Kaon Physics Review

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Flavianet School

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Content of the Lectures

1. **Building the Standard Model (SM) with strange particles**
   - Introduction
   - CP-Violation
2. **Probing the SM and looking for New Physics**
   - Ultra Rare Decays
3. **Precision tests of Weak Interaction Universality**
   - Leptonic Decays
   - Semileptonic Decays
4. **Precision tests of the Strong Interaction**
   - pi –pi scattering
   - Radiative Decays

Kaon Mesons

Particle	Mass (MeV)		Lifetime (ns)		$c\tau$ (cm)	$c\tau$ @E=100 GeV
K^+	493.677	0.016	12.380	0.021	371	750 m
K^0	497.614	0.024				
K^0_L			51.7	0.4	1551	3.1 Km
K^0_S			0.08958		2.68	5.4 m

Main Decay Modes

K^+

$\mu^+\nu$	63 %	
$\pi^+\pi^0$	21 %	
$\pi^+\pi^+\pi^-$	6 %	
$\pi^+\pi^0\pi^0$	2 %	
$\pi^0\mu^+\nu$	3 %	(called $K^+_{\mu 3}$)
$\pi^0 e^+\nu$	5 %	(called K^+_{e3})

K^0_S

$\pi^+\pi^-$	69 %
$\pi^0\pi^0$	31 %

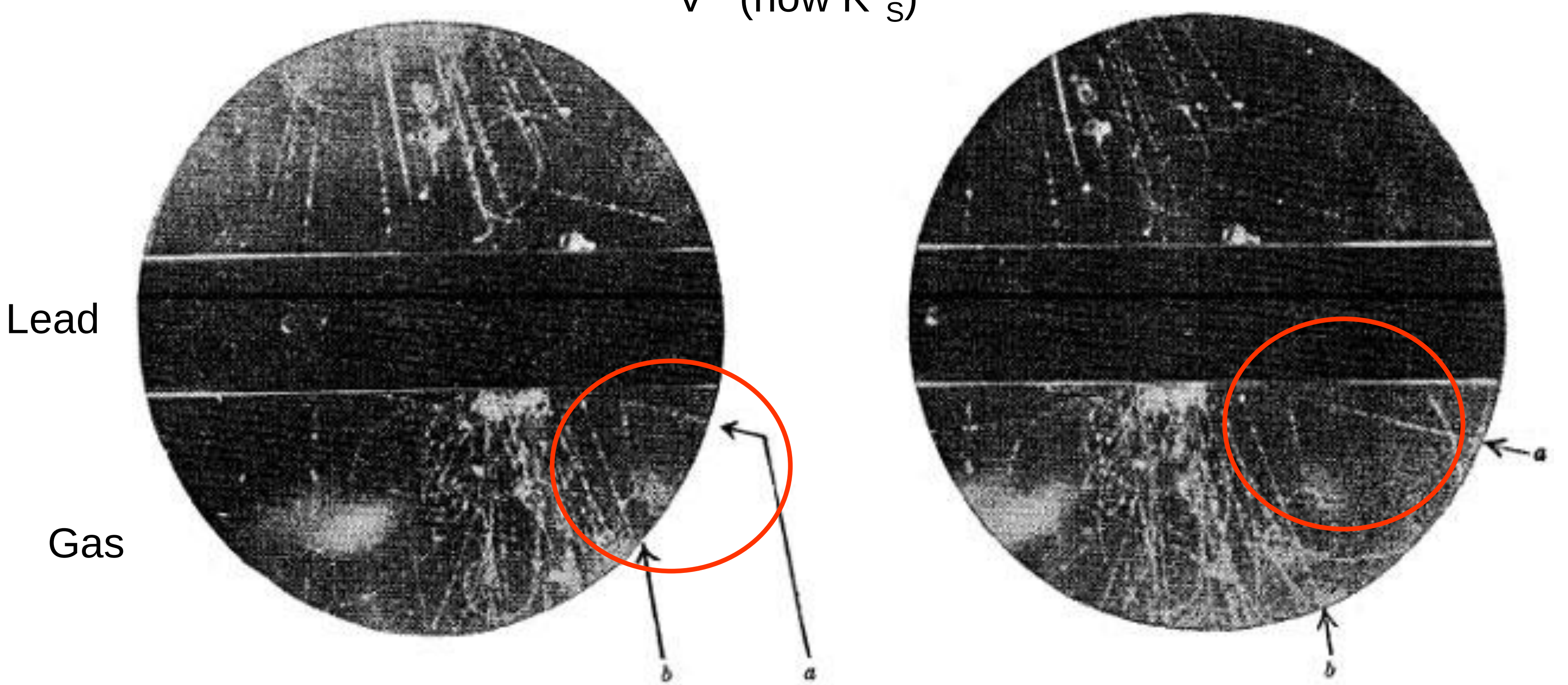
K^0_L

$\pi^0\pi^0\pi^0$	19.5%	
$\pi^+\pi^-\pi^0$	13%	
$\pi\mu\nu$	27%	(called $K^0_{\mu 3}$)
$\pi e\nu$	40.5 %	(called K^0_{e3})

$$I(J^P)=1/2(0^-)$$

Discovery of the Kaon

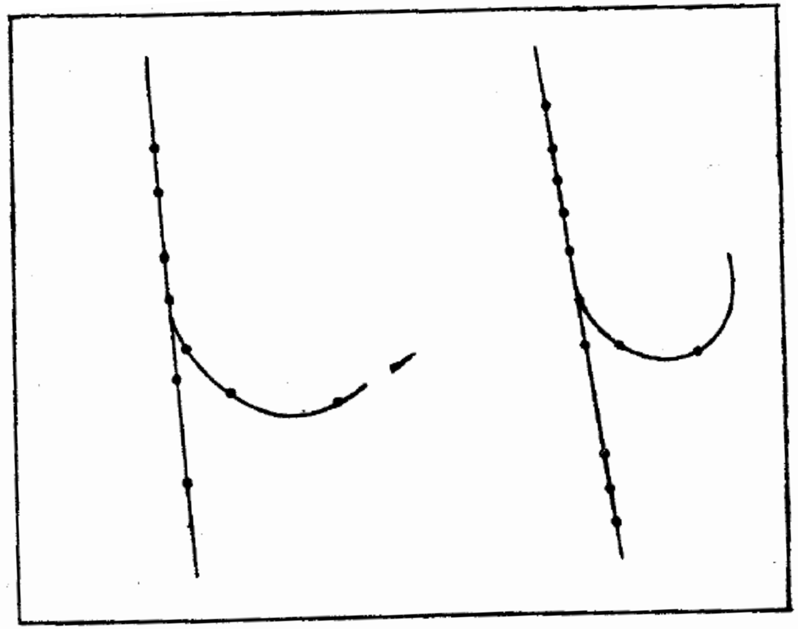
V^0 (now K^0_S)



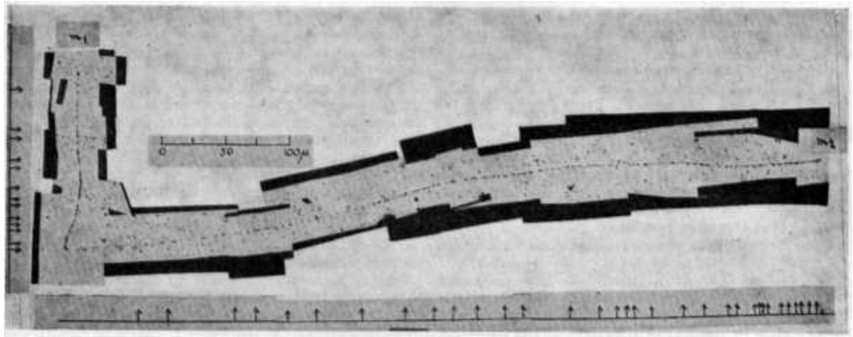
Rochester & Butler, 1947 in a cloud chamber exposed to **cosmic rays**

" Forked tracks of a very striking character "

Historical Interlude



Dessin stéréoscopique de la collision.

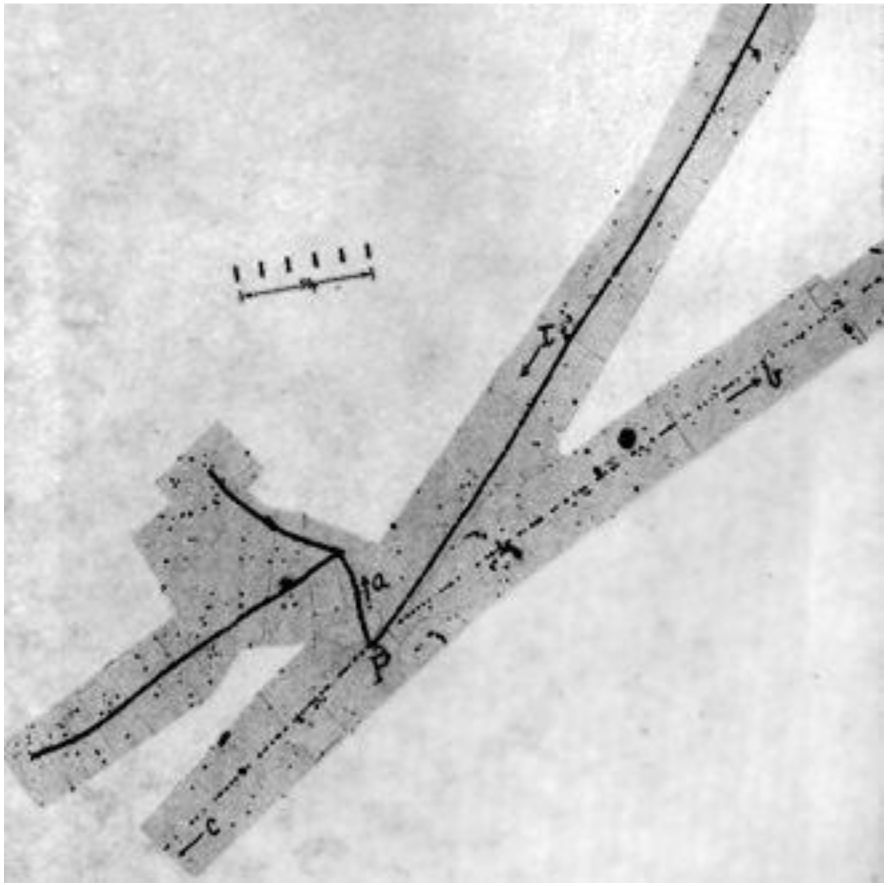


Pion decay in nuclear emulsion
Lattes, Occhialini, Powell, 1947

Leprince-Ringuet and L'Héritiere, Wilson Chamber, 1943
Scattering of a positively charged particle on an atomic electron. If the scattering is assumed to be **elastic**, the implied mass of the particle is **990 m_e ~ 500 MeV!**

- **With hindsight, it looks as though the kaon was discovered even before the pion!**

Discovery of the τ^+ (now K^+)$\rightarrow\pi^+\pi^+\pi^-$



Old Name	New Name
τ	$K_{\pi3}$: $K^+\rightarrow\pi^+\pi^+\pi^-$
V_1^0	$\Lambda^0\rightarrow p\pi^-$
V_2^0 (θ^0)	$K^0_S\rightarrow\pi^+\pi^-$
κ	$K_{\mu2}$: $K^+\rightarrow\mu^+\nu$
	$K_{\mu3}$: $K^+\rightarrow\mu^+\pi^0\nu$
χ (θ^+)	$K_{\pi2}$: $K^+\rightarrow\pi^+\pi^0$
V^+, Λ^+	$\Sigma^+\rightarrow p\pi^0$, $n\pi^+$

"Stripped" emulsion technique, Bristol group, 1949

Dalitz and the θ/τ paradox

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**

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

How can θ and τ be the same particle???

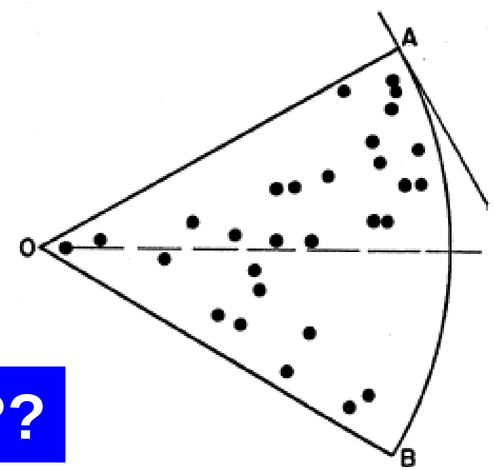
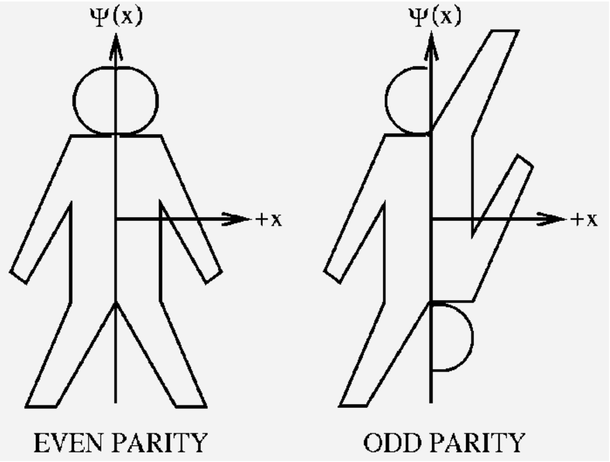


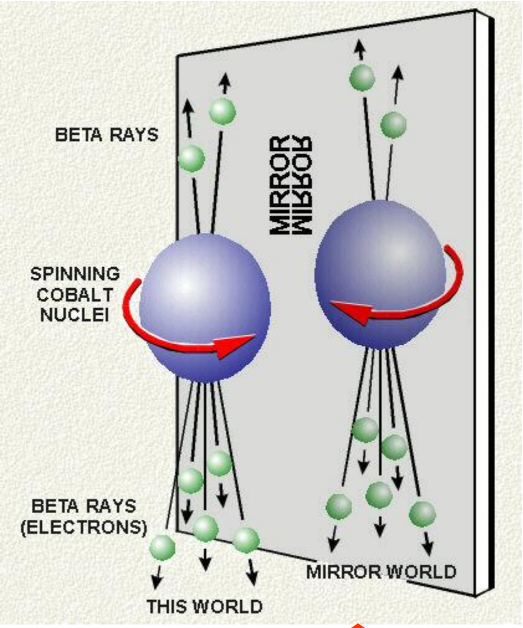
FIG. 4. The data on twenty-nine τ-meson decay events.

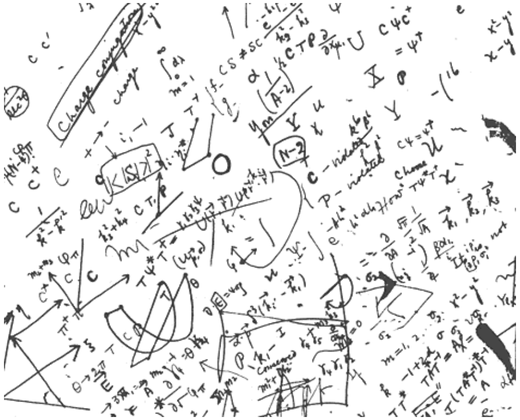
Parity Violation

T. D. Lee

C. N. Yang

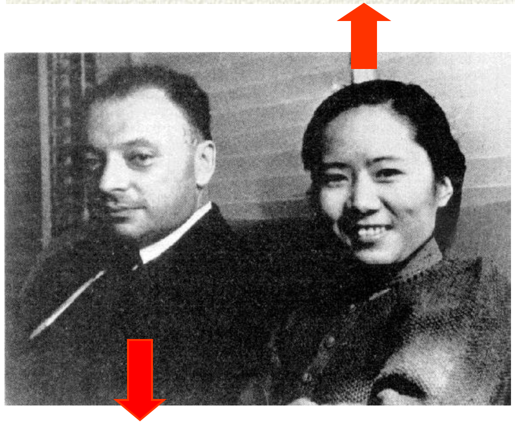






Allegedly "original" doodle which led to the P non-conservation conjecture

The paradox was resolved when experiments (C.S. Wu et al. 1957) carried out according to C.N. Yang and T.D. Lee's theoretical calculations (1956) indeed indicate that parity is not conserved in weak interactions



"God is a little left-handed"

Associated Production

Fowler et al. 1954
Data from the Cosmotron

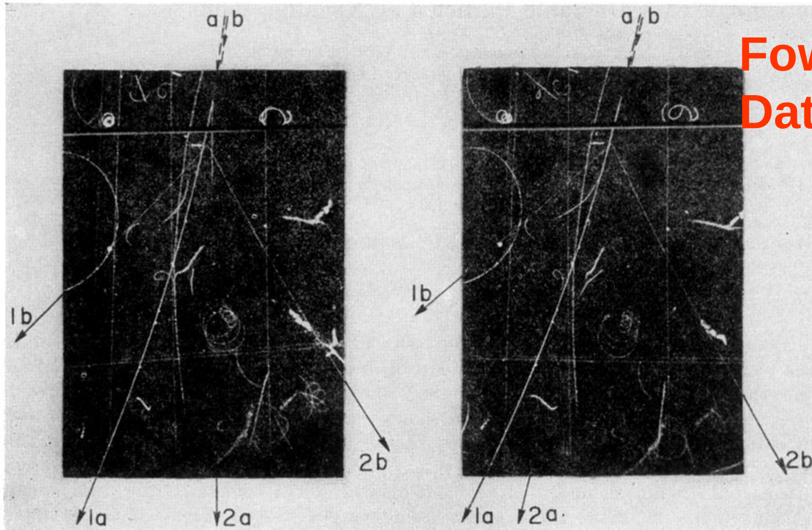


FIG. 1. Case C. Diffusion cloud-chamber photograph of two neutral V particles (a) and (b), whose lines of flight are almost colinear. (a) is believed to be a Λ^0 decaying into a proton (1a) and a negative π meson (2a). Tracks 1*a* and 2*a* practically coincide in the right view. (b) is probably a ϑ^0 decaying into π^+ (1b) and π^- (2b).

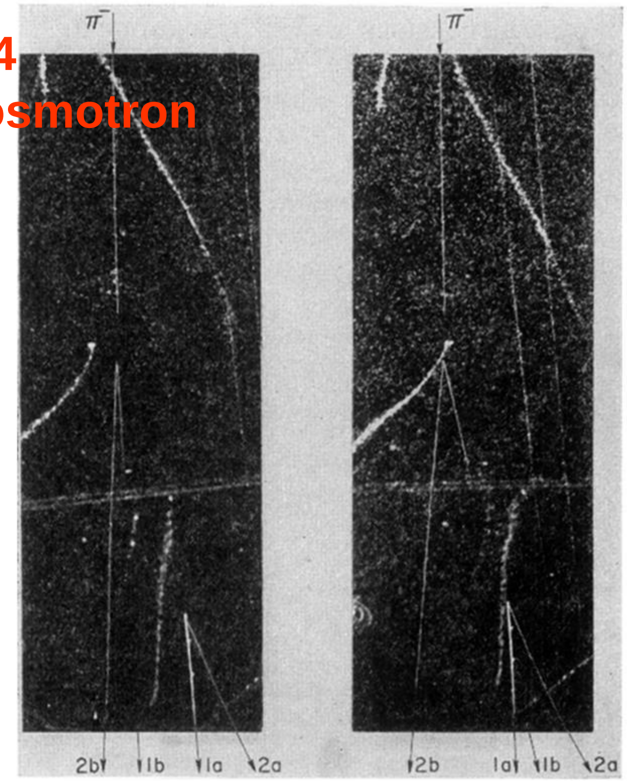
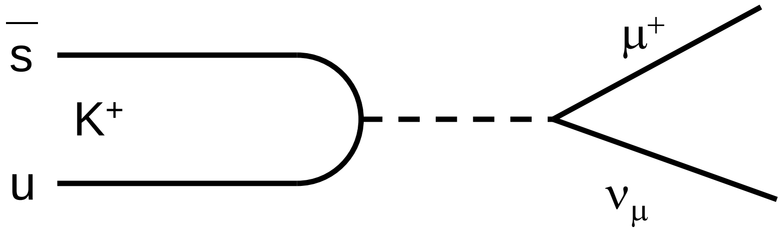


FIG. 2. Case D. Photograph of a 1.5-Bev π^- producing two neutral V particles in a collision with a proton. Tracks 1a and 2a, believed to be proton and π^-, respectively, are the decay products of a Λ^0. A ϑ^0 is probably seen to decay into π^+ (1b) and π^- (2b). Because of the rather "foggy" quality of this picture tracks 1b, 2a, and 2b have been retouched for better reproduction.

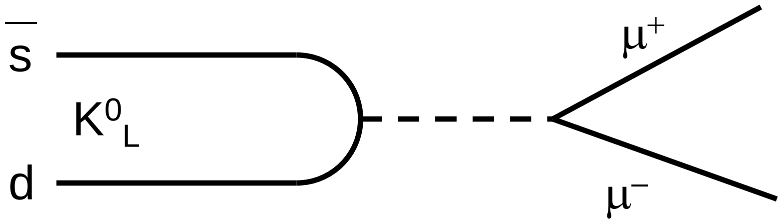
- **The new particles were copiously produced in association by the strong interaction. Their lifetime should have been ten order of magnitude shorter if the decay was mediated by the strong interaction**
- **Gell-Mann & Pais: the new unstable particles possess a new quantum number "strangeness" conserved in strong interactions**

Absence of $\Delta S=1$ neutral currents

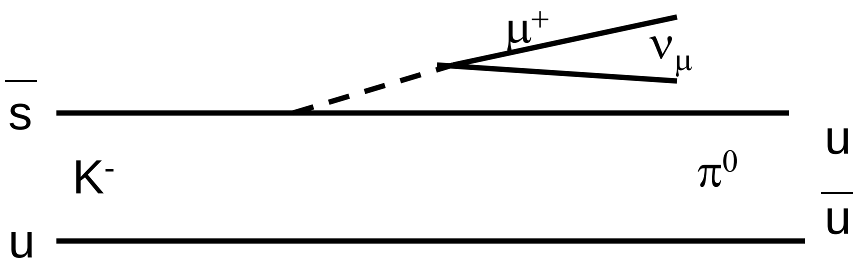


BR($K^+ \to \mu^+\nu$)~63%

??

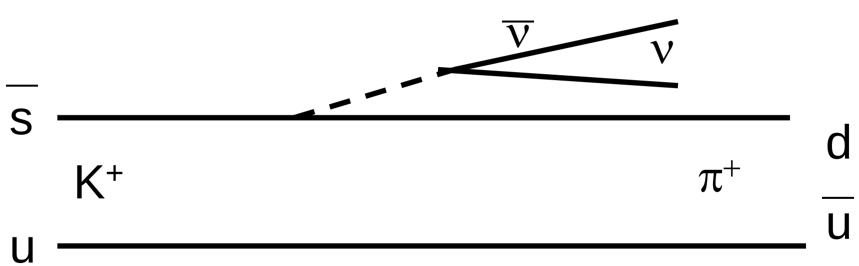


BR($K^0_L \to \mu^+\mu^-$) < 2.1×10^{-7}
(M. Foeth, M. Holder et al.,1969)



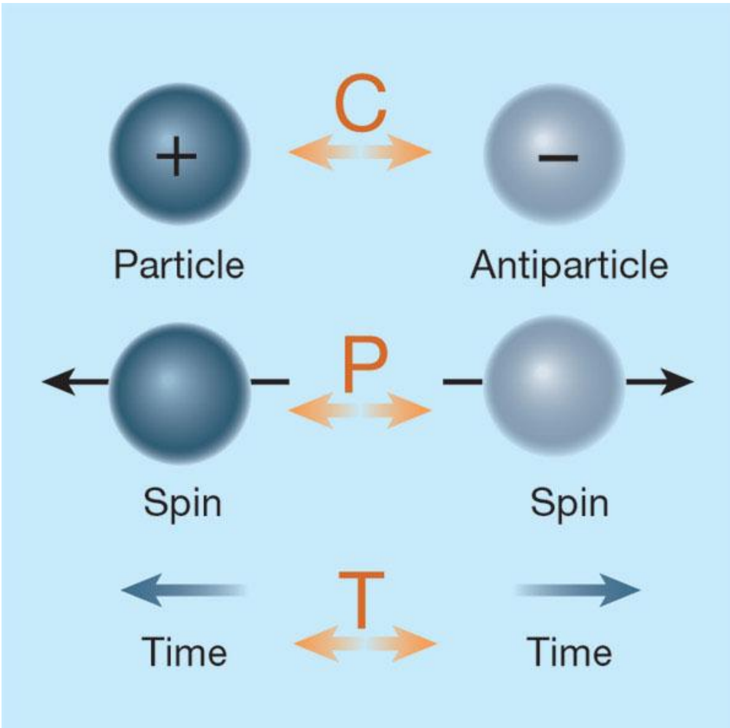
BR($K^+ \to \pi^0\mu^+\nu$)~3%

??



BR($K^+ \to \pi^+\nu\nu$) < 1.2×10^{-6} (1970)

More on Discrete Symmetries



L. Landau, 1957: "As 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….

Properties of the K^0 system

- Symmetry for combined inversion (CP) leads to the prediction of two neutral kaons (Gell-Mann and Pais, 1955)

- Defined **CP**:

$$|K_1\rangle = \left(K^0 + \overline{K}^0\right)/\sqrt{2} \qquad \text{CP= +1}$$

$$|K_2\rangle = \left(K^0 - \overline{K}^0\right)/\sqrt{2} \qquad \text{CP= -1}$$

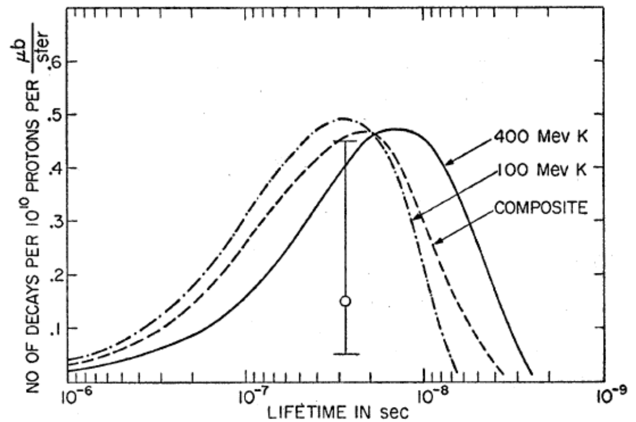
CP(2π)=+1 short-lived

$$\tau_S = 89\,\text{ps}$$

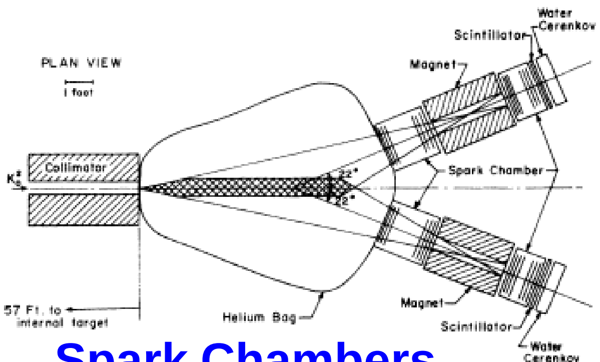
CP(3π)~-1 Long-lived

$$\tau_L = 52\,\text{ns}$$

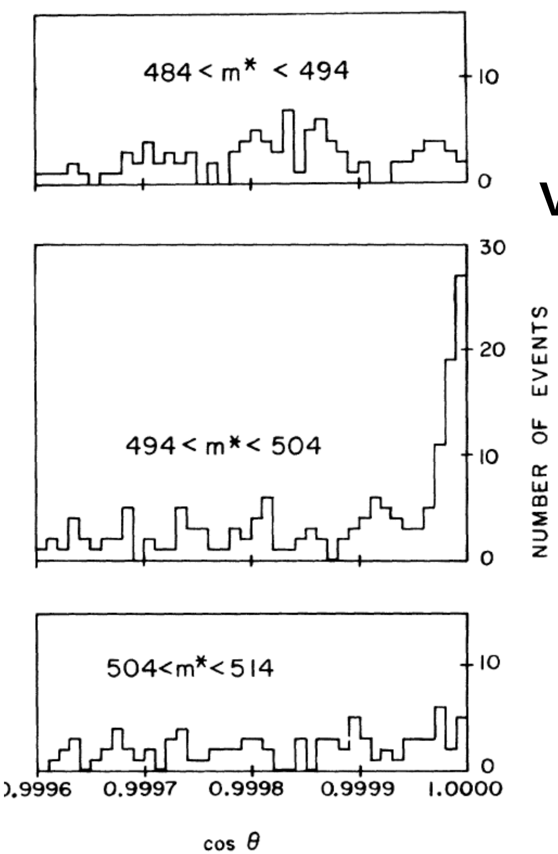
- The long-lived neutral kaon (K^0_L) was observed in a cloud chamber (Lande et al., 1956)



$K^0_L \to \pi^+\pi^- \quad \Rightarrow$ CP



Spark Chambers



V.L.Fitch R.Turlay J.W.Cronin J.H.Christenson

*Phys. Rev. Lett. 13 (**1964**) 138.*

$$\left|K_L^0\right\rangle = \frac{\varepsilon\left|K_1\right\rangle + \left|K_2\right\rangle}{\sqrt{1+\varepsilon^2}}$$

$$\left|K_S^0\right\rangle = \frac{\left|K_1\right\rangle + \varepsilon\left|K_2\right\rangle}{\sqrt{1+\varepsilon^2}}$$

$$|\varepsilon| = (2.229 \pm 0.010) \times 10^{-3}$$

CP Violation in Kaons

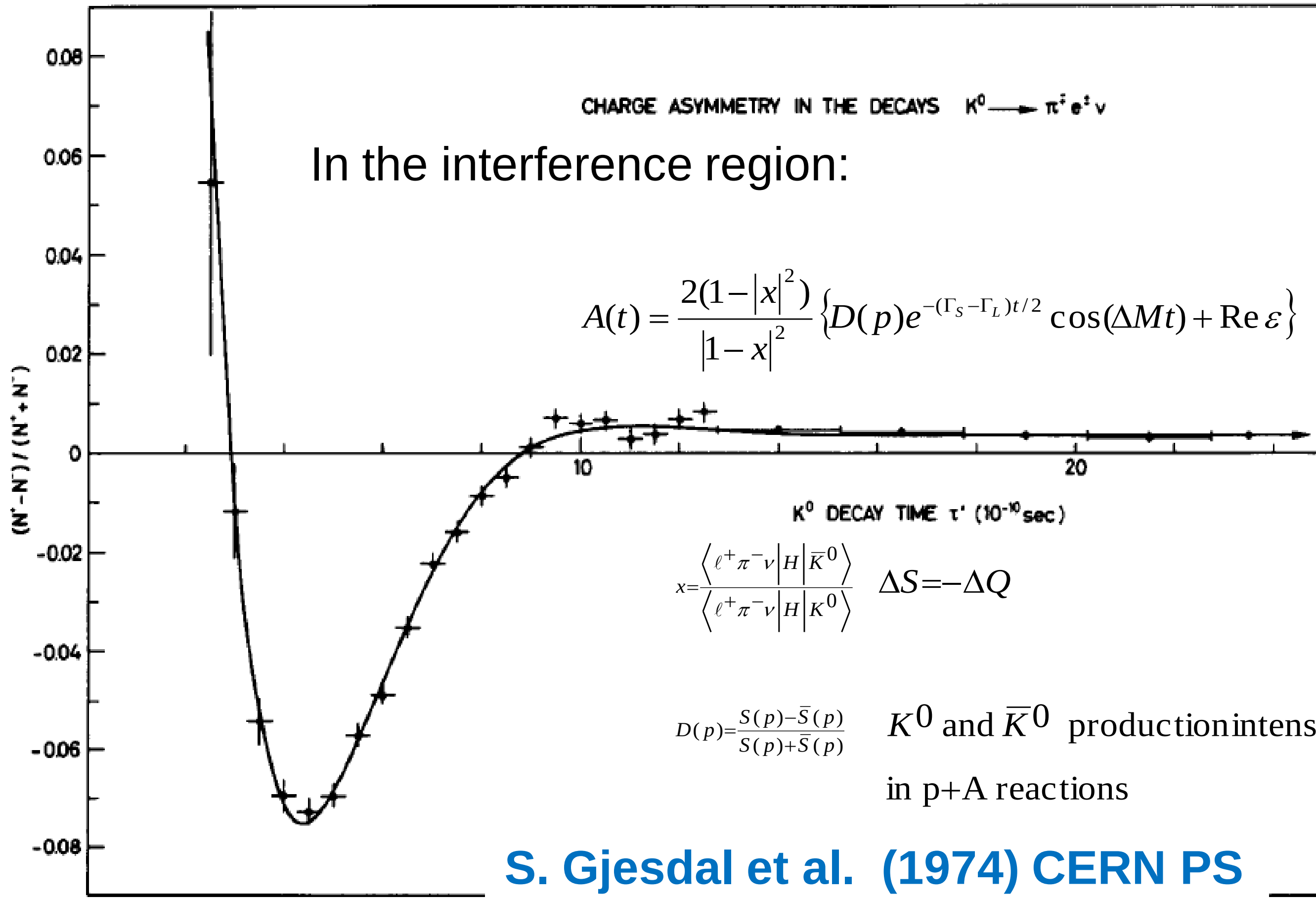
$$\eta_{00} \equiv \frac{\left\langle \pi^0\pi^0 \middle| H \middle| K_L^0 \right\rangle}{\left\langle \pi^0\pi^0 \middle| H \middle| K_S^0 \right\rangle} \qquad \eta_{+-} \equiv \frac{\left\langle \pi^+\pi^- \middle| H \middle| K_L^0 \right\rangle}{\left\langle \pi^+\pi^- \middle| H \middle| K_S^0 \right\rangle}$$

$$\eta_{00} \equiv \varepsilon - 2\varepsilon' \qquad \eta_{+-} \equiv \varepsilon + \varepsilon'$$

$$\delta_L = \frac{\Gamma(K_L^0 \to \ell^+\nu_\ell\pi^-) - \Gamma(K_L^0 \to \ell^-\nu_\ell\pi^+)}{\Gamma(K_L^0 \to \ell^+\nu_\ell\pi^-) + \Gamma(K_L^0 \to \ell^-\nu_\ell\pi^+)} = \frac{2\,\mathrm{Re}(\varepsilon)}{1+\varepsilon^2}$$

$$\mathrm{Re}\,\frac{\varepsilon'}{\varepsilon} = \frac{1}{6}\left(1 - \frac{\left|\eta_{00}\right|^2}{\left|\eta_{+-}\right|^2}\right) = \frac{1}{6}\left(1 - \frac{\Gamma(K_L^0 \to \pi^0\pi^0)}{\Gamma(K_S^0 \to \pi^0\pi^0)} \times \frac{\Gamma(K_S^0 \to \pi^+\pi^-)}{\Gamma(K_L^0 \to \pi^+\pi^-)}\right)$$

Charge Asymmetry



In the interference region:

$$A(t) = \frac{2(1-|x|^2)}{|1-x|^2}\left\{D(p)e^{-(\Gamma_S-\Gamma_L)t/2}\cos(\Delta M t) + \mathrm{Re}\,\varepsilon\right\}$$

$$x = \frac{\langle \ell^+\pi^-\nu|H|\bar{K}^0\rangle}{\langle \ell^+\pi^-\nu|H|K^0\rangle} \quad \Delta S = -\Delta Q$$

$$D(p) = \frac{S(p)-\bar{S}(p)}{S(p)+\bar{S}(p)}$$ K^0 and $\bar{K}^0$ production intensities in p+A reactions

S. Gjesdal et al. (1974) CERN PS

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

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

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**

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

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

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

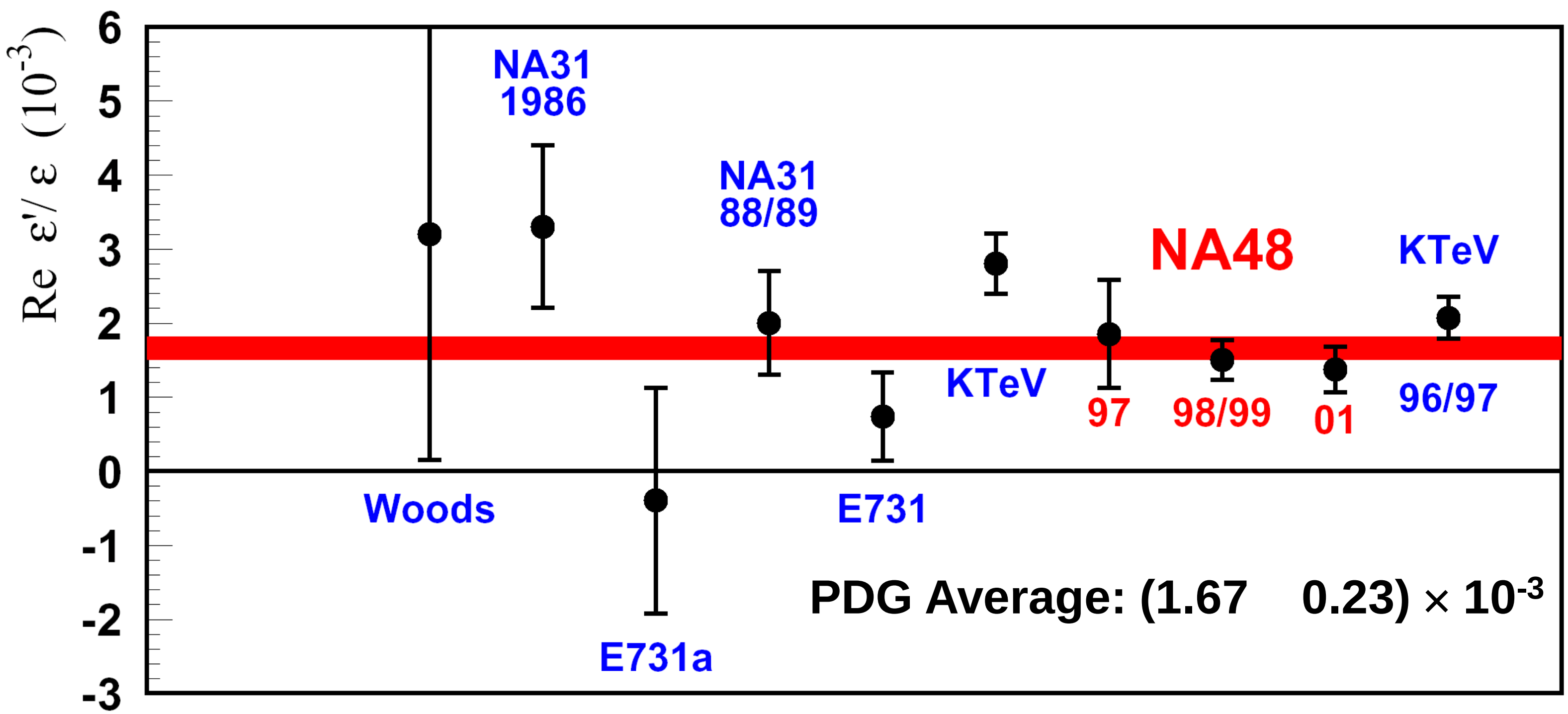
In consequence…

If ε' ≠0 particle and antiparticle decay rates differ:

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

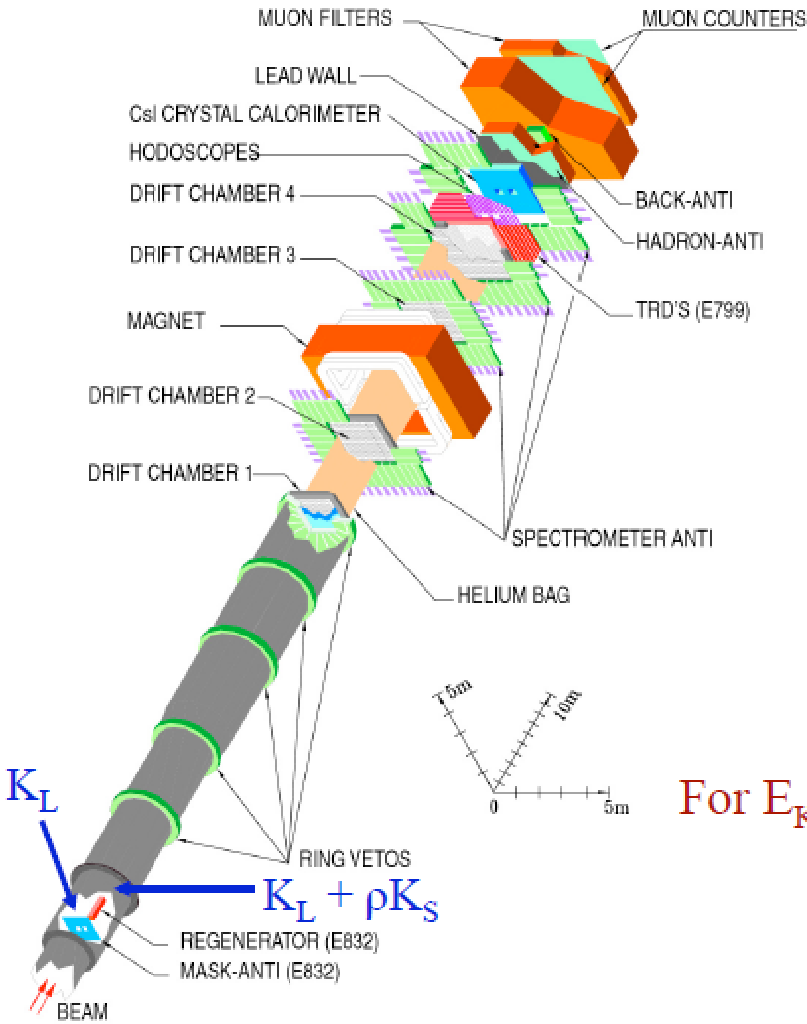
Re ε’/ε measurements versus time

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



…..In 2009 the full statistics result from KTeV became available→

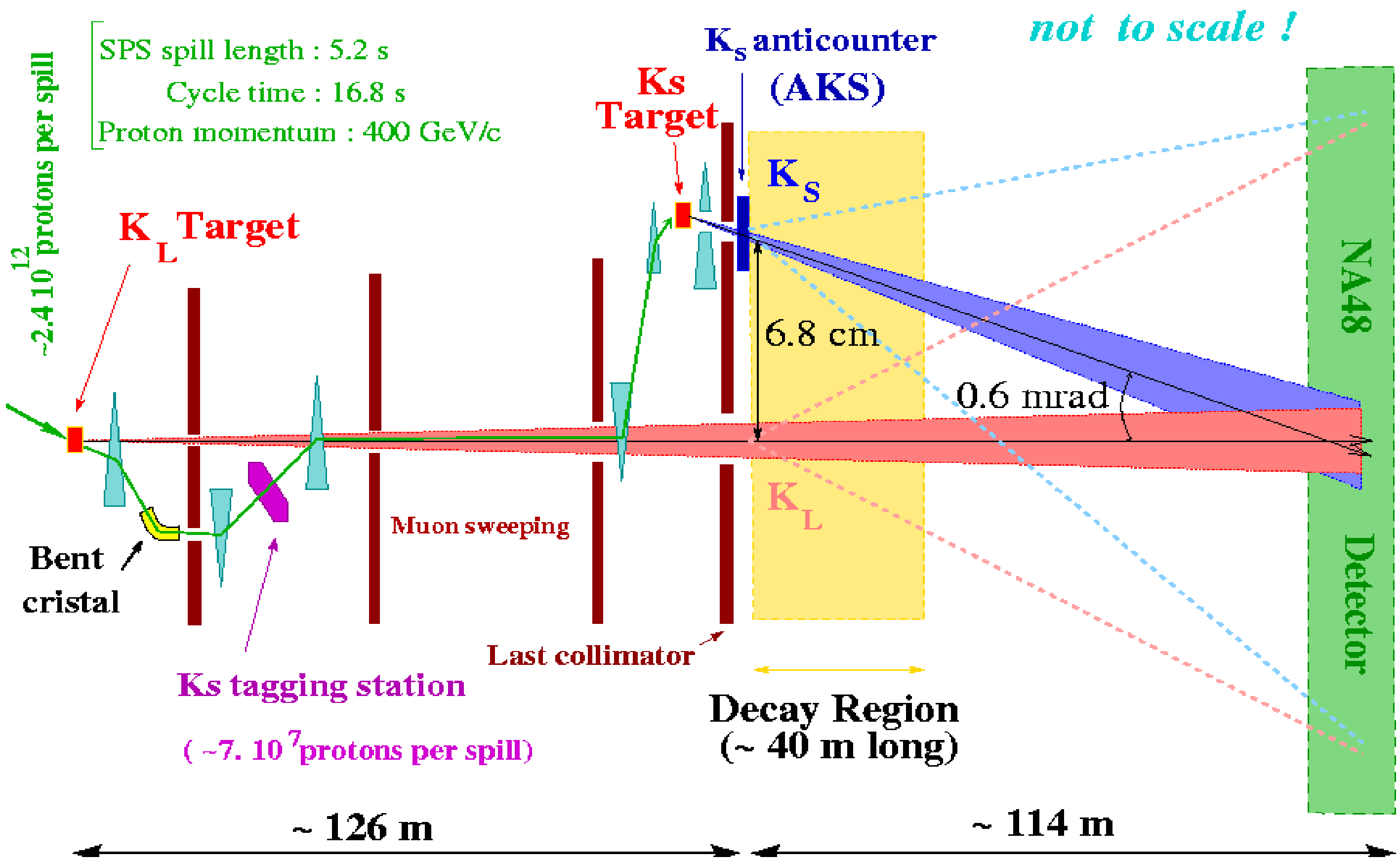
The KTeV Detector



- Charged particle momentum resolution < 1% for p>8 GeV/c; Momentum scale known to 0.01% from $K \to \pi^+\pi^-$
- CsI energy resolution < 1% for E_γ > 3 GeV; energy scale known to 0.05% from $K \to \pi e \nu$.

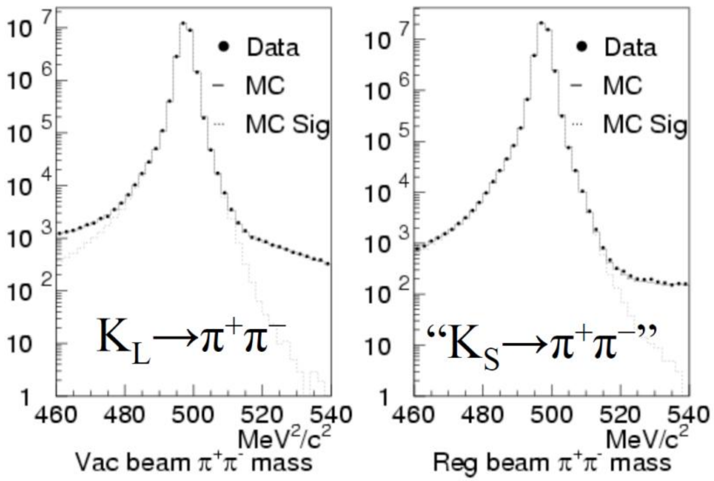
For $E_K \sim 70$ GeV, K_S: $\gamma\beta c\tau \sim 3.5$m
K_L: $\gamma\beta c\tau \sim 2.2$ km

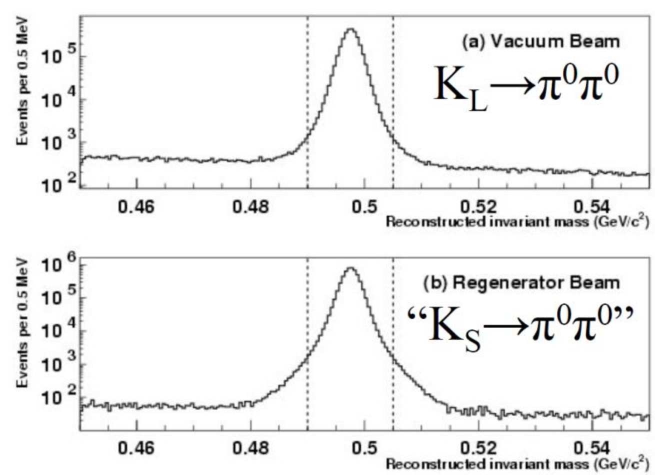
NA48 Simultaneous K_L and K_S beams



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

KTeV Mass plots (full statistics)

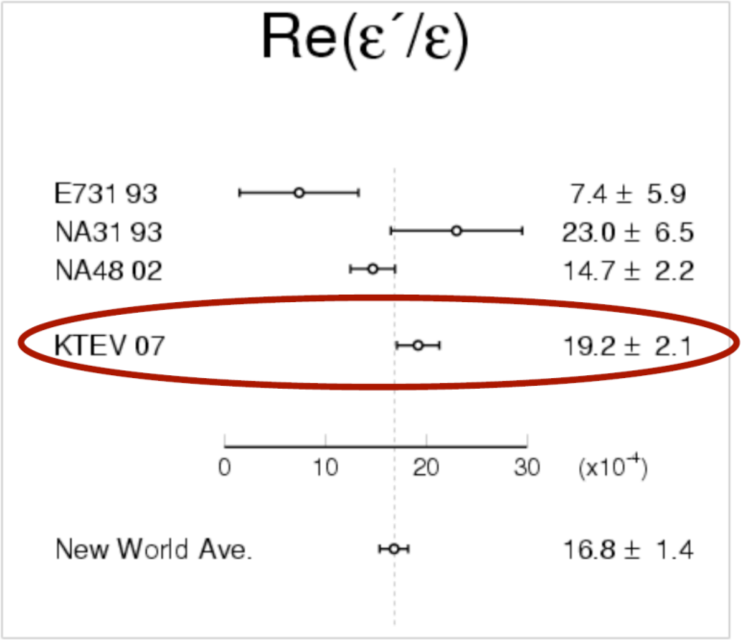




Mass resolution is ~1.5 MeV/c^2
for both decay modes.

KTeV Final (2009)

KTeV Result: $\mathrm{Re}(\varepsilon'/\varepsilon) = [19.2 \pm 1.1(\mathrm{stat}) \pm 1.8(\mathrm{syst})] \times 10^{-4}$
$= (19.2 \pm 2.1) \times 10^{-4}$



World average:
$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.8 \pm 1.4) \times 10^{-4}$
(confidence level = 13%)

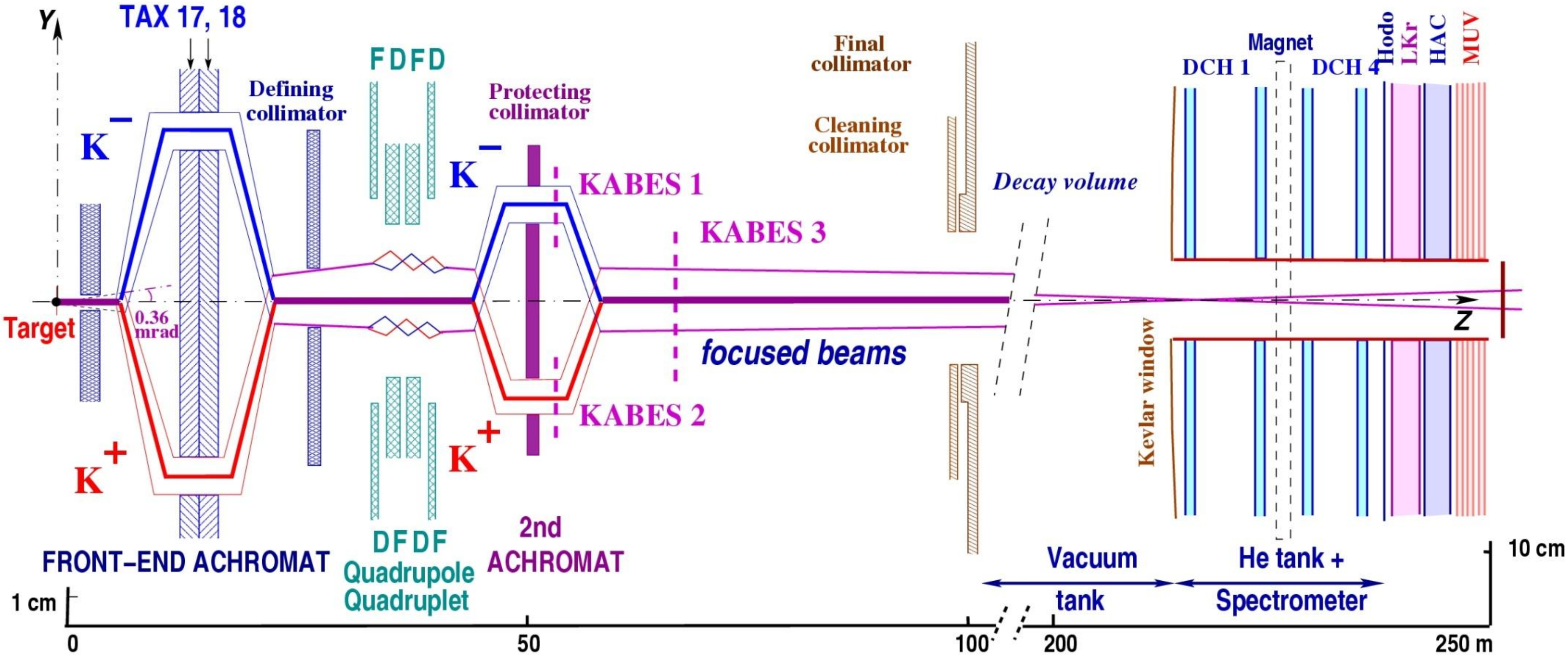
(KTeV 2003: $\mathrm{Re}(\varepsilon'/\varepsilon) = [20.7 \pm 1.5(\mathrm{stat}) \pm 2.4\ (\mathrm{syst})] \times 10^{-4}$)

NA48/2: Search for CP-Violation in Charged Kaon Decays

–Simultaneous K^+ and K^- beams,

–Superimposed in space,

–Momentum bite (60±3) GeV/c



NA48/2: Improved Limits on Direct CP-Violation in K $\rightarrow 3\pi$

$A^c_g = (-1.5 \quad 2.2\,) \times 10^{-4}$

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

2.0 x 10^9 K^+

1.1 x 10^9 K^-

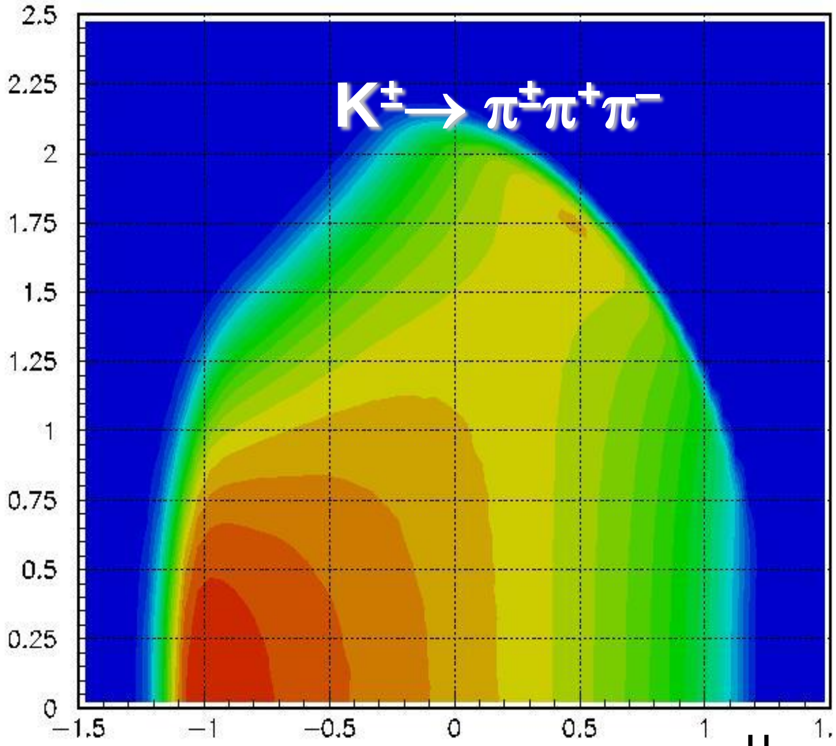
Eur.Phys.J.C52:875-891,2007

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

5.9 x 10^7 K^+

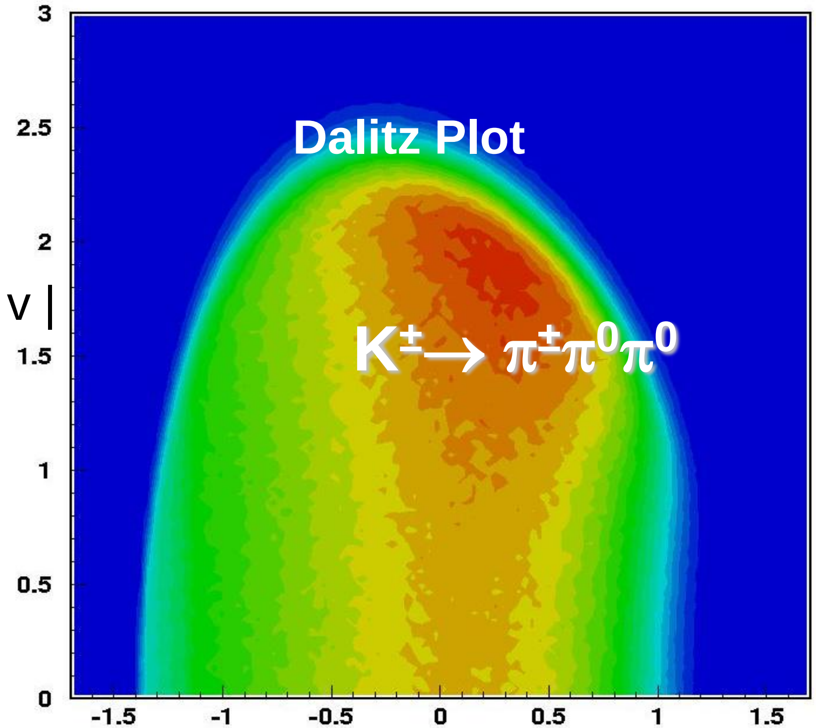
3.2 x 10^7 K^-

| v |



u

| v |



u

$$u = \frac{s_3 - s_0}{m_\pi^2}, \quad v = \frac{s_2 - s_1}{m_\pi^2}, \quad s_i = (P_K - P_i)^2,\ i = 1,2,3; \quad s_0 = \frac{s_1 + s_2 + s_3}{3}$$

Models 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)

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

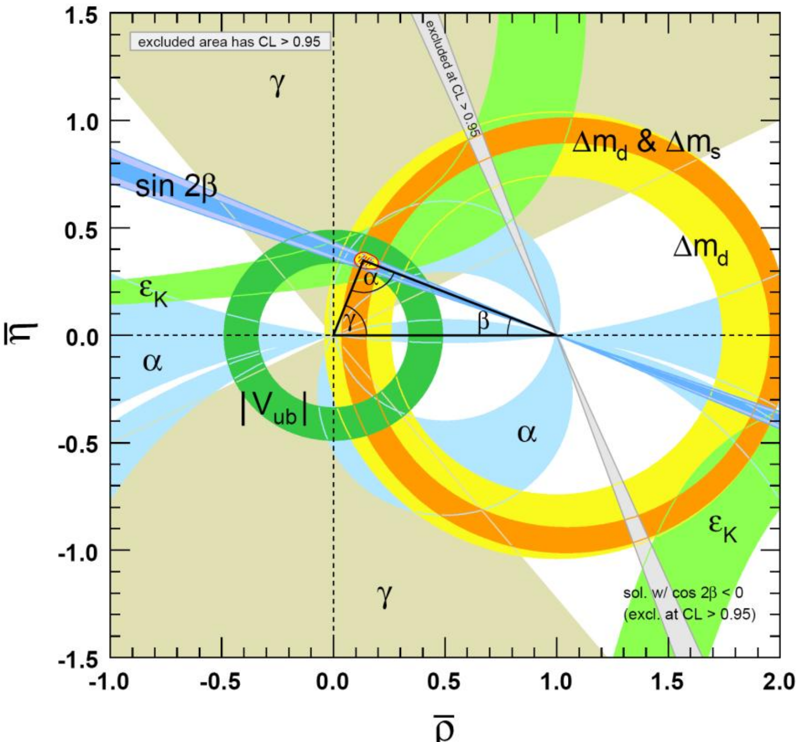
$N_g=3 \quad N_{phase}=1 \Rightarrow$ CP-Violation Possible

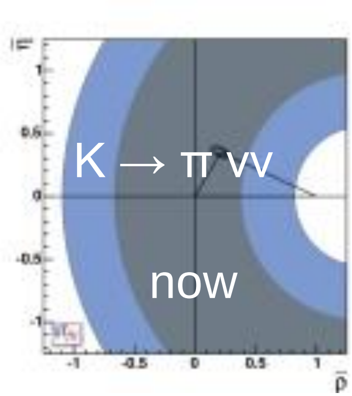
  - When proposed, not even the charmed quark had yet been discovered!!
  - Important experimental implications:
    - Three families of quarks
    - A second Manifestation of CP-Violation in Kaon decays: $\varepsilon' \neq 0$
    - CP-Violation observable in other systems (B mesons)

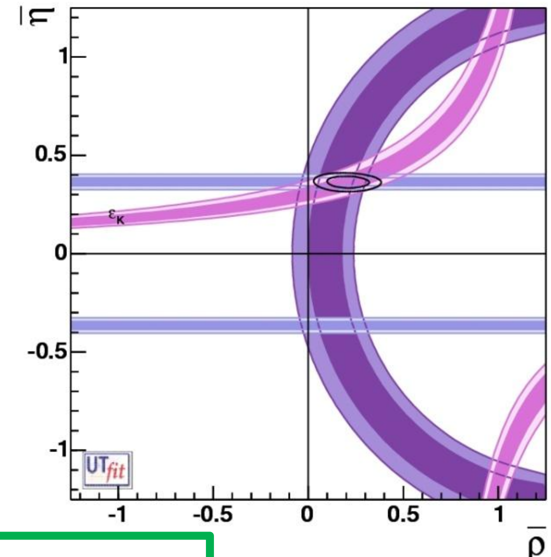
All experimental manifestations of CP-Violation (K and B decays and mixing) are so far consistent with "just" one complex phase in the CKM matrix ("Standard Model")

Now we must look for patterns of deviation….

Kaons and Unitarity Triangle







$$BR(K_L^0 \to \pi^0 \nu\bar{\nu}) = \kappa_L \frac{\mathrm{Im}\left(V_{td}V_{ts}^*\right)^2 X^2(x_t)}{\lambda^{10}}$$

$$|\varepsilon_K| = C_\varepsilon B_K A^2 \lambda^6 \bar{\eta}\{-\eta_1 S_0(x_c)(1-\lambda^2/2) + \eta_3 S_0(x_c, x_t) + \eta_2 S_0(x_t) A^2 \lambda^4 (1-\bar{\rho})\}$$

$$(\sigma\bar{\eta})^2 + (\bar{\rho} - \bar{\rho}_0)^2 = \frac{\sigma\, BR(K^+ \to \pi^+ \nu\bar{\nu})}{\bar{\kappa}_+ |V_{cb}|^4 X^2(x_t)}$$

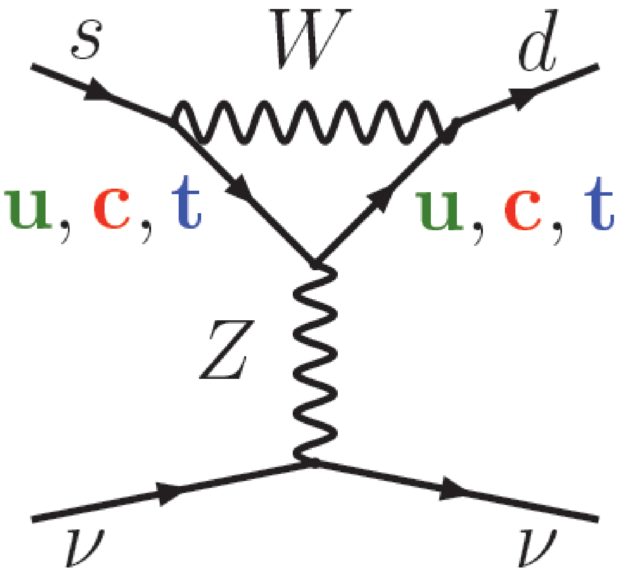
$$\bar{\kappa}_+ = r_{K^+} \frac{3\alpha^2 BR(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \Theta_W} = 7.5 \times 10^{-6}$$

$$\sigma = \left(1 - \frac{\lambda^2}{2}\right)^{-2}$$

$$\frac{\varepsilon'}{\varepsilon} = \mathrm{Im}\, V_{td} V_{ts}^* \times \left[P^{1/2} - \frac{1}{\omega} P^{3/2} \right]$$

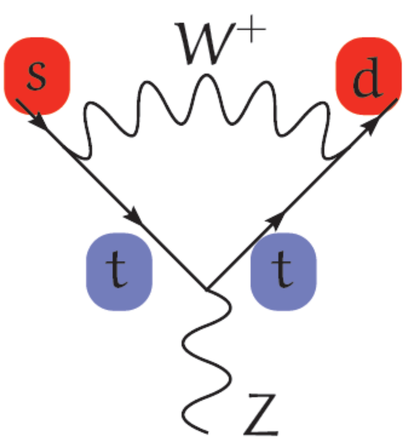
Ultra-rare K Decays

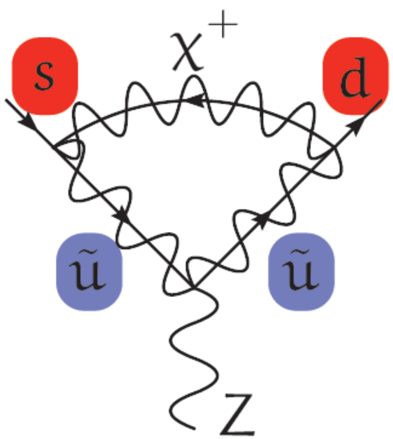
$$\boxed{K \to \pi\nu\bar{\nu}}$$



- The contribution to these processes due to the Standard Theory is strongly suppressed ($<10^{-10}$) and calculable with excellent precision (~%)

- They are very sensitive to possible contributions from New Physics





$K \to \pi \nu \bar{\nu}$: Current Status

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]
$K_L^0 \to \pi^0 \nu \bar{\nu}$	0.26 ± 0.04[3]	< 260 (90% CL)[4]

[1] J.Brod, M.Gorbahn, PRD78, arXiv:0805.4119
[2] AGS-E787/E949 PRL101, arXiv:0808.2459
[3] M. Gorbahn
[4] KEK-E391a arXiv:0911.4789v1

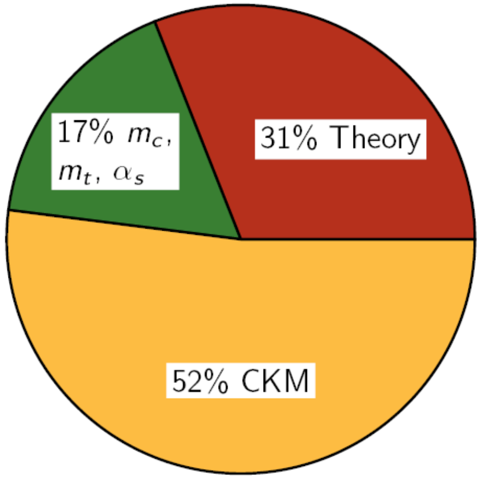
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Physics Motivation

In the Standard Model:

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

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

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

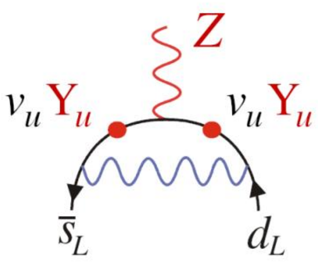


[J. Brod @ CKM'08]

Kaon Rare Decays and NP

Courtesy of C. Smith

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

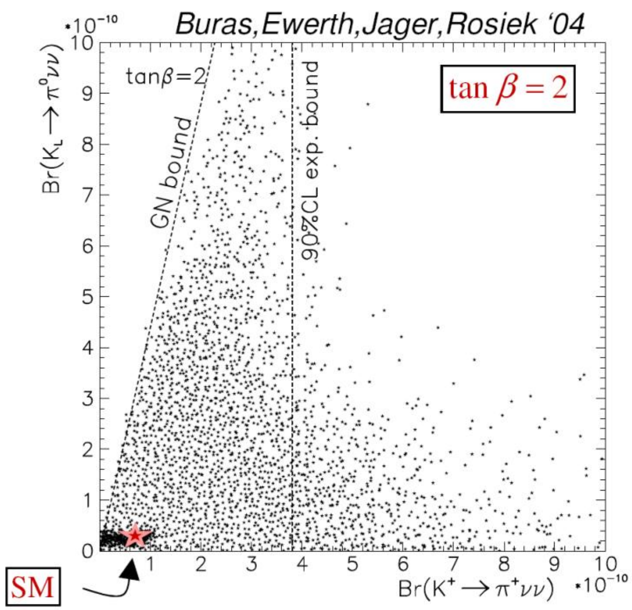


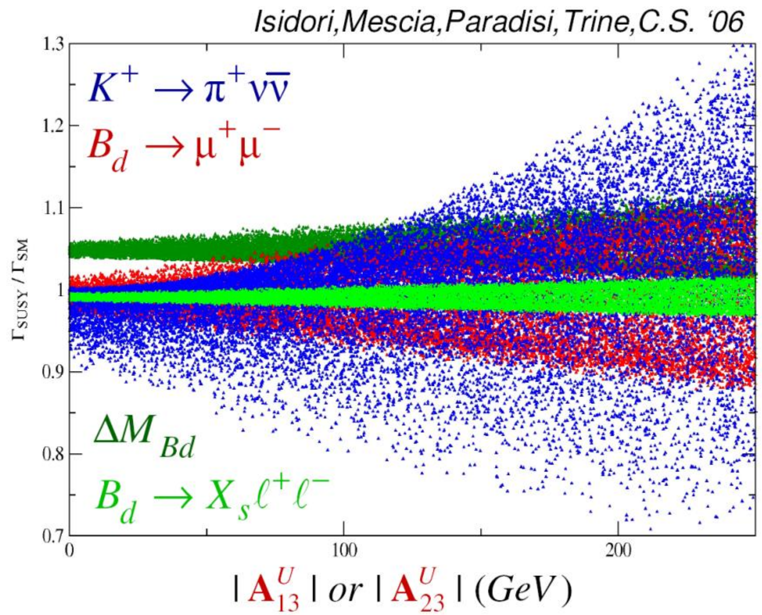
- $SU(2)_L$ breaking: $SM: v_u^2 \mathrm{Y}_u^{*32} \mathrm{Y}_u^{31} \sim m_t^2 V_{ts}^* V_{td}$

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

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

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





(courtesy by Christopher Smith)

Courtesy of S. Jaeger

ε'/ε

$Re(\varepsilon'/\varepsilon)_{exp} = 16.8\,(1.4)\times10^{-4}$

Z penguin

$Re(\varepsilon'/\varepsilon)_{th} = Im\,\lambda_t\,[-3 + 12\,R_6 + R_8 - (2 + 10\,R_8\,C) + \dots]$

$\langle Q_6\rangle_{I=0}$ $\langle Q_8\rangle_{I=2}$

$R_6, R_8 = O(1) \Rightarrow$ cancellation $\Rightarrow$ large uncertainty

lattice: RBC/UKQCD expect O(20%) error on [...] w/in 3y

N Christ, talk at Kaon09

new physics: $Im\,\lambda_t\,C \rightarrow Im\,\lambda_t\,C + Im\,C_{NP}$

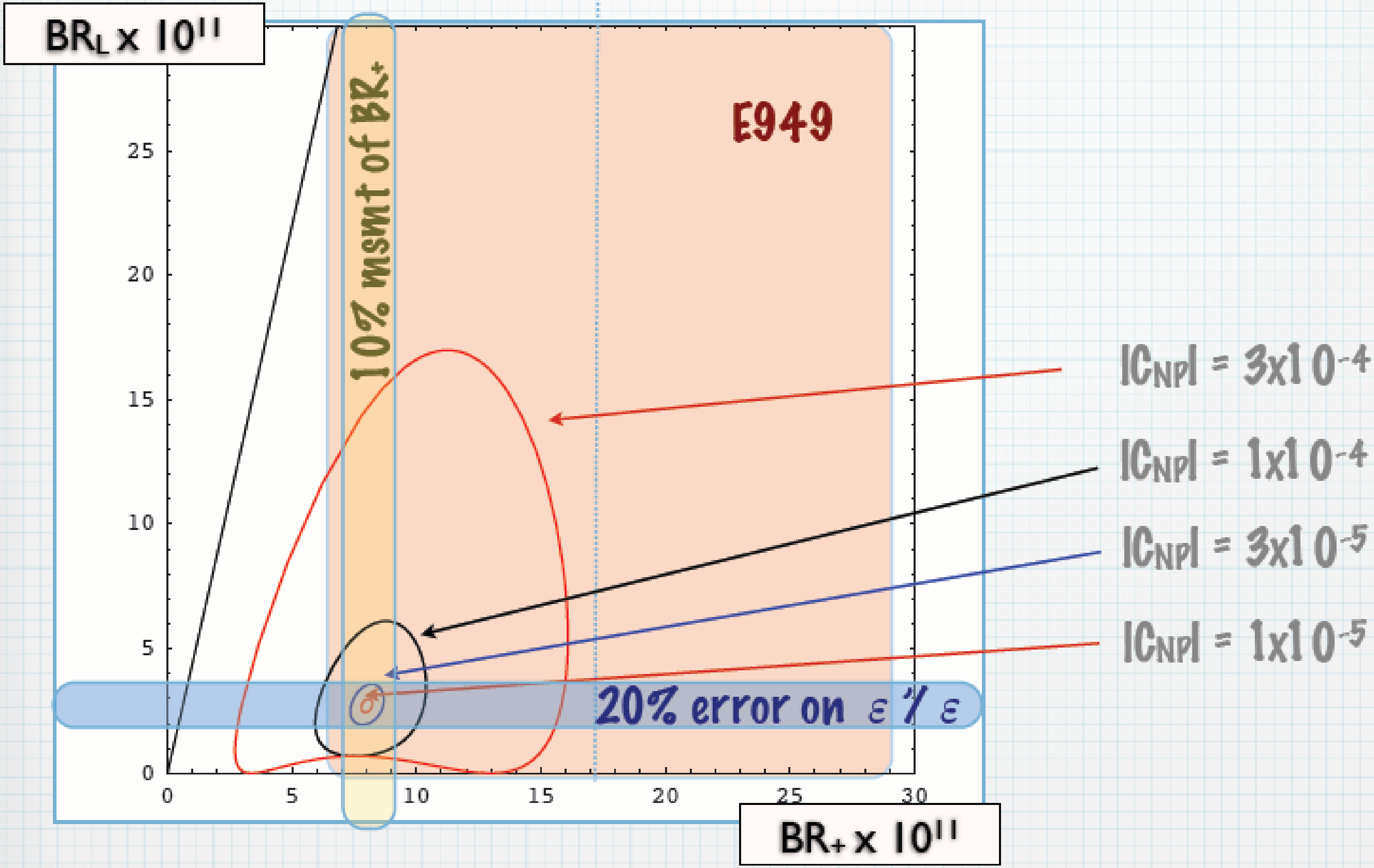
SM=exp value would constrain* $|\,Im\,C_{NP}\,| < 3\times10^{-5}$ (20%SM)

would still allow O(40%) effect in $K_L \to \pi\nu\nu$

*neglecting possible cancellations with other contributions to ε'/ε

Courtesy of S. Jaeger

combination



Neutral Beams for $K^0_L \rightarrow \pi^0 \nu\bar{\nu}$

"Pencil"

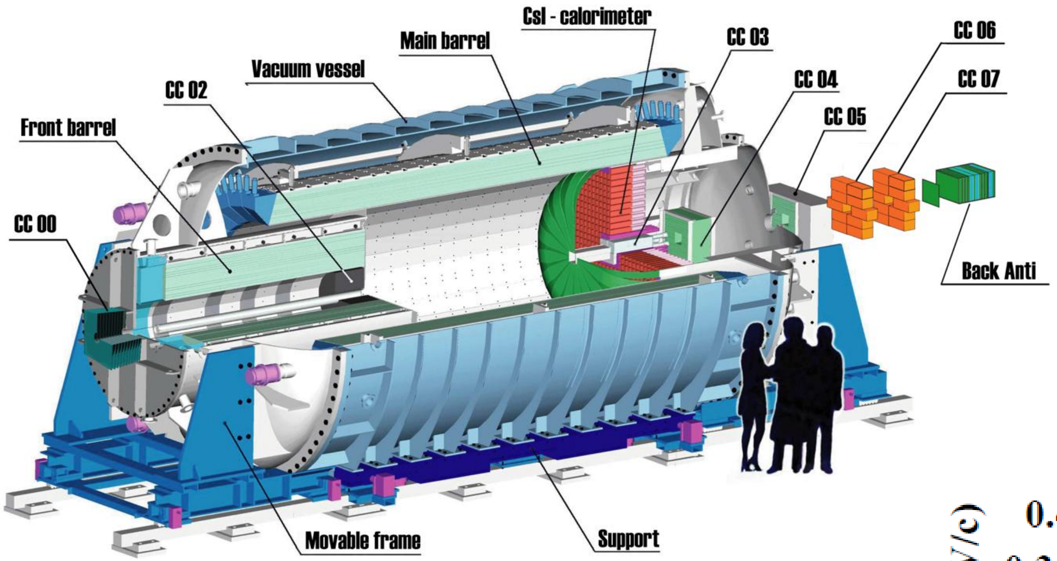
- π^0 + "nothing"
- P_T cut for $\Lambda \rightarrow n\pi^0$ & $K^0_L \rightarrow 2\pi^0$ suppression
- hermetic calorimetry

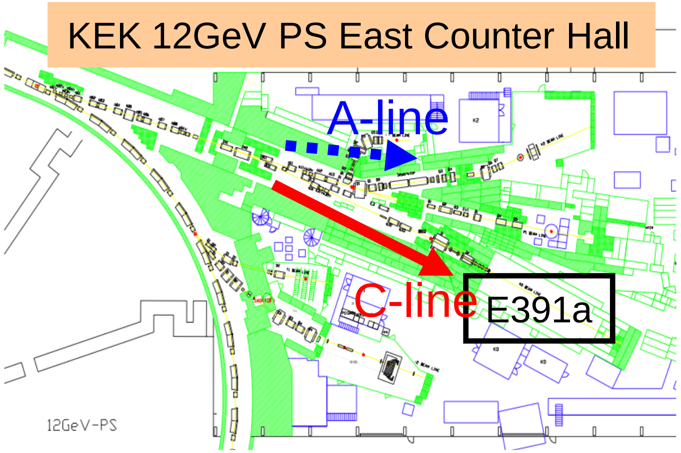
"Microbunched"

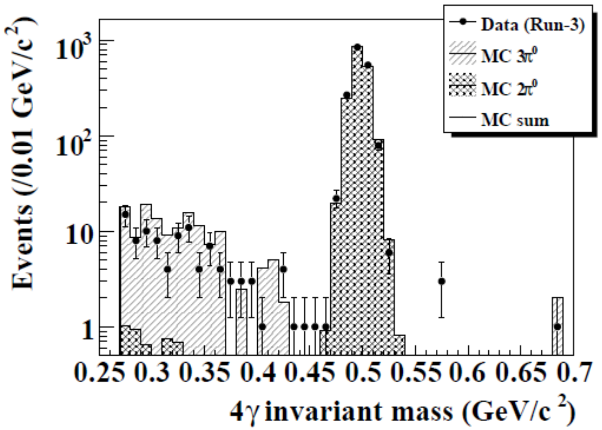
- E_K from Time Of Flight
- Low(er) Kaon Energy
- KOPIO BNL Concept further elaborated for FNAL (Bryman@KAON09)

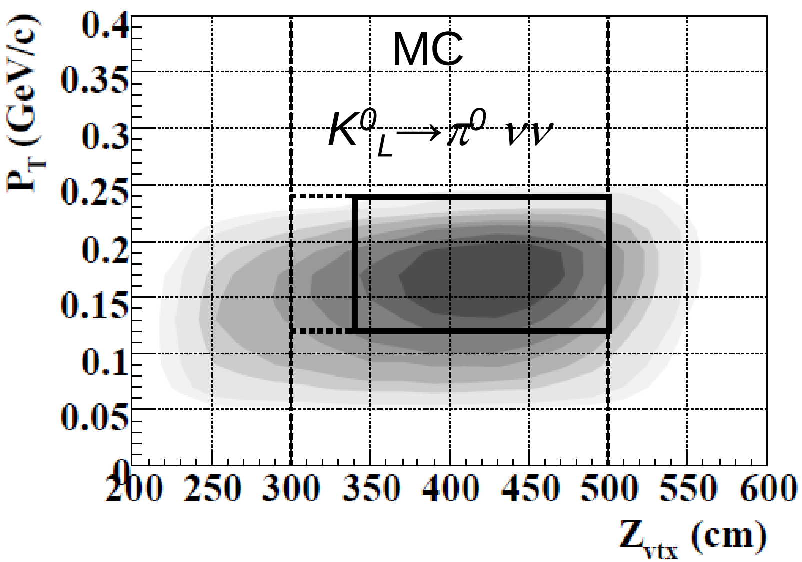
Exp	Machine	UL 90% CL	Notes
KTeV	Tevatron	$< 5.7 \times 10^{-7}$ ($\pi^0 \rightarrow ee\gamma$)	
E391a	KEK-PS	$<2.6 \times 10^{-8}$	
KOTO	J-PARC		Aim at 2.7 SM evts / 3 y
KLOD	U70		Excellent Design
KOPIO			Opportunity at Project X (IC2) ?

E391a @ KEK PS


CsI - calorimeter
Main barrel
Vacuum vessel
CC 02
Front barrel
CC 00
CC 03
CC 04
CC 05
CC 06
CC 07
Back Anti
Movable frame
Support


KEK 12GeV PS East Counter Hall
A-line
C-line
E391a
12GeV-PS

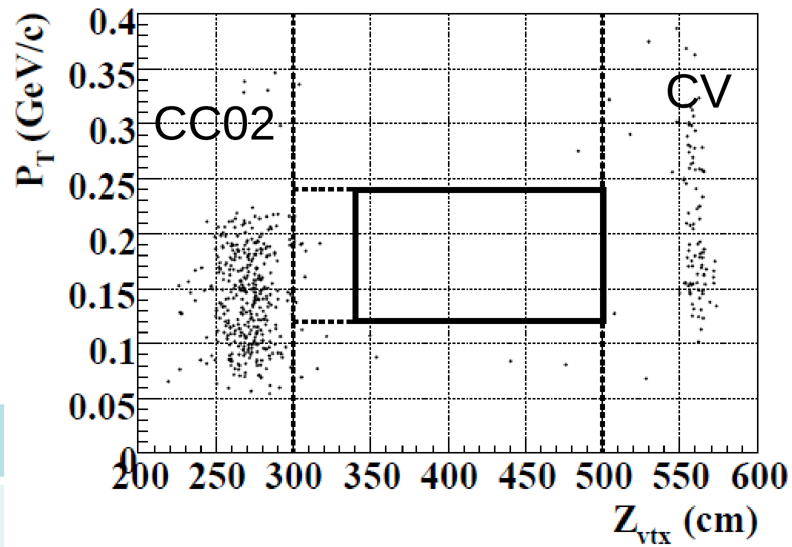

Data (Run-3)
MC 3π⁰
MC 2π⁰
MC sum
Events (/0.01 GeV/c²)
4γ invariant mass (GeV/c²)


MC
$K^0_L \rightarrow \pi^0 \nu\nu$
P_T (GeV/c)
Z_{vtx} (cm)

E391a Final Result

- **arXiv:0911.4789v1**
- **Based all full statistics (2004-2005) including reanalysis of already published data**
- **At these sensitivities backgrounds from kaon decays are negligible w.r.t. neutron induced ones**

Signal Acceptance ~1%
Flux $8.7 \times 10^9\, K^0_L$



Background		Estimated # evt
Beam Halo neutron	CC02-π^0 CV-π^0 CV-η	0.66 0.39 <0.39 0.19 0.13
$K^0_L \rightarrow \pi^0\pi^0$		(2.4 1.8) x 10^{-2}
Other	Backward π^0	<0.05
Total		**0.87 0.41**

$B(K^0_L \rightarrow \pi^0\, \nu\nu) < 2.6 \times 10^{-8}$ 90% CL

Factor of x3 improvement

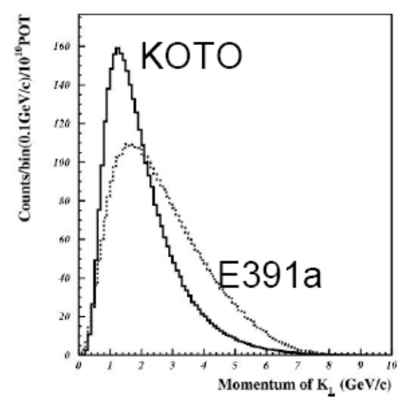
KOTO (E14) @ JPARC

Aim for **Flux x Run Time x Acceptance = 3000 x E391a**

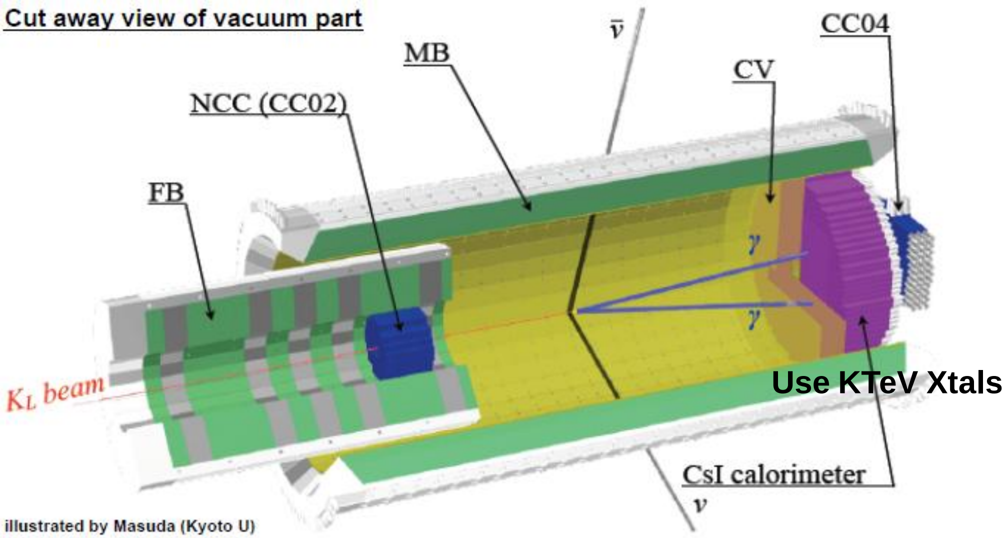
	KOTO	E391a (Run2)	
Proton energy	30 GeV	12 GeV	
Proton intensity	2e14	2.5e12	
Spill/cycle	0.7/3.3sec	2/4sec	
Extraction Angle	16 deg	4 deg	
Solid Angle	9μStr	12.6μStr	
KL yield/spill	7.8e6	3.3e5	x30 /sec
Run Time	3 Snowmass years =12 months.	1 month	x10
Decay Prob.	4%	2%	x 2
Acceptance	3.6%* *without Back splash loss	0.67%	x5

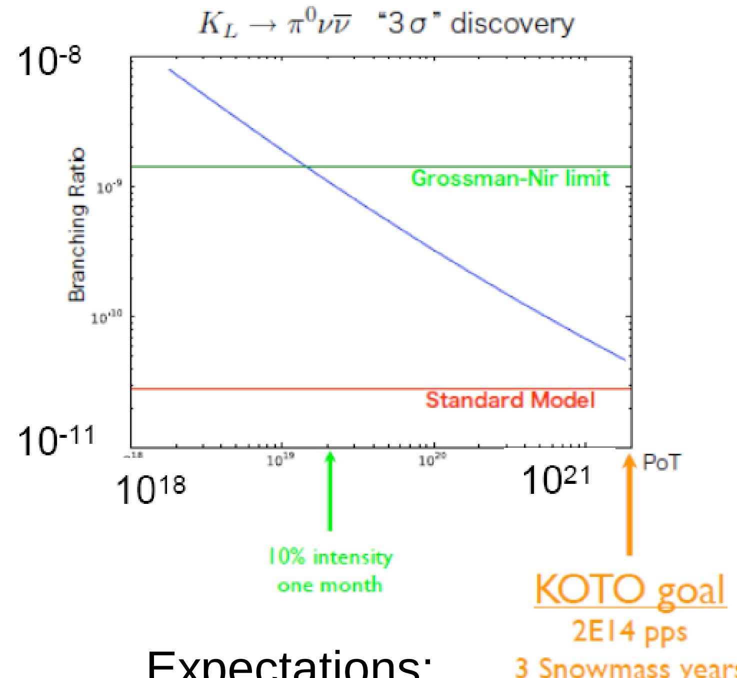
Main Ring Parameters:
L=1.6 Km
30 GeV
2 x 10^{14} ppp
0.3 MW
0.7 s spill / 3.3 s

Details in H. Nanjo KAON'09



KOTO @ JPARC





Schedule (H. Nanjo, KAON2009)

2009

- Beamline construction
- Beam Survey

2010

- CsI Calorimeter Construction
- Engineering run with CsI calorimeter

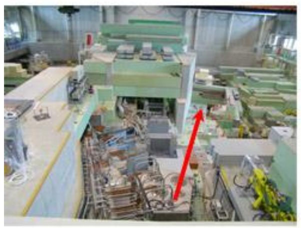
2011

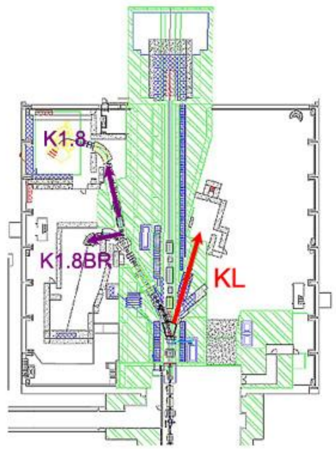
- Physics Run start

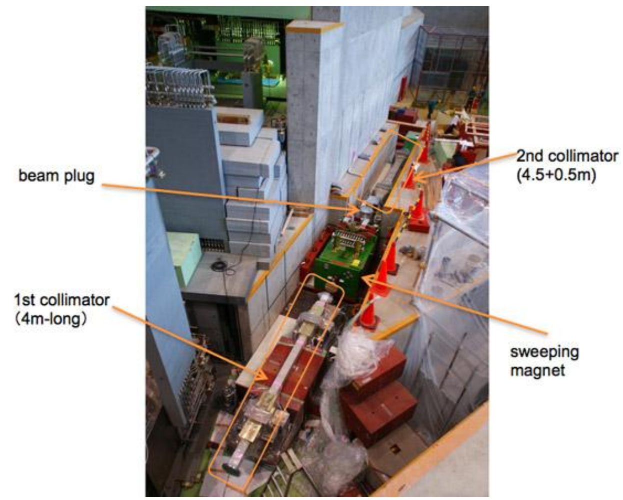
Expectations:

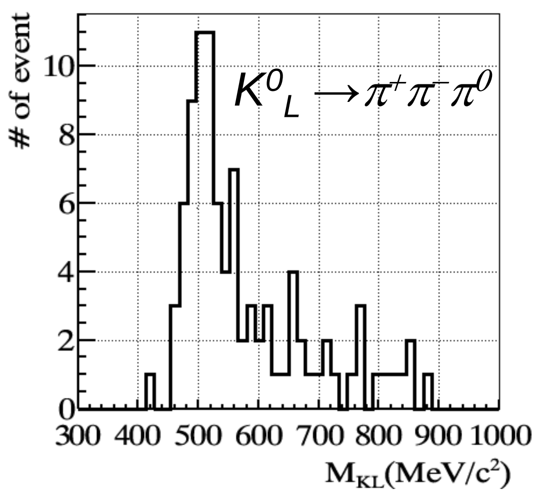
Signal	$K^0_L \to \pi^0 \nu\nu$	2.7
K^0_L Background	$\pi^0\pi^0$	1.7
	$\pi^+\pi^-\pi^0$	0.08
	$e^+\pi^- \nu$	0.02
Halo Neutrons		0.38

“Confirmation of neutral kaons in the KL beam line at Hadron Hall, J-PARC” Dec 7, 2009



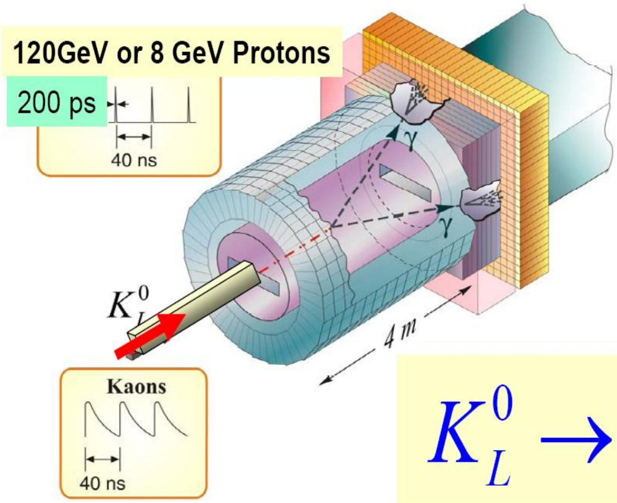




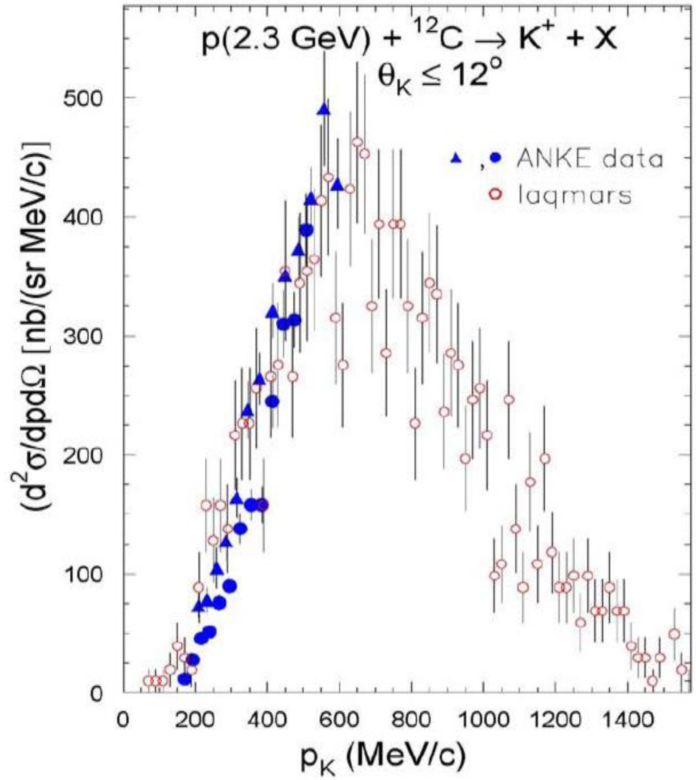


Beam Survey

Plans for K^0_L @ FNAL Project X



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



- KOPIO-like: TOF to determine Kaon Energy
- Knowledge of E_K allows rejection of two body decays
- Pointing Calorimeter
- 4 π veto for neutral and charged particles
- Small Beam instead of flat beam

- Project X (IC2): CW p LINAC ~3 GeV
- Excellent bunch timing
- High flux of low energy K^0_L

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

"Stopped"

- Work in Kaon frame
- High Kaon purity (Electro-Magneto-static Separators)
- Compact Detectors

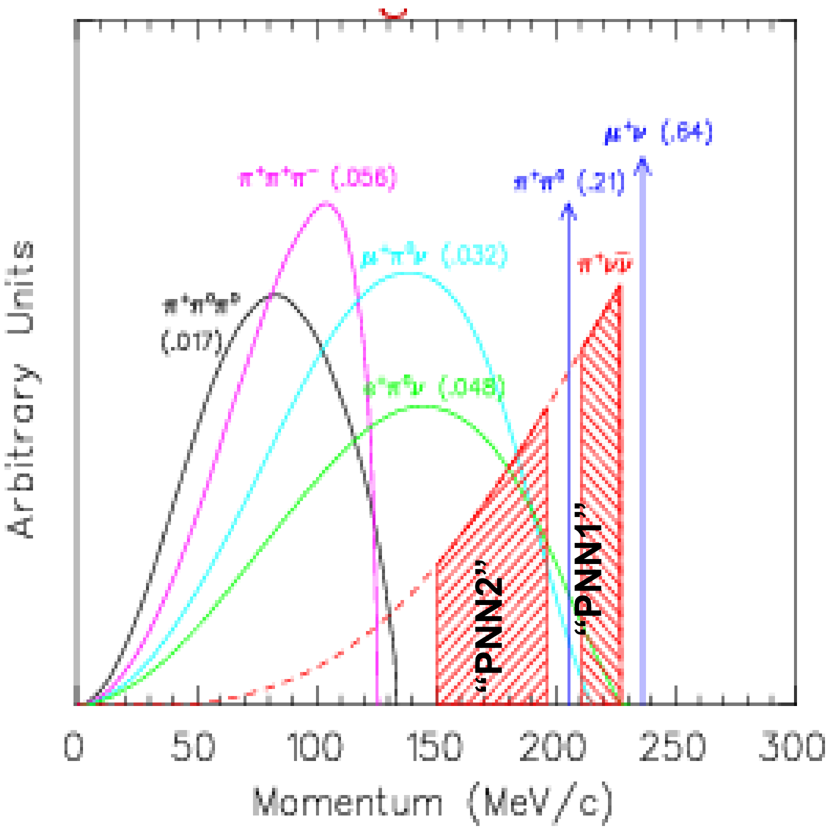
"In-Flight"

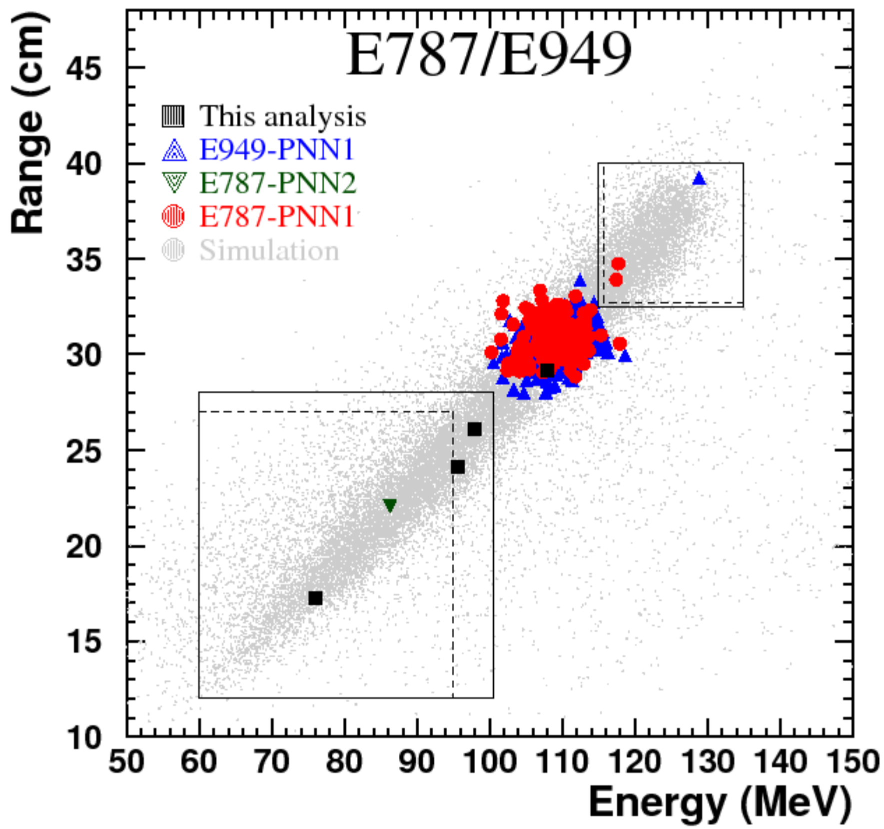
- Decays in vacuum (no scattering, no interactions)
- RF separated or Unseparated beams
- Extended decay regions

Exp	Machine	Meas. or UL 90% CL	Notes
	Argonne	$< 5.7 \times 10^{-5}$	Stopped; HL Bubble Chamber
	Bevatron	$< 5.6 \times 10^{-7}$	Stopped; Spark Chambers
	KEK	$<1.4 \times 10^{-7}$	Stopped; $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
E787	AGS	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	Stopped
E949	**AGS**	$\mathbf{(1.73^{+1.15}_{-1.05}) \times 10^{-10}}$	**Stopped; PPN1+PPN2**
NA62	**SPS**		**In-Flight; Unseparated**
P996	FNAL		Stopped; Tevatron as stretcher ring?

E787/E949: Final Result

arXiv:0903.0030v1 PRD79:092004,2009

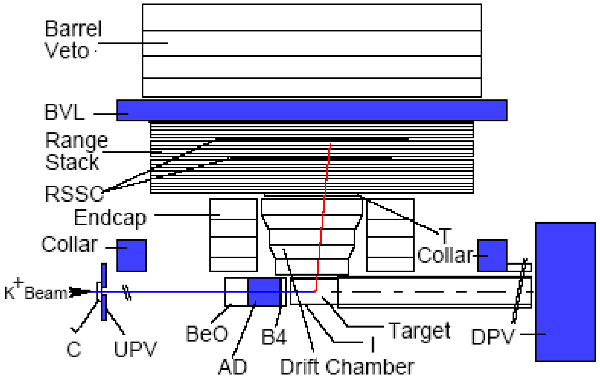


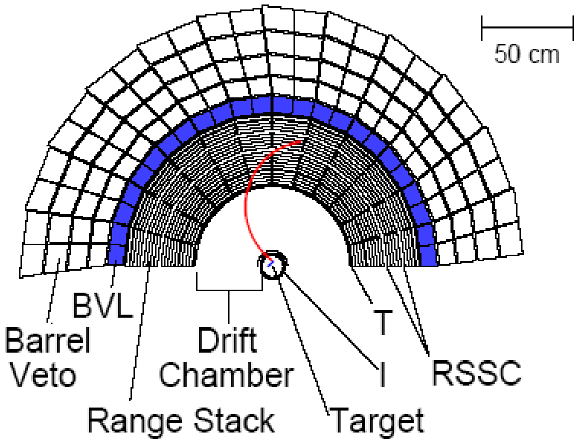


$$B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

E787/E949 Technique

"The entire AGS beam of 65 x 10^{12} (Tp/ spill) at a momentum of 21.5 GeV/c was delivered to the E949 K^+ production target"





- Duty Factor: 2.2 s / 5.4 s **~ 40%**
- 1 int. length Pt target
- Before separators: 500 π : 500 p : 1 K
- After separators: Purity **K:π ~ 3-4 : 1**
- Incoming **710 MeV/c** K^+ identified by Č and slowed down by BeO and Active Degrader
- **~27%** K^+ stopped in the target (1.6 MHz)
- 1 T solenoid

K^+: Č x B4 x Target

π^+: Delayed Coincidence
Range
Energy
Momentum
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$

Stopped Kaon Redux?

Can one improve significantly over the E949 PNN1 efficiency figures?

Selection	α	Notes
$K\mu 2$	0.38	Beam,T, RS rec.
$K\pi 2$	0.88	E, range, selection
Pscat	**0.62**	Rej. of beam scat.
$\pi \rightarrow \mu \rightarrow e$	**0.35**	Decay chain
Trig	**0.18**	Trigger eff.
PS	**0.36**	Phase Space
nucl.	**0.50**	Pion interaction
T2	0.94	topology
fs	**0.77**	Stopping Fraction
"Standard"	1.7×10^{-3}	Total efficiency

- "Only" ~22% (.77 x .28) of kaons stopped in target

- The product of the red factors (1.5×10^{-2}) Is a high price to pay: $1/(1.5 \times 10^{-2}) \sim$ **66x**

Possible Improvements (Bryman@KAON09):

1. Lower Kaon Momentum to increase the stopped kaon fraction
2. Larger Beam acceptance

→ **4-5x**

3. Detector Improvement: finer RS segmentation; LXe γ veto

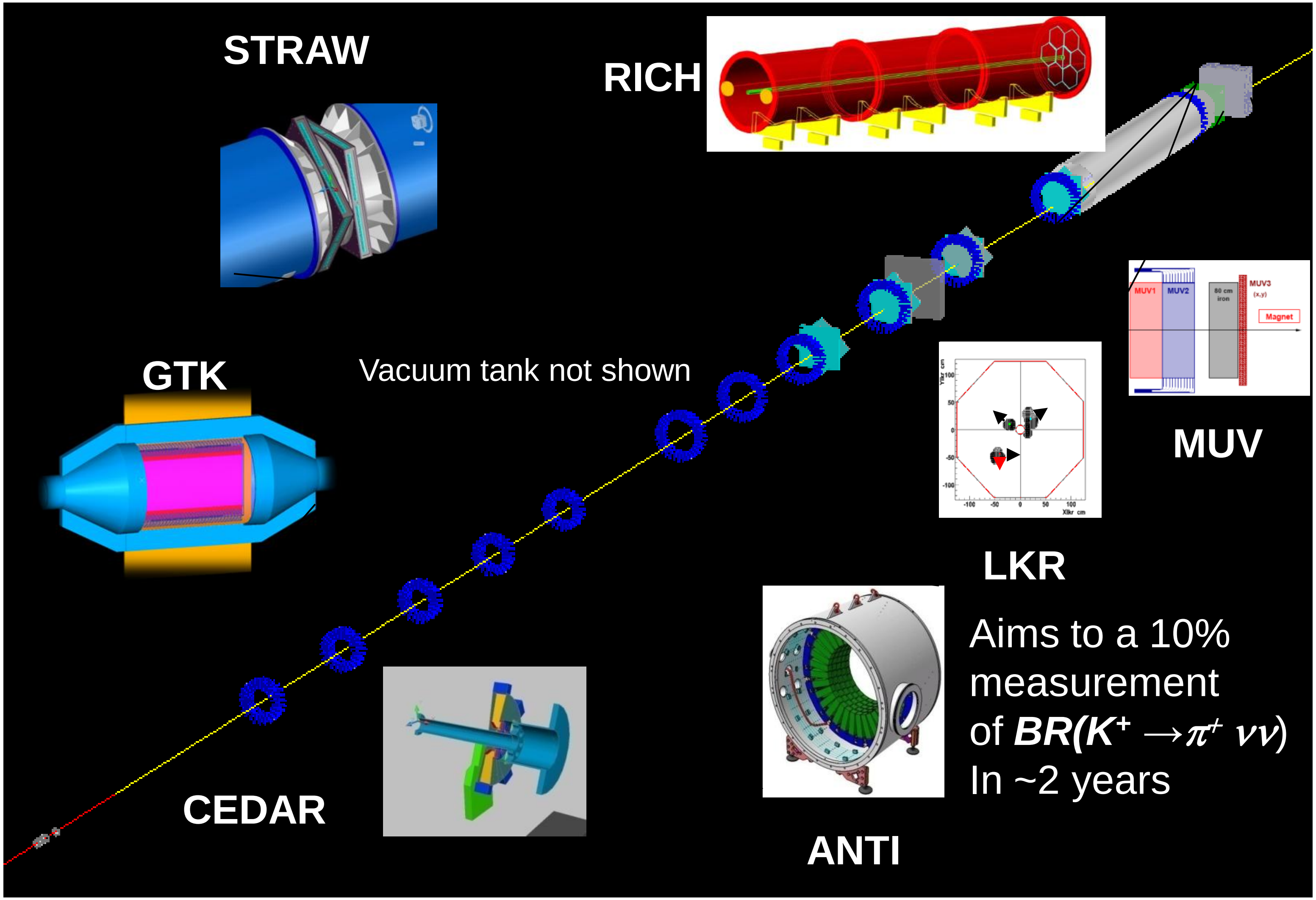
→ **> 5x**

Stopped Kaons at Fermilab: P996

- **The status of P996 is that the Fermilab PAC has stated that "Proposal meets the criteria for Stage-I [scientific] approval" .**
- **P996 as proposed requires 3-5 years of running the Tevatron after RunII as a 150 GeV Stretcher to reach a 1000 event SM sensitivity.**
- **Fermilab and the P996 collaboration are now in discussions with the Department of Energy exploring the possibility of running the Stretcher after RunII**

(Update kindly provided by Bob Tschirhart from Fermilab)

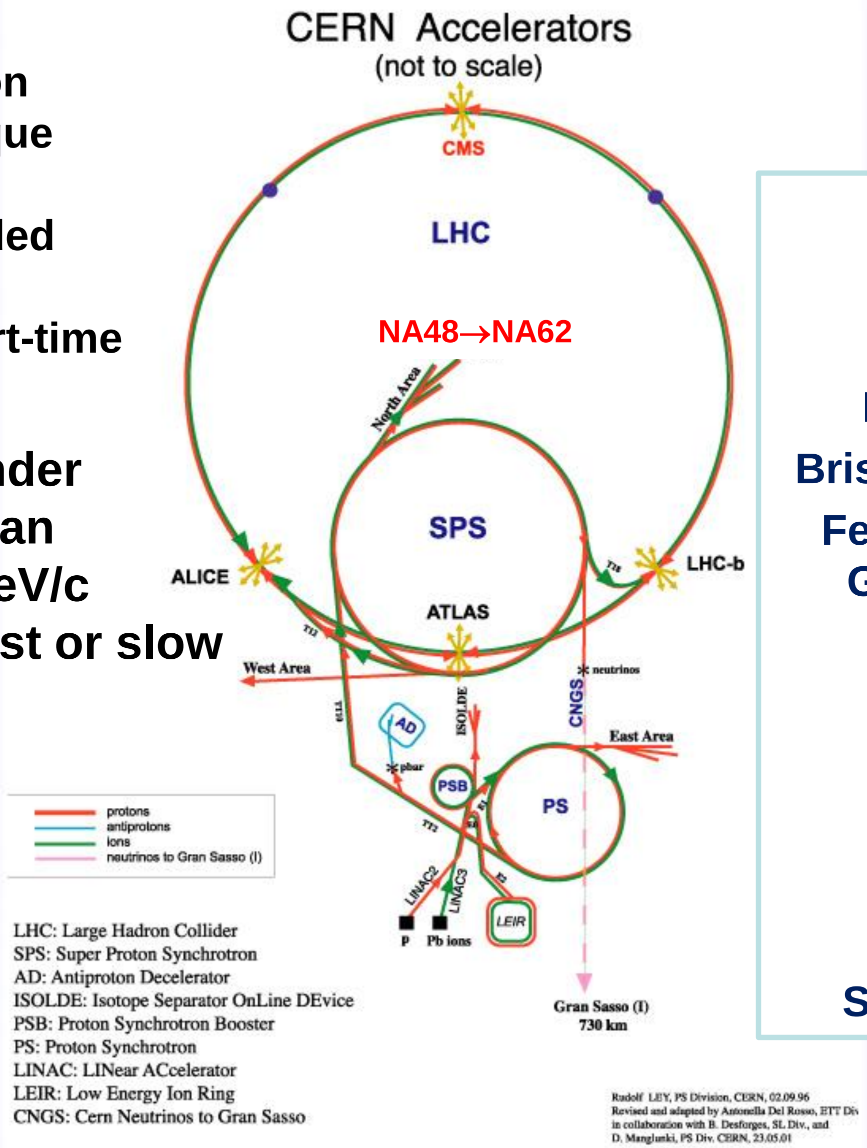
K^+ Decays in flight:NA62



The CERN proton Complex is unique

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

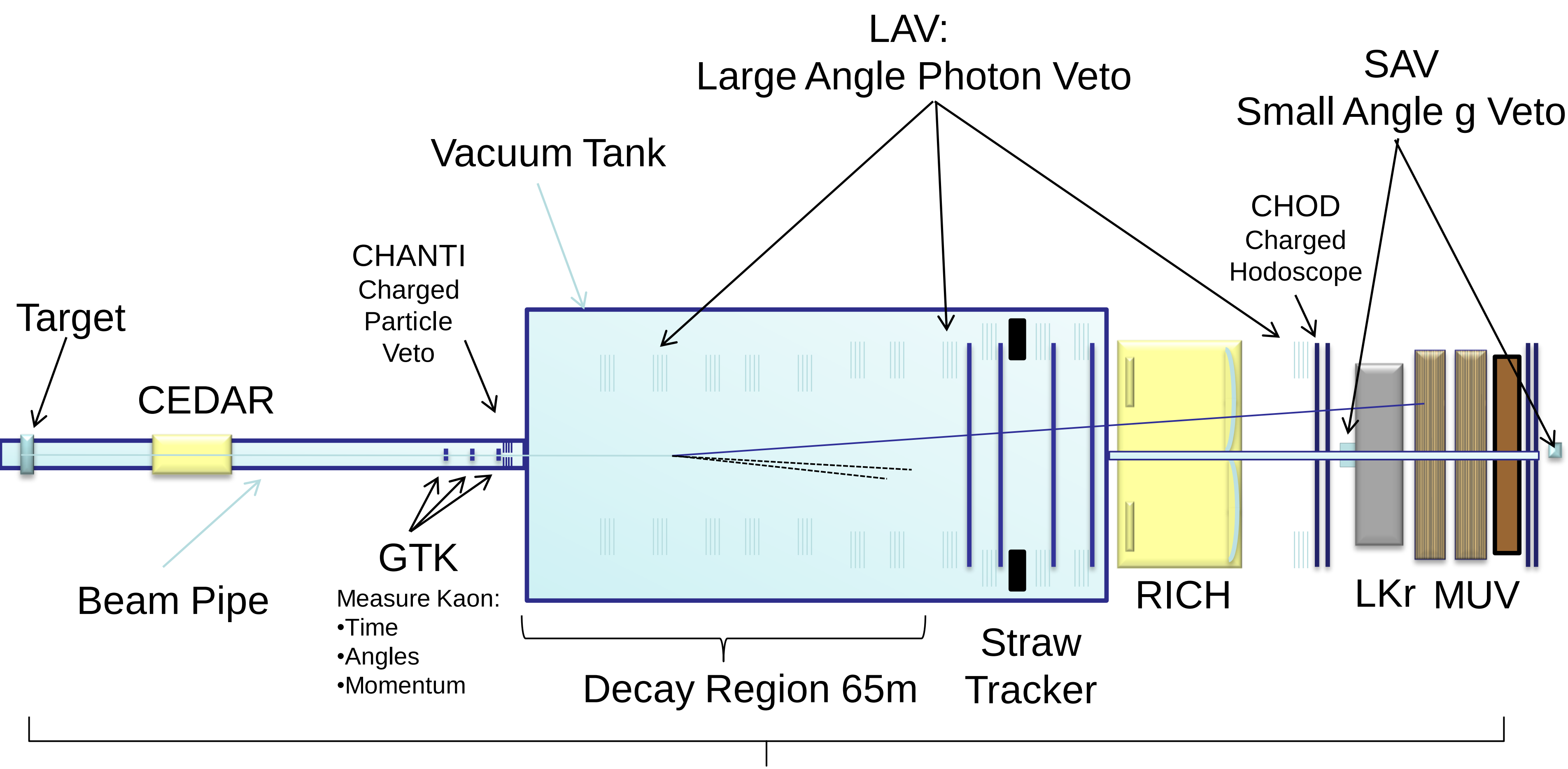
For the remainder of the time it can provide 400 GeV/c protons for fast or slow extraction



NA62:

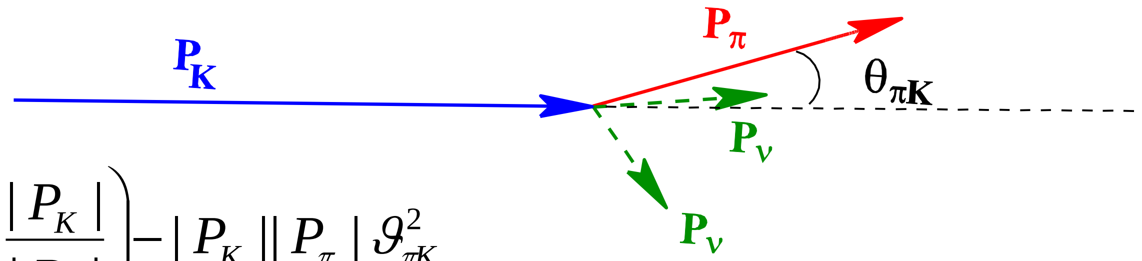
Birmingham, Bratislava
Bristol, CERN, Dubna,Fairfax,
Ferrara, Florence, Frascati,
Glasgow, IHEP Protvino,
INR Moscow,
Liverpool, Louvain,
Mainz, Merced, Naples,
Perugia, Pisa,
Rome I, Rome II,
San Luis Potosí,
SLAC,Sofia,TRIUMF,Turin

NA62 Detectors



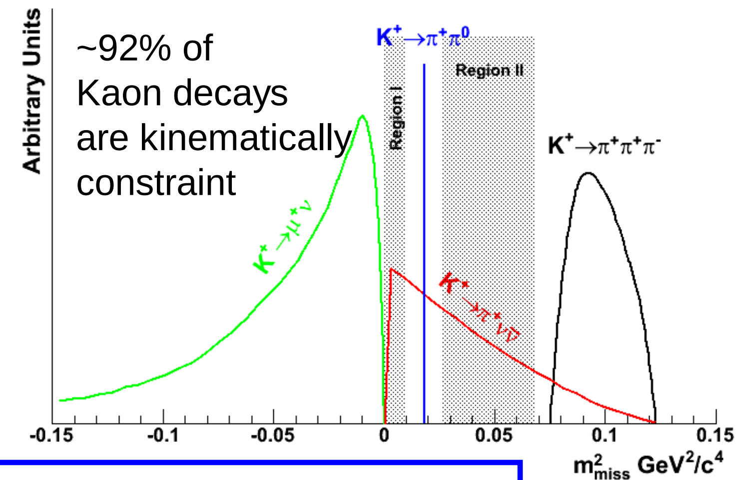
Drawing by Ferdinand Hahn

Background Rejection



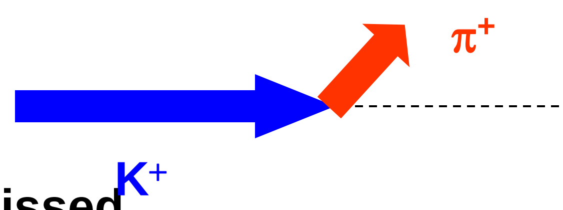
$$m^2_{miss} \approx m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right)+m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\vartheta^2_{\pi K}$$

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



Signature:

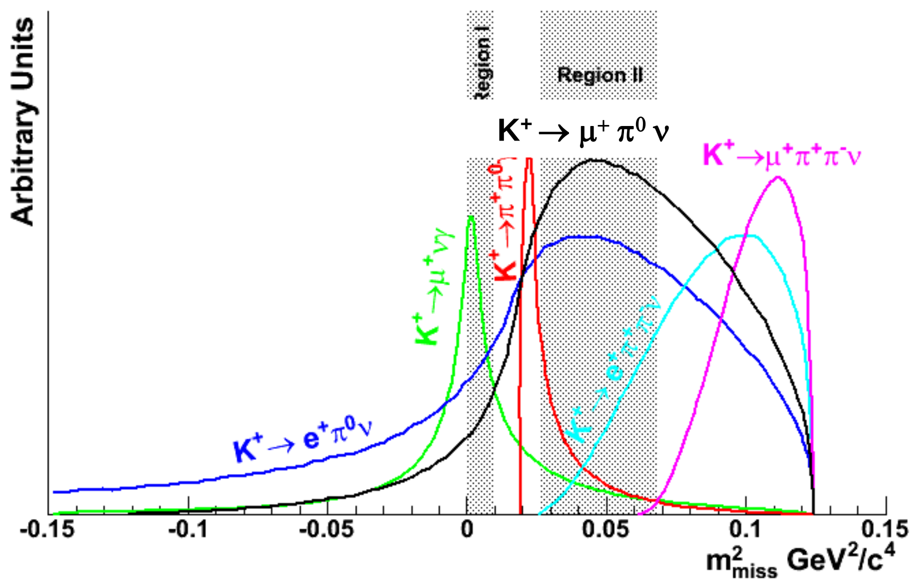
- **Incoming high momentum (75 GeV/c) K^+**
- **Outgoing low momentum (< 35 GeV/c) π^+**
- **For $K_{\pi2}$ P(π^0) > 40 GeV/c: it can hardly be missed**



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}



NA62 Sensitivity

Decay Mode	Events
Signal: $K^+ \to \pi^+ \nu \bar{\nu}$ SM *[flux = 4.8×10^12 decay/year]*	55 *evt/year*
$K^+ \to \pi^+ \pi^0$ $[\eta_{\pi 0} = 2\times10^{-8}\ (3.5\times10^{-8})\ ]$	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

NA62 Focused R&D

- **Gigatracker (GTK) : Beam tracker (10^9 part/s) based on Si micro pixels with ~100 ps time resolution; thickness of one station ~0.5% X_0**
- **Straw Tracker (STRAW) : To be operated in the vacuum tank: total thickness for 16 views ~1 % X_0**
- **P.I.D. (π/μ) up to P = 35 GeV/c**

Neon RICH with 17 m focal length spherical mirrors

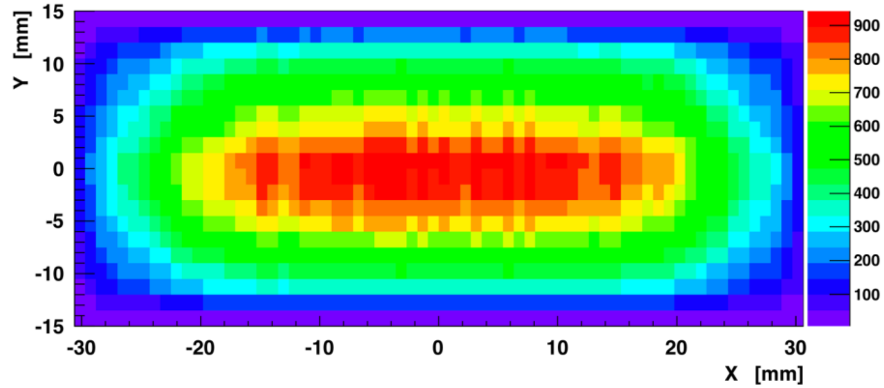
- **Hermetic Coverage: π^0 suppression factor ~ 10^8**

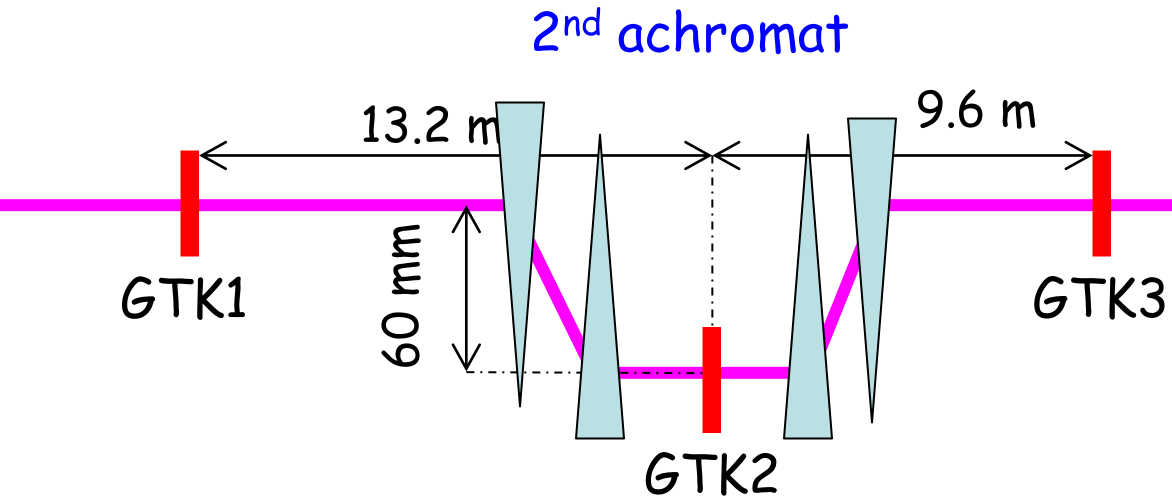
Employ high performance calorimeters as photon vetoes: Liquid Krypton (NA48) + Lead Glass (OPAL)

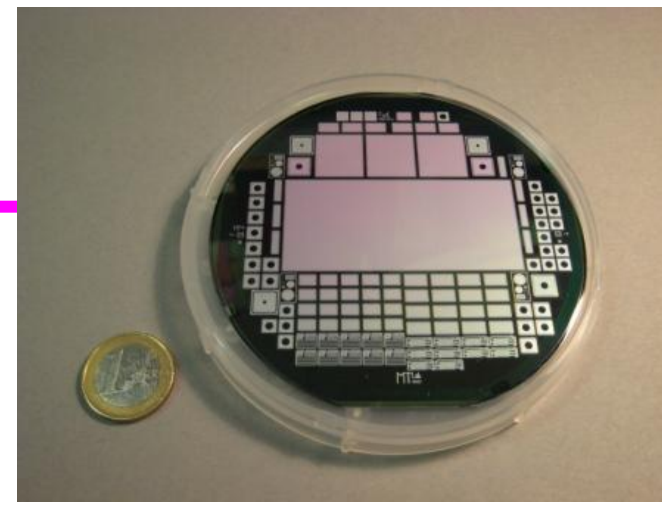
NA62 Beam & GTK

SPS primary p: 400 GeV/c
Unseparated beam:

- **75 GeV/c**
- **750 MHz**
- **π/K/p (~6% K^+)**







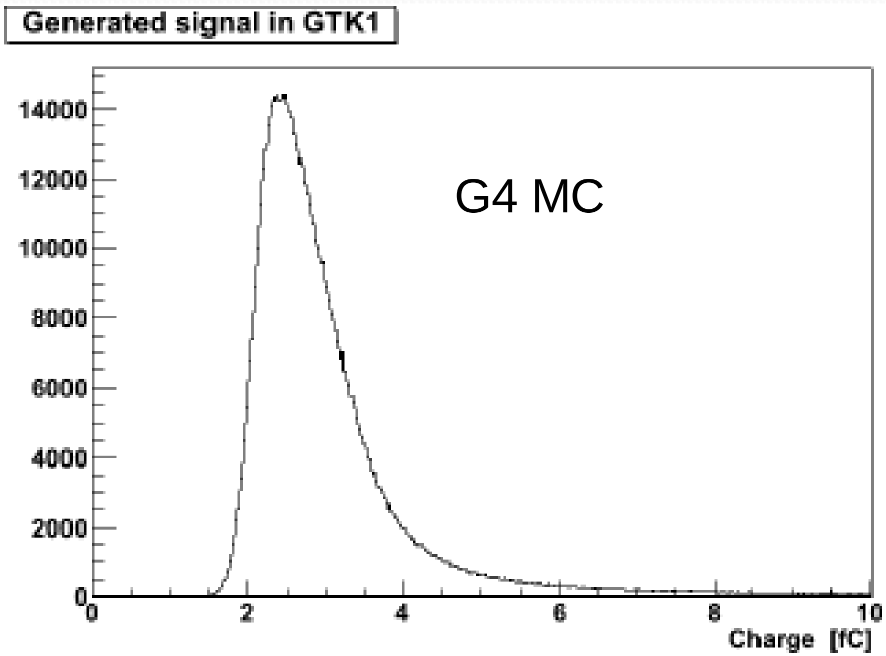
- **Sensitivity is NOT limited by protons flux but by beam (GigaTracKer (GTK))**
- **Similar amount of protons on target as NA48 (~5 10^{12} / pulse)**

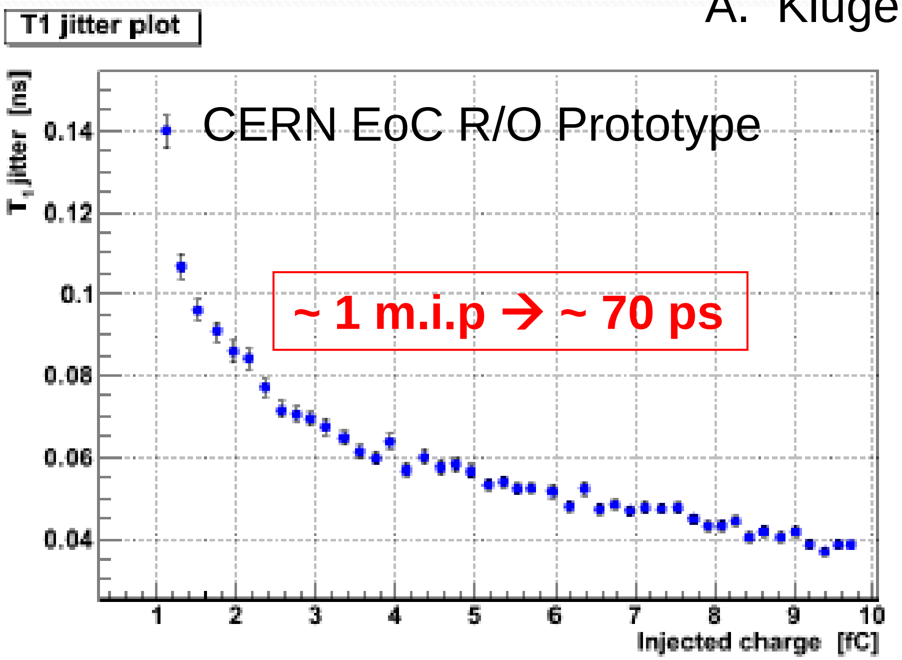
First Results from GTK Tests

M. Fiorini
M. Noy
A. Kluge

Preliminary

Charged weighted time jitter measured with test pulses



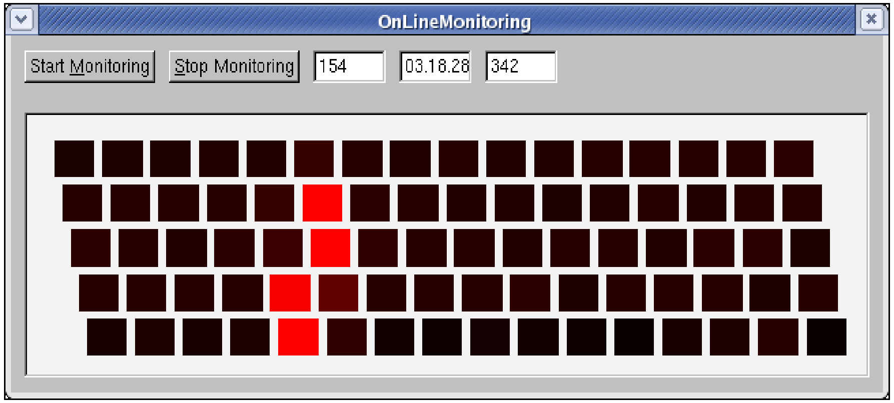


- taking into account the energy distribution of particle hits in the Gigatracker, one can extract a weighted average value for the jitter on T_1

"We come from Research to working Prototype"
Flavio Marchetto

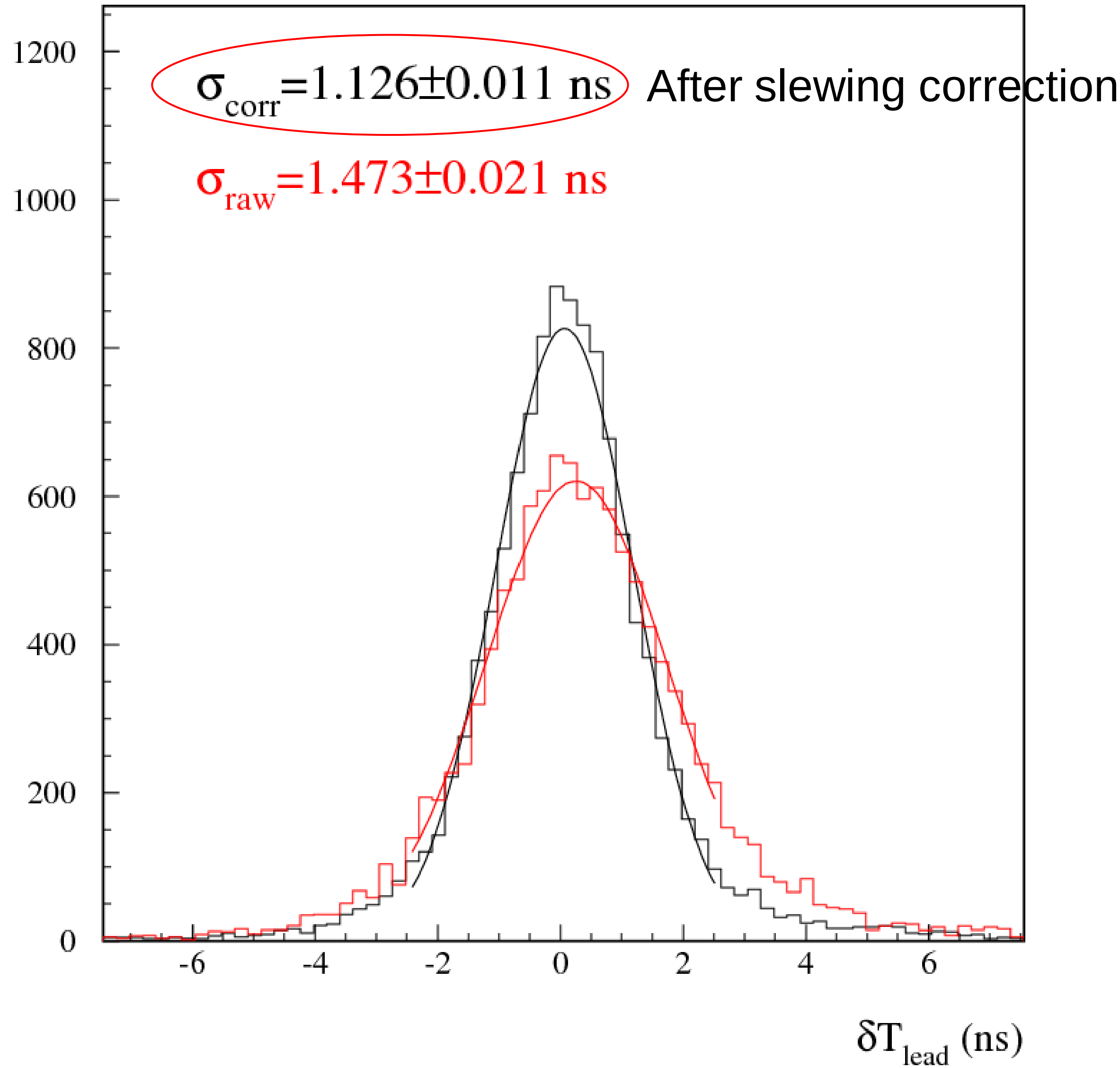
LAV ANTI-A1

- **In summer 2009 the first station A1 was built at LNF and shipped to CERN. It is now mounted on the blue tube**
- **A test beam run with the complete system including prototype front-end electronics (FEE) was performed at the end of October 2009**



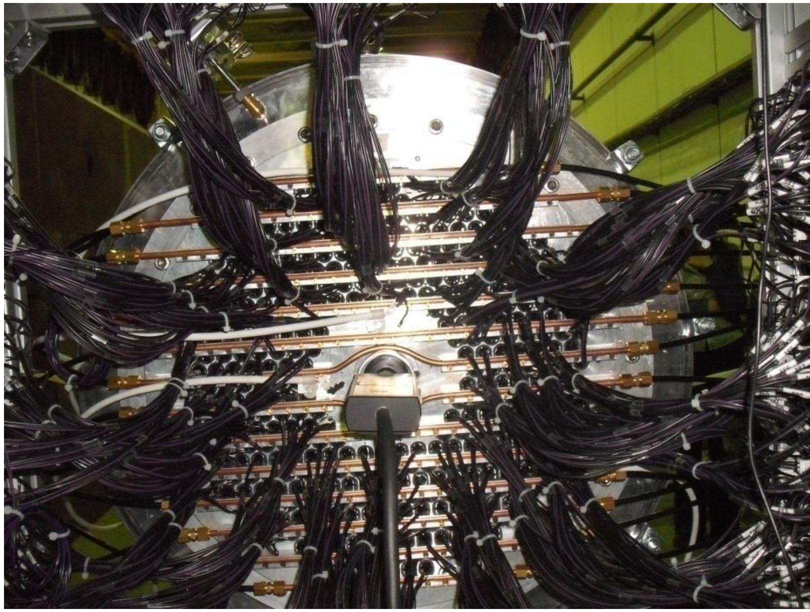
LAV Time resolution

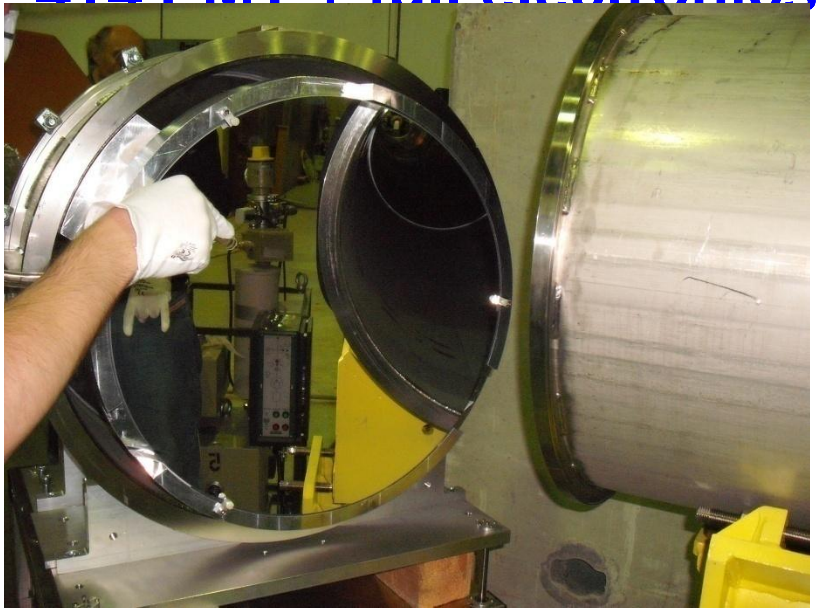
- 4 GeV electrons
- Time differences between two subsequent blocks
- Slewing correction
- Q obtained from time over threshold



RICH 2009 prototype test beam

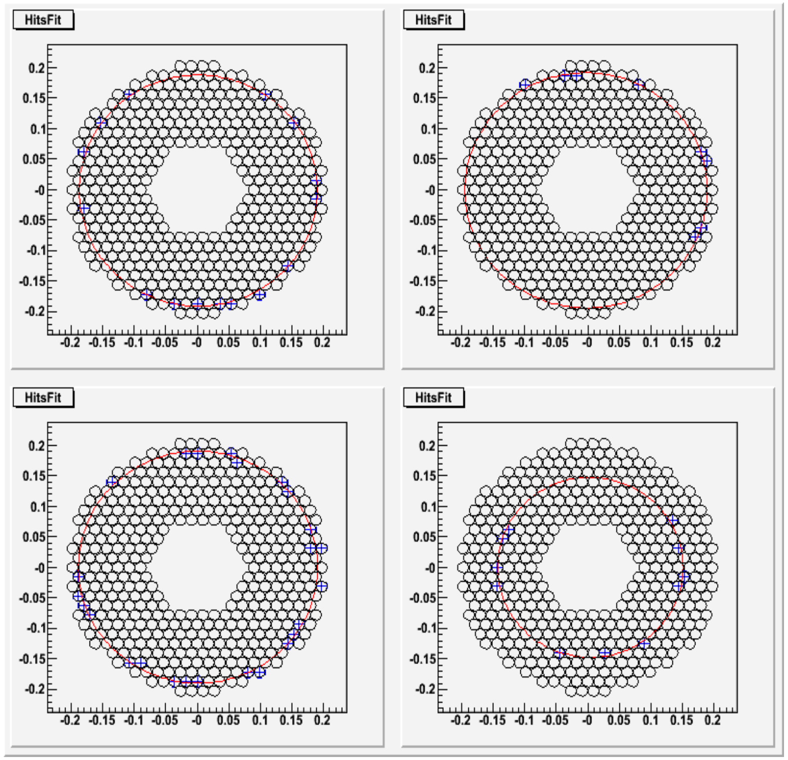
- 12.5.-27.6.2009: test beam
- 1 mirror with f=17m, 50 cm wide
- 414 PMT + full electronics

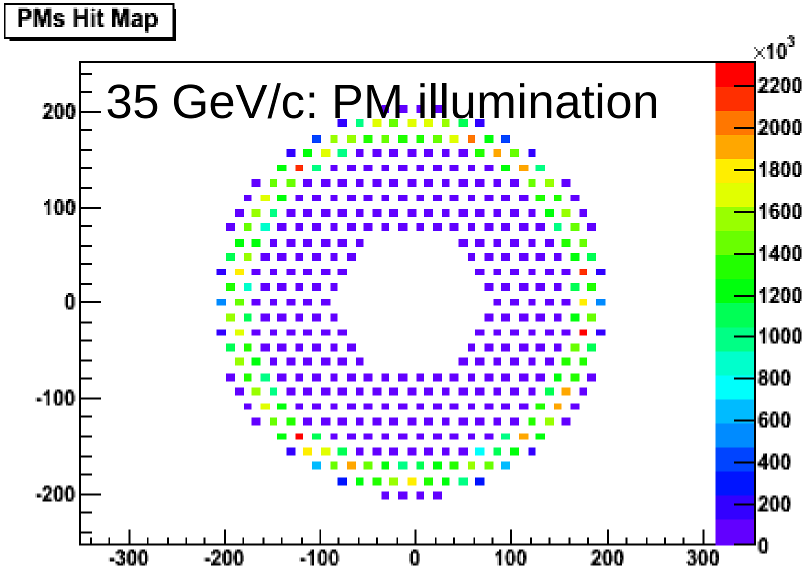




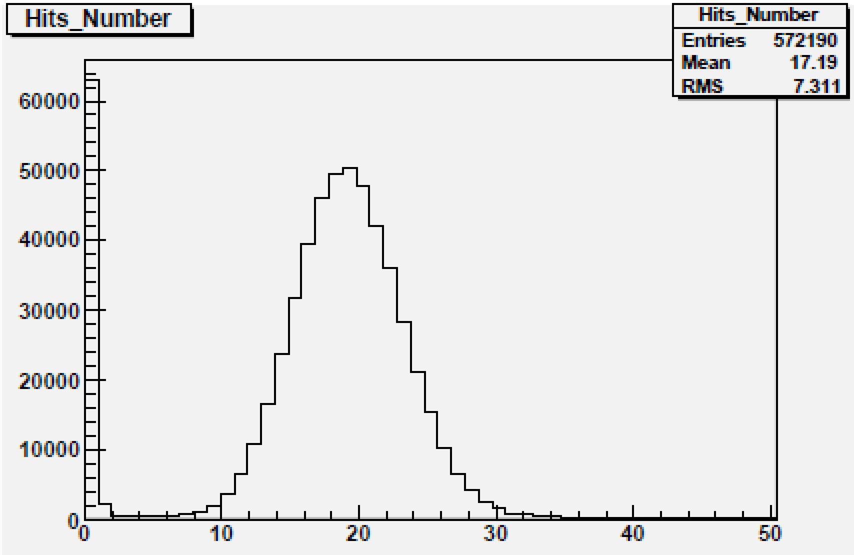
2009 test beam

20 GeV/c: 3 positrons and 1 pion events

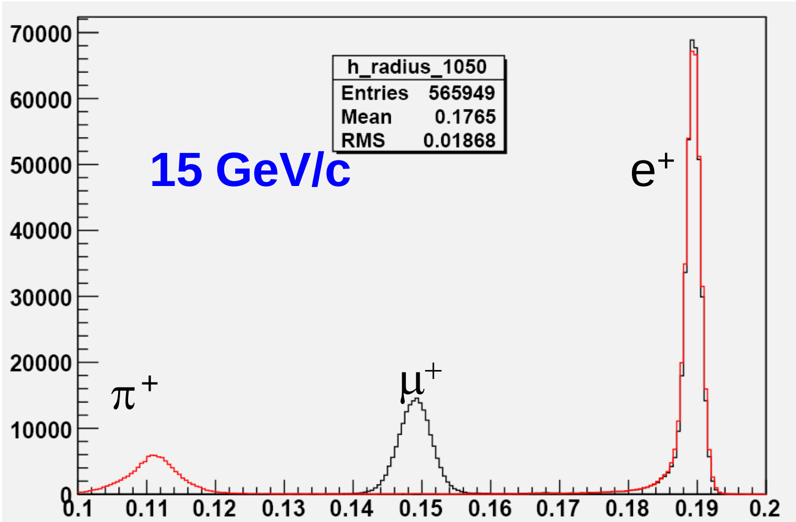


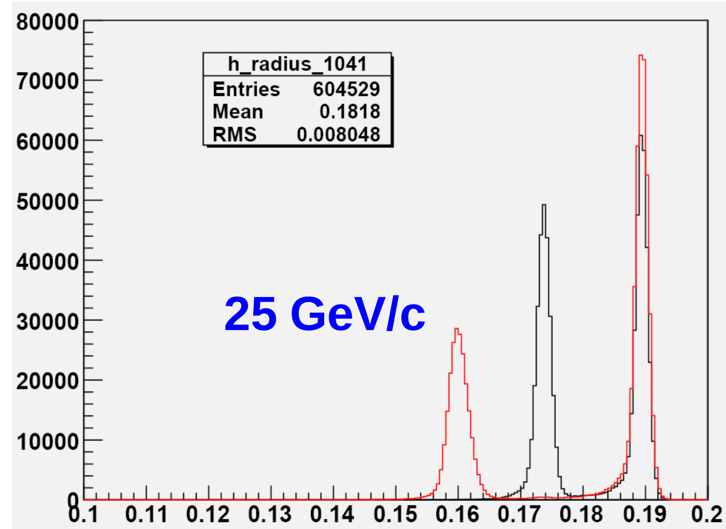


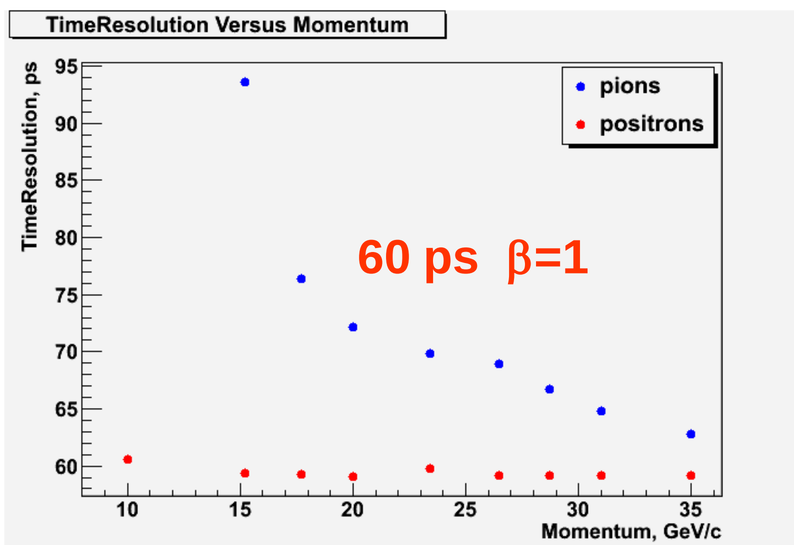
N. of hits
per event
at 35 GeV/c

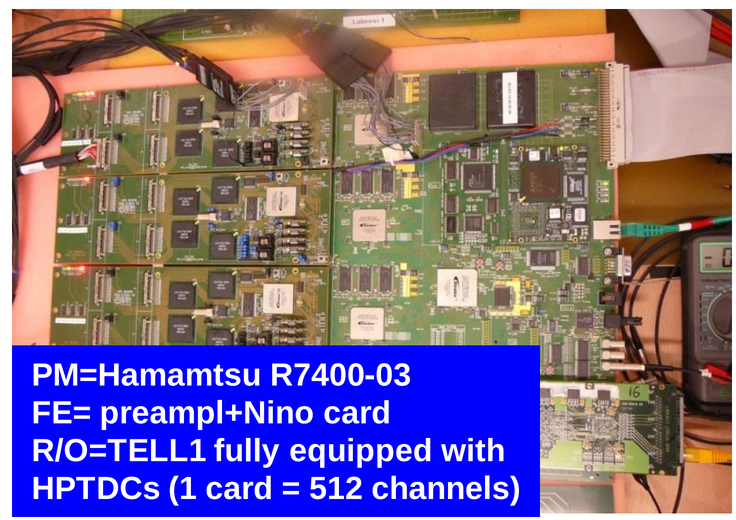


RICH Test, June 2009, Preliminary



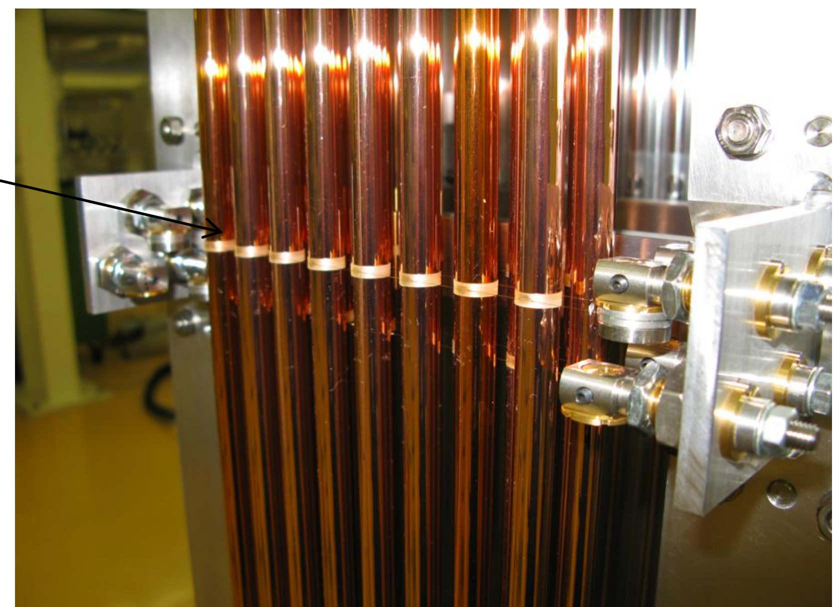






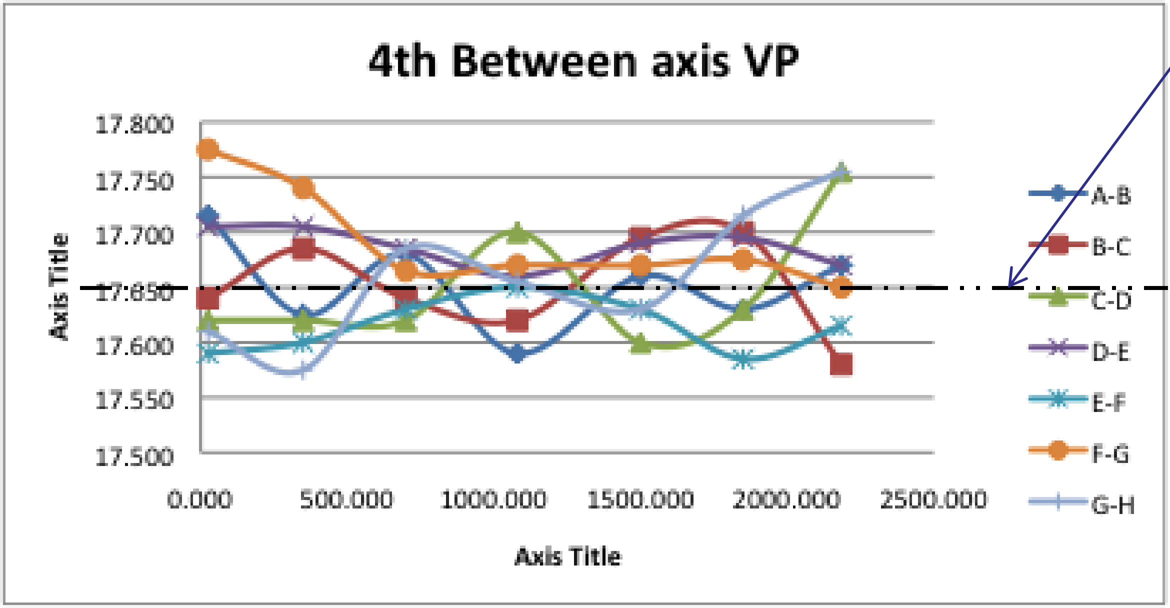
64 Straw technology Prototype

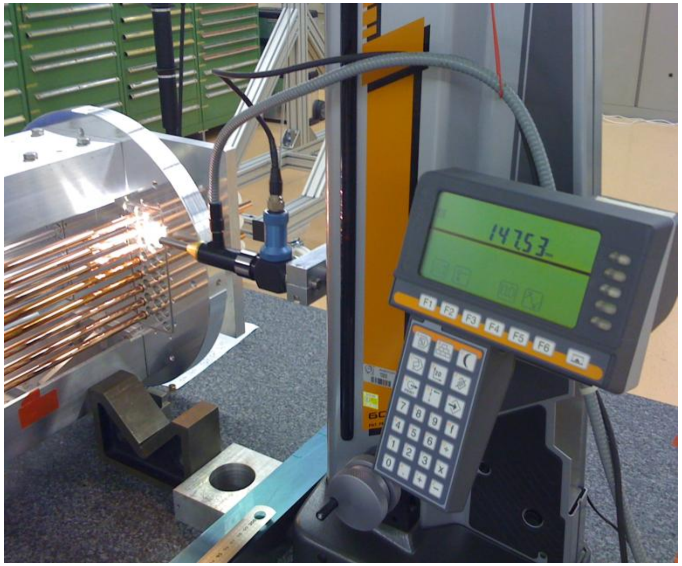
- The straws are installed in vertical position
- Pretension is 1.5 kg
- Spacer validated over 2.1 m.

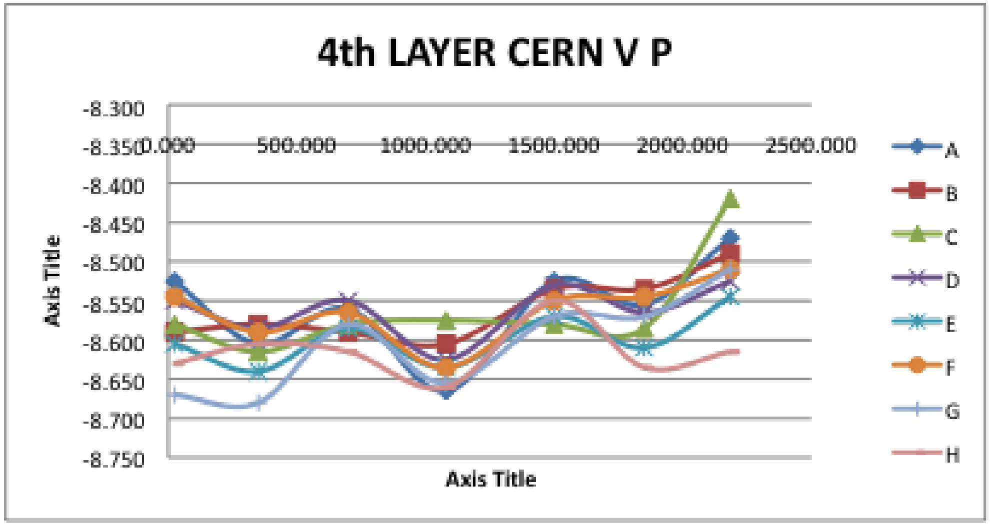


Straw straightness

Nominal

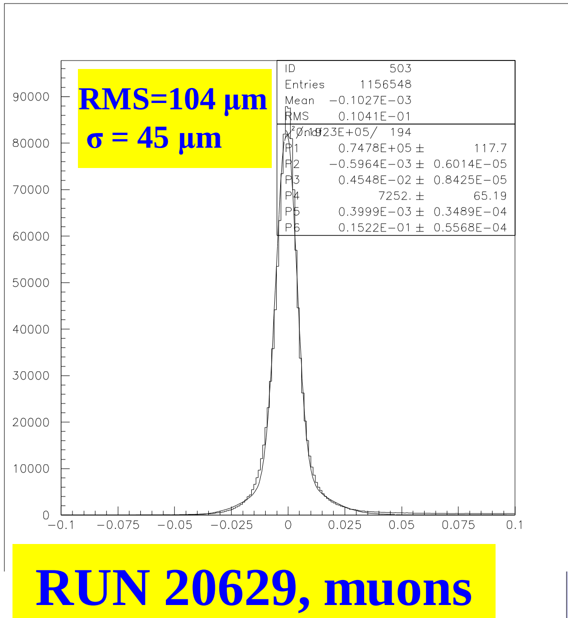


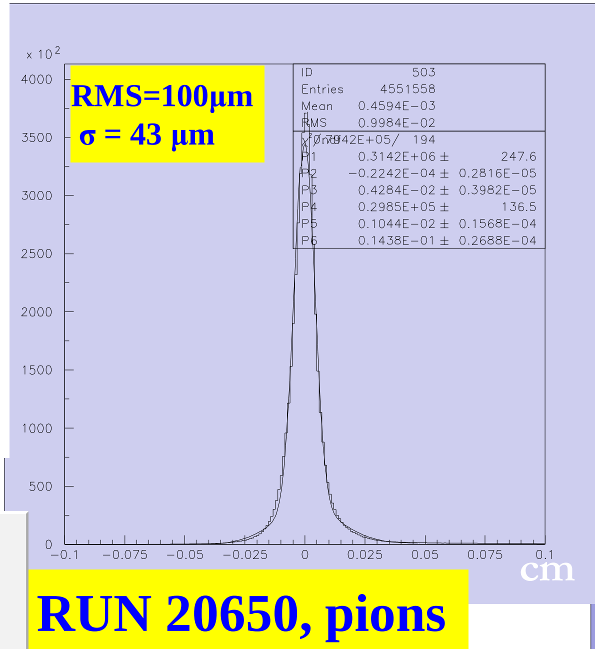




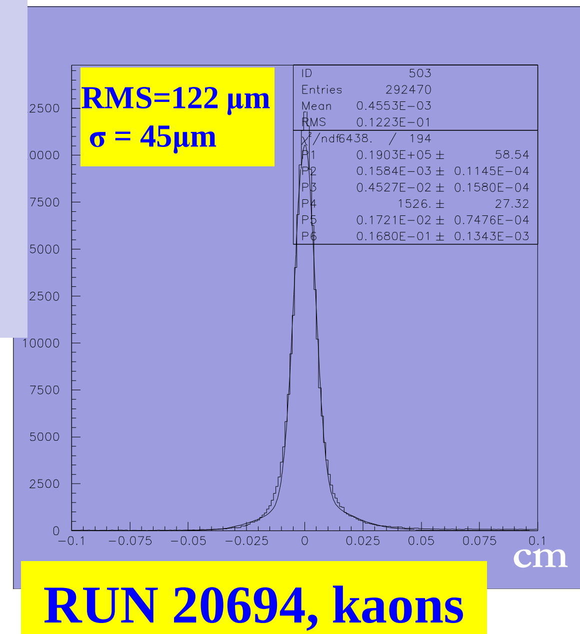
STRAW Prototype: Beam Test

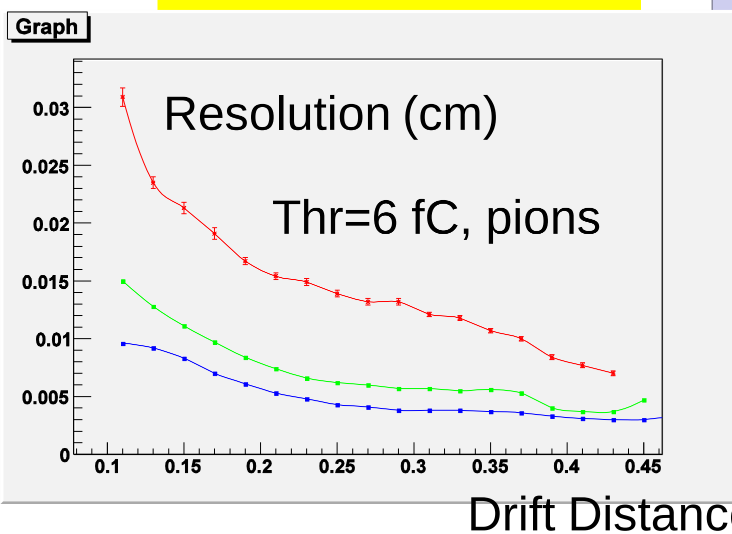
Residuals





full length Straw Prototype: 2.1 m long Operated in Vacuum



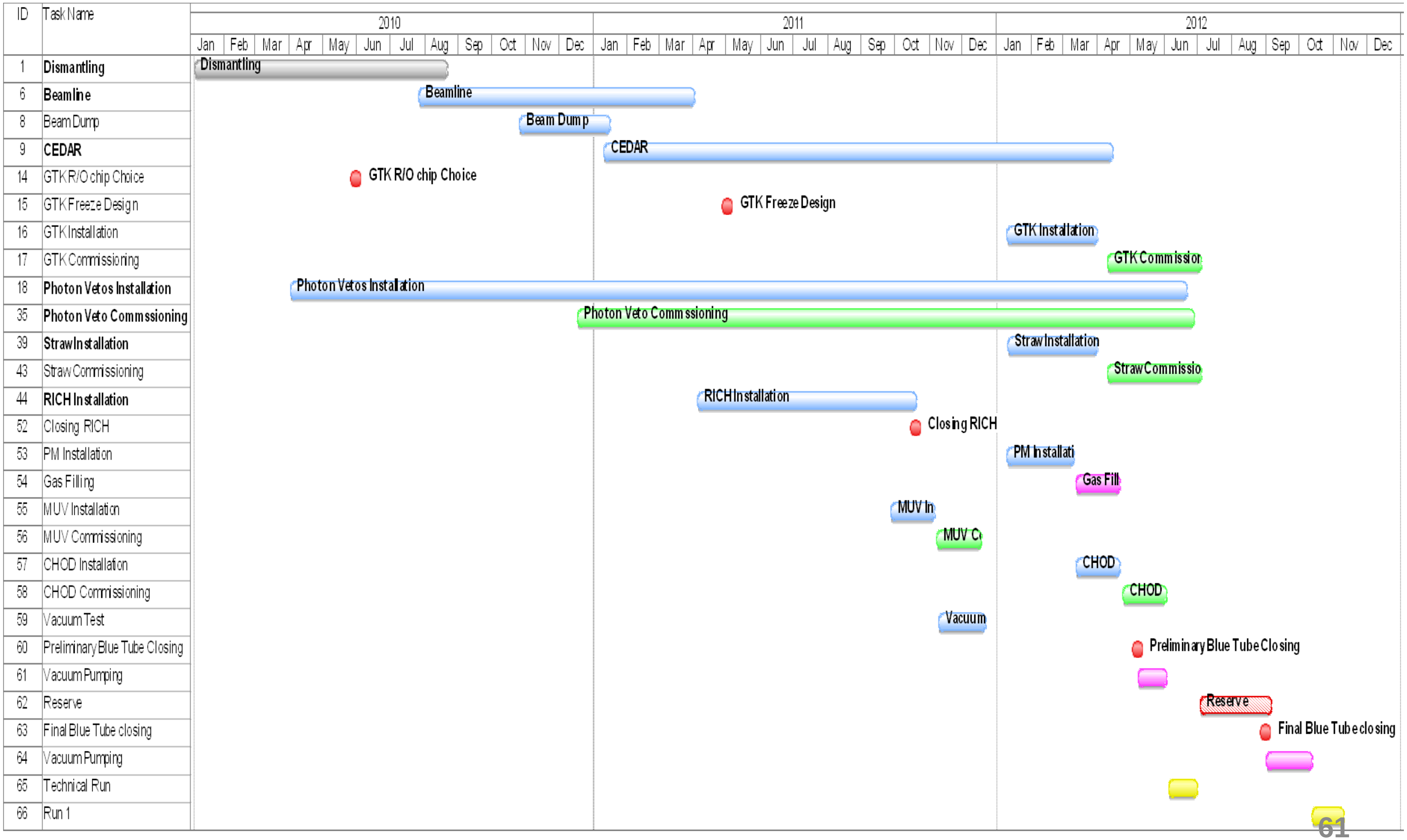


2200V
2300V
2400V

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

NA62 Planning

Preliminary



Wrap-up of Part 1

- We have reviewed how the "Standard Model" was largely built studying the properties of the strange mesons
- We have seen that ε_K provides one of the strongest constraints on the Unitarity Triangle...
- …And that perhaps soon (3 years?) LQCD could finally provide a precise prediction for ε'
- Finally, we have reviewed the strong experimental program which is underway to study ultra-rare kaon decays