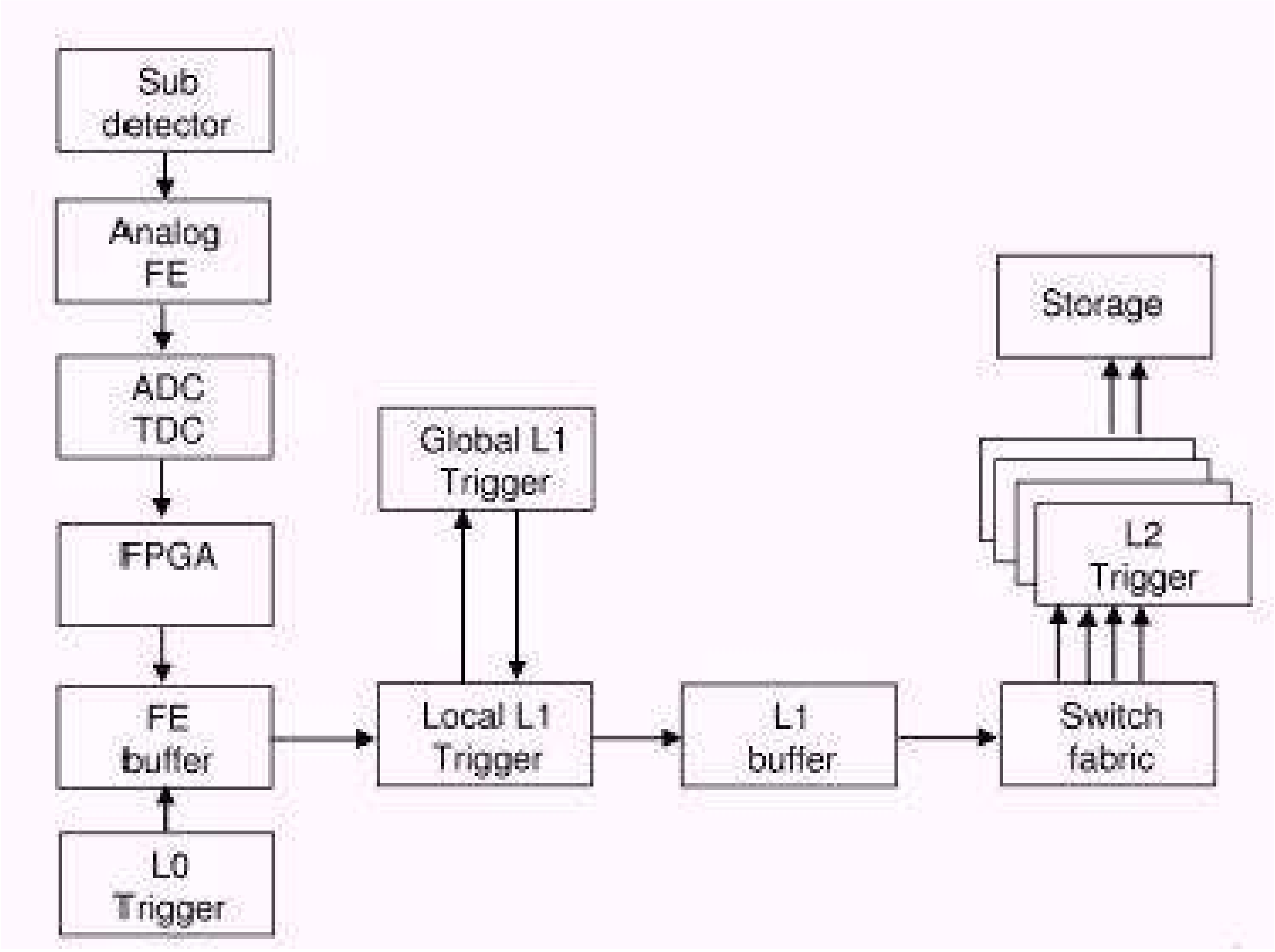
P326 Simulation





Resolution – $8x10^{-3}$ GeV^2/c^4

Trigger

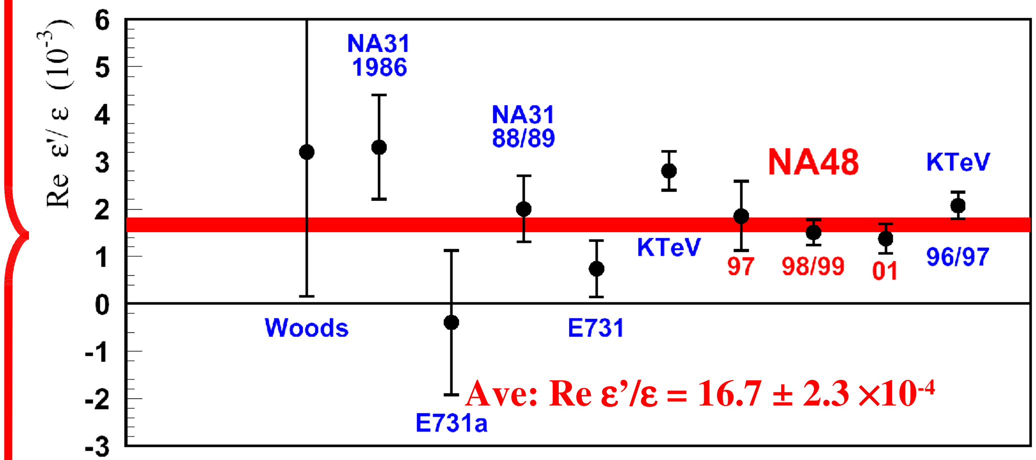

Sub detector
Analog FE
ADC TDC
FPGA
FE buffer
L0 Trigger
Global L1 Trigger
Local L1 Trigger
L1 buffer
Switch fabric
L2 Trigger
Storage

Kaons@CERN:NA48

NA48: ε'/ε	1997
ε'/ε	1998
ε'/ε	1999
no K_L spectrometer / NA48/1 K_S	2000
ε'/ε lower inst. intensity	2001
NA48/1: K_S	2002
NA48/2: $K^{\pm}$	2003
	2004

Direct CP-Violation established!

Re ε'/ε = 14.7 ± 2.2 ×10^{-4}



+ K_L Rare Decays

First observation of
$K^0_S \to \pi^0 e^+e^-$ and $K^0_S \to \pi^0 \mu^+\mu^-$

Search for Direct CP-Violation
in charged kaon decays