The Kaon Physics Programme at CERN

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15th International Seminar on HEP Quarks'08
Sergiev Posad, Russia, May 23-29, 2008

Forward

- The Standard Model (SM) was largely built from kaons
  - Theta-tau puzzle and the fall of Parity Conservation
  - Strangeness and flavour conservation in Strong Interactions
  - Universality of the Weak Interaction
  - Absence of Flavour Changing Neutral Currents (FCNC) and GIM Mechanism
  - CP-Violation
  - Kobayashi-Maskawa ansatz and its implications
- Kaon decays continue to be a powerful tool to
  - Probe the SM and look for New Physics in quark decays
  - Study non-perturbative aspects of the Strong Interaction
  - Look for non-universal lepton couplings

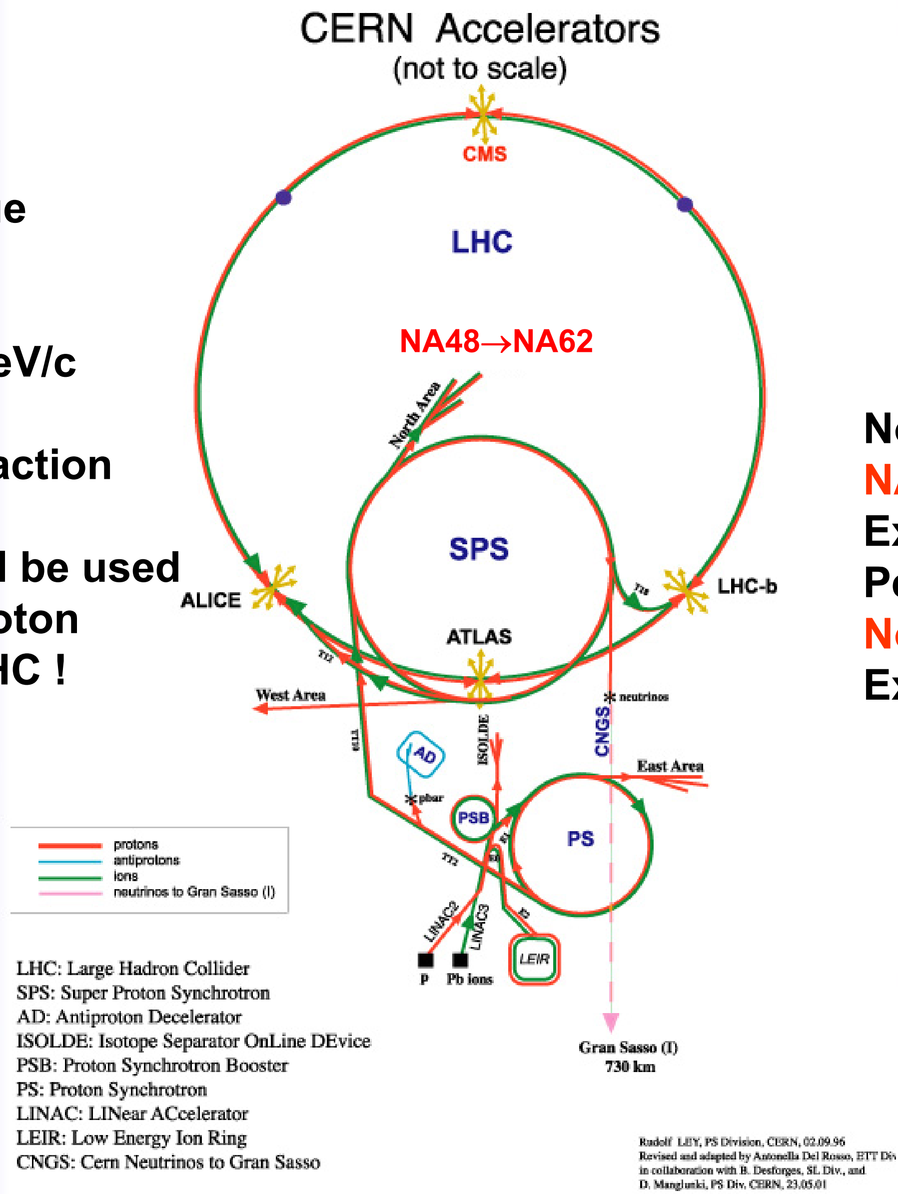
Content of the Presentation

- For recent results from NA48/1 and NA48/2 on radiative kaon and hyperon decays see N. Molokanova talk in parallel session #1 (24/5)
- Here I will remind briefly some highlights from the CERN Kaon programme…
- …and I will give the status of the new initiative to study ultra-rare decays at the CERN SPS (NA62)
- For complementarity between different kaon experiments see V. Duk and M. Doroshenko at the parallel session #1 (24/5)

The CERN proton Complex is unique

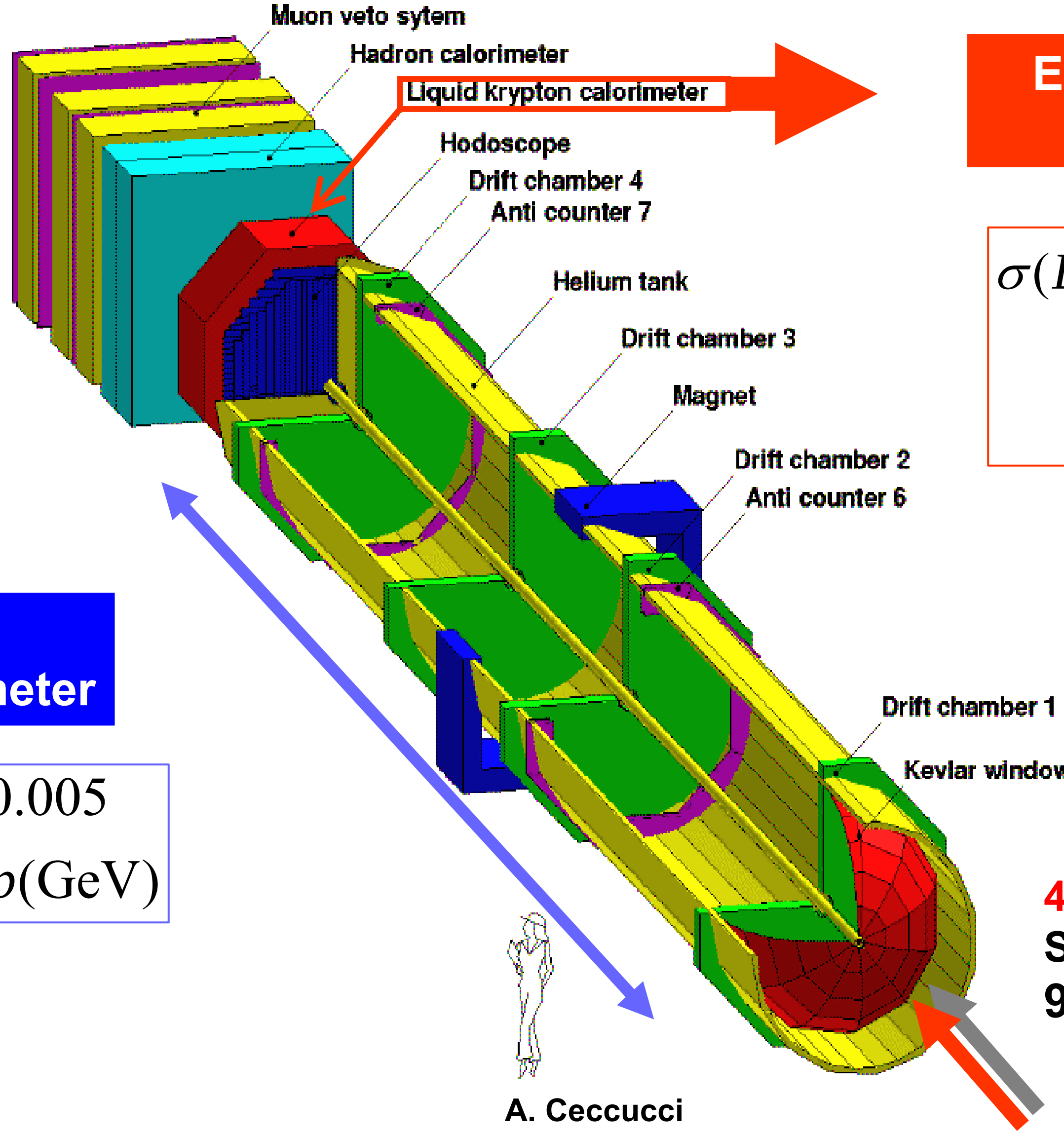
The SPS delivers Protons of 400 GeV/c Momentum with Fast or slow extraction

Soon the SPS will be used --part time--as proton injector to the LHC !



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

NA48 Detectors to Study Kaon Decays



EM Calorimeter (LKr)

$$\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09 \;/ E \oplus 0.0042$$

Magnetic Spectrometer

$$\sigma(p)/p = 0.005 \oplus 0.000\,09\, p(\mathrm{GeV})$$

400 GeV/c protons from SPS on Be target

90 m long decay tank

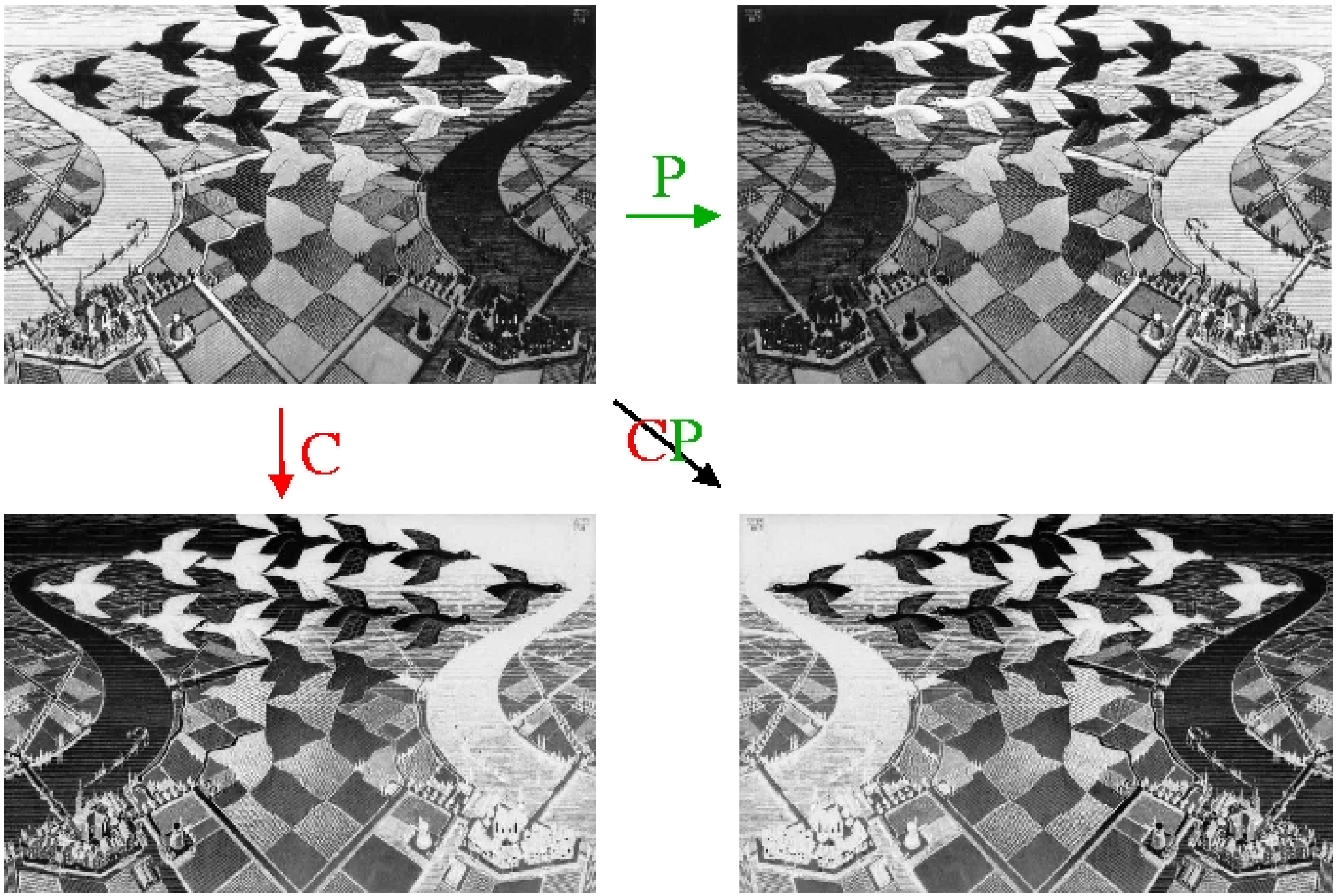
Kaons@SPS: Data Taking so far

- Direct CP-Violation In Neutral Kaons
- Rare decays
- Semileptonic decays

1997	NA48: ε'/ε	
1998	ε'/ε	
1999	ε'/ε	
2000	K_L / no spectrometer NA48/1 K_S	• $K^0_{S,L}$ in Neutral Final States
2001	ε'/ε lower inst. intensity	
2002	NA48/1: K_S	• K^0_S Rare Decays • Neutral Hyperon radiative and semileptonic decays
2003	NA48/2: $K^\pm$	
2004	NA48/2: $K^\pm$	
2007	NA62: K^+	• Lepton Universality

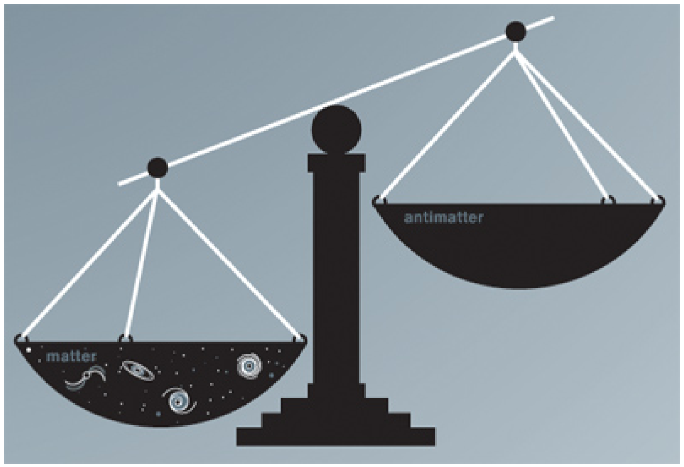
- Search for Direct CP-Violation in $K^\pm$
- Pion-Pion Scattering

CP Violation



From Gino Isidori:
http://scienzapertutti.lnf.infn.it/P1/schedaCP.html

Sakharov Conditions



$n_q - n_{\bar{q}} / n_q$ (Early Universe)
$\sim n_B / n_\gamma$ (Today)$\sim$**10^{-9}**

Matter and Antimatter
Should exist in equal amount:
Where is all the antimatter gone?

Sakharov Conditions (1967)

To allow for a Matter Anti-Matter unbalance one needs:

1. Baryon number Violation
2. Non-equilibrium (at some stage)
3. C & CP-Violation

But what is at the origin of CP-Violation?

What is the origin of CP-Violation?

- **Super-weak interaction (Wolfenstein)**
  - To be seen only in kaon oscillations and not in decays
  - No other plausible experimental effect
- **Three families of quarks (Kobayashi & Maskawa, 1973)**

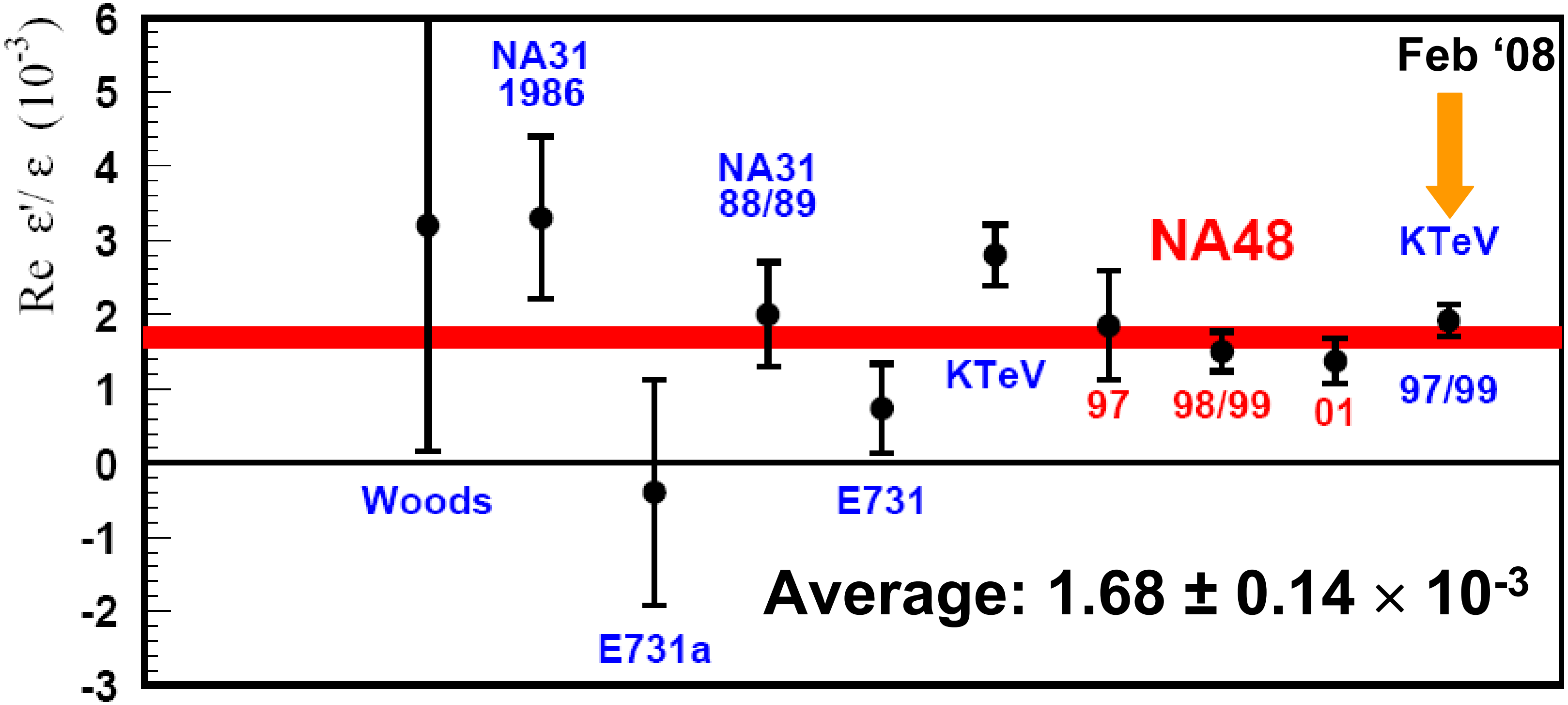
$N_g=2$ $N_{phase}=0$ $\Rightarrow$ No CP-Violation

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

  - When proposed, not even the charmed quark had yet been discovered!!
  - Important experimental implications:
    - Three families of quarks
    - A second Manifestation of CP-Violation in Kaon decays: $\varepsilon' \neq 0$
    - CP-Violation observable in other systems (B mesons)
- **Multi-Higgs models**
- **L/R models**
- **………??**

Direct CP-Violation:
Re ε'/ε measurements versus time

$$R = \frac{\Gamma\left(K_L \to \pi^0\pi^0\right)}{\Gamma\left(K_S \to \pi^0\pi^0\right)} \Big/ \frac{\Gamma\left(K_L \to \pi^+\pi^-\right)}{\Gamma\left(K_S \to \pi^+\pi^-\right)} \approx 1 - 6\ \mathrm{Re}\left(\varepsilon'/\varepsilon\right)$$



NA48/2: Search for Direct CP-Violation in $K \rightarrow 3\pi$

$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$

$u=(s_3-s_0)/m_\pi^2$, $v=(s_2-s_1)/m_\pi^2$

$s_i = (P_K - P\pi_i)^2$ i=3 for π with odd charge

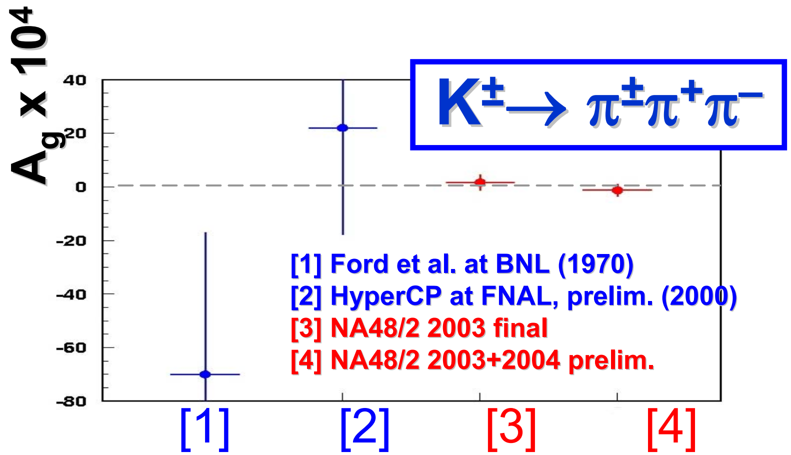
$s_0 = (s_1+s_2+s_3)/3$

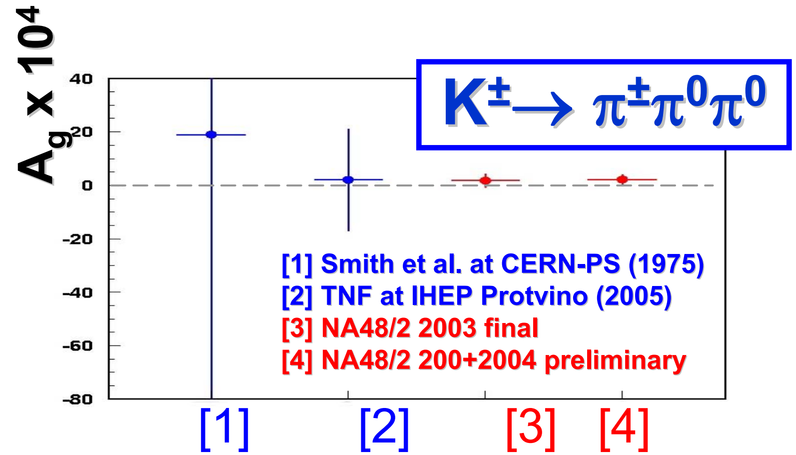
$A_g = (g^+ - g^-)/(g^+ + g^-) \sim \Delta g/(2g)$

$A_g > 10^{-5}$ would signal Direct CP-Violation beyond the Standard Model

The experiment was performed using a narrow-band 60 GeV/c achromatic beam to concurrently collect K^+ and K^- decays

NA48/2 Final Results: hep-ex:07070697



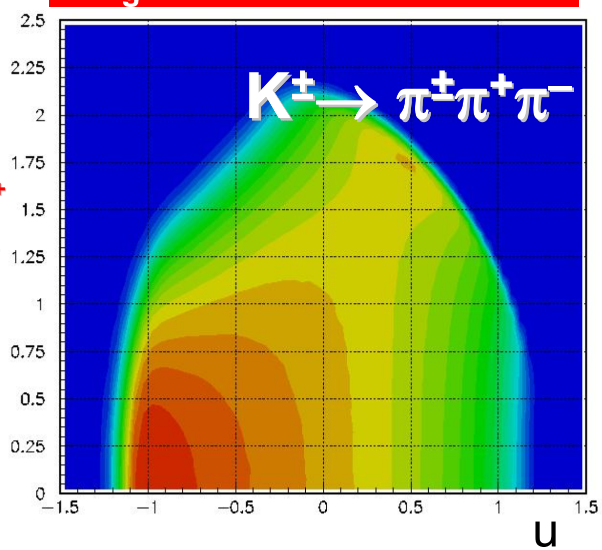


$A^c_g = (-1.5 \pm 2.1) \times 10^{-4}$

$A^n_g = (1.8 \pm 1.8) \times 10^{-4}$

2.0×10^9 K^+

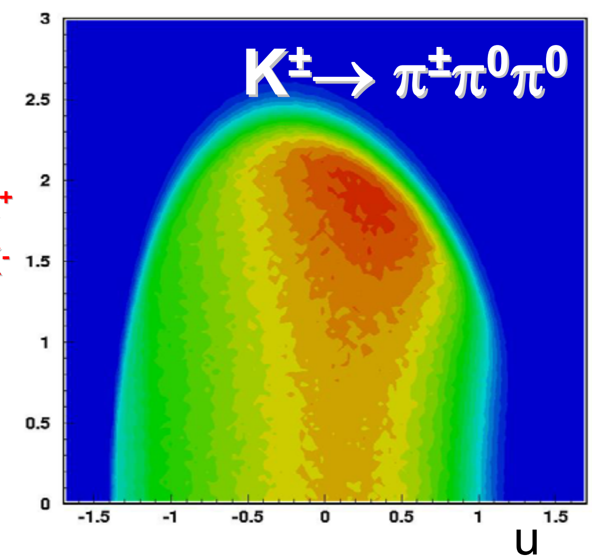
1.1×10^9 K^-



5.9×10^7 K^+

3.2×10^7 K^-

Dalitz Plots



CP-Violation and Quark Mixing: Outlook

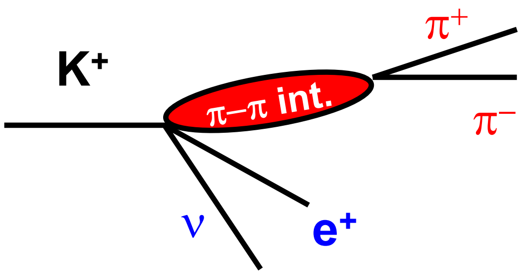
- NA48/2 has closed another window of opportunity
- Current experimental manifestations of CP-Violation (K and B decays and mixing) seem to be consistent with one complex phase in the CKM matrix ("Standard Model")
- Precise experimental probes are required to detect deviations from the Standard Model
- A promising road is provided by the study of ultra-rare kaon decays

Important by-product of NA48/2
CP-Violation Studies: $\pi - \pi$ Scattering

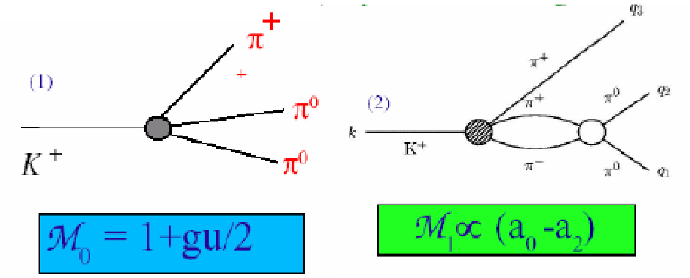
- It is the simplest non-trivial hadron scattering process
- It is an ideal laboratory to test low energy QCD
- Theoretically is very attractive (no spin!)
- Experimentally hampered by the lack of real pion targets!

NA48/2 $\pi\pi$ Scattering Measurements

1. $\pi\pi$ scattering in $K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\overset{(-)}{\nu}$ decays (Ke4)



2. $\pi\pi$ scattering in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ decays

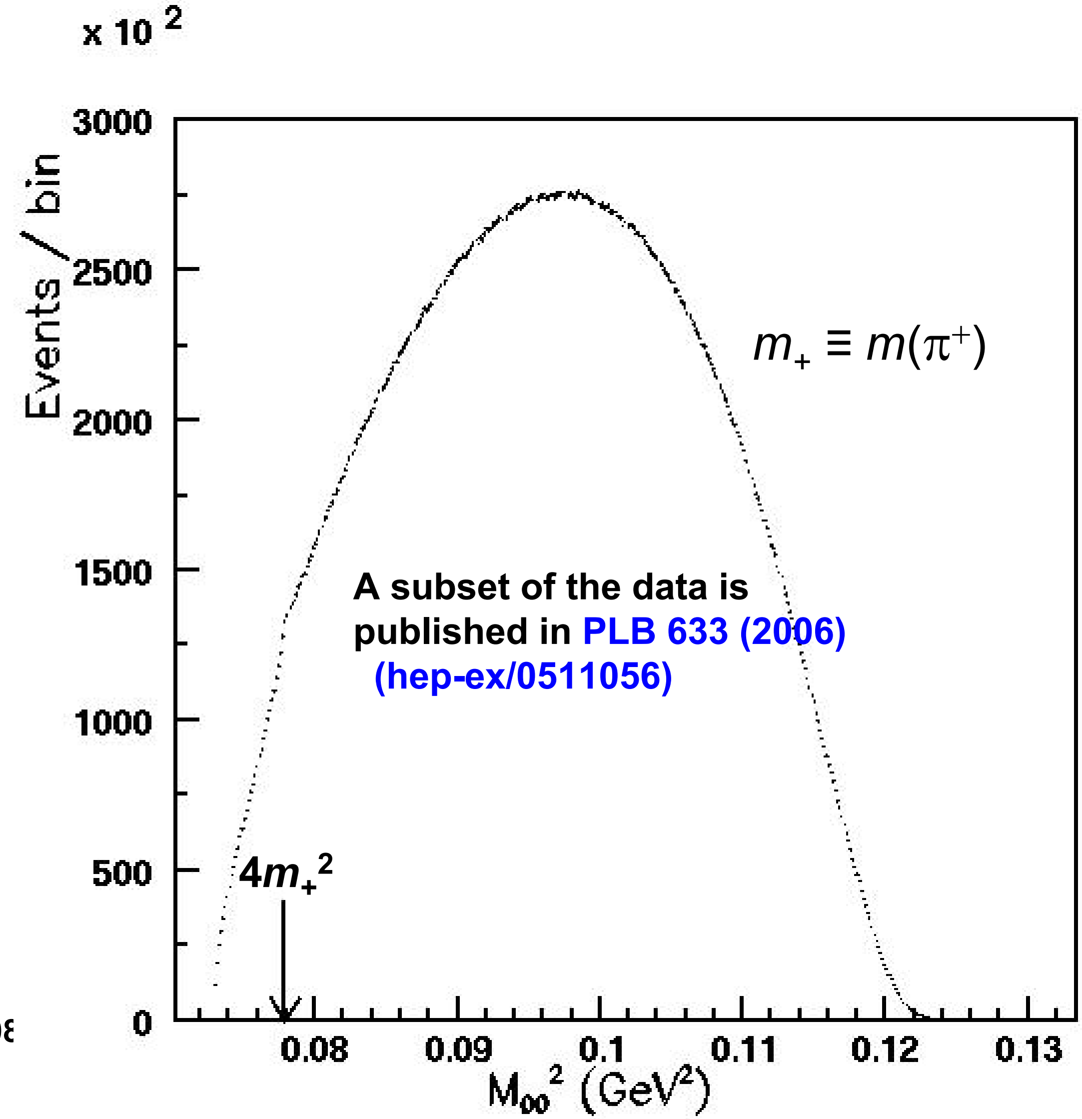


Unexpected Discovery!

$\Gamma \sim |M_0+M_1|^2$

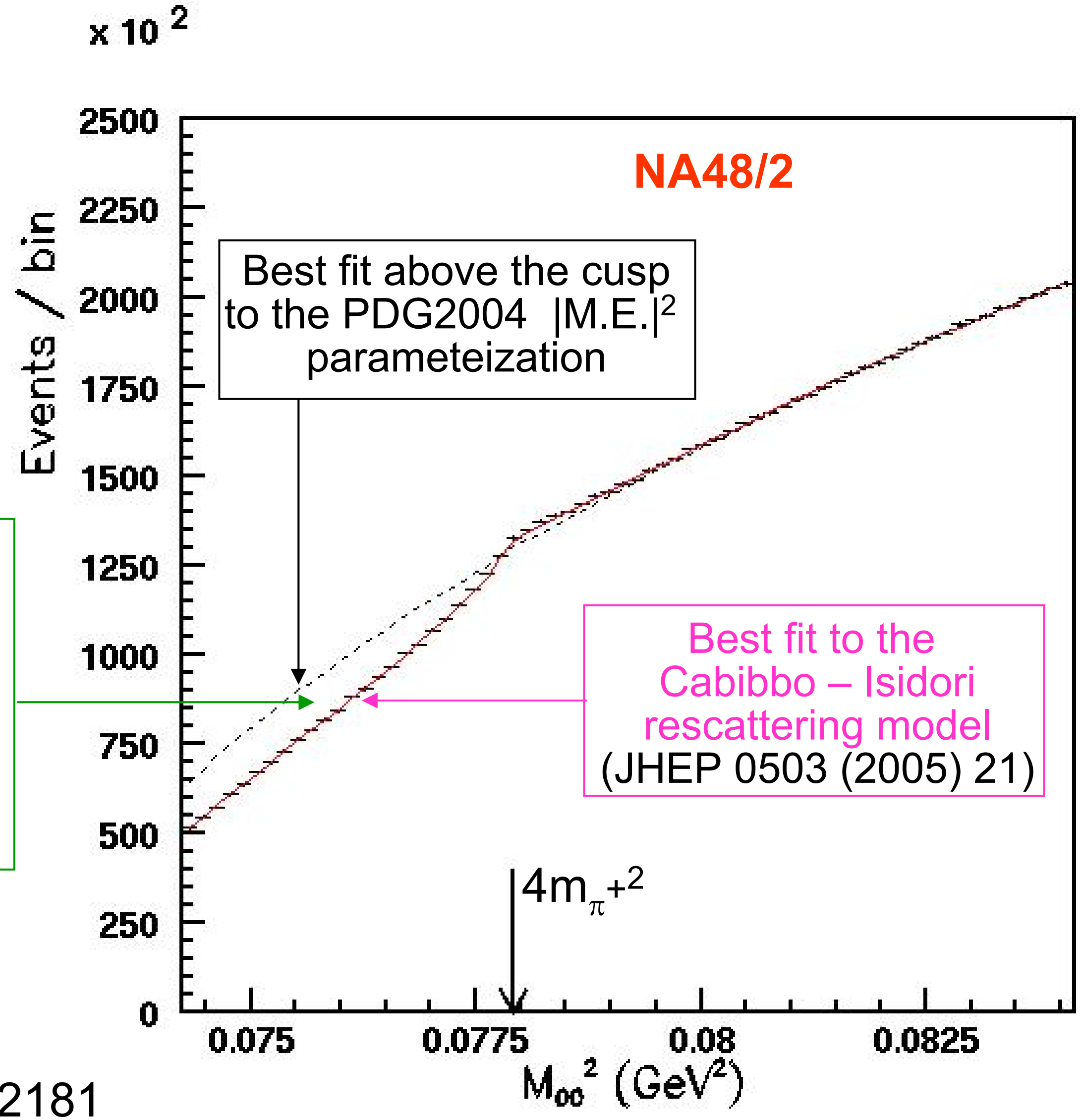
NA48/2 Unexpected Discovery

Observation of a cusp structure in the $\pi^\circ\pi^\circ$ invariant mass distribution at $M_{\pi^\circ\pi^\circ} = 2m_{\pi+}$ in high statistics study of $K^\pm \rightarrow \pi^\pm\pi^\circ\pi^\circ$ decay



59,624,170 fully Reconstructed $K^\pm \rightarrow \pi^\pm\pi^\circ\pi^\circ$ events (2003+2004)

ZOOM ON THE CUSP REGION

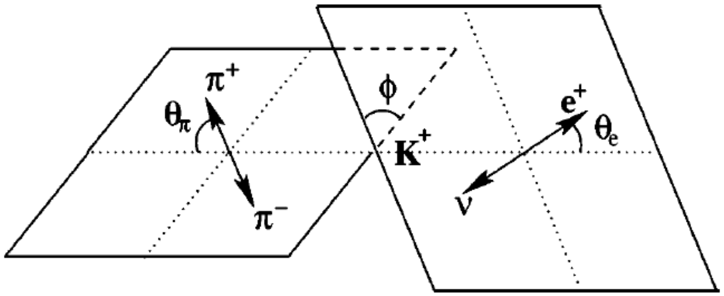


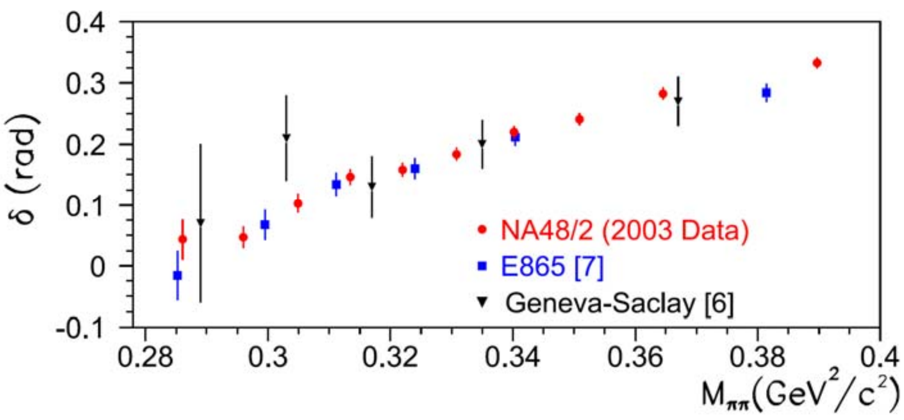
Destructive interference
between virtual
(below threshold)
$K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ states
followed by $\pi^+\pi^- \rightarrow \pi^\circ\pi^\circ$
and the $K^\pm \rightarrow \pi^\pm \pi^\circ\pi^\circ$ amplitude.
Integrated event deficit ~13%

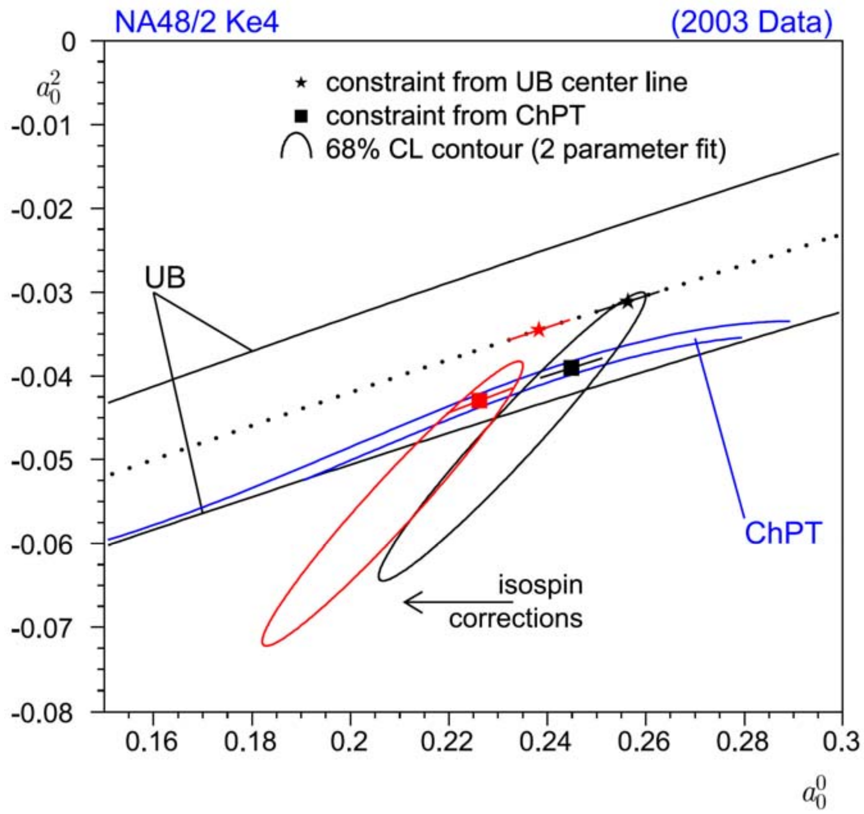
N. Cabibbo, PRL 93 (2004) 12181

a new method to measure $a_0 - a_2$ and its sign

NA48/2: ππ Scattering Length: $K^+ \to \pi^+\pi^- e\nu$







Phase shift (δ) measurements

Eur. Phys. J. C54, 411-423 (2008)

CKM Unitarity and Rare Kaon Decays

The unitarity of the CKM matrix can be expressed by triangles in a complex plane.
There are six triangles, one is more "triangular":

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$$

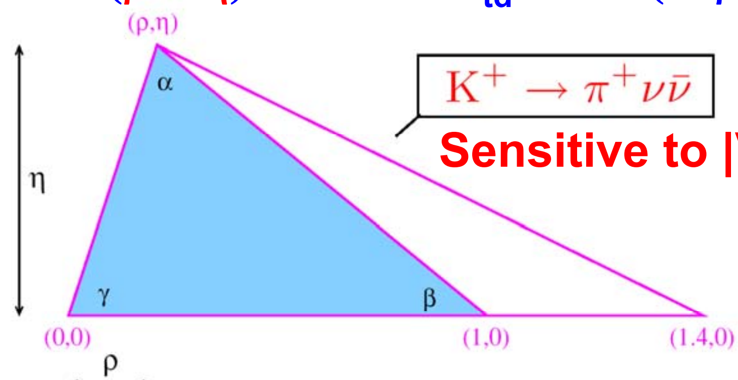
It is customary to employ the Wolfenstein parameterization:

$V_{us} \sim \lambda$ $V_{cb} \sim \lambda^2 A$ $V_{ub} \sim \lambda^3 A(\rho - i\eta)$ $V_{td} \sim \lambda^3 A(1-\rho-i\eta)$

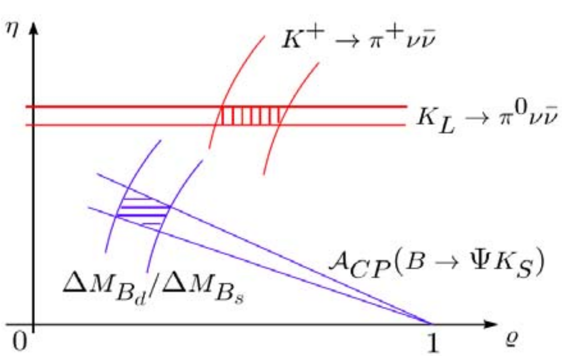
~~CP~~

$$K_L \to \pi^0 \nu\bar{\nu}$$

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



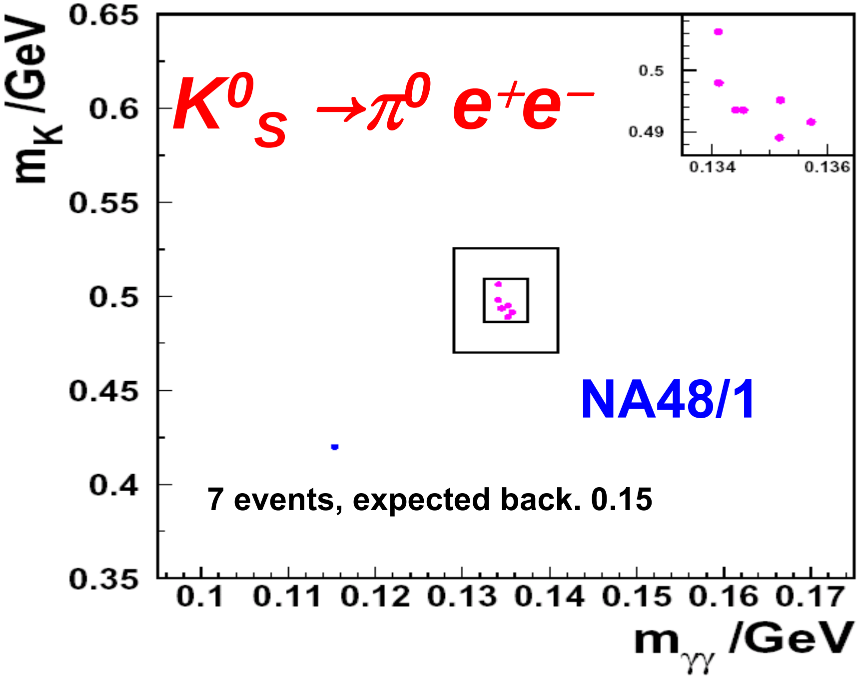
Sensitive to $|V_{td}|$

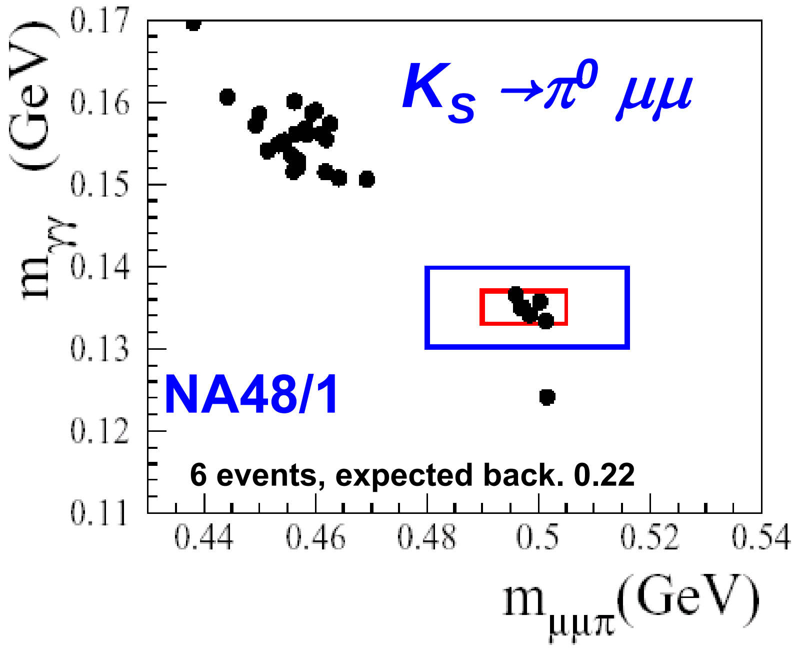


- It is important to check that the unitary triangle is the same for all heavy quarks.
- The s-quark is just as important as the b-quark.
- If experiment shows that there are differences between the flavors this would be an important discovery.

NA48/1: K^0_S rare decays

Examples of rare decays studies performed at CERN
Important to determine CP-Violation from mixing in K^0_L decays





$BR(K_S \to \pi^0 ee) \times 10^9 =$
$5.8\ ^{+2.8}_{-2.3}(stat) \pm\ 0.8(syst)$

PLB 576 (2003)

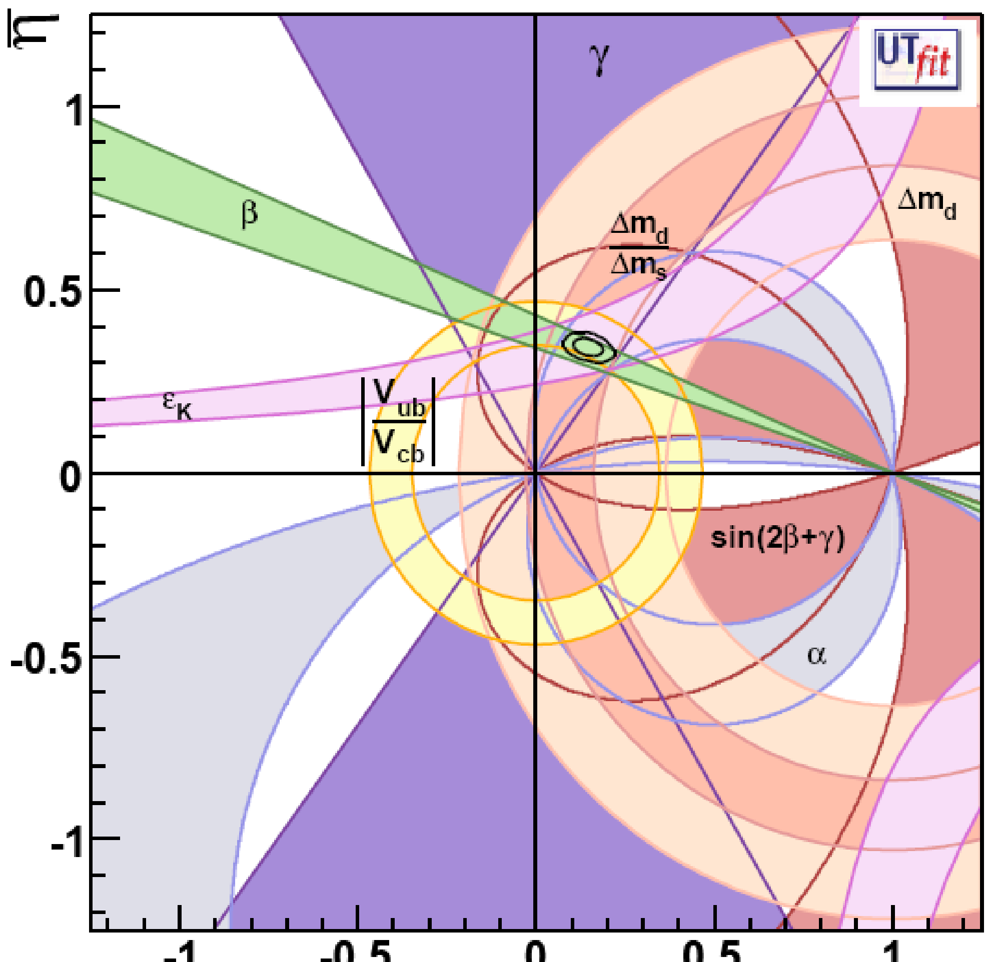
$BR(K_S \to \pi^0 \mu\mu) \times 10^9 =$
$2.9\ ^{+1.4}_{-1.2}(stat) \pm\ 0.2(syst)$

PLB 599 (2004)

"CKM Unitarity Triangle"

The KM Mechanism for CP-Violation is very successful

Sin 2β ($2\phi_1$)

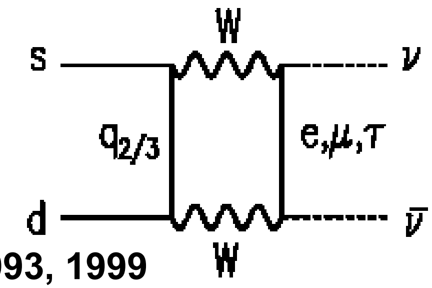


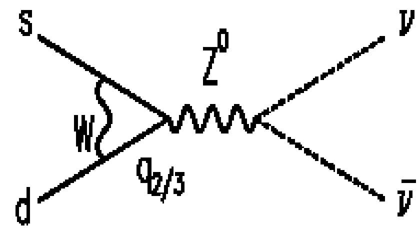
What will we learn next??

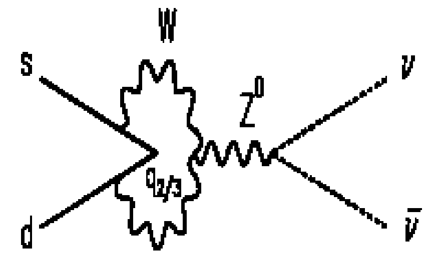
Paradigm shift:
use precise probes to see deviations from SM

$K\to\pi\,\nu\bar{\nu}$: SM Theoretical Prediction

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







NLO Calculation:
Buchalla & Buras: 1993, 1999
Misiak, Urban: 1999

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

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

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

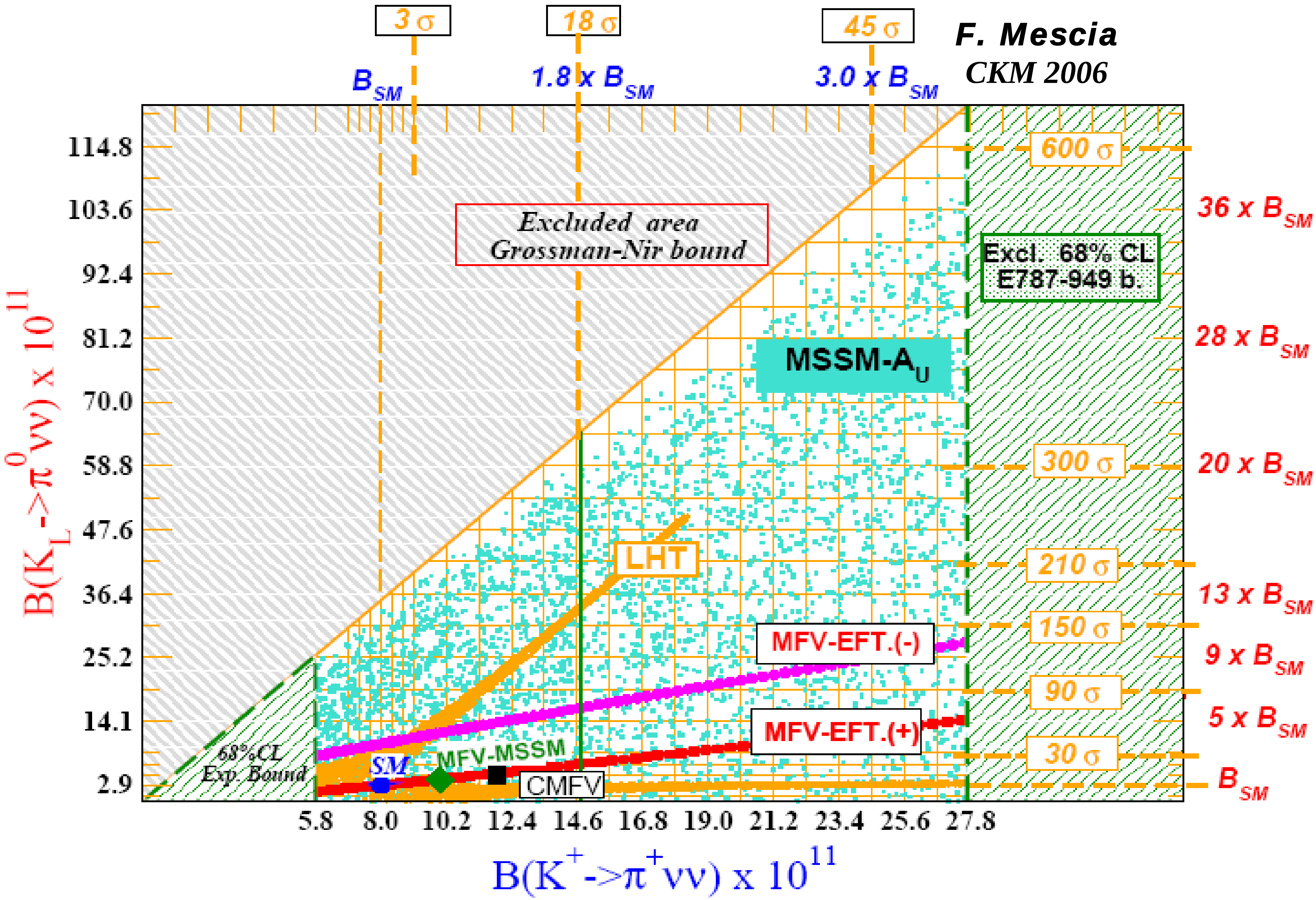
top contributions

charm contribution
NNLO
Buras, Gorbahn, Haisch, Nierste
hep-ph/0508165

The uncertainty of the SM prediction is mostly due to uncertainty of the CKM parameters and not to hadronic matrix elements:

- $BR(K^+\to\pi^+\nu\nu) \approx (1.6\times10^{-5})|V_{cb}|^4[\sigma\eta^2+(\rho_c-\rho)^2] \to (8.0\pm1.1)\times10^{-11}$
- $BR(K_L\to\pi^0\nu\nu) \approx (7.6\times10^{-5})|V_{cb}|^4\eta^2 \to (3.0\pm0.6)\times10^{-11}$

New Physics Reach of the K → π νν decays



Long History

- $K^+ \rightarrow \pi^+ \nu\nu$

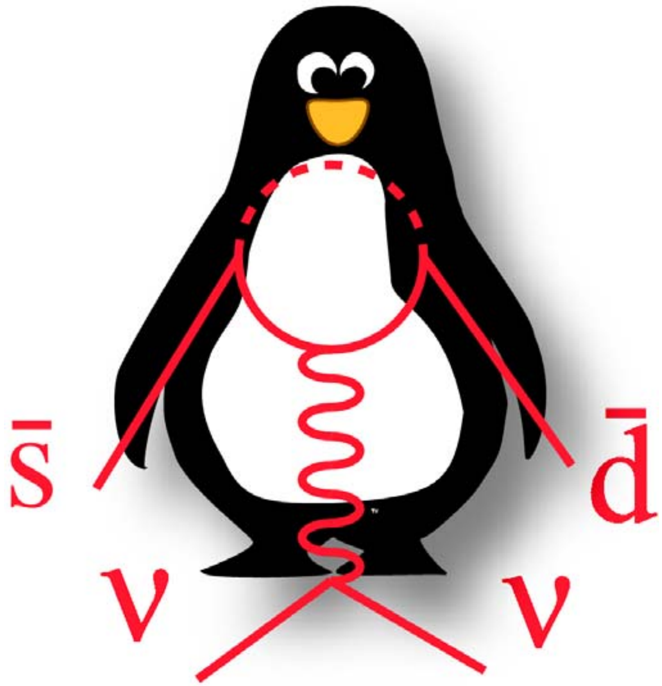
  E787/E949 $BR(K^+ \rightarrow \pi^+ \nu\nu) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$

  - **BNL E787 together with the upgrade E949 published 3 events, see also recent long article:** PRD 77, 052003 (2008)
  - **E949 run only for a very short time before being terminated**
  - **An In flight experiment at Fermilab (CKM) was cancelled**
- $K^0_L \rightarrow \pi^0 \nu \nu$
  - **BR < 6.7 × 10^{-8} 90%CL (E391a @ KEK)**
  - **KOPIO cancelled**
  - **Next steps E14 @ JPARC (Awaiting Stage II Approval)**
  - **KLOD @ U70 (Proposed)**

Proposal to Measure the Rare Decay $K^{+}\to\pi^{+}\,\nu\,\nu$ at the CERN SPS

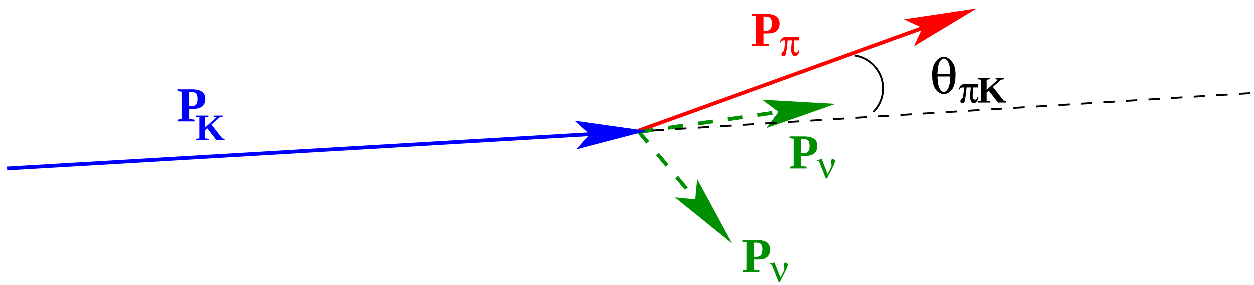
NA62

CERN-SPSC-2005-013
SPSC-P-326



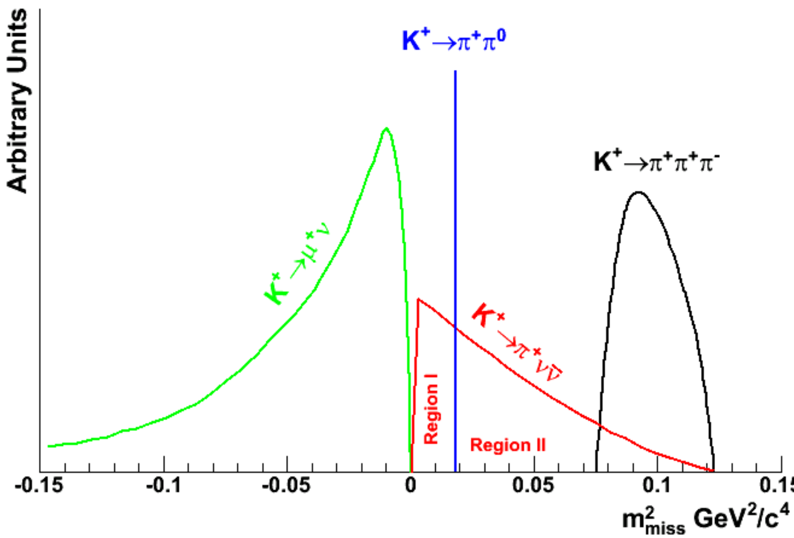
Bern, Birmingham, CERN, Dubna, Ferrara, Fairfax, Florence, Frascati, IHEP, INR, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosi, SLAC, Sofia, Triumf, Turin

Principle of the Experiment



1) Kinematical Rejection

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



2) Photon vetoes to reject $K^+\to\pi^+\pi^0$:

P(K^+) = 75 GeV/c

Requiring P(π^+) < 35 GeV/c

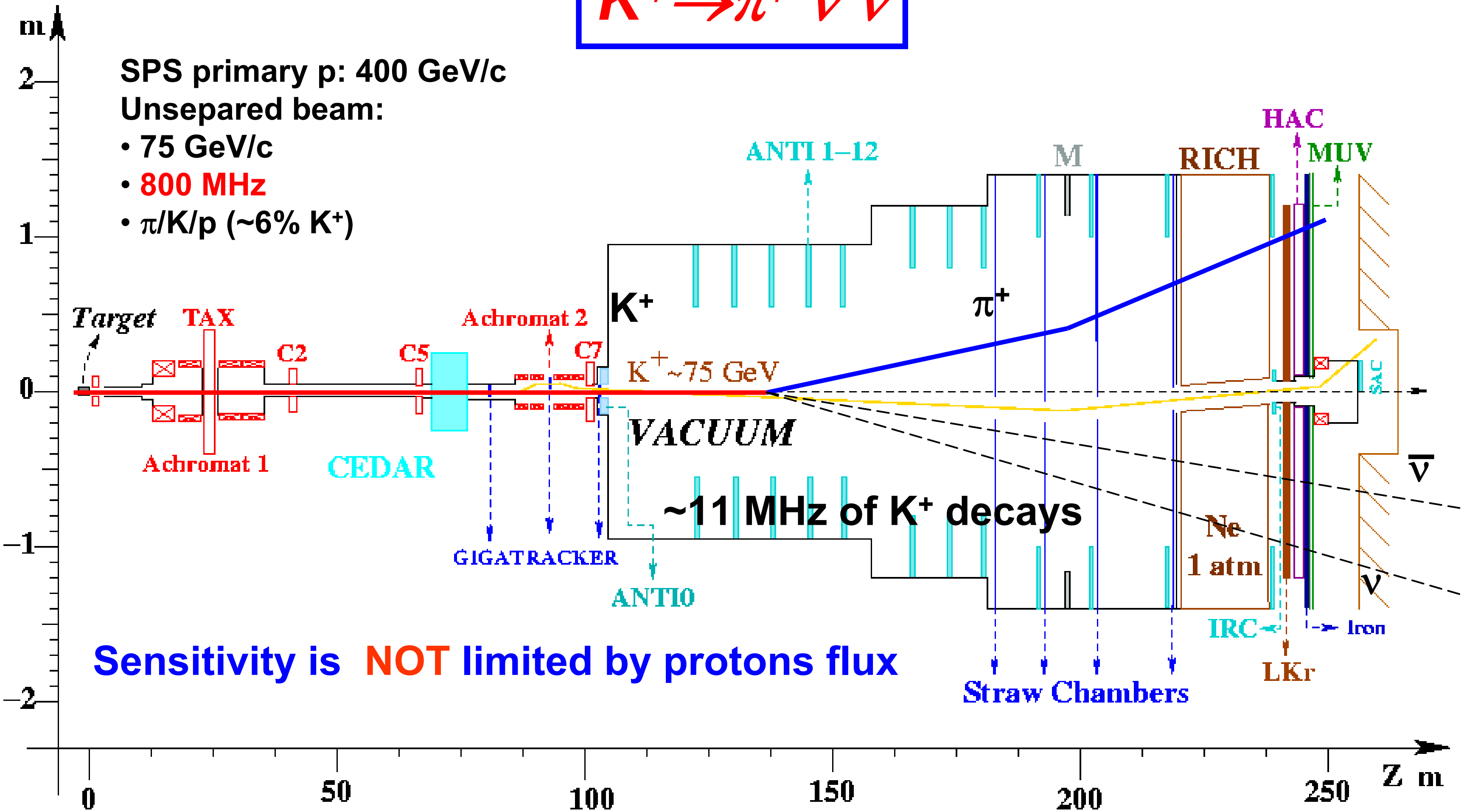
P(π^0) > 40 GeV/c ➡ It can hardly be missed in the calorimeters

3) PID (RICH) for $K^+\to\mu^+\nu$ rejection

Updated 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

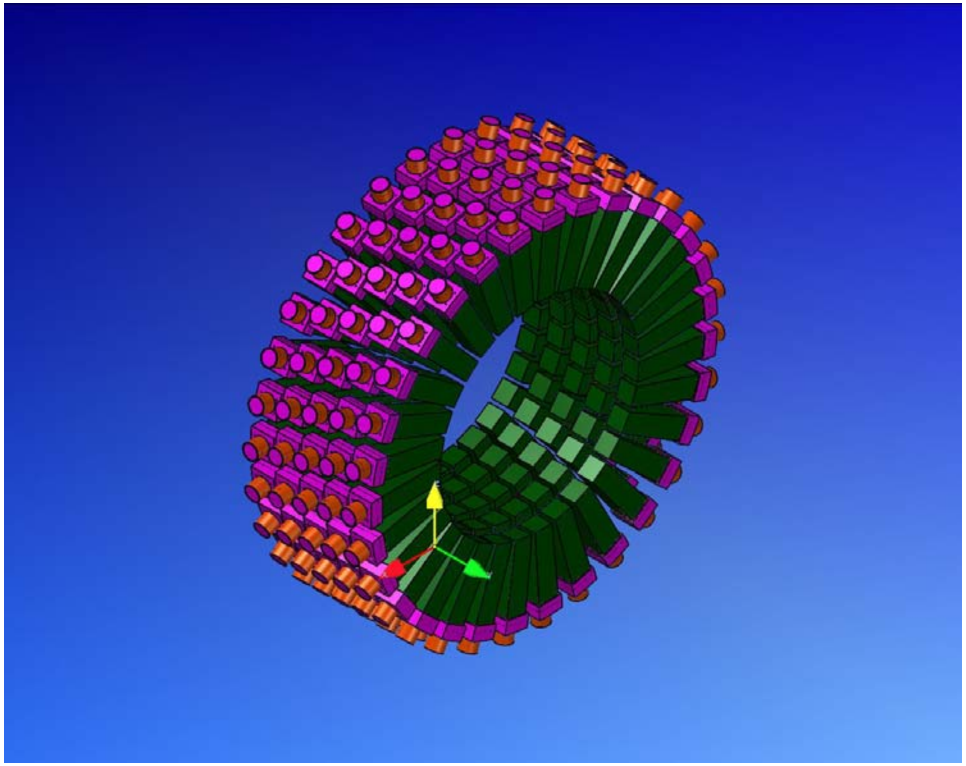
P-326 Sensitivity

Decay Mode	Events
Signal: $K^+ \to \pi^+ \nu\nu$ *[flux = 4.8×10^{12} decay/year]*	**55** *evt/year*
$K^+ \to \pi^+ \pi^0$ *[$\eta_{\pi 0}$ = 2×10^{-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%)**

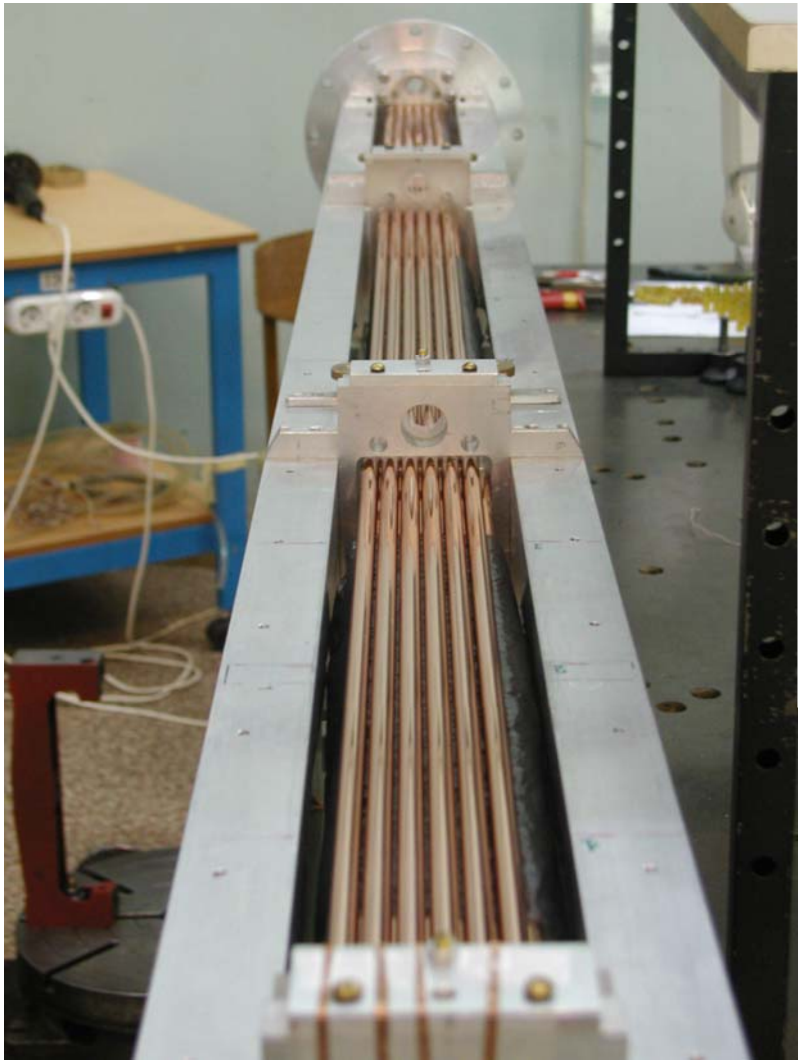
Status of the R&D

Large Angle Veto: OPAL Lead-Glass

- During the 2007 run we have exposed a few Lead-Glass blocks to radiation doses similar to those expected during the experiment lifetime
- No radiation damage was measured
- An engineering designed for the integration of the Lead-Glass in the experiment was prepared and was used to obtain industrial offers for the mechanics

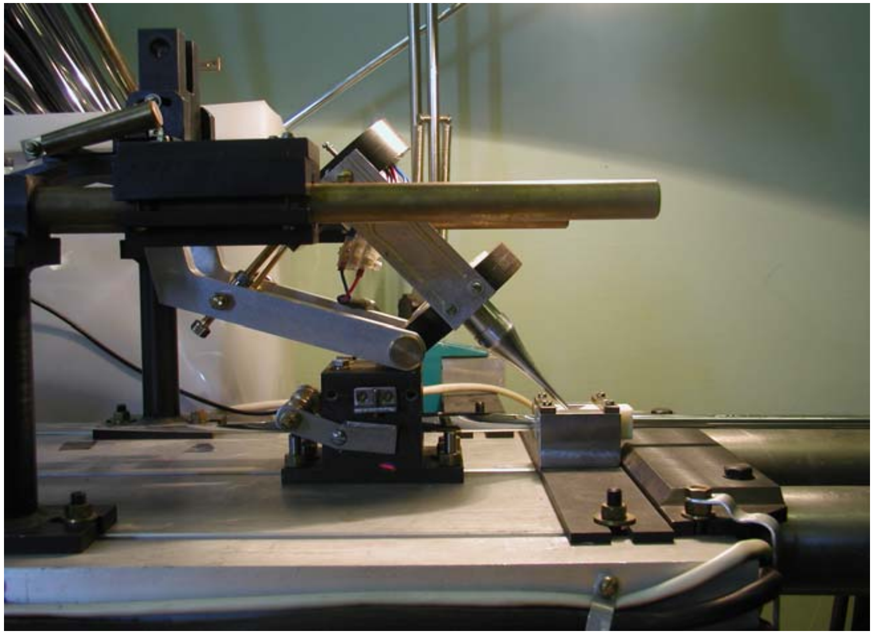


STRAW Prototype built in 2007

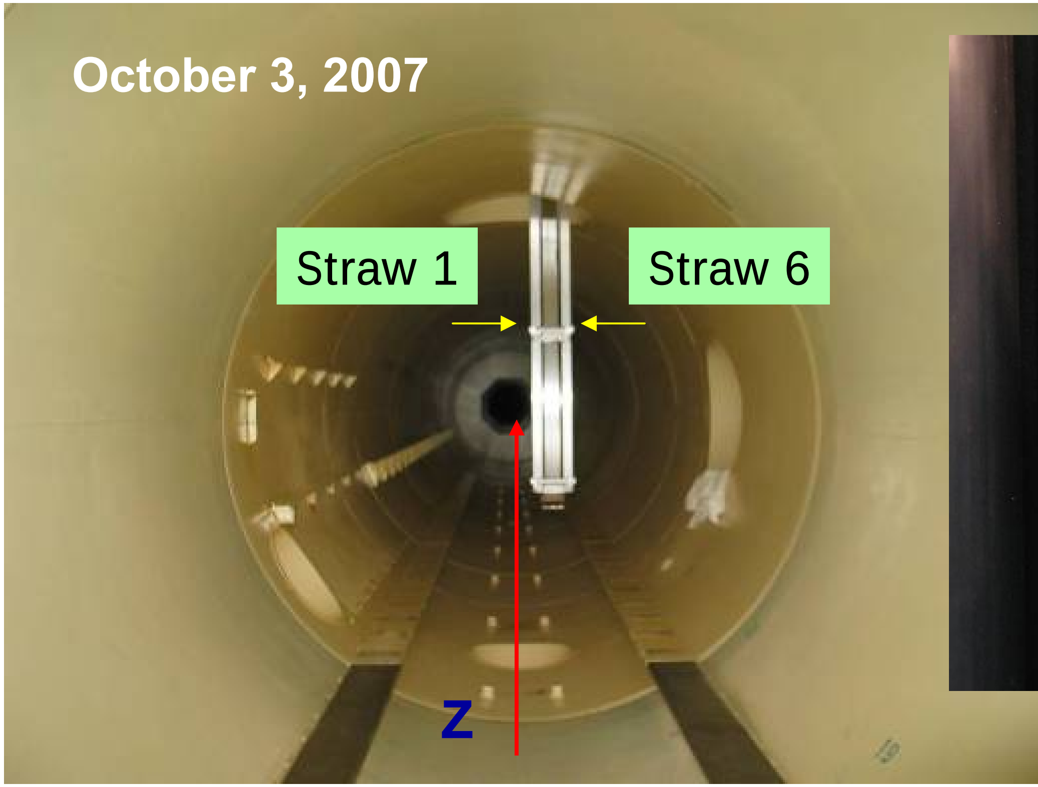


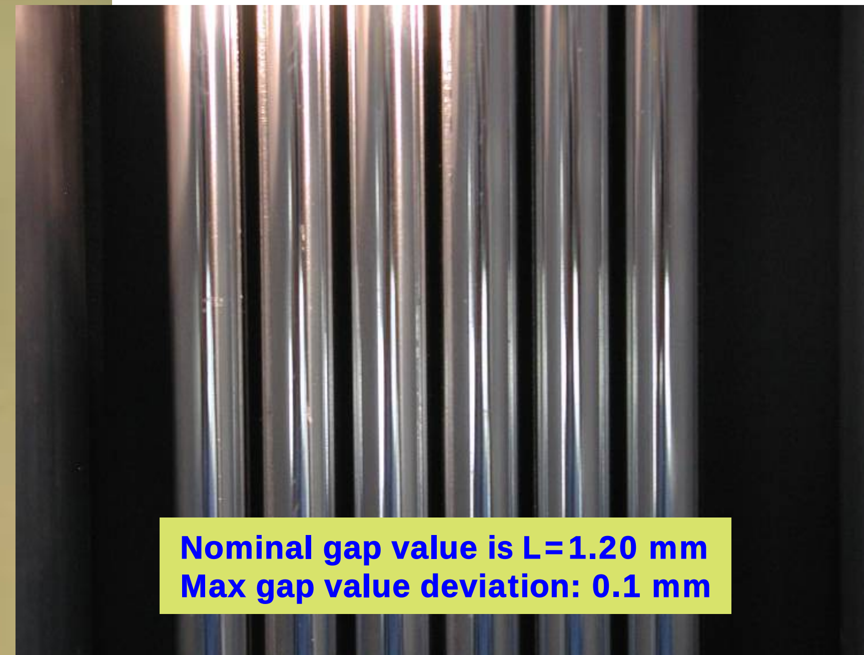
Ultrasound Welded mylar (linear weld, no glue!)

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



Straw Prototype inside the Vacuum Tube

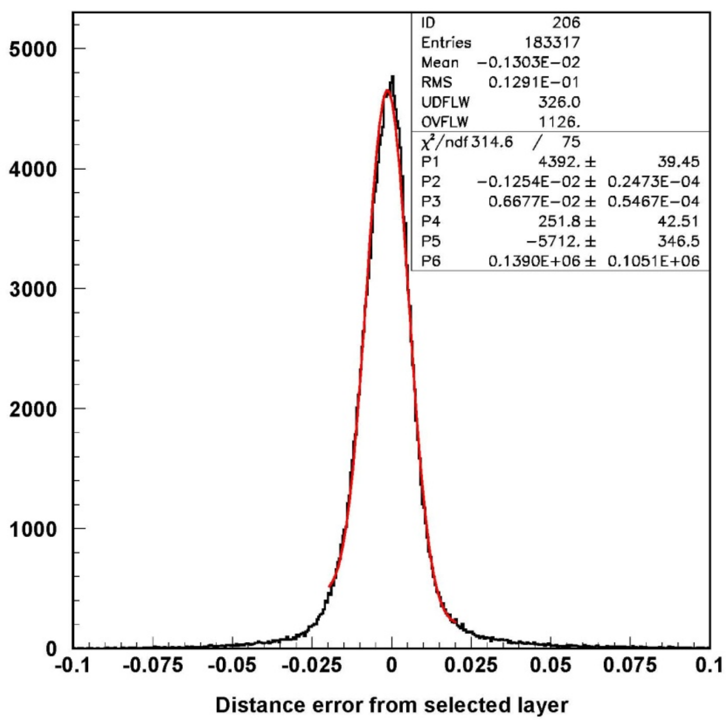




- Data were collected with hadron, muon and kaon decays
- The test in the actual vacuum tank enabled one to address realistic issues

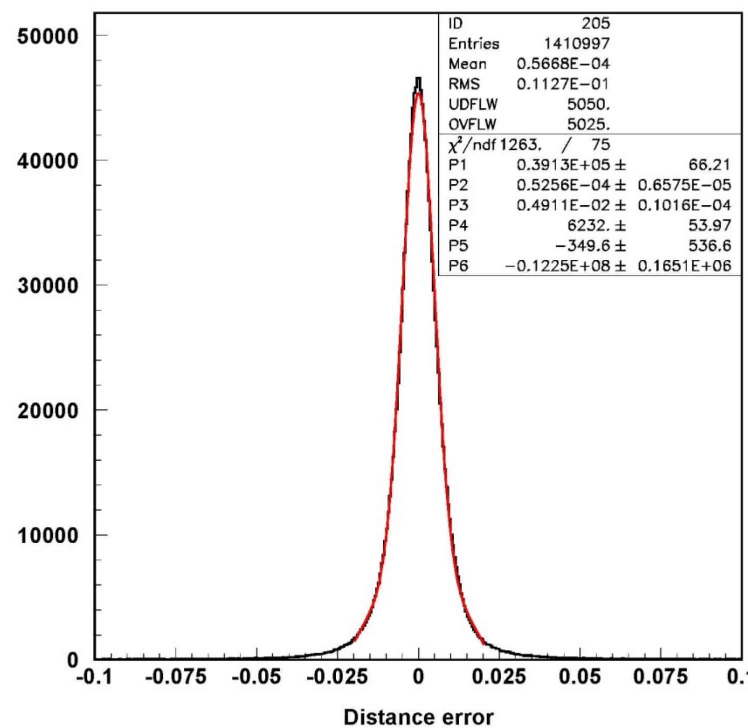
Aluminum straws (preliminary)

Resolution



R.M.S.=130 μm
sigma=67 μm

Residuals



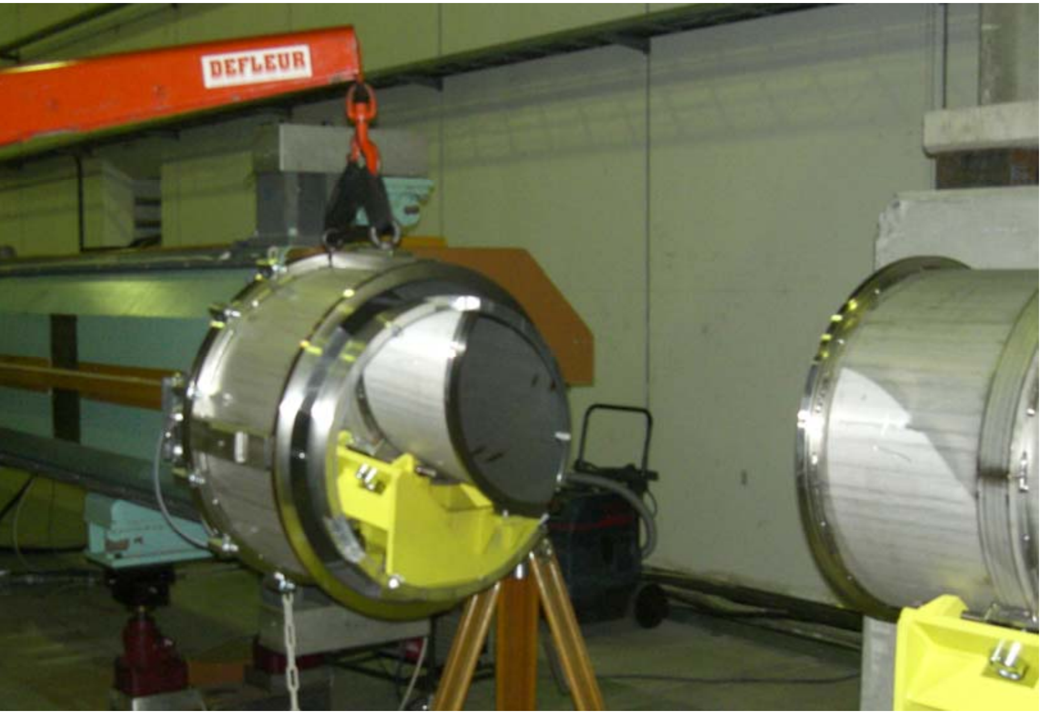
R.M.S.=113 μm
sigma=49 μm

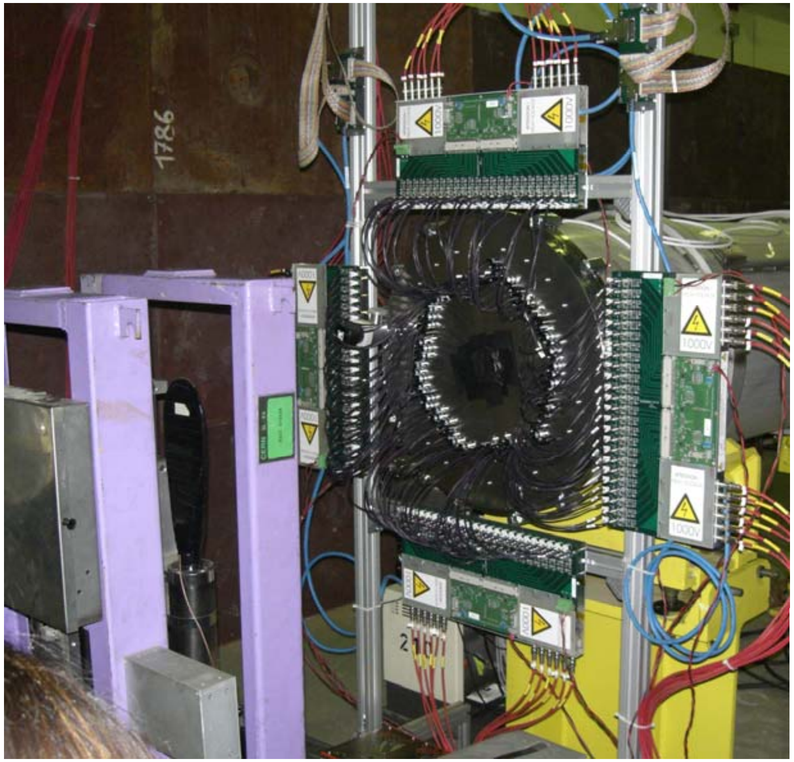
The RICH prototype

- Full scale (longitudinal) RICH prototype
- 18 m long tube, vacuum resistant
- Mirror: ϕ=50cm, f=17.01m
- 96 PMs Hamamatsu R 7400 U
- Test: negative beam from SPS@200 GeV/c

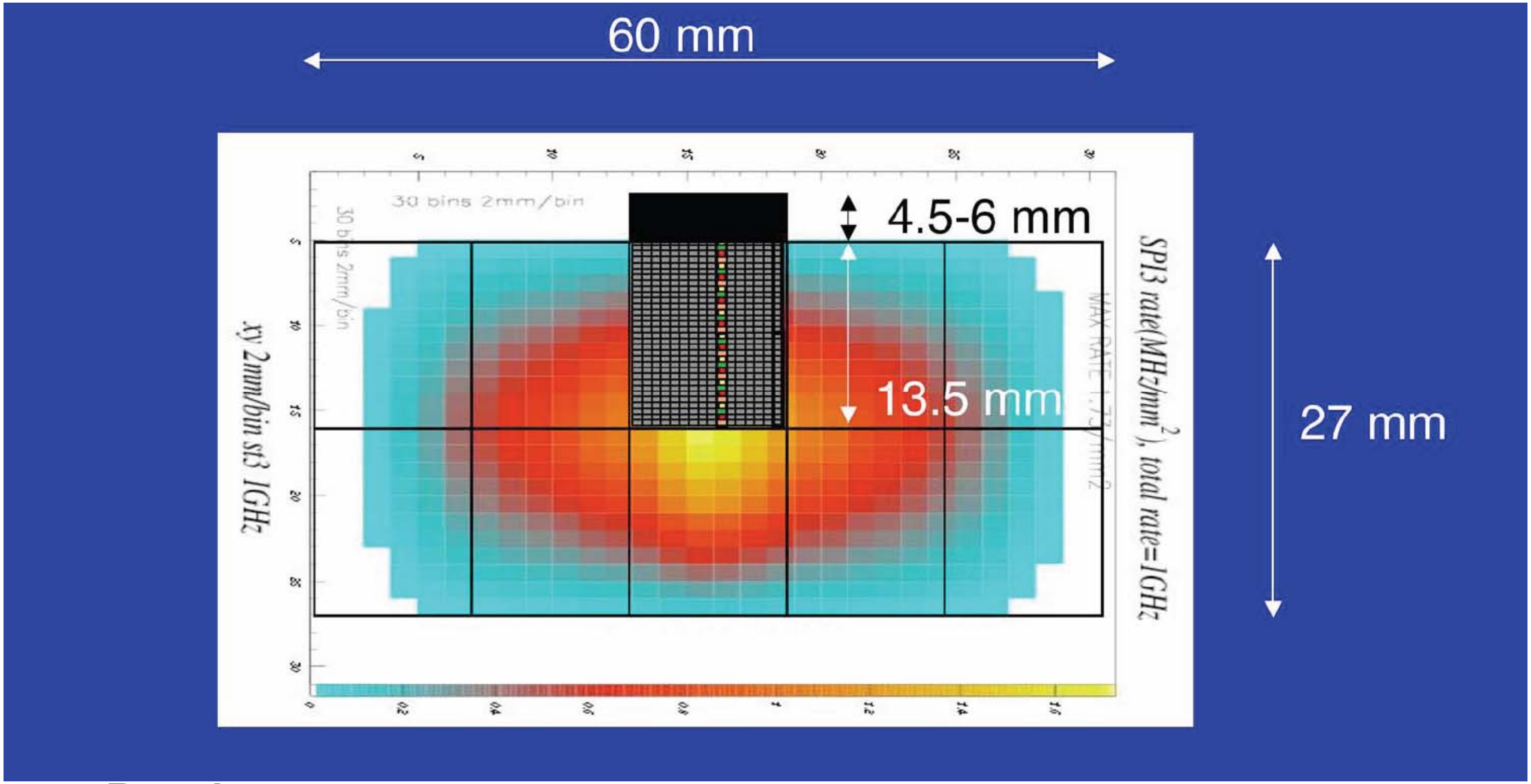
Achieved time resolution:
75 ps per event

In 2008 the prototype
Will be equipped with
~400 PMTs





Gigatracker (Silicon μ–pixel)



<u>**Requirements:**</u>

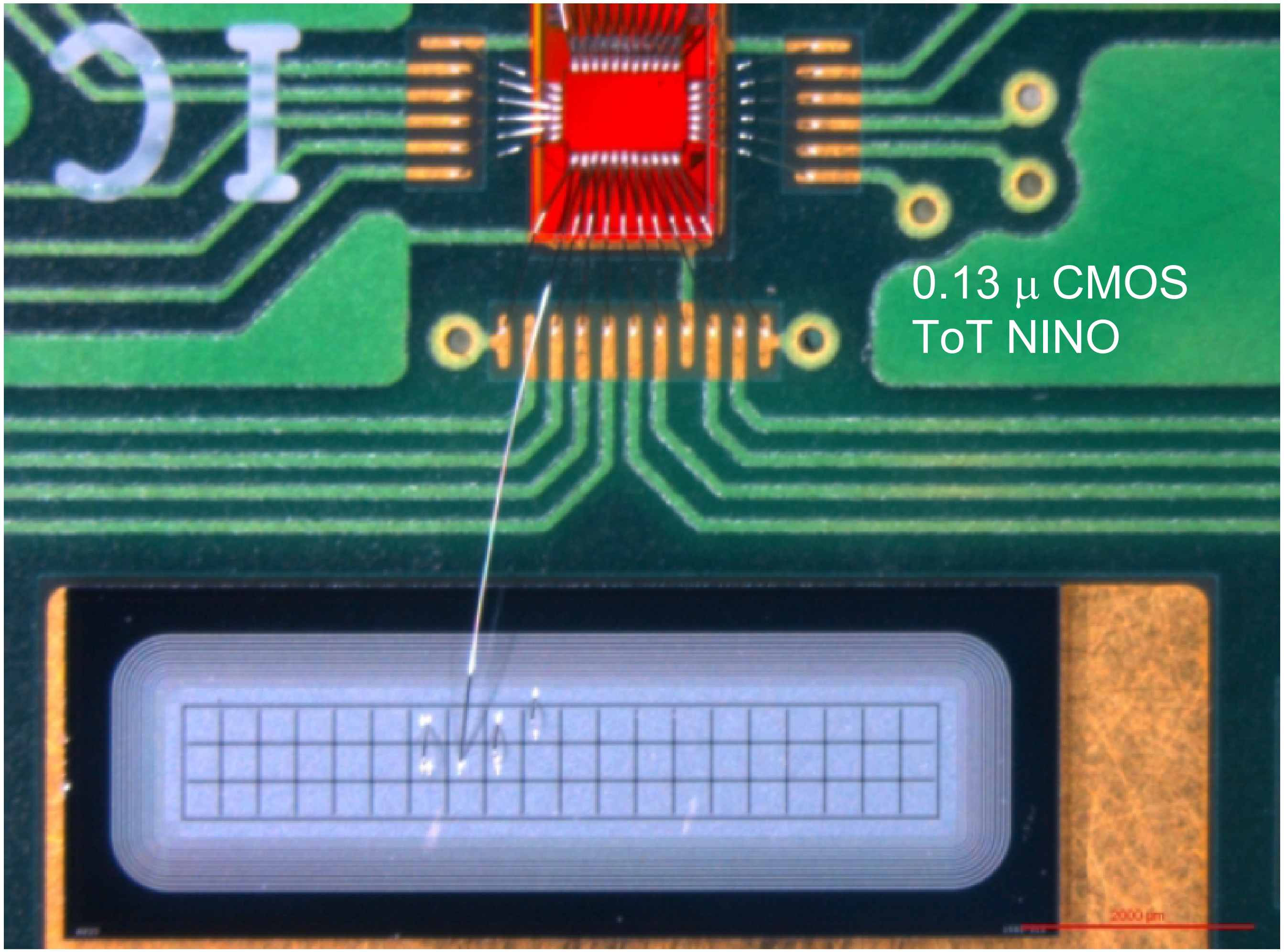
Time resolution: 200 ps / station

Material Budget: < 0.5 % X_0 / station

Driven by the experience with the thin hybrids of the ALICE SPD

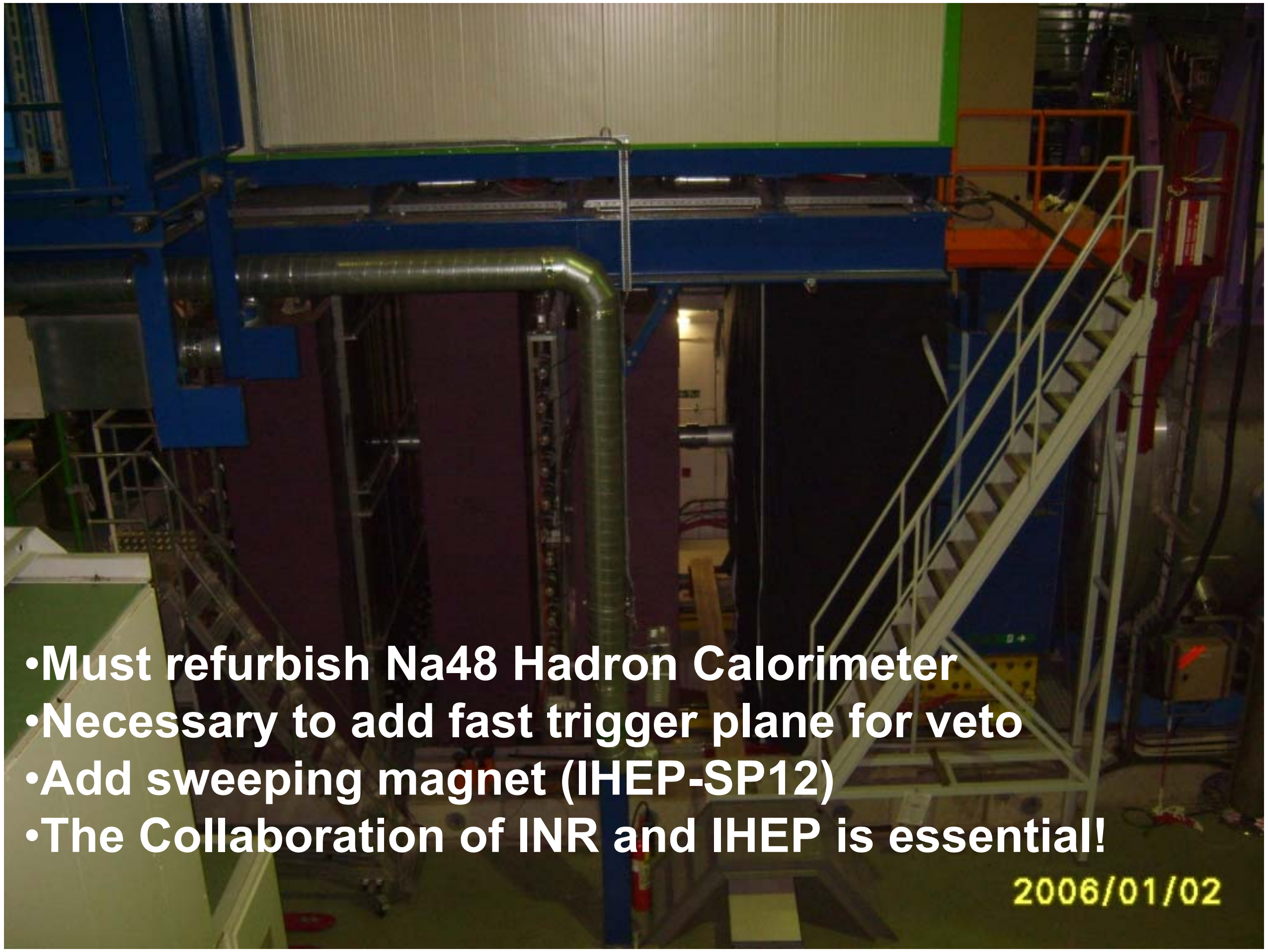
IRST Diode with NINO chip

Next step:
~8 x 8 matrix prototype
Bump-bonded to R/O chip for Beam Test



Fadmar Osmić – P326 GTK Meeting, September 10, 2007 -7-

Muon Detector



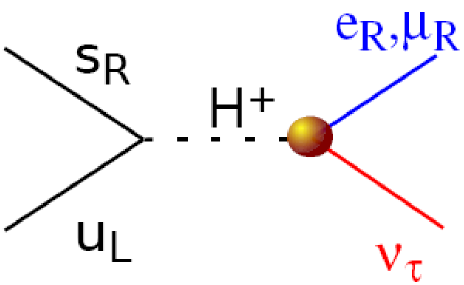
Status of NA62

- We are in the phase of completing the R&D and preparing the construction
- Some Funding agency, and notably INFN, have already approved the full programme
- We foresee construction during the 2009-2011 period and first data taking for $K^+ \rightarrow \pi^+ \nu \nu$ in 2011-2012
- The New Collaboration is growing and the best way to blend the new groups is to do physics together
- In 2007 the New Collaboration NA62 has collected 5 months of proton data at the SPS to study lepton universality in kaon leptonic decays

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

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)} \;,\quad i = e, \mu, \tau$$

Masiero, Paradisi, Petronzio, hep-ph/0511289 PRD74,(2006)



$$eH^\pm \nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$R_K(SM) = (2.472 \pm 0.001) \times 10^{-5}$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi} \delta_{RR}^{31}$$

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \;\; t_\beta = 40 \;\; M_{H^\pm} = 500\mathrm{GeV}$$

$$\Downarrow$$

$$\Delta r_{K\,SUSY}^{e-\mu} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right) |\Delta_R^{31}|^2 \tan^6\beta \approx 10^{-2}$$

Variations of the order of 1% to with respect to **R_K(SM)** may be present from breaking of μ-e universality in SUSY (maximum effect possible -3.2%)

World average (PDG): R_K = (2.44 ± 0.11) x 10^{-5}
from three experiments: 1972 (112 evts); 1975 (534 evts); 1976 (404 evts)
From the analysis of NA48/2 2003 data (~ 4000 events):

R_K = (2.416 ± 0.043 ± 0.024) x 10^{-5} (~ 4000 evts) presented at HEP2005, Lisbon

Ratio of Leptonic Meson Decays

$$R_M = \frac{\Gamma(M \to e\nu(\gamma))}{\Gamma(M \to \mu\nu(\gamma))} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{1-\left(\frac{m_e}{m_M}\right)^2}{1-\left(\frac{m_\mu}{m_M}\right)^2}\right)^2 \times \left(1+\delta R_M\right)$$

The latest theoretical predictions give:

R_π= (1.2352 ± 0.0001) × 10^{-4}

R_K= (2.477 ± 0.001) × 10^{-5}

Experimental Situation

$\pi \to e\nu$

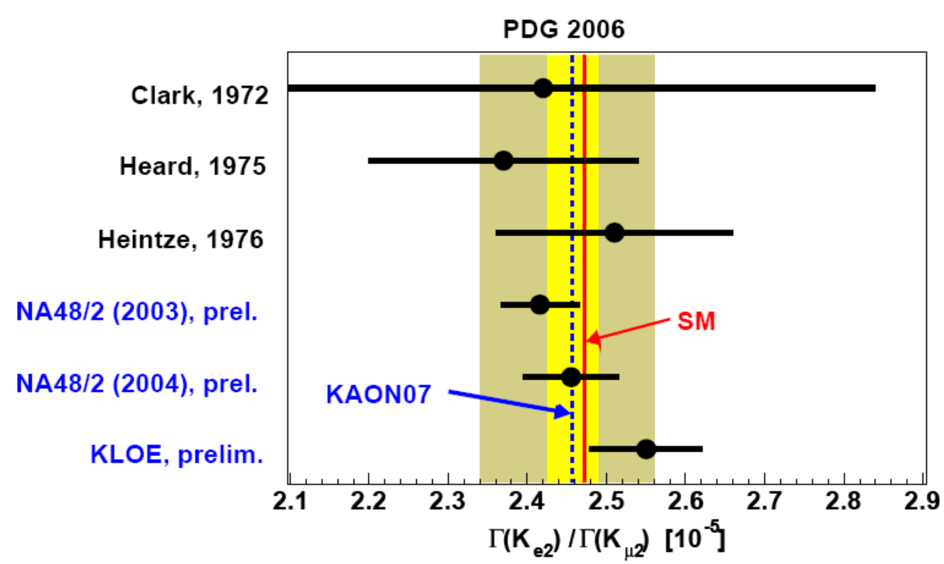
$R_{e/\mu}^{\exp\pi}$ ($\pm 0.4\%$)

$1.2265(34)(44)x10^{-4}$ TRIUMF (1992)

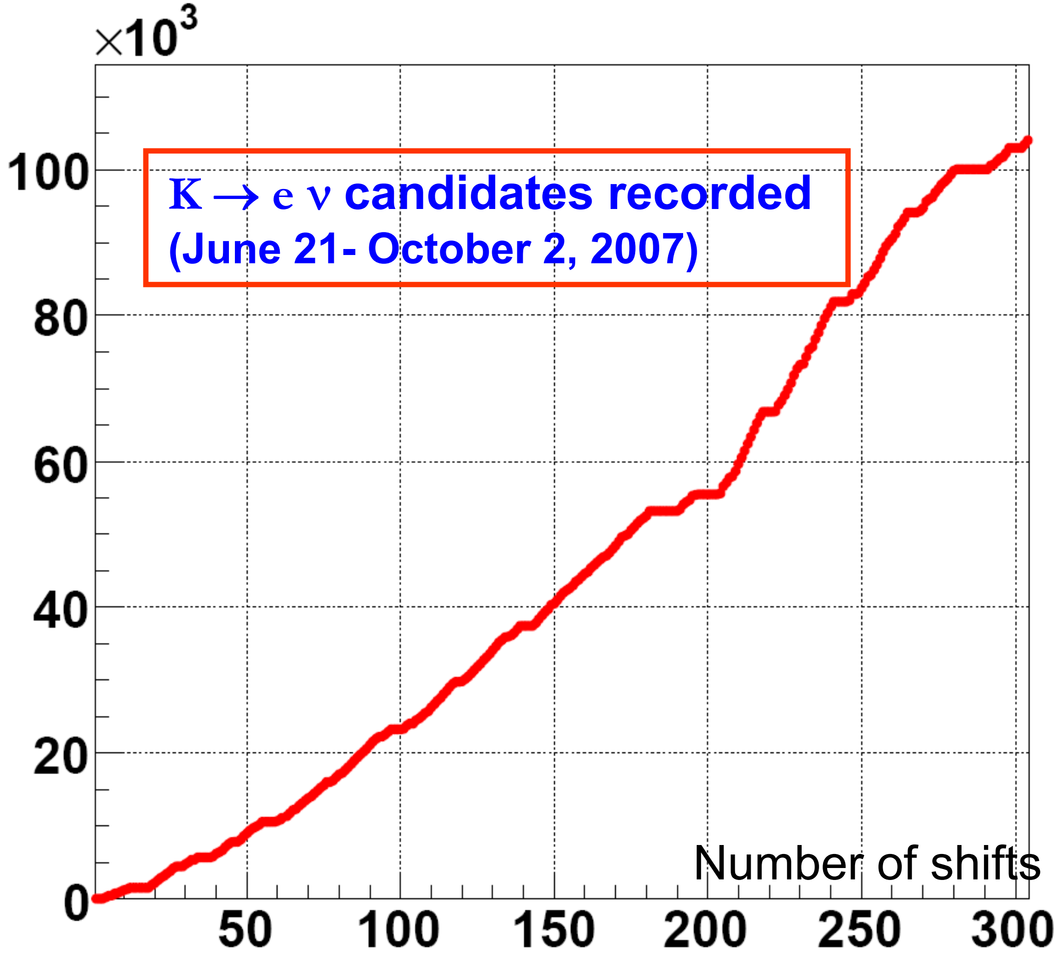
$1.2346(35)(36)x10^{-4}$ PSI (1993)

New experiments planned at TRIUMF and PSI to reach <0.1% on R_π

$$R_K = 2.457 \pm 0.032 \times 10^{-5}$$

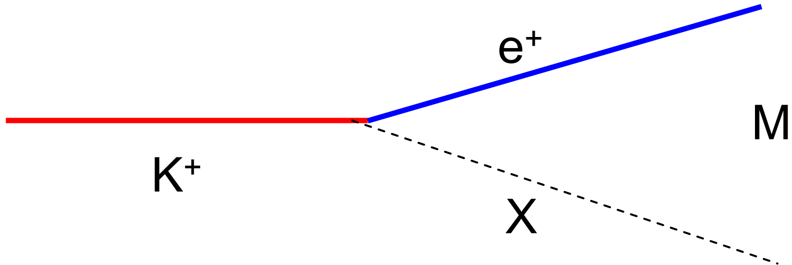


NA62: 2007 data taking for R_K

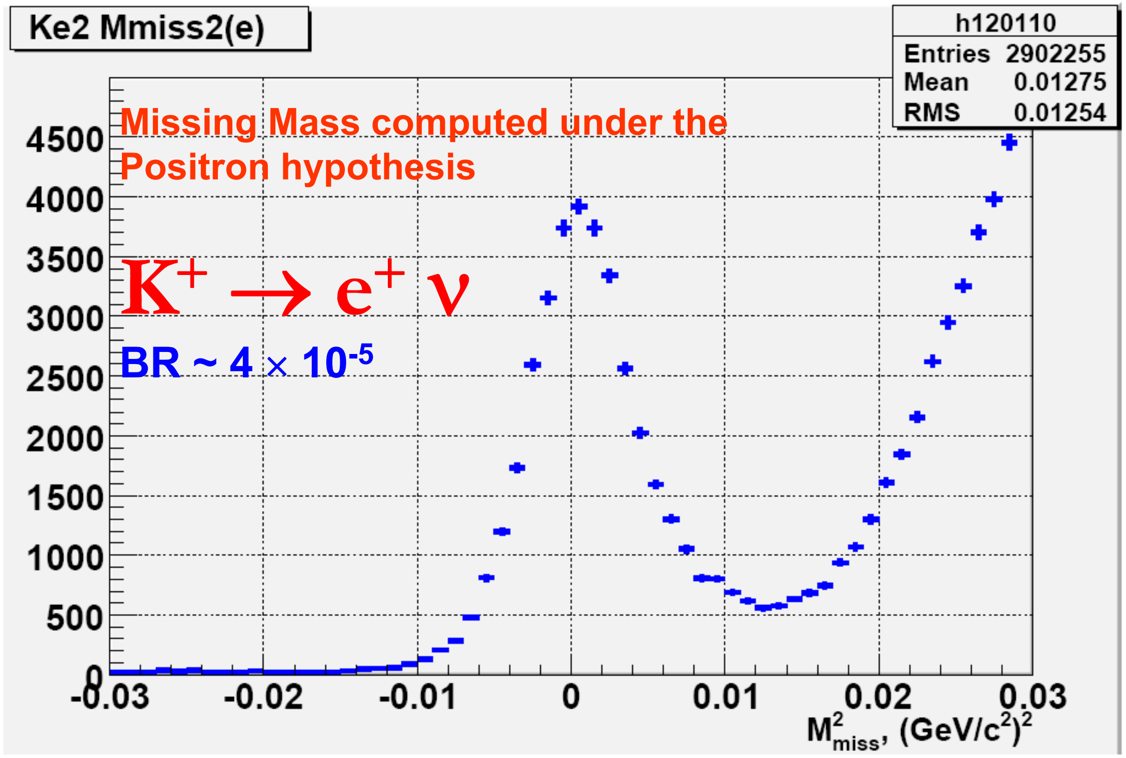


NA62 has accumulated more than 100 k $K \rightarrow e\,\nu$ events in **2007** to push the error on R_K from ~2% to ~0.3%

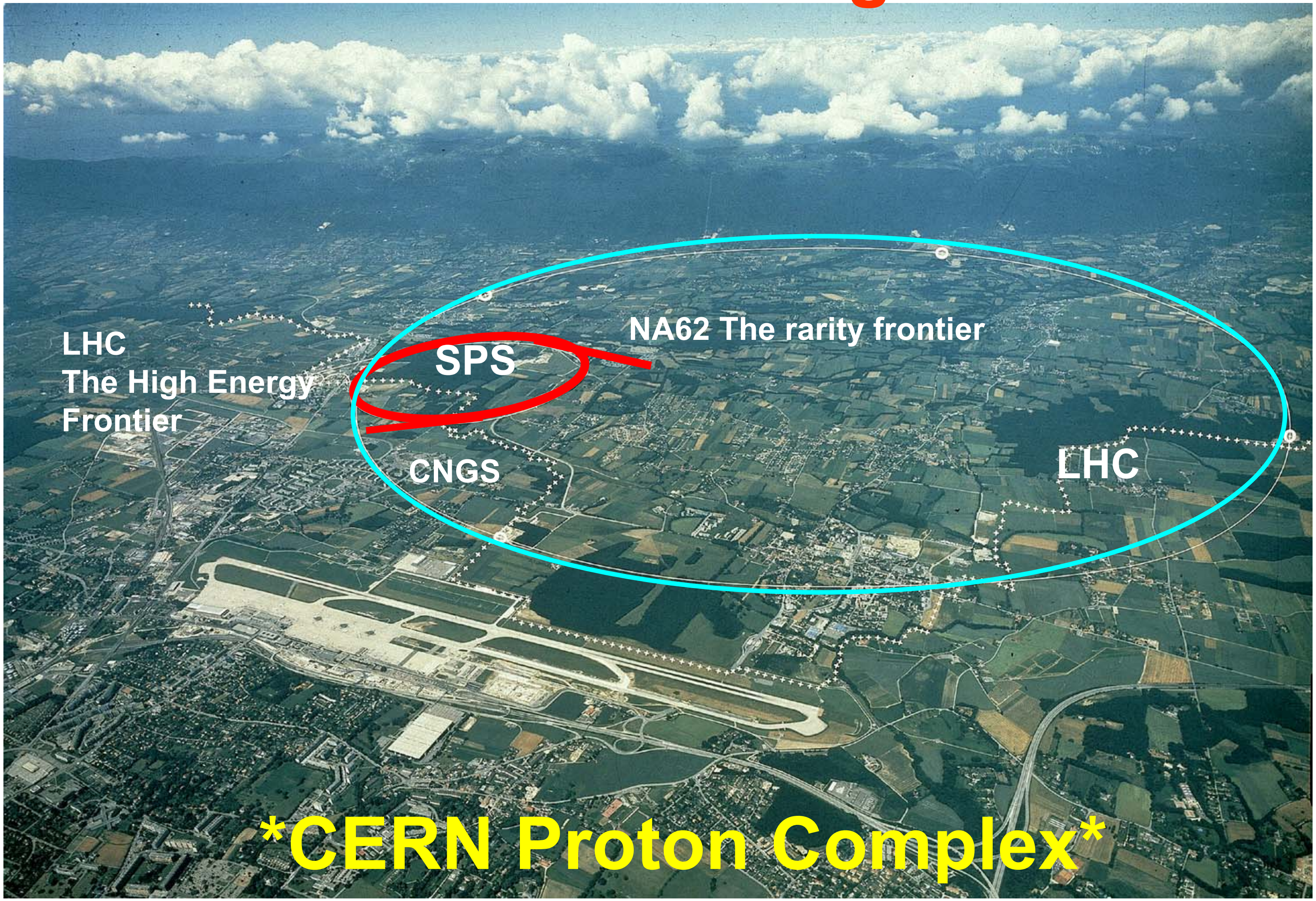
Subset of the NA62 data (2007)



$M^2_{miss} = 0$ for $X=\nu$



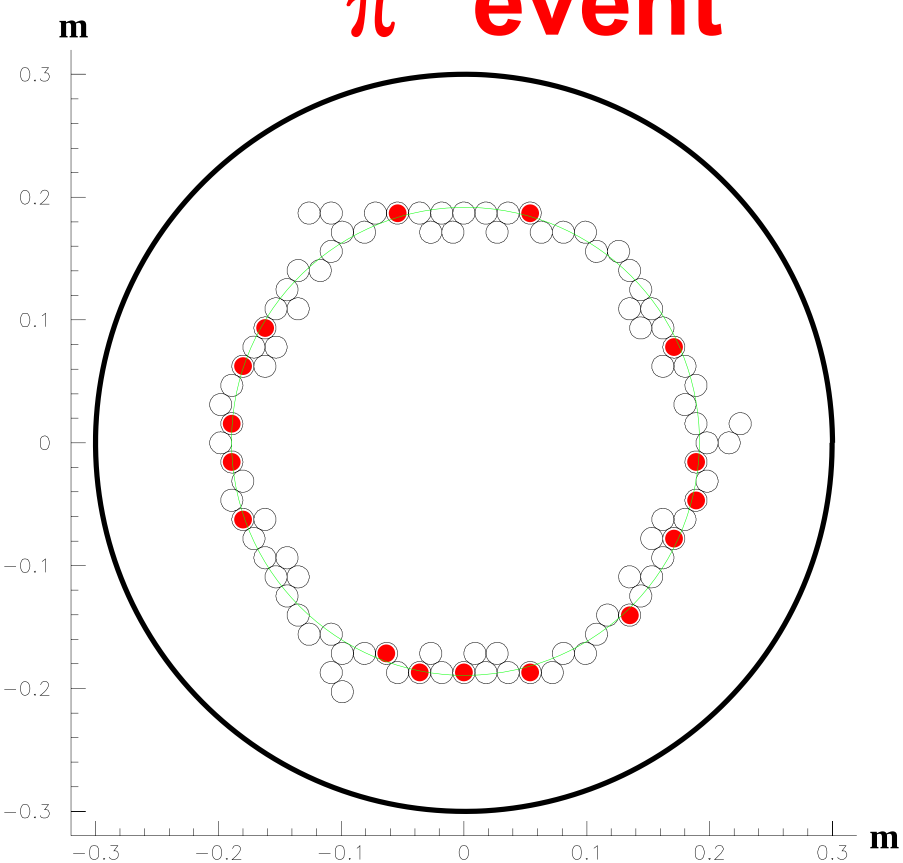
Kaons@CERN:
Glorious Past & Bright Future !



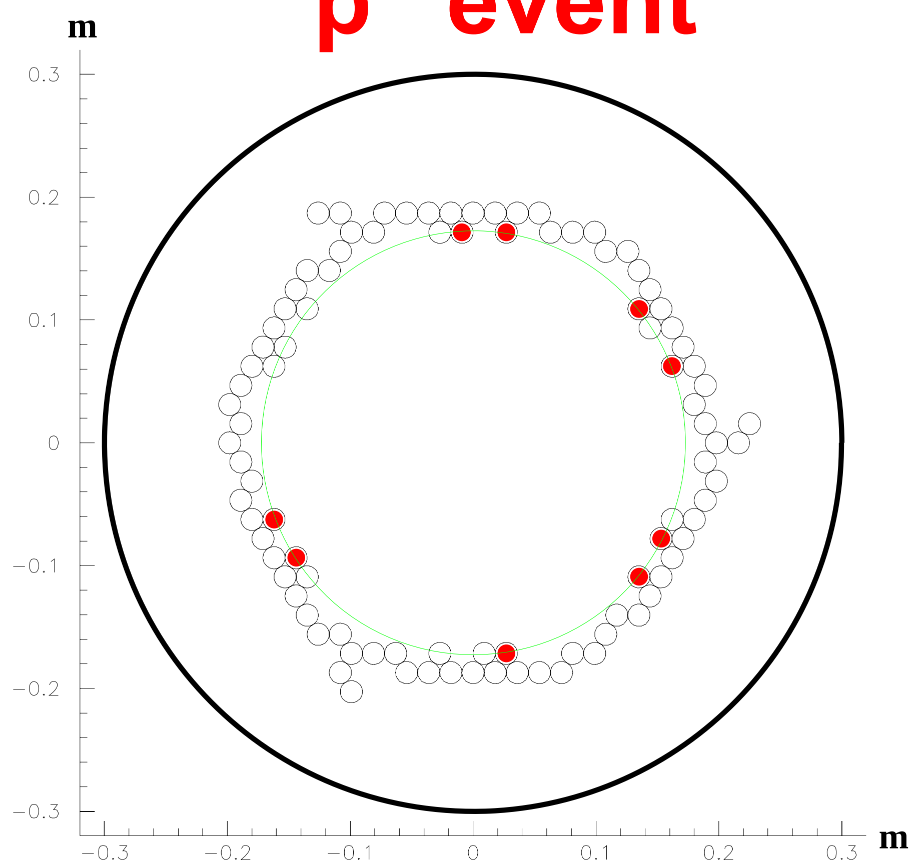
Spare Slides

- **400 GeV/c p on T4 → 200 GeV/c negative beam (Δp/p≈1.8%, 30 μrad)**
- **At production: 94.3% π, 4.9% K, 0.7%p**
- **After 910 m: 96.2% π, 3.0% K, 0.8% p**

“π” event



“$\bar{p}$” event



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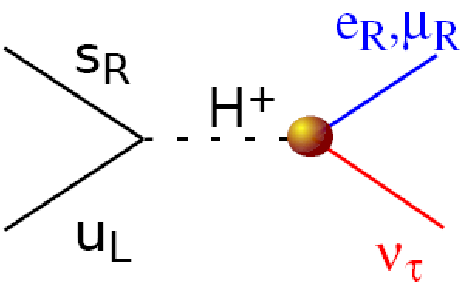

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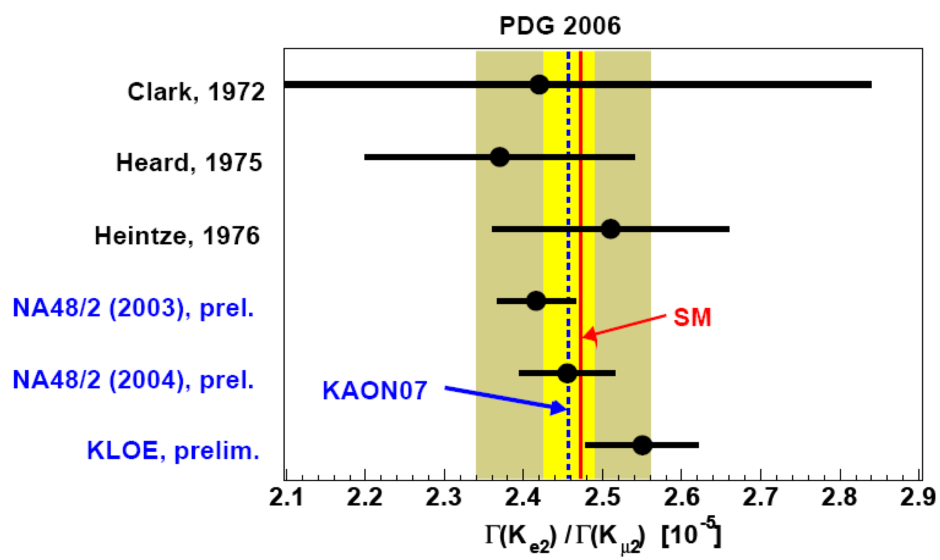

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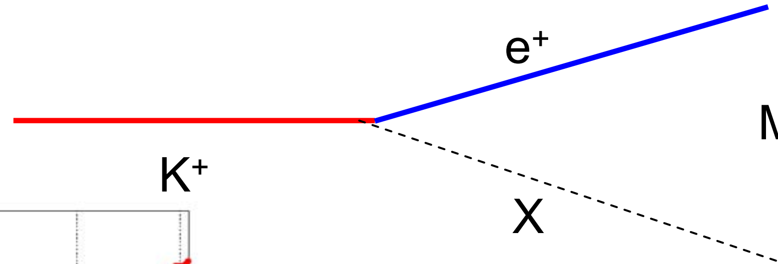

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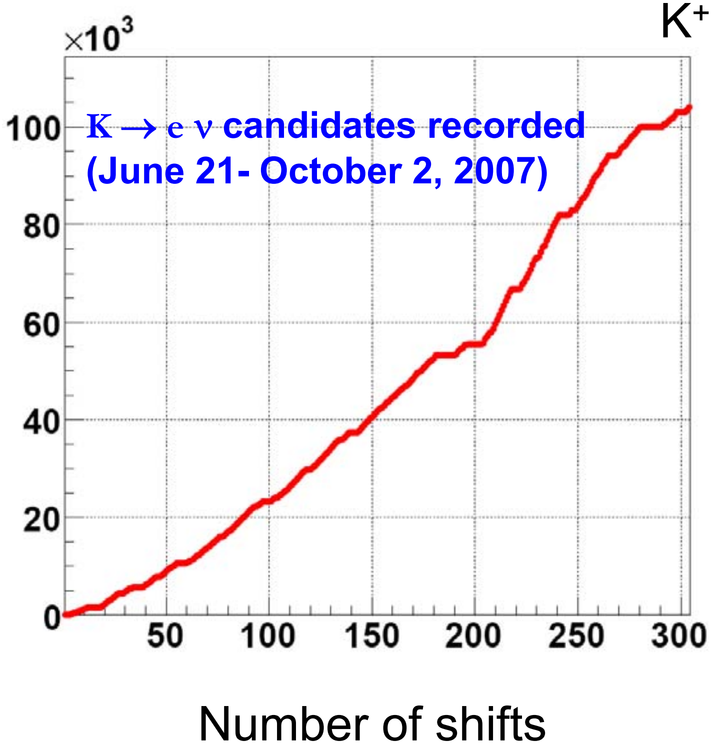
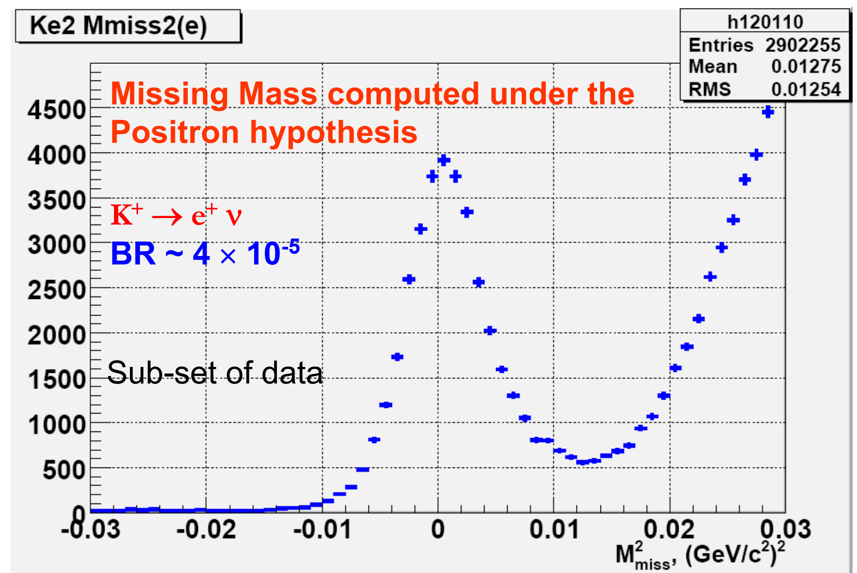




NA62 has accumulated more than 100 k $K \rightarrow e\,\nu$ events in **2007** to push the error on R_K from ~2% to ~0.3%

ε': CP-Violation in $K^0 \to 2\pi$ decays

$$\left.\begin{matrix}(\pi^+\pi^-)\\(\pi^0\pi^0)\end{matrix}\right\} CP = +1$$

Subtle differences between K_L and K_s decays to 2π due to different contributions from isospin I=0 and 2.

INDIRECT CPV

DIRECT CPV

$$\frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

$$\frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$$

$$\langle 2\pi | K_L \rangle = \varepsilon \langle 2\pi | K_1 \rangle + \langle 2\pi | K_2 \rangle$$

In consequence…

If $\varepsilon' \neq 0$ particle and antiparticle decay rates differ:

$$\frac{\Gamma\left(K^0 \to \pi^+\pi^-\right) - \Gamma\left(\overline{K^0} \to \pi^+\pi^-\right)}{\Gamma\left(K^0 \to \pi^+\pi^-\right) + \Gamma\left(\overline{K^0} \to \pi^+\pi^-\right)} = 2\mathrm{Re}(\varepsilon')$$

Compare NA48/2 Statistics with the original Dalitz plot!

Decay of τ Mesons of Known Charge*†

R. H. DALITZ‡
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
(Received February 9, 1954)

The experimental data on the 3π decay of τ mesons is summarized on a convenient two-dimensional plot, both (a) when the π-meson charges are known and (b) when they are not. Some events may be included in plot (a) only if the parent τ meson is assumed positive and arguments supporting this identification for τ mesons decaying in an emulsion are discussed. The dependence of this plot on the τ-meson spin (j) and parity (w) is discussed in general terms and those features depending particularly on w and on its relation with j are emphasized—for example, if the density of events does not vanish at the bottom of the plot, the τ meson must have odd parity and even spin. Simple estimates of the distribution, using only the lowest allowable angular momenta and a "short range" approximation, may be modified by final-state meson-meson attractions, whose effects are discussed qualitatively. The available data are insufficient for any strong conclusion to be drawn but rather suggest even spin and odd parity for the τ meson; the need for careful assessment of geometrical bias in the selection of experimental material is stressed.

$\theta^+ \rightarrow \pi^+\pi^0$ **even parity**

Same particle??

$\tau^+ \rightarrow \pi^+\pi^+\pi^-$ **odd parity**

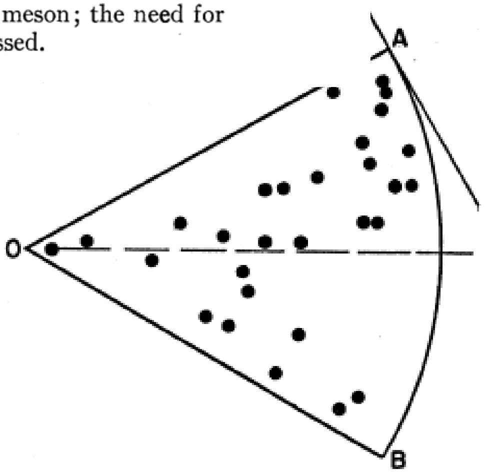
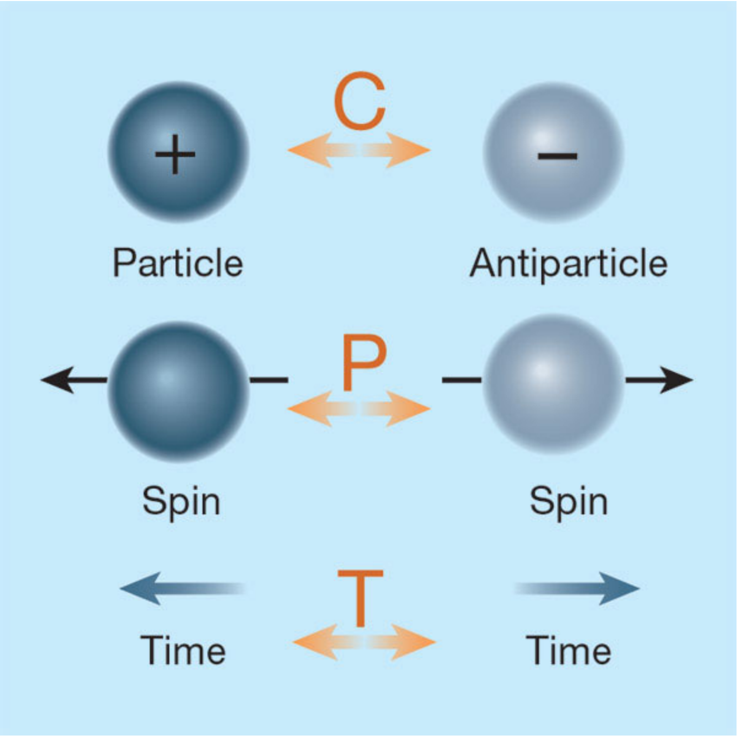
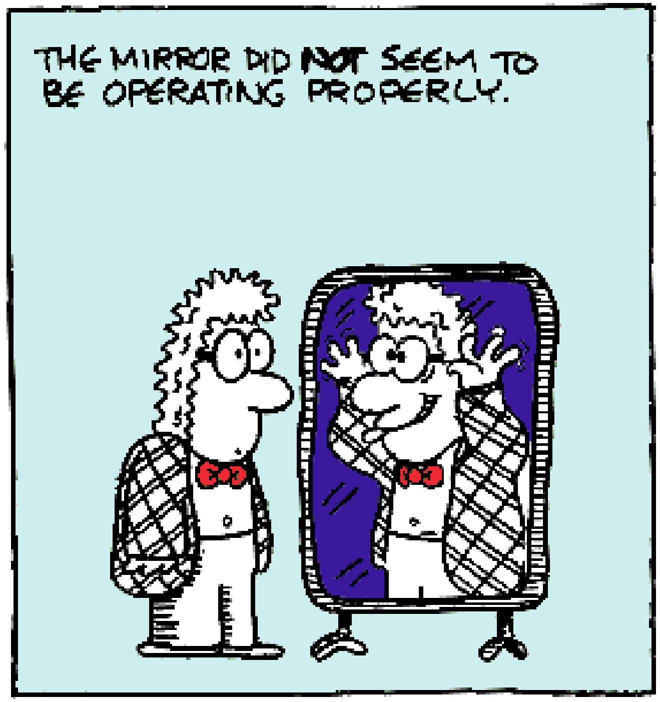


FIG. 4. The data on twenty-nine τ-meson decay events.

Discrete Symmetries



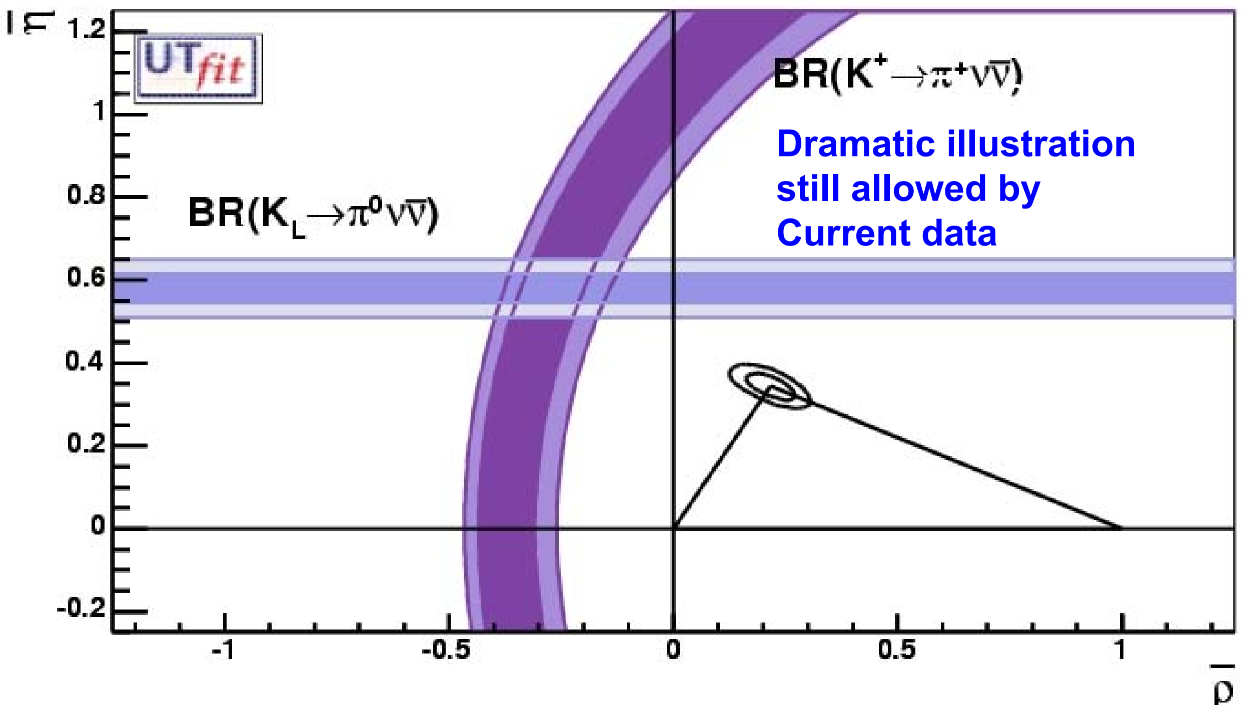


L. Landau, 1957: "Has is well known, the unusual properties of K-mesons have created a perplexing situation in modern physics….Invariance of the interactions with respect to **combined inversion (CP)** leaves space completely symmetrical….

$K \to \pi \nu\nu$ decays

E787/E949: $BR(K^+ \to \pi^+ \nu\nu) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$

E391a: $BR(K^0_L \to \pi^0 \nu\nu) < 2.1 \times 10^{-7}$ @90%CL



The uncertainty of the SM prediction is mostly due to uncertainty of the CKM parameters and not to hadronic matrix elements:

- $BR(K^+\to\pi^+\nu\nu) \approx (1.6\times10^{-5})|V_{cb}|^4[\sigma\eta^2+(\rho_c-\rho)^2] \to (8.0 \pm 1.1)\times10^{-11}$
- $BR(K_L\to\pi^0\nu\nu) \approx (7.6\times10^{-5})|V_{cb}|^4\eta^2 \to (3.0 \pm 0.6)\times10^{-11}$

Time resolution per event: 75 ps