

Mario, Enrico & i mesoni K

Una breve storia della violazione di CP,
del mescolamento e dei decadimenti
rari dei mesoni K vista attraverso
alcuni dei contributi di **Mario Calvetti**
ed **Enrico Iacopini**



Augusto Ceccucci/CERN

I K ed il Modello Standard

- Oggi tendiamo a dimenticarci, ma molti aspetti del Modello Standard (MS) sono stati costruiti sulle proprietà dei mesoni K
 - Violazione di Parità (paradosso θ - τ)
 - Produzione forte e decadimento debole
 - La stranezza ed il modello a quark
 - Violazione di CP nei $K_L \rightarrow 2\pi$: superdebole o millidebole?
 - Assenza delle FCNC \rightarrow Meccanismo di GIM
 - Violazione di CP Diretta ($\varepsilon'/\varepsilon \neq 0$)
 - Limiti più stringenti sull'esistenza di fisica oltre MS

Stranezza (Gell Mann, Pais)

$$\vartheta_0 \quad S = +1$$

Secondo Jim Cronin, durante un seminario a Chicago, Gell Mann aveva introdotto S come numero quantico Conservato dalle interazioni forti e violato dalle interazioni deboli con entrambi gli stati $S = +/-1$ che potevano decadere in $\pi^+\pi^-$

$$\bar{\vartheta}_0 \quad S = -1$$

θ

E. Fermi: “ If **both** decay into $\pi^+ \pi^-$, how can they be different?”

$$\vartheta_1 = \frac{1}{\sqrt{2}} (\vartheta_0 + \bar{\vartheta}_0) \quad \rightarrow \pi\pi$$

$$\vartheta_2 = \frac{1}{\sqrt{2}} (\vartheta_0 - \bar{\vartheta}_0) \quad \rightarrow \pi\pi\pi$$

La conservazione di C [poi di CP dal 1957...] distingue i due autostati

$$\theta_{1,2} \rightarrow K_{1,2}$$

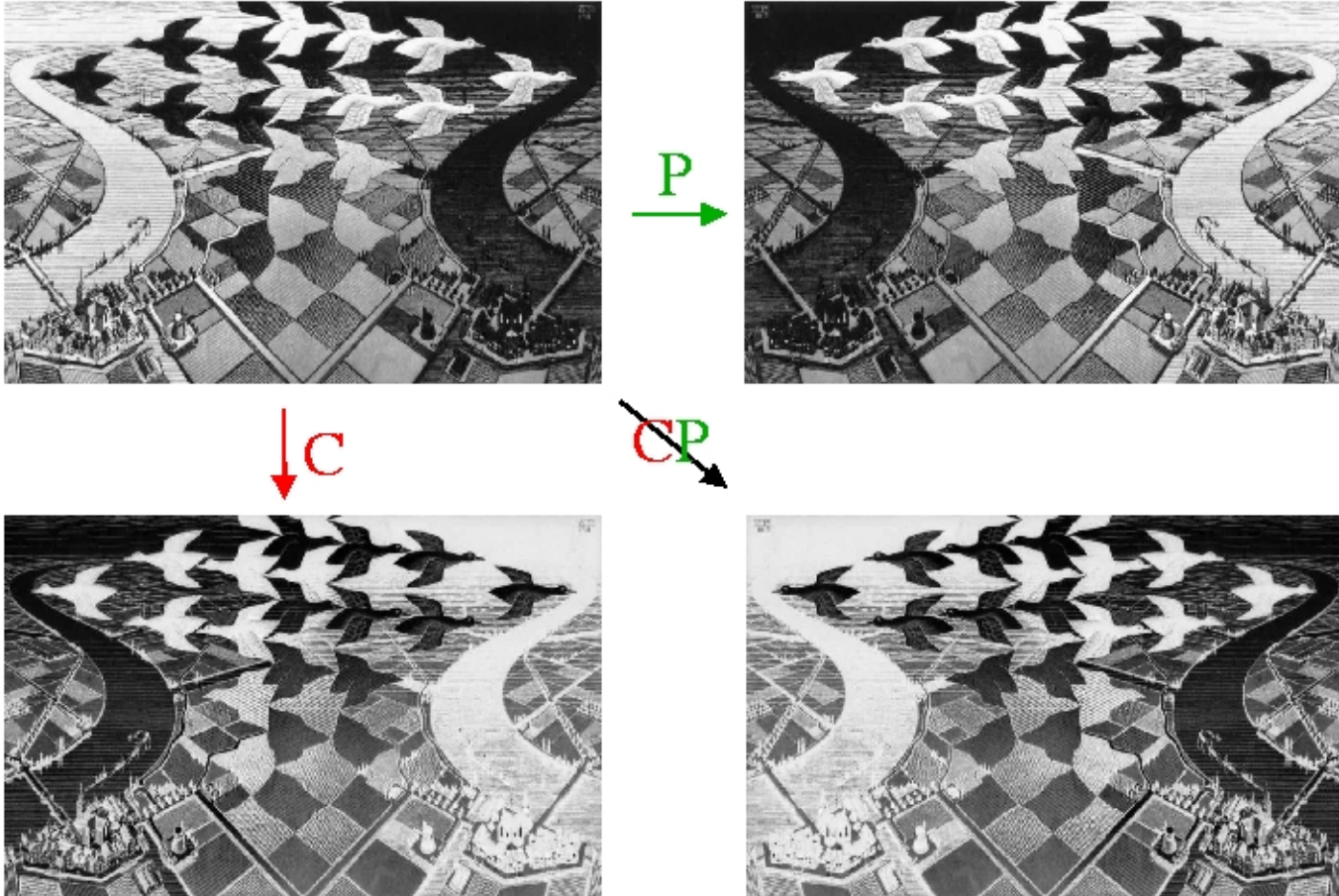
P & C



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....

Per salvare la simmetria dello spazio alla luce della violazione di Parità Landau ipotizza la simmetria per l'operazione combinata di Parità e Coniugazione di carica (P e C)

Simmetria CP

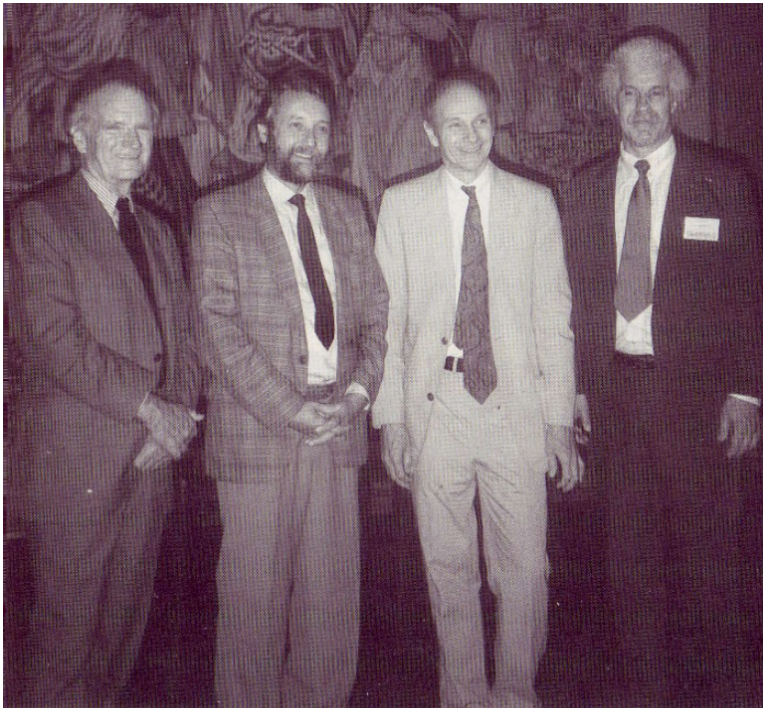


From Gino Isidori:

<http://scienzapertutti.Inf.infn.it/P1/schedaCP.html>

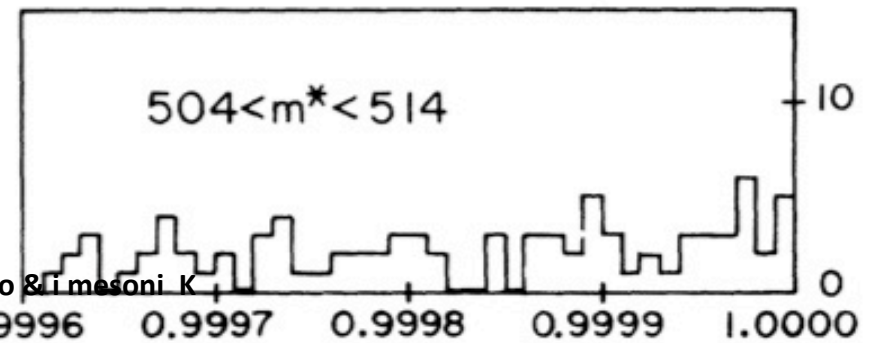
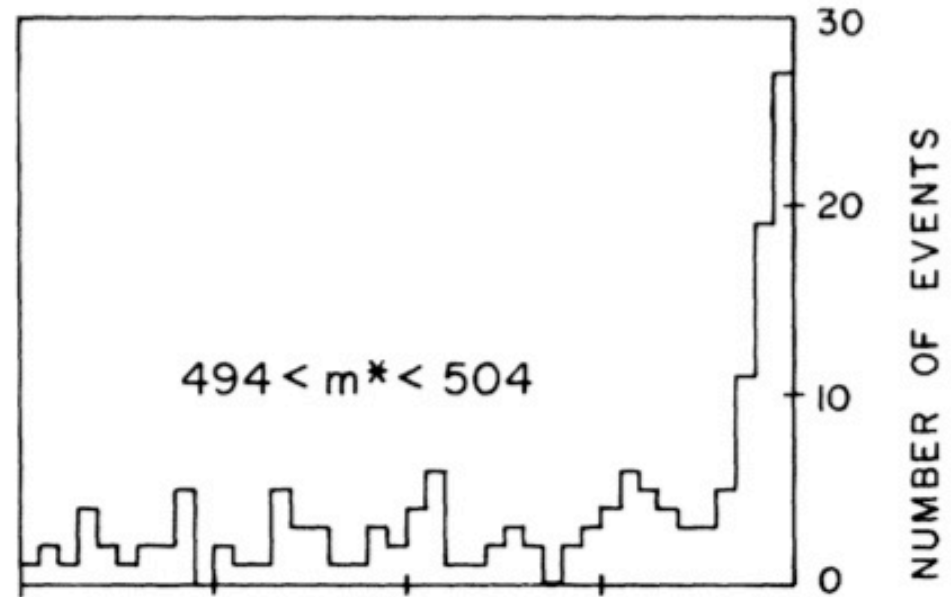
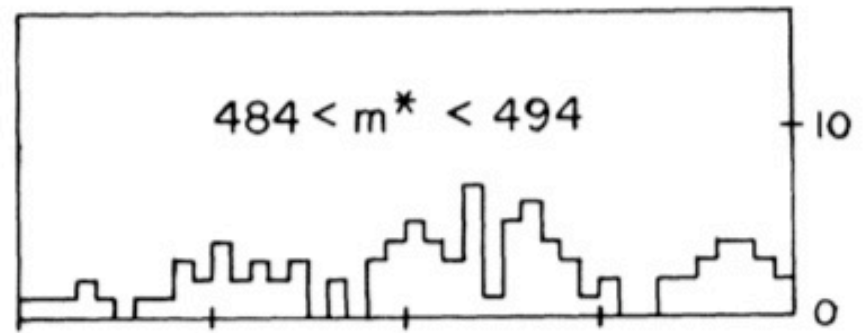
1964

5211 $K_2 \rightarrow \pi^+ + \pi^-$ candidates



From left : Val Fitch, René Turlay, Jim Cronin and Jim Christenson.

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The ratio of the decay amplitudes of K_2 to K_1 to $\pi^+ \pi^-$
 $\pi^0 \pi^0$ is given by:

$$\eta_{+-} = \epsilon + \frac{i}{\sqrt{2}} \frac{\text{Im } A_2}{A_0} e^{i(\delta_2 - \delta_0)} = \epsilon + \epsilon'$$

$$\eta_{00} = \epsilon - i\sqrt{2} \frac{\text{Im } A_2}{A_0} e^{i(\delta_2 - \delta_0)} = \epsilon - 2\epsilon'$$

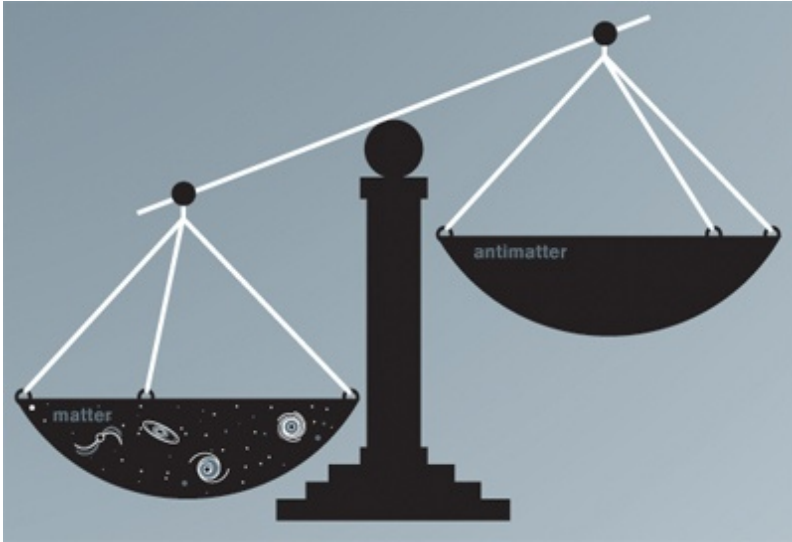
**By 1965 $|\eta_{+-}|$ measured to be
 $(2.04 \pm 0.14) \times 10^{-3}$
 and coherence established**

Jim Cronin

If $\epsilon' \gg \epsilon$ then $|\eta_{00}| = 2 |\eta_{+-}|$

If ϵ'/ϵ small then $|\eta_{00}/\eta_{+-}| = |1 - 3\epsilon'/\epsilon|$

Condizioni di Sakharov



Andrei Sakharov (1967)

Per permettere uno sbilanciamento fra Materia e Antimateria, si devono soddisfare **tre condizioni**:

1. Violazione del Numero Barionico
2. Non-equilibrio termodinamico
3. Violazione delle simmetrie **C & CP**



Scanned at the American Institute of Physics

La violazione di CP ed i mesoni K neutri

$$|K_{S,L}\rangle = \frac{1}{\sqrt{(1+|\varepsilon|^2)}} [(1+\varepsilon)|K^0\rangle \pm (1-\varepsilon)|\bar{K}^0\rangle] \quad \phi_{SW} \approx \tan^{-1} \frac{2(m_L - m_S)}{\Gamma_S - \Gamma_L} \approx (43.52 \pm 0.05)^\circ$$

$$\eta_{+-} = \varepsilon + \varepsilon' \quad \eta_{+-} = A(K_L^0 \rightarrow \pi^+\pi^-) / (K_S^0 \rightarrow \pi^+\pi^-)$$

$$\eta_{00} = \varepsilon - 2\varepsilon' \quad \eta_{00} = A(K_L^0 \rightarrow \pi^0\pi^0) / (K_S^0 \rightarrow \pi^0\pi^0)$$

$$\varepsilon = \tilde{\varepsilon} + i \frac{\text{Im} A_0}{\text{Re} A_0}$$

Violazione Indiretta

$$\sqrt{2}\varepsilon' = ie^{i(\delta_2 - \delta_0)} (\text{Re} A_2 / \text{Re} A_0) \times (\text{Im} A_2 / \text{Re} A_2 - \text{Im} A_0 / \text{Re} A_0)$$

$$|\eta_{00} / \eta_{+-}|^2 \approx 1 - 6 \text{Re} \varepsilon' / \varepsilon = 1 - 6\varepsilon' / \varepsilon$$

Violazione Diretta

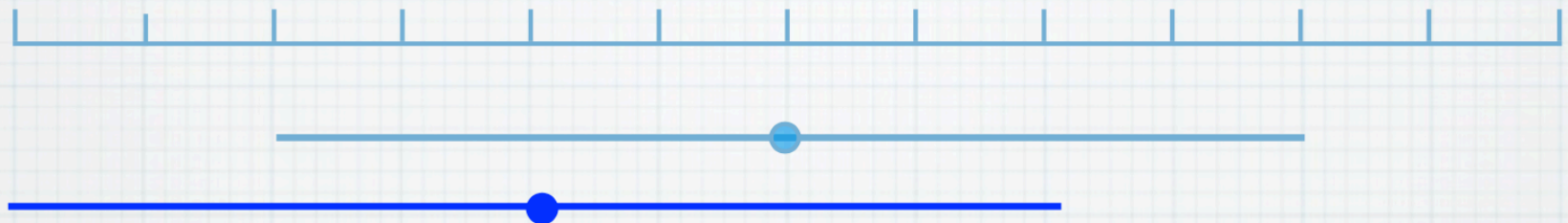
Taku Yamanaka

In mid 1970's

 $\text{Re } \varepsilon'/\varepsilon$
-0.03

0

0.03

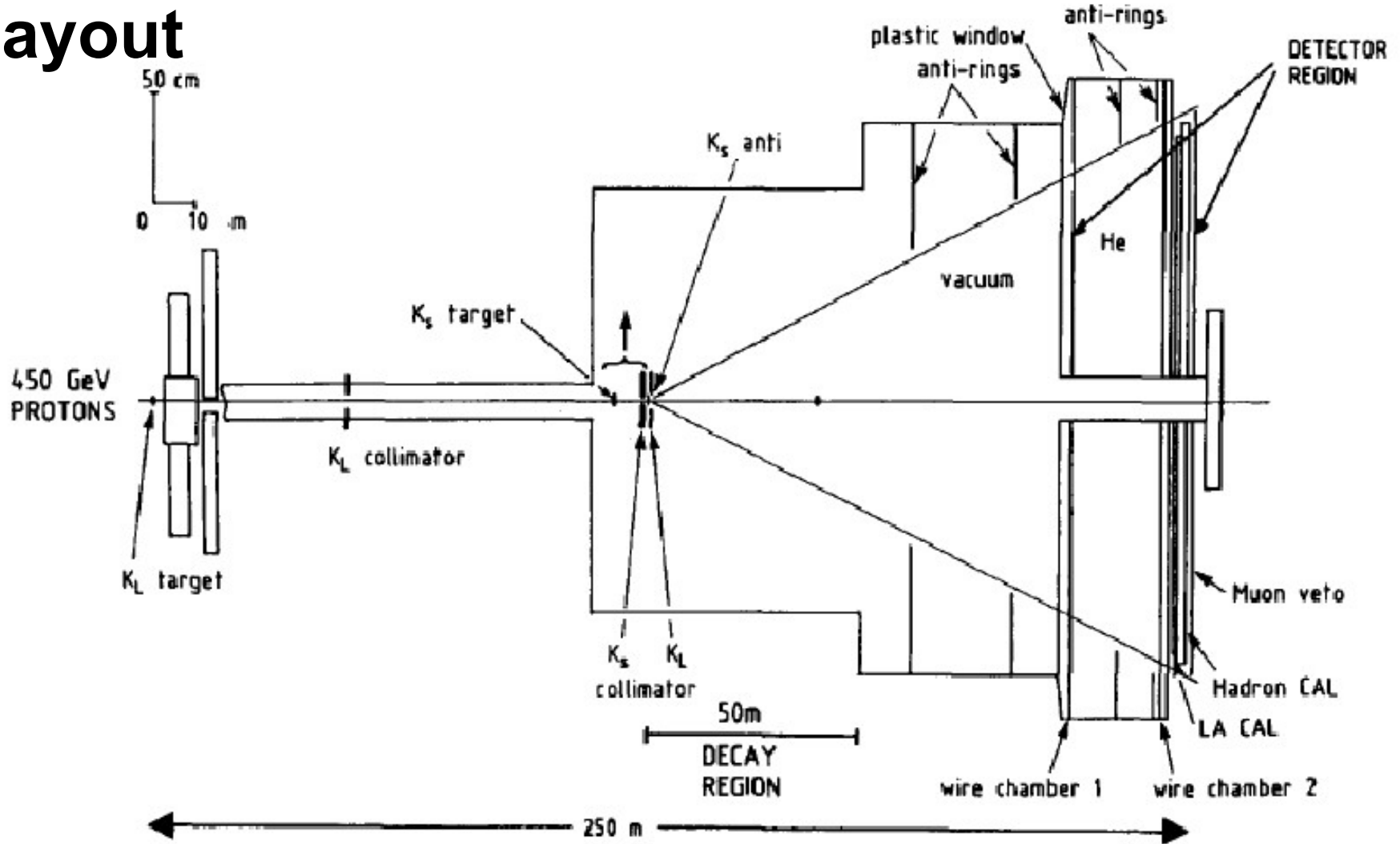


Kleinknecht, *Ann. Rev. Nucl. Sci.*, 26, 1 (1976)

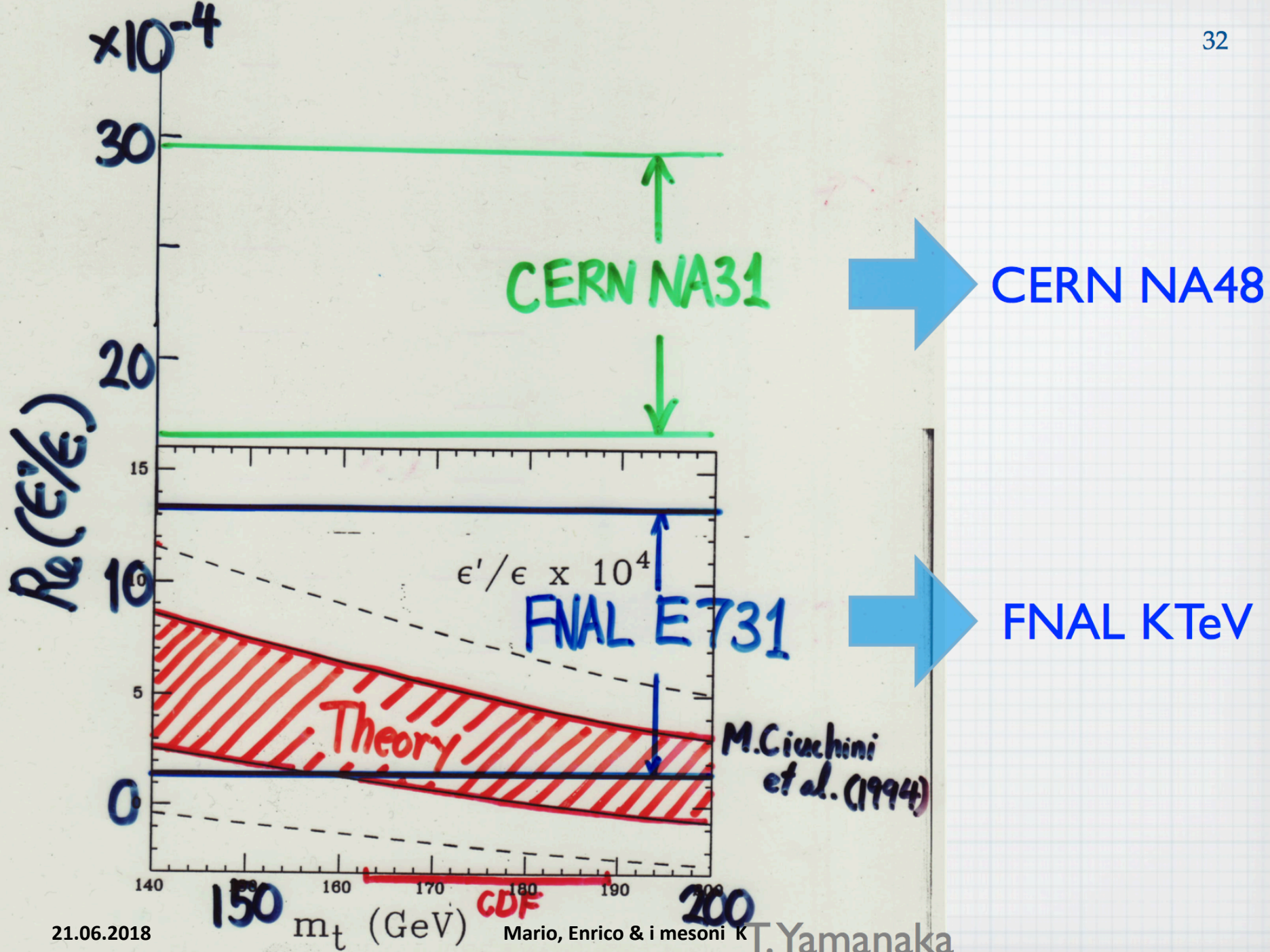
- * “It is not easy to improve substantially the experimental precision. A decision between superweak and milliweak models of CP violation will therefore probably have to come from other experimental information **outside the K^0 system**”

CERN NA31

layout



Alternating K_S and K_L beams with movable K_S target



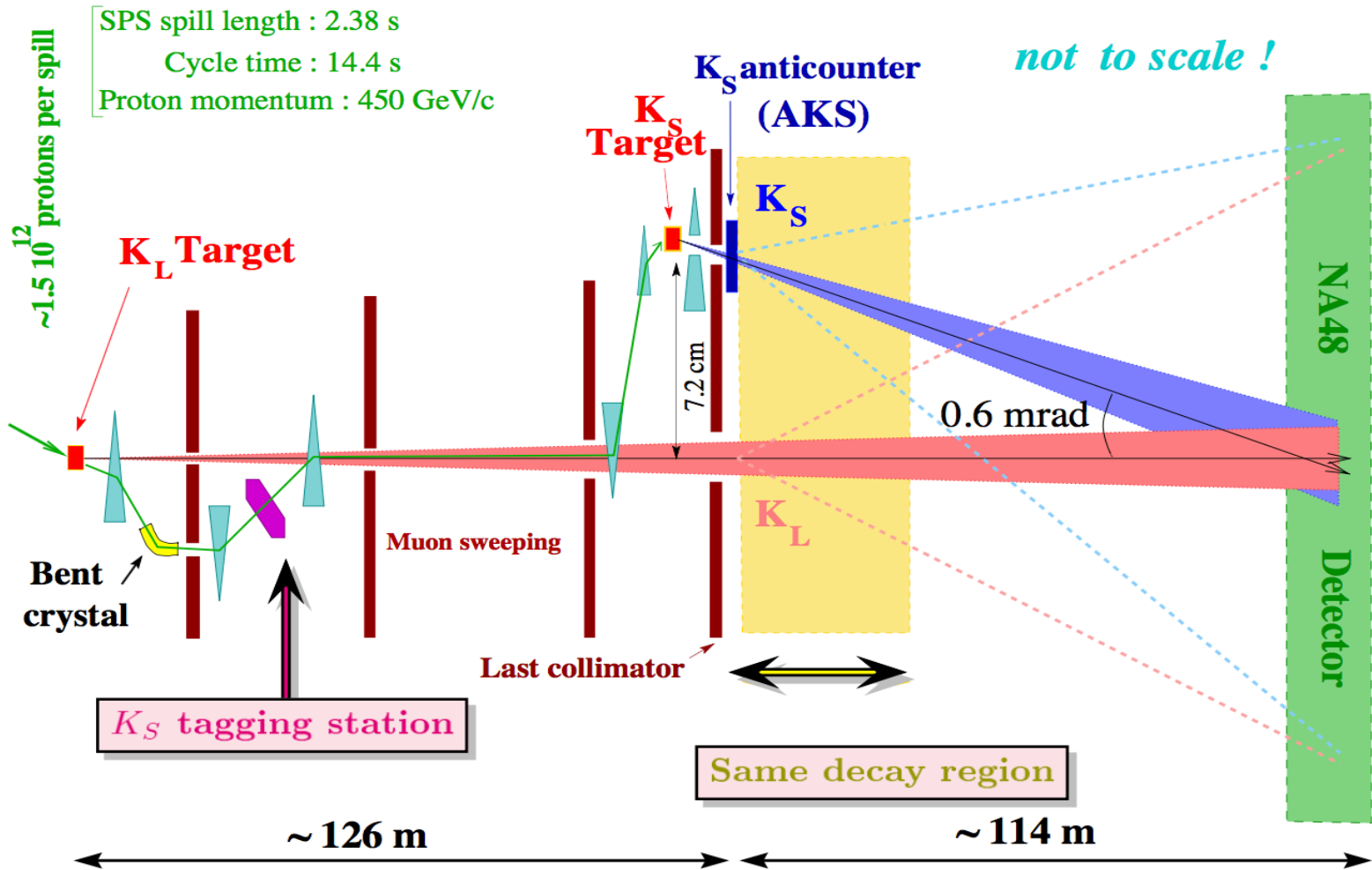
150

m_t (GeV)

CDF

200

NA48 simultaneous and collinear K_S and K_L beams



K_S and K_L beams are distinguished by proton tagging upstream of the K_S target

NA48 detector

Main subdetectors:

◆ Magnetic spectrometer (4 DCHs):

- high efficiency;
- $\Delta p/p = 1.0\% \oplus 0.044\% * p$ [GeV/c]

◆ Hodoscope

- fast trigger;
- precise time measurement ($\sigma_t = 150$ ps).

◆ Liquid Krypton EM calorimeter (LKr)

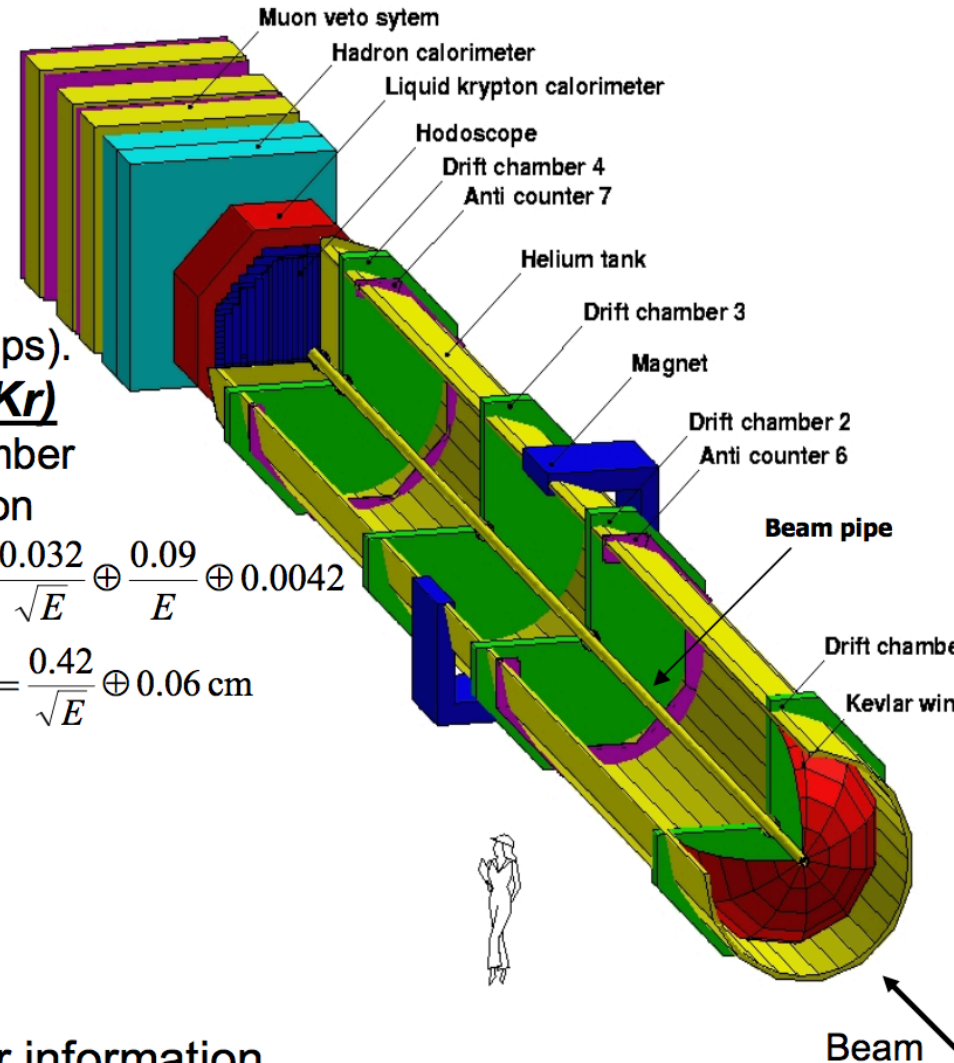
- Quasi-homogeneous ionization chamber
- Active volume of ~ 10 m³ liquid krypton
- Energy resolution (E in GeV): $\frac{\sigma(E)}{E} = \frac{0.032}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.0042$
($\sigma(E) \approx 142$ MeV for $E = 10$ GeV)
- Space resolution (E in GeV): $\sigma_x = \sigma_y = \frac{0.42}{\sqrt{E}} \oplus 0.06$ cm
($\sigma(x) = \sigma(y) \approx 1.5$ mm for $E = 10$ GeV)

◆ Muon veto system

- 2+1 planes 25x25 cm² $\sigma(t) = 350$ ps

Trigger:

- ◆ L1 Hodoscope, DCH multiplicity
- ◆ L2 ON-line processing of DCH & LKr information



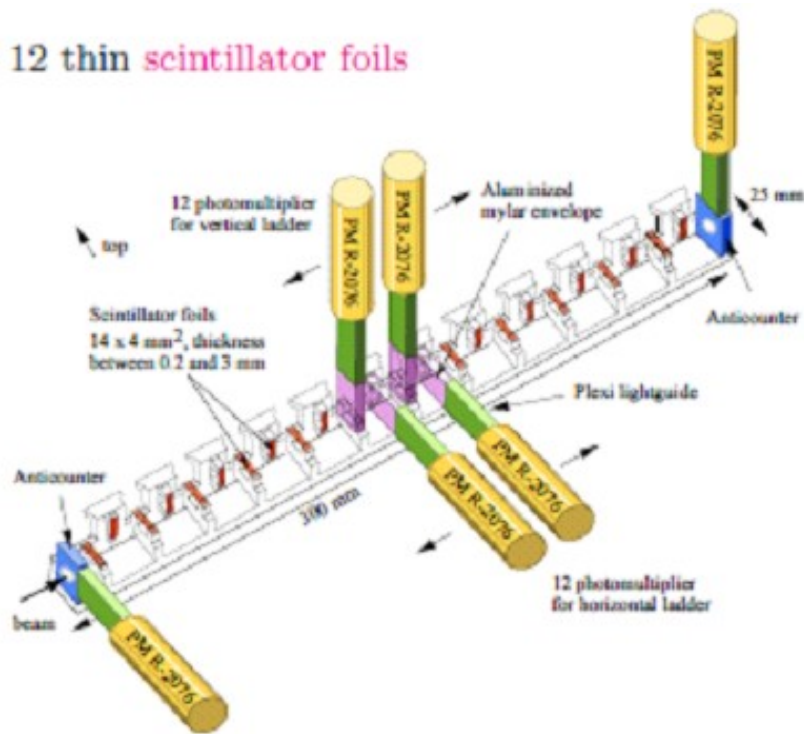
NA48, circa 1995



Grazie alla Leadership di Mario come Spokesperson NA48 decolla

Tagger protoni bersaglio K_S

2×12 thin scintillator foils

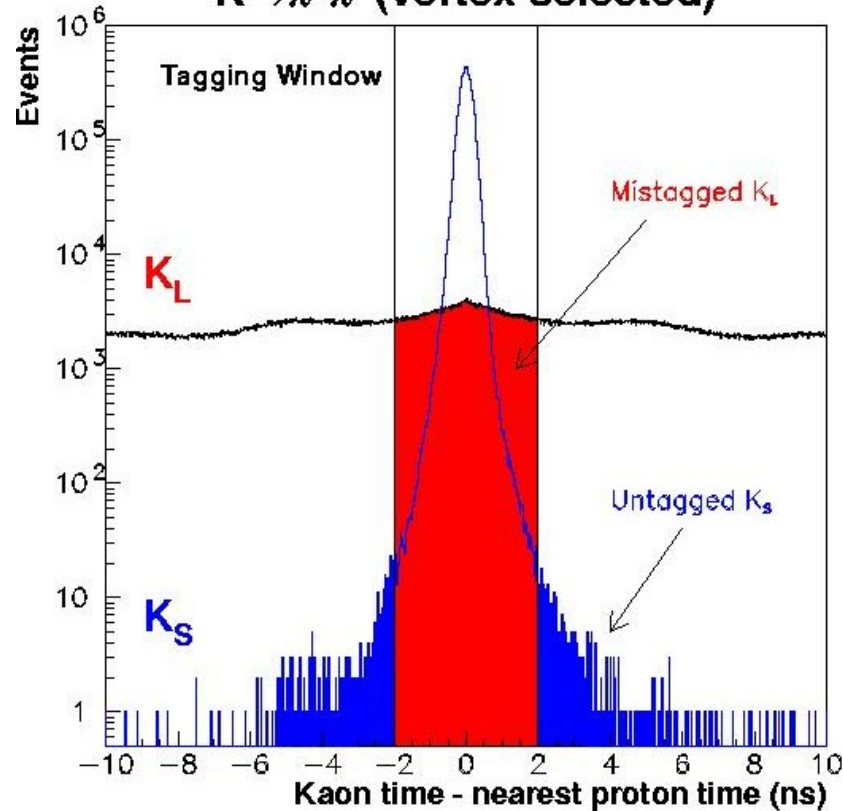


Proton rate: ≈ 30 MHz

- Raccolta simultanea dei quattro modi di decadimento
- Distinguere il K_S “taggando” il protone prima che incida sul bersaglio del fascio corto

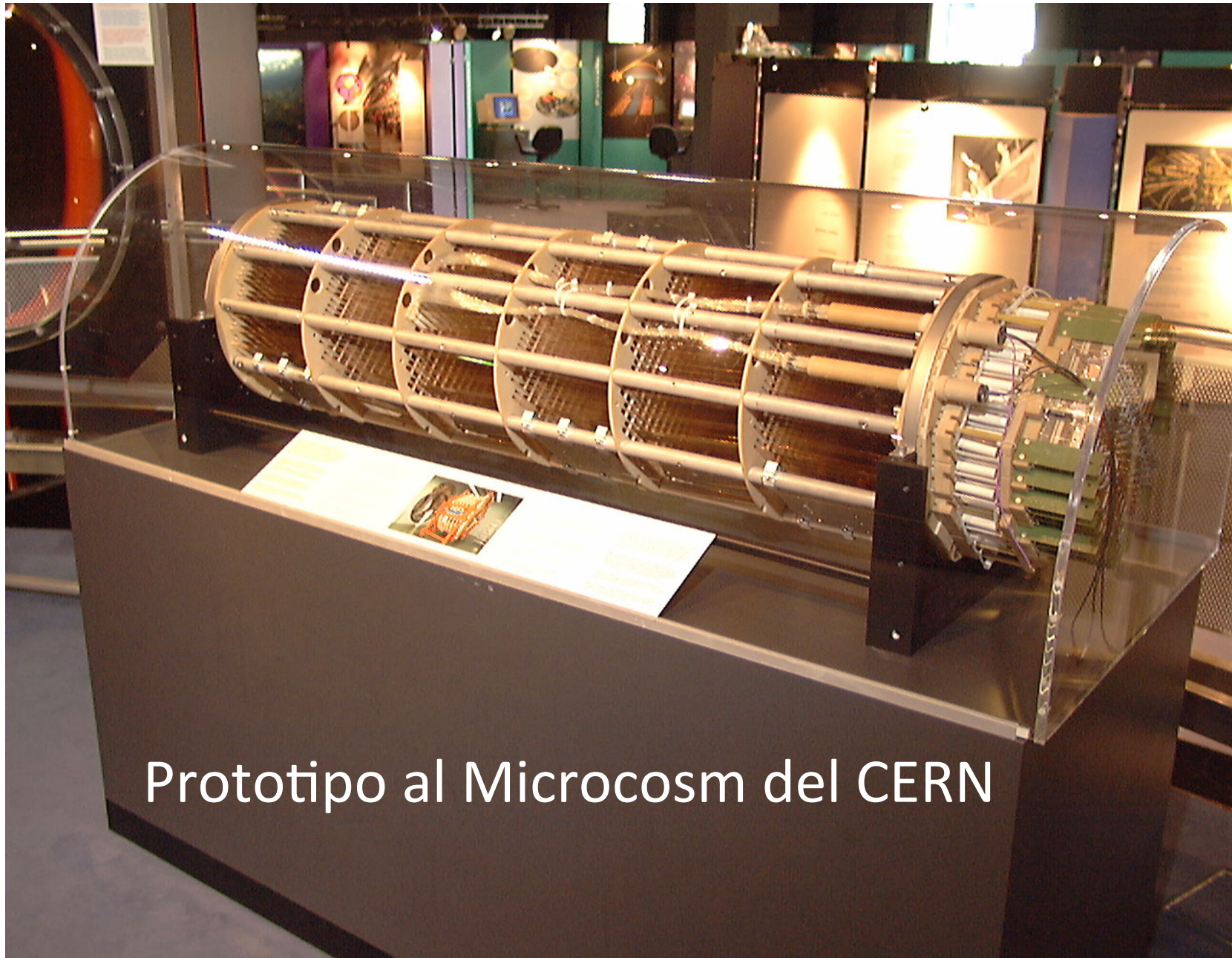
Mario aveva chiarissima l'importanza del tagging e svolse un ruolo cruciale su tutti gli aspetti di Timing di NA48

$K \rightarrow \pi^+ \pi^-$ (vertex selected)



Mario e il calorimetro LKr

- Mario diventa **“spokesperson”** di **NA48** per mettere un po d’ordine...
- Dopo aver dato contributi fondamentali al tagger, all’hadroscopio ed al trigger, e` ora di concentrarsi sulla costruzione del **calorimetro a krypton liquido (LKr)**...
- Dopo aver creato un forte gruppo di fisica dei K a **Perugia** si sposta a **Firenze** dove il successo si ripete

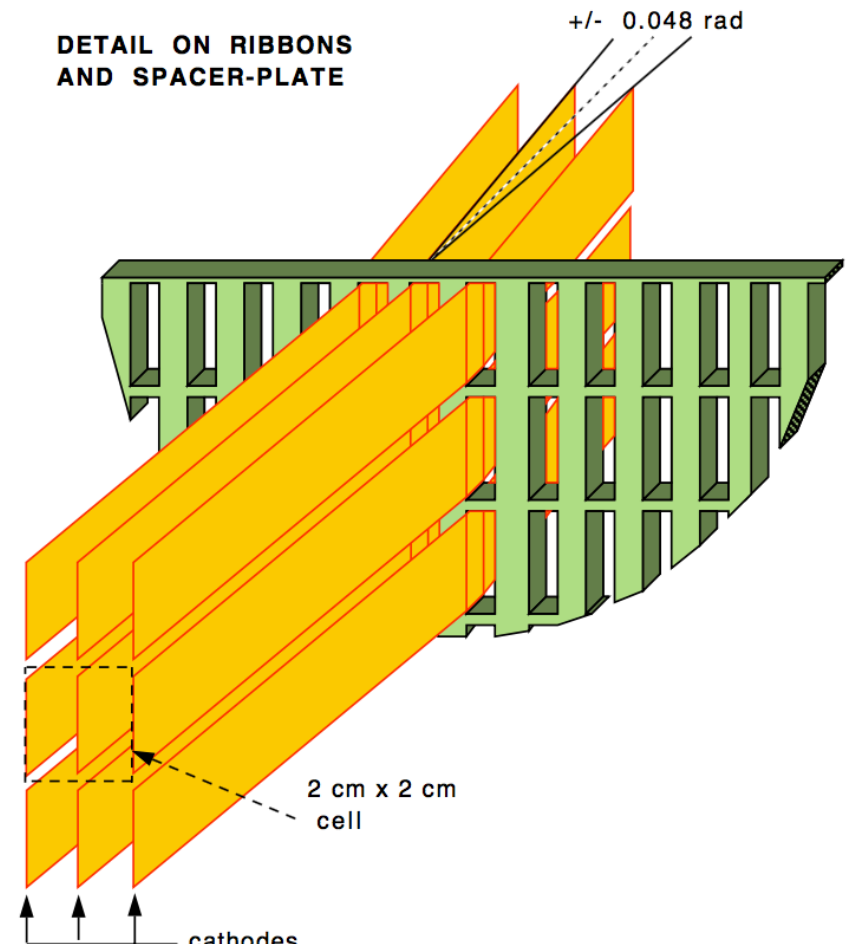


Prototipo al Microcosm del CERN

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NA48: Struttura Elettrodi LKR & Hodoscopio Neutro



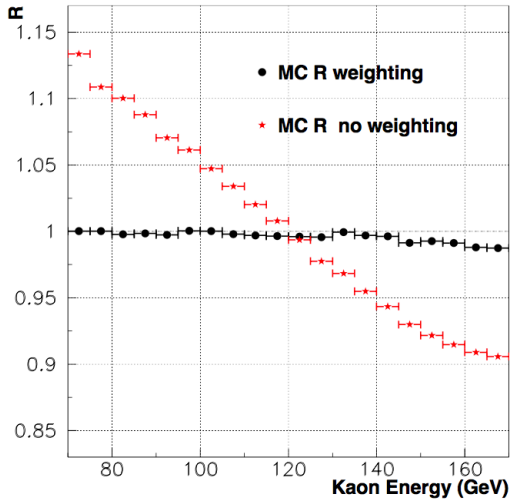
Soddisfatti e Orgogliosi



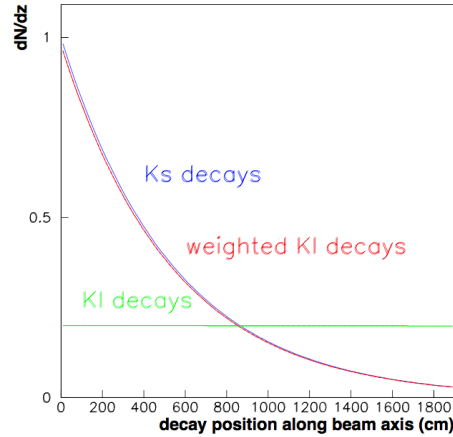
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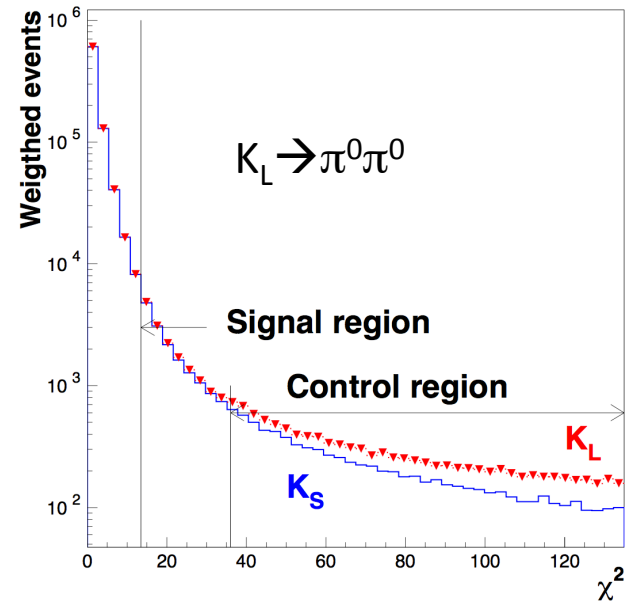
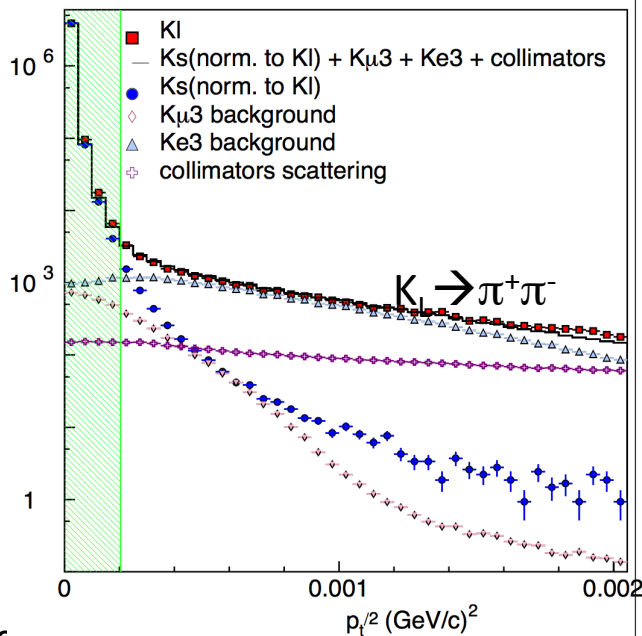
Minimizzazione correzione accettazione e fondi



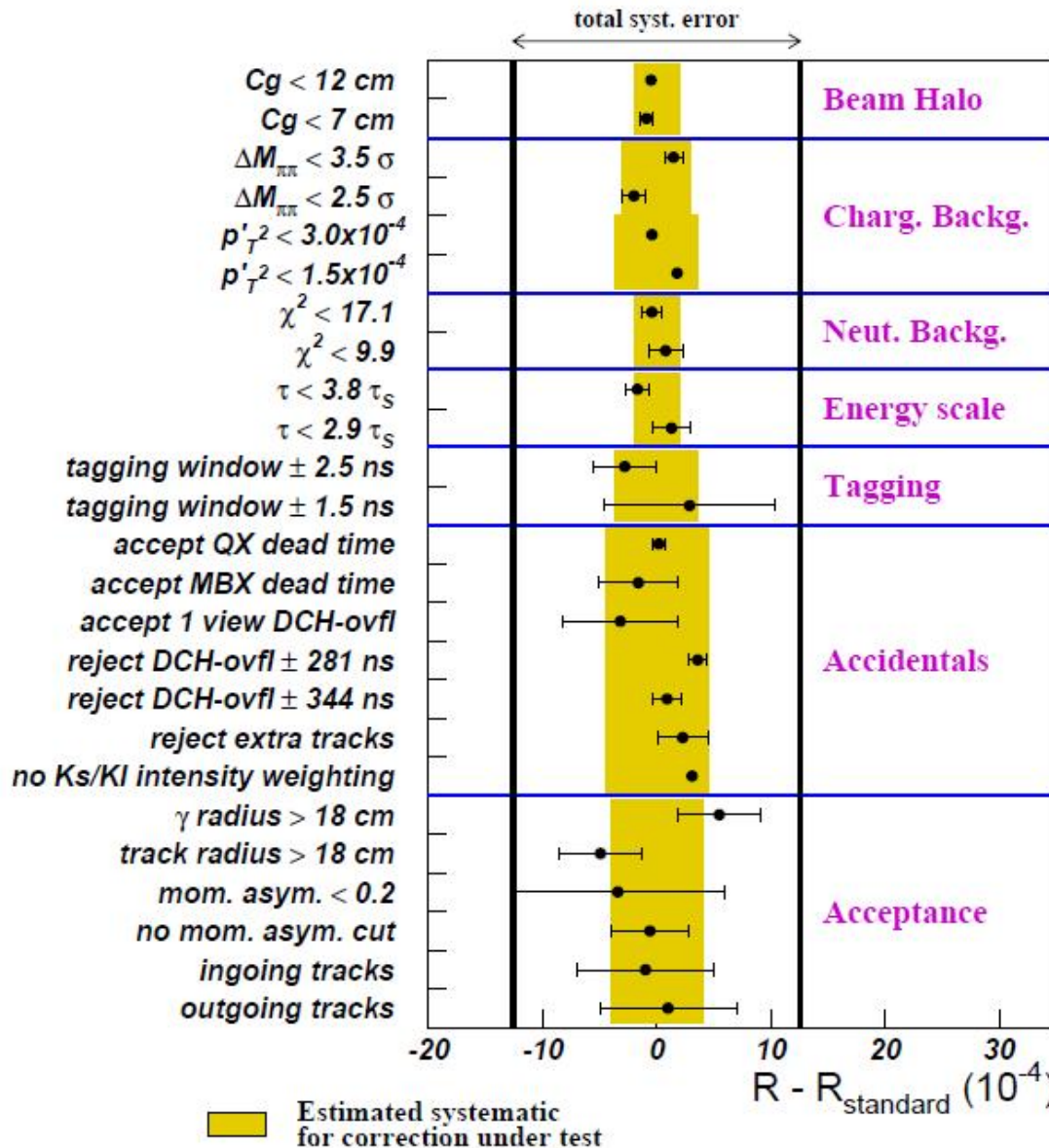
e fondi



Weight K_L events with
 $W \approx e^{-t}(1/\tau_{K_S} - 1/\tau_{K_L})$
 \Rightarrow Same decay vertex distribution for K_S and **weighted K_L**
Gain : correction decreased
Price : increase in stat. error



NA48 SYSTEMATICS



Quattro anni di presa dati
(1997-98-99, 2001)

Risultato finale NA48
(2002):

$$\epsilon' / \epsilon = (14.7 \pm 2.2) \cdot 10^{-4}$$

About 1990 massive experiments built at CERN and Fermilab

Final results presented in 2002

Epsilon prime is non-zero!

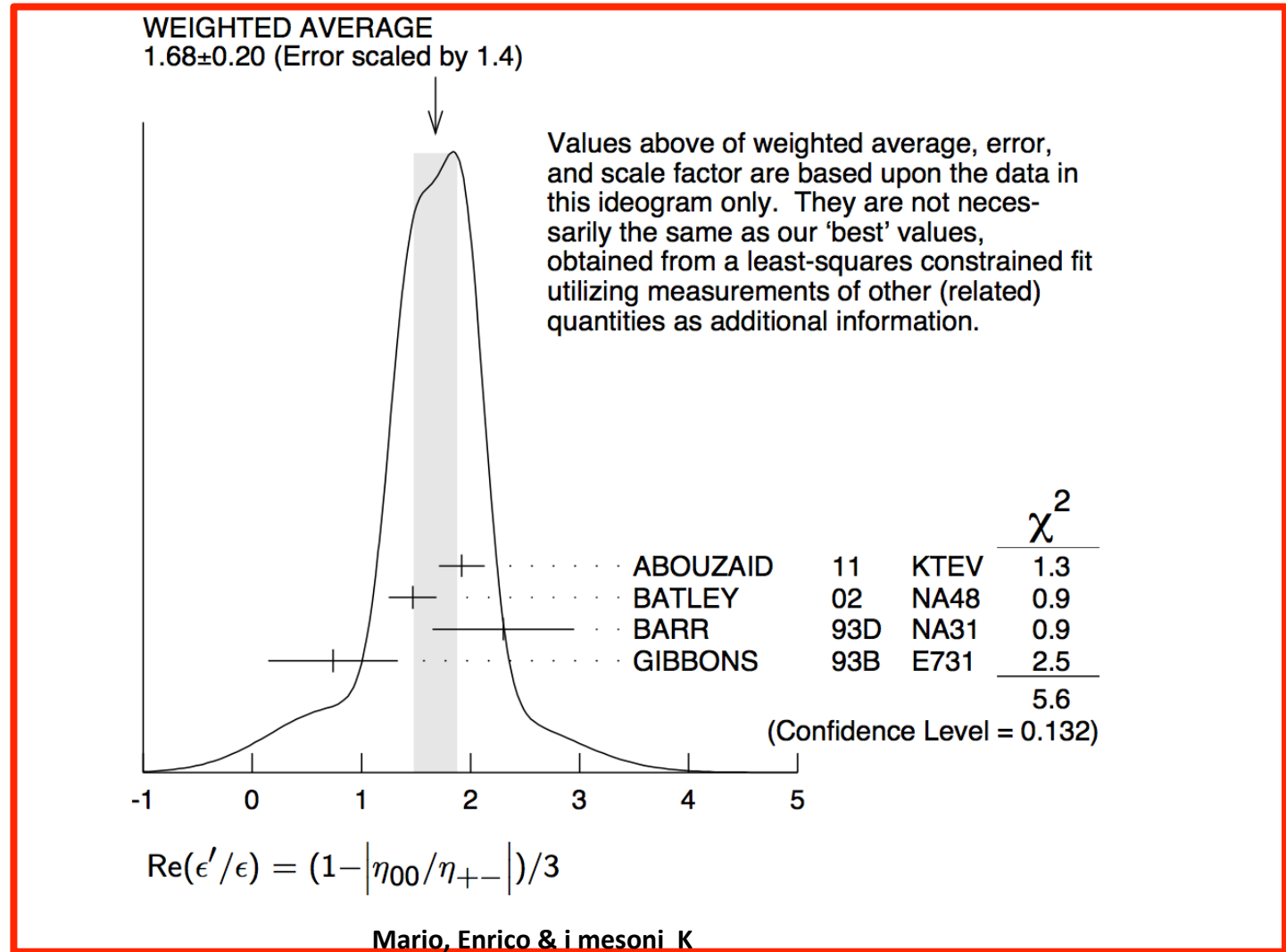
$$\frac{\Gamma(K_L \rightarrow \pi^+ \pi^-) / \Gamma(K_S \rightarrow \pi^+ \pi^-)}{\Gamma(K_L \rightarrow \pi^0 \pi^0) / \Gamma(K_S \rightarrow \pi^0 \pi^0)} = \left| \frac{\eta_{+-}}{\eta_{00}} \right|^2 \approx 1 + 6 \operatorname{Re}(\epsilon'/\epsilon).$$

$$\begin{aligned} \operatorname{Re}(\epsilon'/\epsilon) &= [19.2 \pm 1.1(\text{stat}) \pm 1.8(\text{syst})] \times 10^{-4} && \text{KTEV} \\ &= [19.2 \pm 2.1] \times 10^{-4}. \end{aligned}$$

$$\begin{aligned} \operatorname{Re}(\epsilon'/\epsilon) &= (14.7 \pm 1.4 \pm 0.9 \pm 1.5) \times 10^{-4} && \text{NA48} \\ &= (14.7 \pm 2.2) \times 10^{-4} \end{aligned}$$

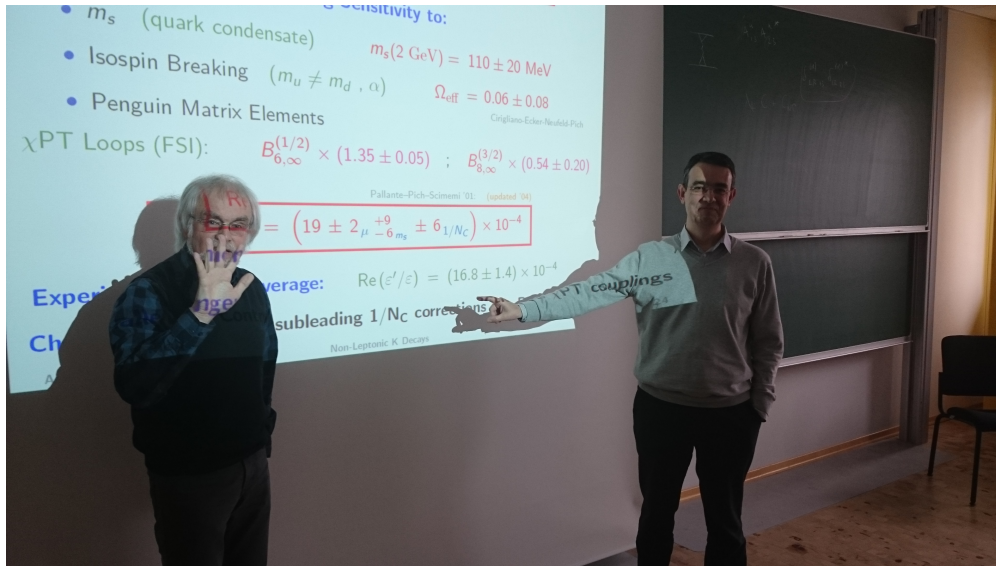
1.66 ±0.23 OUR FIT	Error includes scale factor of 1.6.
1.68 ±0.20 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.
1.92 ±0.21	¹ ABOUZAID 11 KTEV Assuming CPT
1.47 ±0.22	BATLEY 02 NA48
0.74 ±0.52 ±0.29	GIBBONS 93B E731
• • • We use the following data for averages but not for fits. • • •	
2.3 ±0.65	^{2,3} BARR 93D NA31

ε' / ε PDG 2018

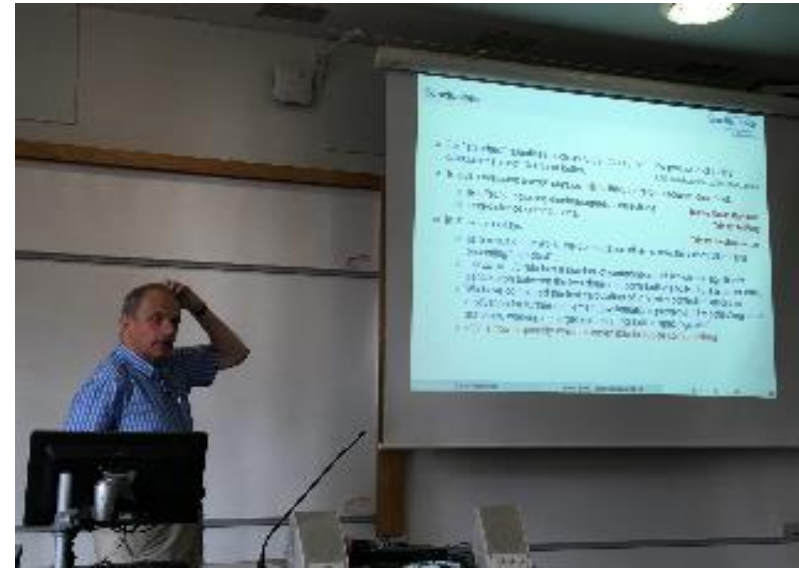


Re(ϵ/ϵ'): Theoretical Predictions

$$\frac{\epsilon'}{\epsilon} = 10^{-4} \left[\frac{\text{Im } \lambda_t}{1.4 \cdot 10^{-4}} \right] \left[a(1 - \hat{\Omega}_{eff})(-4.1 + 24.7 B_6^{(1/2)}) + 1.2 - 10.4 B_8^{(3/2)} \right]$$



A. Buras and T. Pich, MITP Mainz, “NA62 Physics Handbook”



C. Sachruda, Kaon2016:
“ ϵ'/ϵ is now a quantity which is amenable to lattice calculations”

Experiment: 1.7×10^{-3}

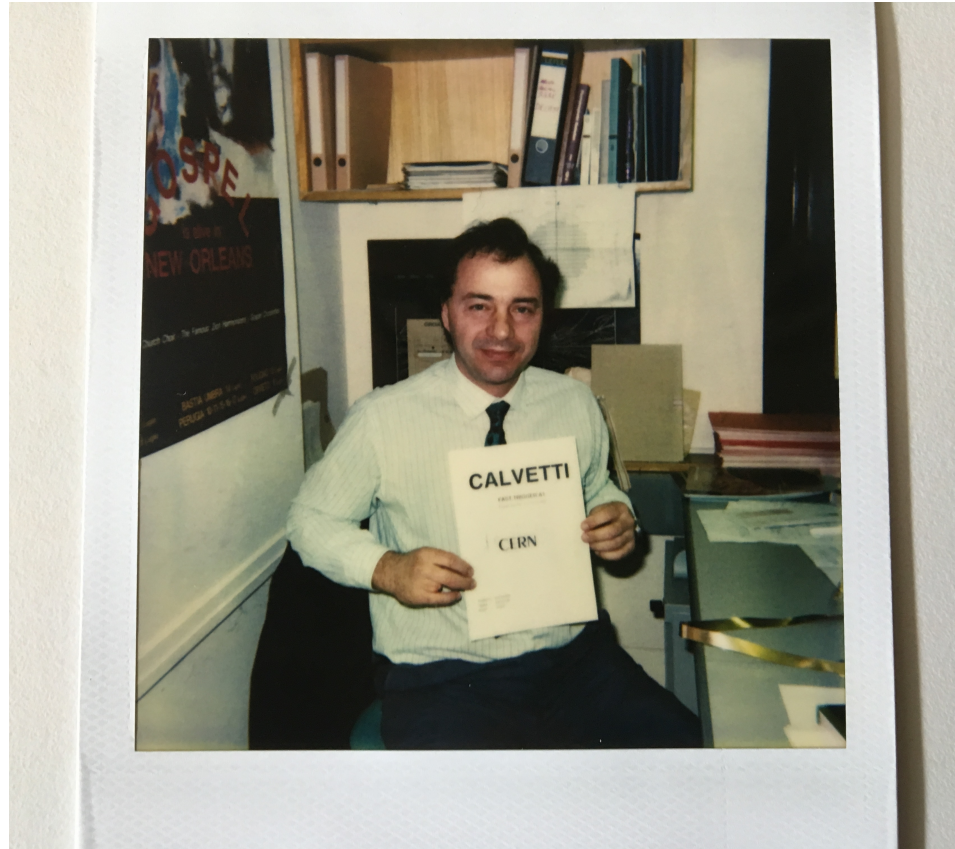
Prediction: 0.5 or 1.9 $\times 10^{-3}$?

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Ascoltatore Sempre Attento

- Mario ascolta sempre con grande attenzione
- Sei sempre sotto esame: **vuole realmente capire se quello che dici e` sensato**
-Ricordo ancora quando lo convinsi (davvero?) di come valesse la pena studiare CPT nel 2000 quando non c'erano le camere a filo
- Ne uscì un bell'articolo... vedi pagina seguente



CPT?

NA48/1 PLB 610 (2005)

$$(1 + i \tan \phi_{SW}) [\text{Re}(\epsilon) - i \text{Im}(\delta)] = \sum_{\text{final states } f} A(K_L \rightarrow f)^* A(K_S \rightarrow f) / \Gamma_S$$

Relazione di Bell-Steinberger

$$\epsilon_S = \epsilon + \delta$$

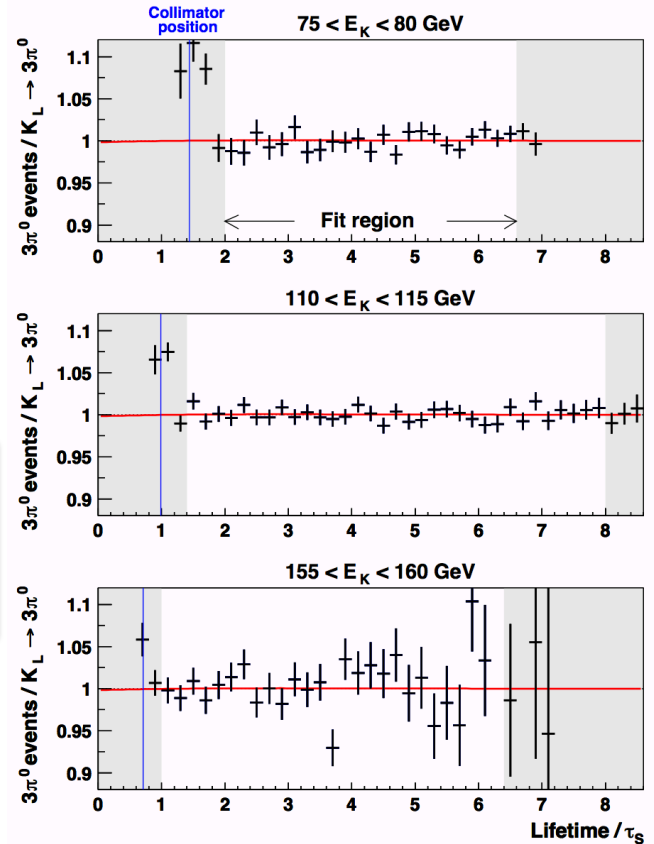
$$\epsilon_L = \epsilon - \delta$$

α_f	$10^3 \times \text{Re}(\alpha_f)$	$10^3 \times \text{Im}(\alpha_f)$
$\alpha_{+-} = \eta_{+-} \text{Br}(K_S \rightarrow \pi^+ \pi^-)$	1.146 ± 0.015	1.084 ± 0.016
$\alpha_{00} = \eta_{00} \text{Br}(K_S \rightarrow \pi^0 \pi^0)$	0.511 ± 0.008	0.488 ± 0.008
$\alpha_{+\gamma} = \eta_{+\gamma} \text{Br}(K_S \rightarrow \pi^+ \pi^- \gamma)$	0.003 ± 0.000	0.003 ± 0.000
$\alpha_{l3} = 2 \frac{\text{Im} \alpha_f}{\Gamma_L} \text{Br}(K_L \rightarrow \pi \nu) \times$ $[\text{Re}(\epsilon) - \text{Re}(y) - i(\text{Im}(x_+) + \text{Im}(\delta))]$	-0.001 ± 0.007	0.005 ± 0.006
$\alpha_{+-0} = \frac{\text{Im} \alpha_f}{\Gamma_L} \eta_{+-0}^* \text{Br}(K_L \rightarrow \pi^+ \pi^- \pi^0)$	0.000 ± 0.002	0.000 ± 0.002
$\alpha_{000} = \frac{\text{Im} \alpha_f}{\Gamma_L} \eta_{000}^* \text{Br}(K_L \rightarrow 3\pi^0)$	-0.001 ± 0.007	0.001 ± 0.008
$\sum \alpha_f$	1.658 ± 0.024	1.581 ± 0.025

$$\text{Im}(\delta) = (-0.2 \pm 2.0) \times 10^{-5},$$

$$\text{Re}(\epsilon) = (166.4 \pm 1.0) \times 10^{-5}.$$

$$m_{K^0} - m_{\overline{K^0}} = (-0.2 \pm 2.8) \times 10^{-19} \text{ GeV}/c^2,$$



$$I_{3\pi^0}(t) \propto e^{-\Gamma_L t} + |\eta_{000}|^2 e^{-\Gamma_S t}$$

$$+ 2 D(p) (\text{Re}(\eta_{000}) \cos(\Delta m t) - \text{Im}(\eta_{000}) \sin(\Delta m t))$$

$$\times e^{-\frac{1}{2}(\Gamma_S + \Gamma_L) t}$$

Decadimenti semileptonici

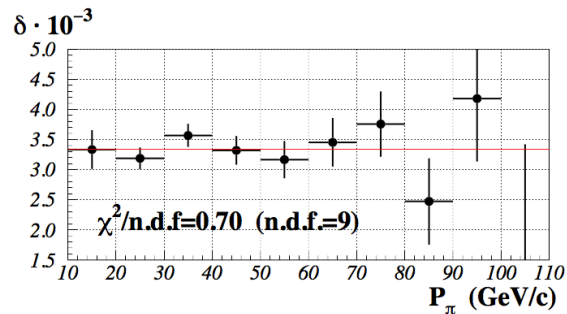
- **Mario** propose di raccogliere dei dati con un trigger di minimum bias per misurare l'asimmetria di carica nei decadimenti semileptonici del K_L sia per gli elettroni che per i muoni in modo da testare l'universalità leptonica
- Potremmo dire che Mario era in anticipo sui tempi....visto l'interesse attuale suscitato dalle "anomalie" nei B
- Tesi di dottorato di un promettente G. Ruggiero attualmente "Physics Co-ordinator" e colonna di NA62
- Purtroppo i dati vennero persi a causa di un malfunzionamento di un disco
- L'analisi dell'asimmetria non fu completata, mai pubblicata....peccato
- In compenso pubblicammo fattori di forma, BR e V_{us} ...

Tesi di G. Ruggiero

Result

• Fit

- Corrections applied in bins of pion momentum
- Constant fit until 100 GeV/c



$$\delta = (3.337 \pm 0.070_{stat} \pm 0.071_{syst}) \cdot 10^{-3}$$

• Corrections:

	$\Delta\delta$ (10^{-5})	Error (10^{-5})
E_{tot}	+27.3	± 5.9
E/P	-17.2	± 2.4
Punch through	-0.4	± 3.5
Acceptance	< 0.1	± 1.4
Background	-	< 1.0

Conclusions

• Preliminary result updated and fixed

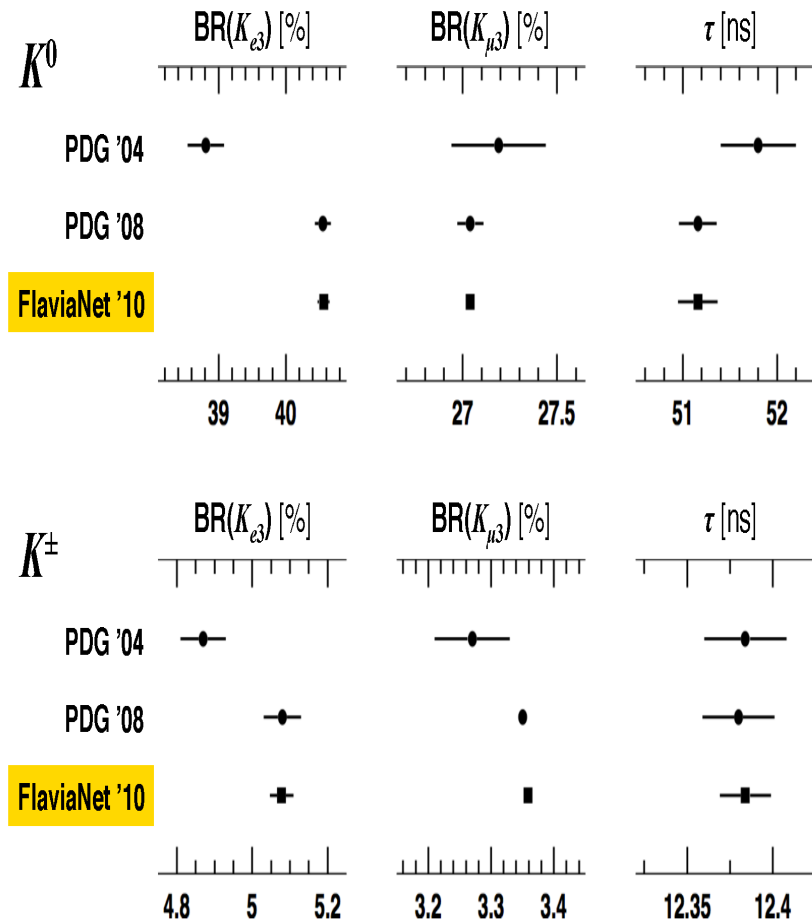
• Time-schedule to implement the "suggestions":

- The reprocessing time depends on the Firenze PC-Farm status (2 days / many months / never).
- The electron interaction effects need a new analysis: it depends on myself (1 hour / 1 year / never).

• I start to write the draft.

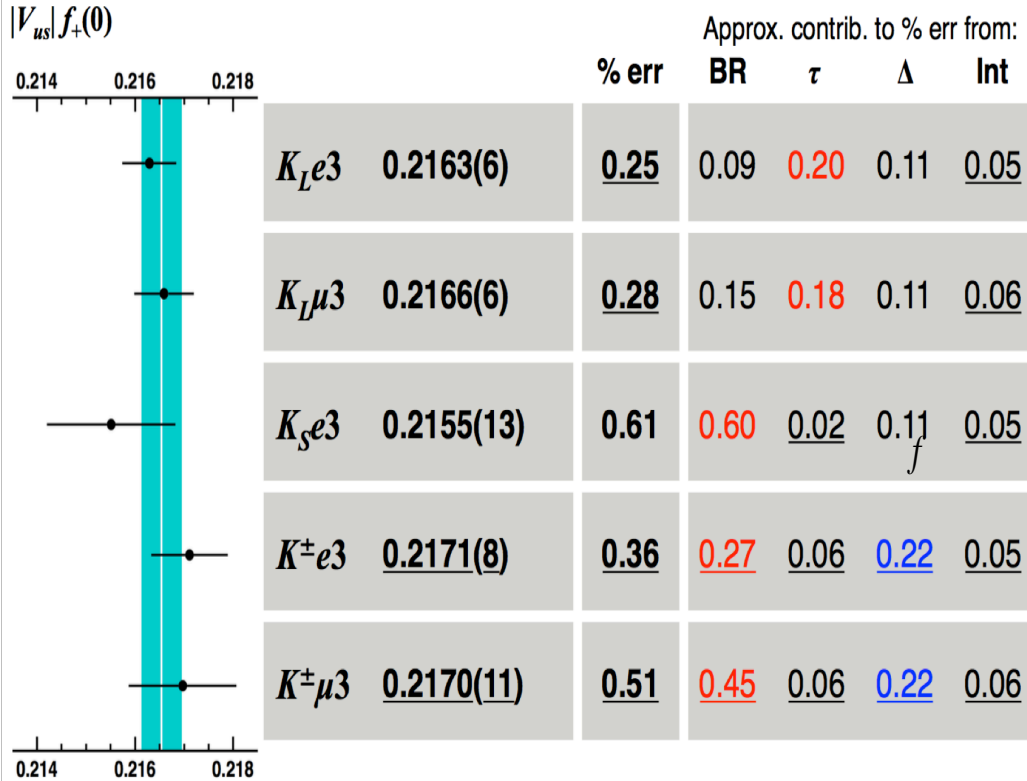
No time estimate yet. Expert working.

Evolution of Experimental Input Semileptonic Decays



V_{us} "Revolution" with experimental input changing $\sim 5\%$ in some cases.....Input from many experiments:

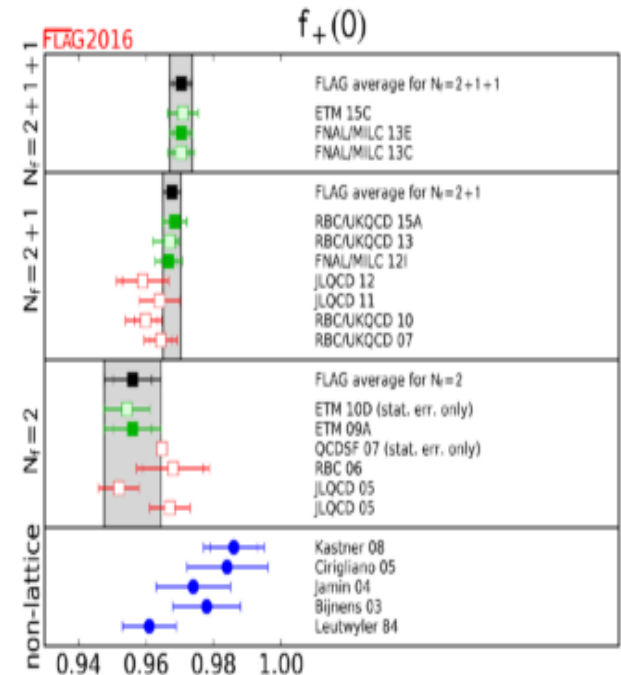
$|V_{us}|f_+(0)$ from world data: Update



Average: $|V_{us}|f_+(0) = 0.21654(41)$ $\chi^2/\text{ndf} = 1.54/4$ (82%)

Experimental determination of $|V_{us}|$ from kaon decays – M. Moulson (Frascati) – CKM 2016, Mumbai, 1 December 2016

27



QCD su reticolo (FLAG 2016)

For: $f_+(0) = 0.9704(32)$

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$N_f = 2+1+1$

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$V_{us} = 0.2231(4)_{ex}(7)_{latt}$

NA48/2

- Il giovane Enrico si appassiona alla ricerca di violazione diretta di CP nei K carichi
- In breve tempo diventa un pilastro della collaborazione

$K^\pm \rightarrow 3\pi$ matrix element:

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

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

$$s_i = (P_K - P_{\pi i})^2, \quad i=1,2,3 \quad (3 = \text{odd } p)$$

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

$$A_g = \frac{g^+ - g^-}{g^+ + g^-}$$



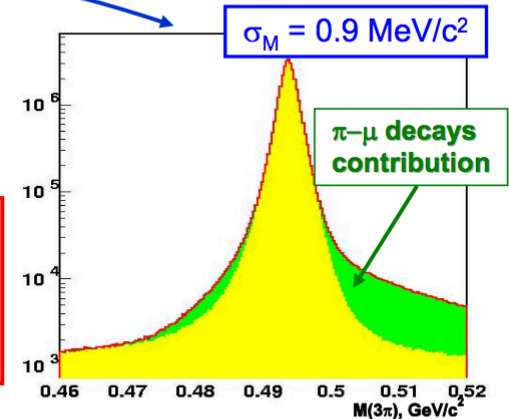
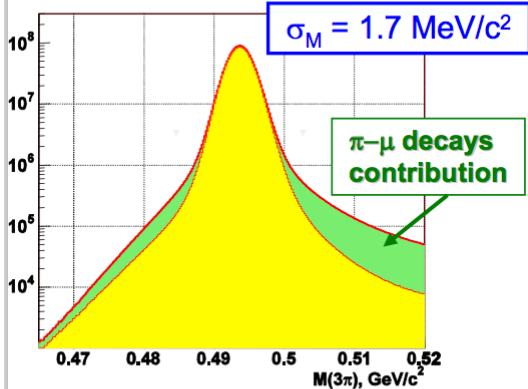
Rivelazione simultanea di K^+ e K^-
Frequente alternanza della polarità
dei magneti

(Esiste una sola altra foto di Enrico senza barba)

Selected events properties



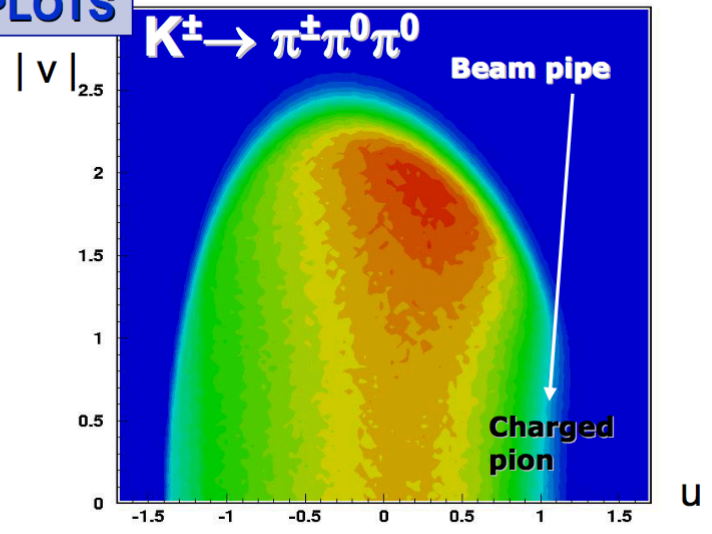
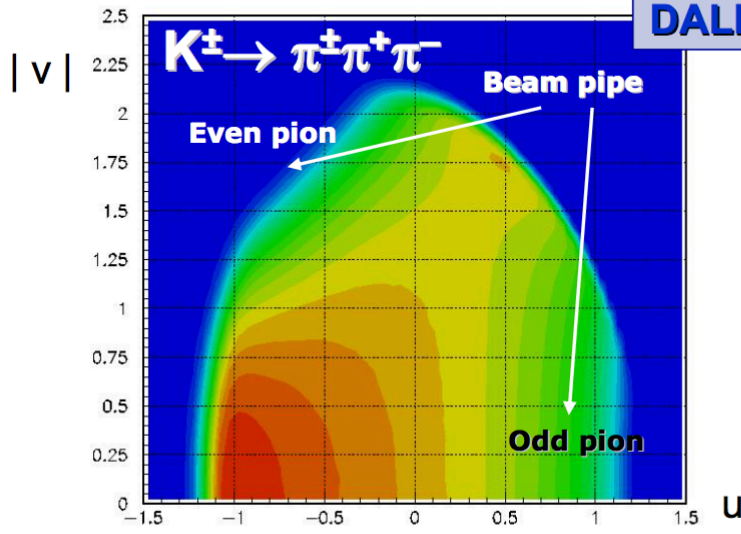
3 π invariant mass



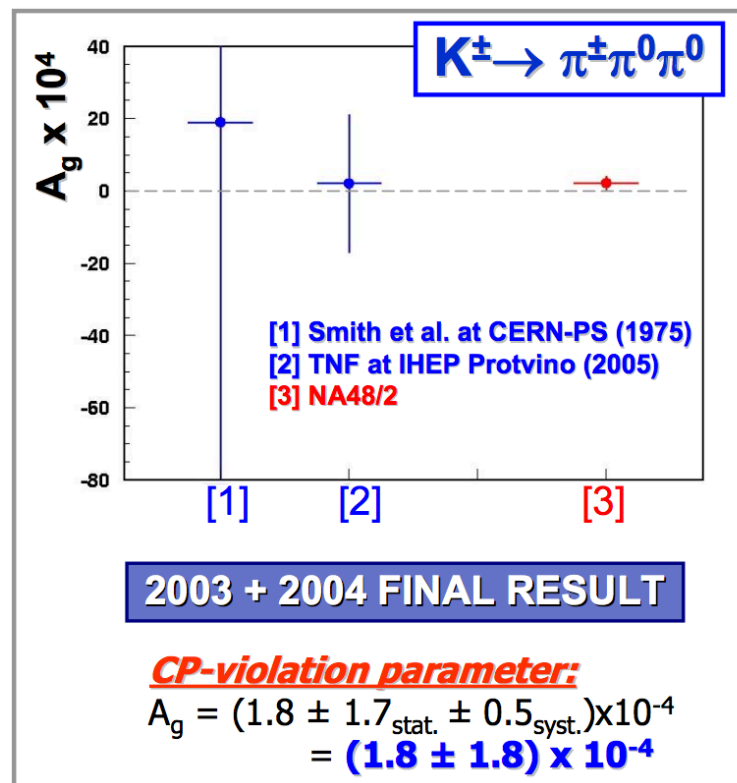
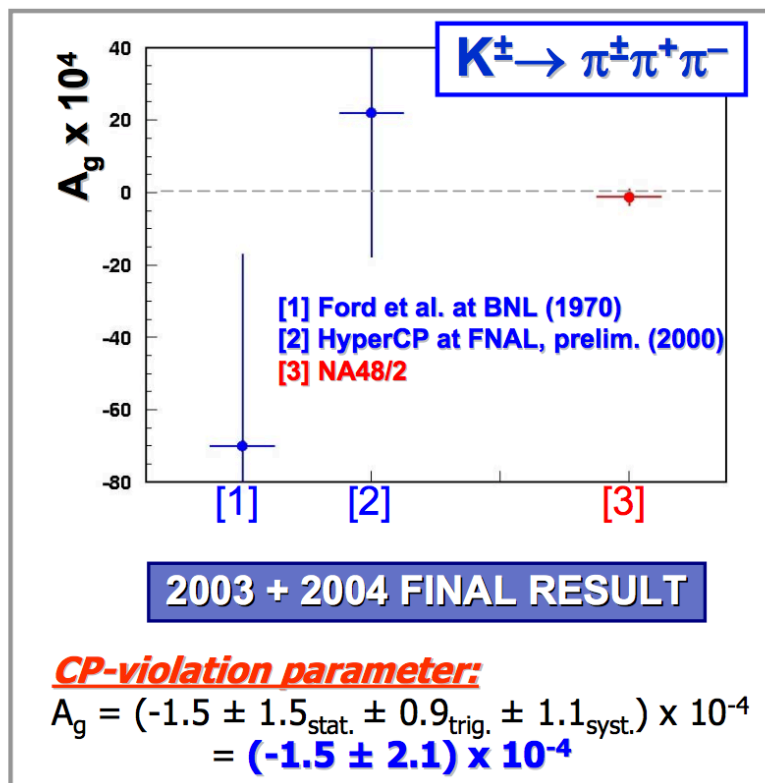
STATISTICS

	$K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$	$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$
K+	2.0×10^9	59×10^6
K-	1.1×10^9	32×10^6
TOT	3.1×10^9	91×10^6

DALITZ PLOTS



A_g results

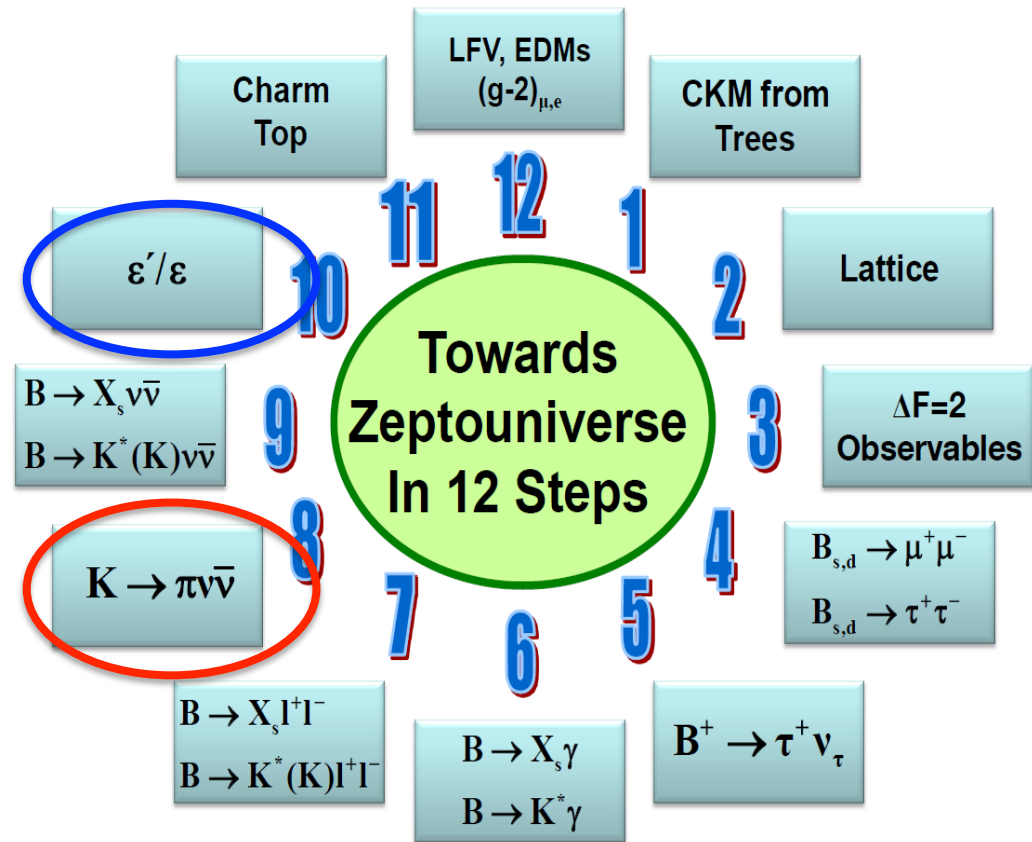


- ◆ The results have **10 times better precision** than the previous measurements;
- ◆ The errors are **dominated by statistics**;
- ◆ The results are consistent with the predictions of the **Standard Model**.
- ◆ For more details: **PLB 634 (2006) 474** and **PLB 638 (2006) 22**

Decadimenti Rari dei K

- ε'/ε ed A_g sono molto sensibili a nuova fisica ma difficili da calcolare.
- auspicabilmente la QCD su reticolo permettera una predizione precisa
- I decadimenti rari dei K permettono di condurre test quantitativi importanti
- Eccellente precisione teorica

K e Zepto-Universo (10^{-21})



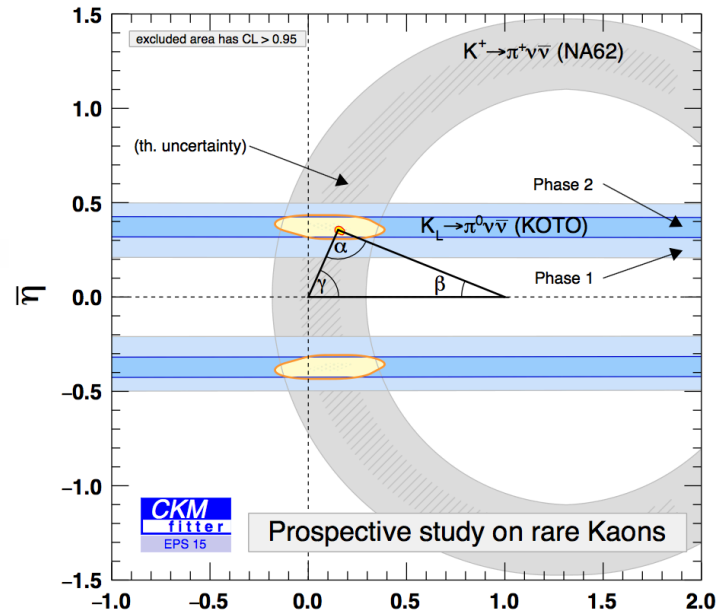
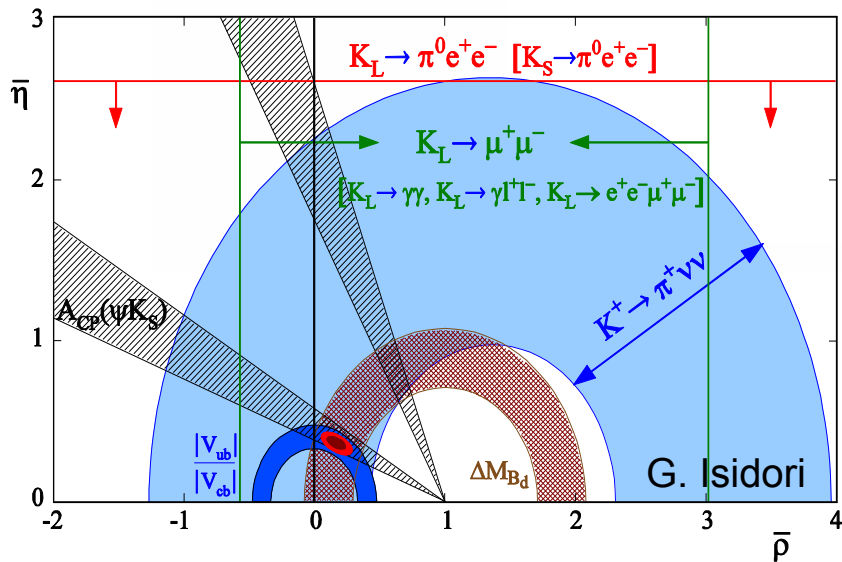
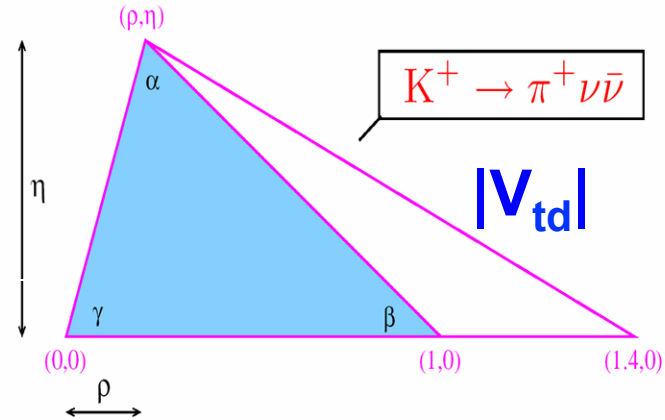
Con Enrico abbiamo iniziato a pensarci molti anni fa...

40 Stockholm2013

A. Buras

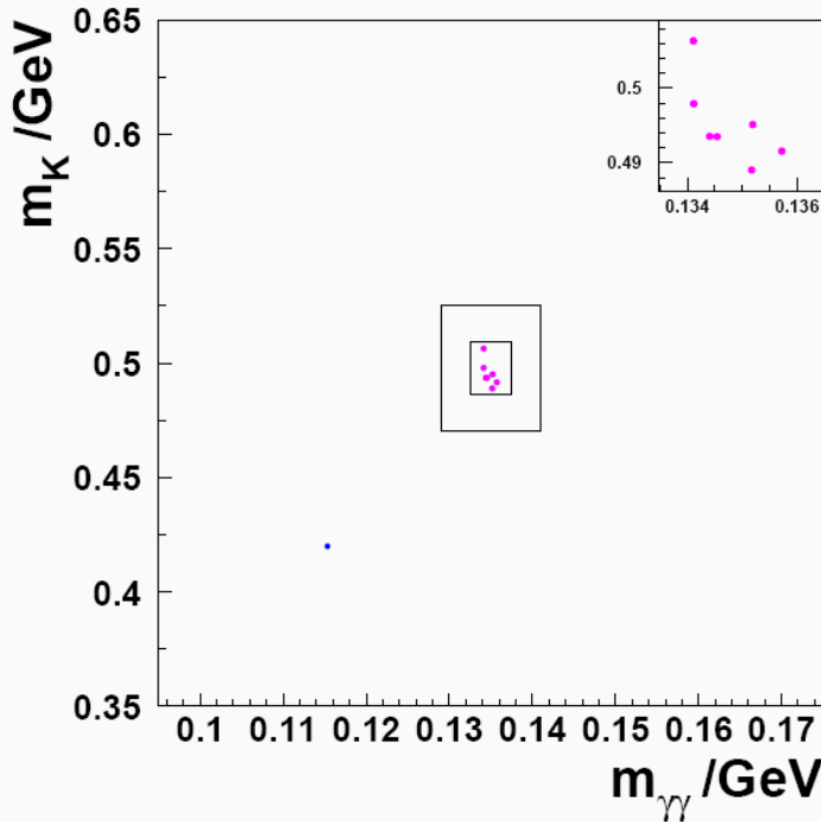
Decadimenti Rari

$$\begin{array}{l}
 K_L \rightarrow \pi^0 \nu \bar{\nu} \\
 K_L \rightarrow \pi^0 e^+ e^-
 \end{array}
 \left\{
 \begin{array}{l}
 K_S \rightarrow \pi^0 e^+ e^- \\
 K_L \rightarrow \pi^0 \gamma \gamma \\
 K_L \rightarrow e e \gamma \gamma
 \end{array}
 \right.$$



NA48/1

BR($K_S \rightarrow \pi^0 e^+ e^-$)



0 events found in control region
7 events found in signal region



Probability BG only $\sim 10^{-10}$



**FIRST OBSERVATION OF
 $K_S \rightarrow \pi^0 e^+ e^-$ with $m_{ee} > 165$ MeV**

$$BR(K_S \rightarrow \pi^0 e^+ e^-)_{m_{ee} > 165} = (3.8_{-1.2}^{+1.5} \pm 0.2) \cdot 10^{-9}$$



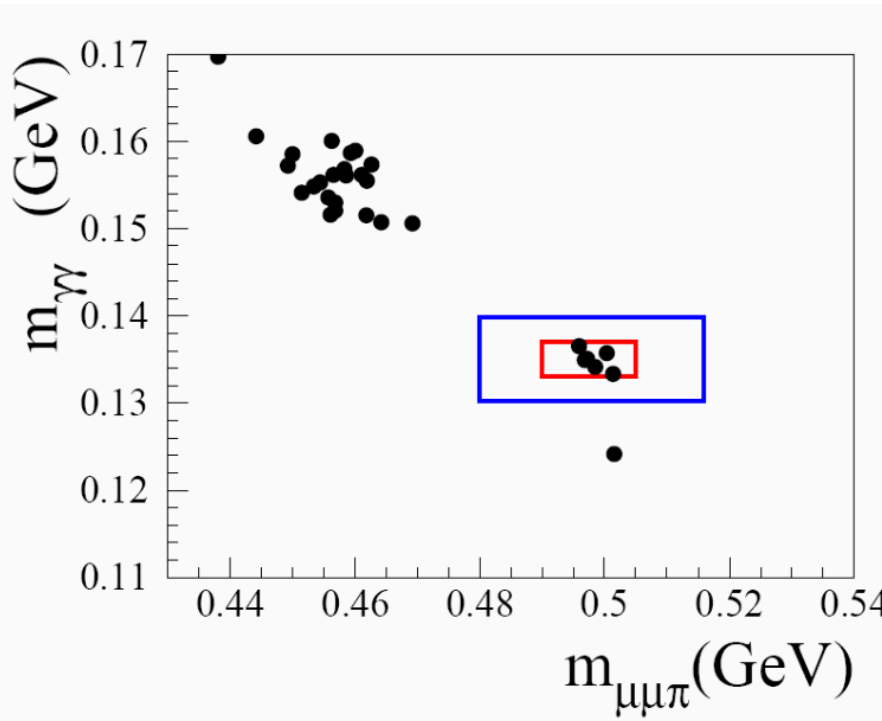
**Using MonteCarlo
with unit form factors**

$$BR(K_S \rightarrow \pi^0 e^+ e^-) = (5.8_{-2.3}^{+2.8} (stat.) \pm 0.3_{syst} \pm 0.8_{theory}) \cdot 10^{-9}$$

NA48/1

PLB 599 (2004)

$BR(K_S \rightarrow \pi^0 \mu^+ \mu^-)$



0 events found in control region
6 events found in signal region

FIRST OBSERVATION OF
 $K_S \rightarrow \pi^0 \mu^+ \mu^-$

$$BR(K_S \rightarrow \pi^0 \mu^+ \mu^-) = (2.9_{-1.2}^{+1.5} (stat.) \pm 0.2_{syst}) \cdot 10^{-9}$$

a_s and K_L estimates

- ✓ a_s can be extracted using both decays:

$$BR(K_S \rightarrow \pi^0 e^+ e^-) = 5.2 \cdot 10^{-9} a_S^2 \Rightarrow |a_s| = 1.06_{-0.21}^{+0.26} + 0.07$$

$$BR(K_S \rightarrow \pi^0 \mu^+ \mu^-) = 1.2 \cdot 10^{-9} a_S^2 \Rightarrow |a_s| = 1.55_{-0.32}^{+0.38} + 0.05$$

- ✓ The results are compatible taking into account experimental errors
- ✓ Using $|a_s|$ and current value of $\text{Im}(\lambda_t)$

$$BR(K_L \rightarrow \pi^0 e^+ e^-)_{CPV} = (17_{IND} \pm 9_{INT} + 5_{DIR}) \cdot 10^{-12}$$

$$BR(K_L \rightarrow \pi^0 \mu^+ \mu^-)_{CPV} = (9_{IND} \pm 3_{INT} + 1_{DIR}) \cdot 10^{-12}$$



Cf. PDG (KTeV) $BR(K_L \rightarrow \pi^0 ee) < 2.8 \cdot 10^{-10}$ 90%CL

M. Raggi NA48 Collaboration

$BR(K_L \rightarrow \pi^0 \mu\mu) < 3.8 \cdot 10^{-10}$ 90%CL

P-326

- Il $K_L \rightarrow \pi^0 e^+ e^- (\mu^+ \mu^-)$ non è facile da perseguire a causa di fondi radiativi irriducibili
- Il $K^+ \rightarrow \pi^+ \nu \nu$ è molto importante (nel modello standard misura $|V_{td}|$) perché è dominato da fisica a corta distanza
- Lo studio di questo decadimento è stato iniziato a BNL con decadimenti del K a riposo
- Decidiamo di proporlo al CERN con decadimenti in volo
- Enrico gioca un ruolo fondamentale nel convincere nove gruppi INFN a partecipare alla proposta ed a coordinare la componente Italiana fino al 2013



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

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

CERN-SPSC-2005-013
SPSC-P-326
11.6.2005

G. Anelli, A. Ceccucci*, V. Falaleev, F. Formenti, A. Gonidec, B. Hallgren,
P. Jarron, A. Kluge, M. Losasso, A. Norton, A. Placci, P. Riedler, G. Ruggiero, G. Stefanini
CERN

S. Bazylev, P. Frabetti, E. Goudzovski, D. Gurev, V. Kekelidze, D. Madigozhin,
N. Molokanova, R. Pismenny, Y. Potrebenikov, A Zinchenko
Dubna

W. Baldini, A. Cotta Ramusino, P. Dalpiaz, C. Damiani, A. Gianoli,
M. Martini, F. Petrucci, M. Savrié, M. Scarpa, H. Wahl
Ferrara

A. Bizzeti, E. Iacopini, M. Lenti
Florence

A. Antonelli, M. Moulson, T. Spadaro
Frascati

S. Gninenko, E. Guschin
INR, Moscow

K. Kleinknecht, B. Renk, R. Wanke
Mainz

R. Winston
Merced

F. Ambrosino, C. Di Donato, M. Napolitano, G. Saracino
Naples

G. Anzivino, P. Cenci, M. Pepe, M. Piccini
Perugia

A. Bigi, R. Casali, G. Collazuol, F. Costantini, L. Fiorini, L. Di Lella, N. Doble,
R. Fantechi, S. Giudici, I. Mannelli, A. Michetti,
G.M. Pierazzini, M. Sozzi
Pisa

G. Britvich, V. Kurshetsov, A. Kushnirenko, L. Landsberg, V. Molchanov, V.Obraztsov,
A. Soldatov, V. Rykalin, O. Tchikilev, O. Yushchenko
Protvino

N. Cabibbo, G. D'Agostini, E. Leonardi, M. Serra, P. Valente
Rome I

B. Peyaud, J. Derre
Saclay

C. Cheshkov, P. Hristov, L. Litov, S. Stoynev
Sofia

C. Biino, F. Marchetto, G. Mazza, A. Rivetti
Turin

*Contact Person, email address: augusto.ceccucci@cern.ch

P-326 → NA62

- Risposta del Direttore della Ricerca del CERN (**Jos Engelen**): “The physics is brilliant but you have no people, no money, and no technology”
- ..Con **Enrico** ci siamo messi a cercare fondi e collaboratori per sviluppare la tecnologia necessaria (RICH, Pixel al Si con 100 ps di risoluzione temporale , Straw che operano in vuoto senza perdite di gas...etc...)
- Approvazione finale di NA62 circa 2009 (**Sergio Bertolucci**)
- Nota bene: **un esperimento chiamato NA62 già esisteva** per studiare l'universalità leptonica con i decadimenti dei K....Unico caso noto al CERN di **due esperimenti approvati con lo stesso nome (!)**
- Costruzione fino al 2014++
- Commissioning fino al 2016 inoltrato
- Ora in presa dati stabile, **~ 20 eventi SM con i dati attesi prima di LS2**
- Goal: **BR($K^+ \rightarrow \pi^+ \nu\nu$) al 10%**: l'approvazione della continuazione della presa dati fino alla fine del 2022 è imminente

“Memorandum of Misunderstanding”

- Enrico è stato capace di far firmare l'MoU all'INFN per ben **DUE VOLTE**
- Grazie a questo fatto (ed alcuni altri...) il nostro MoU divenne noto come “Memorandum of Misunderstanding”



RICH R&D

NIMA 621 (2010)

Pion–Muon separation with a RICH prototype for the NA62 experiment

B. Angelucci^{j,e}, G. Anzivino^{i,d}, C. Avanzini^{j,e}, C. Biino^k, A. Bizzeti^{h,c}, F. Bucci^{h,b}, A. Cassese^{h,b}, P. Cenciⁱ, R. Ciaranfi^h, G. Collazuol^{j,g}, V. Falaleev^a, S. Galeotti^j, S. Giudici^{j,e}, E. Iacopini^{h,b}, G. Lamanna^{j,g}, M. Lenti^h, G. Magazzù^j, E.M. Marinovaⁱ, M. Pepeⁱ, R. Piandani^{i,d}, M. Picciniⁱ, G. Ruggiero^{j,g}, A. Sergi^{i,d,*}, M. Sozzi^{j,e}, M. Veltri^{h,f}

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^f Dipartimento di Matematica Fisica e Informatica, Università di Urbino, I-61029 Urbino, Italy

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ⁱ Sezione INFN di Perugia, I-06100 Perugia, Italy

^j Sezione INFN di Pisa, I-56127 Pisa, Italy

^k Sezione INFN di Torino, I-10125 Torino, Italy

...diedi fondo al poco contante
disponibile per evitare che
il CERN fermasse l'R&D...

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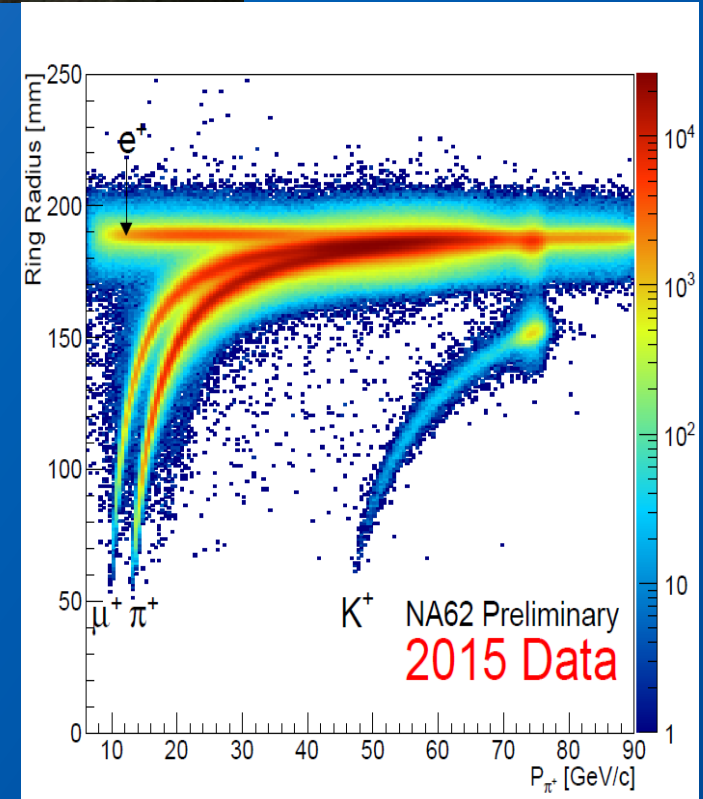
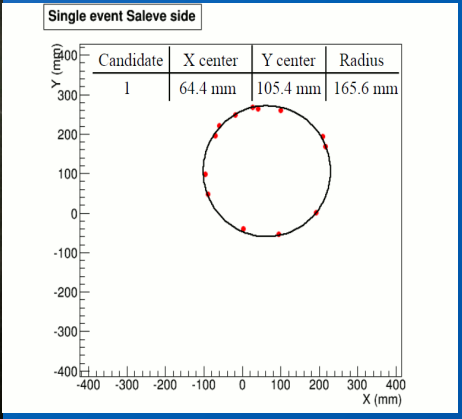
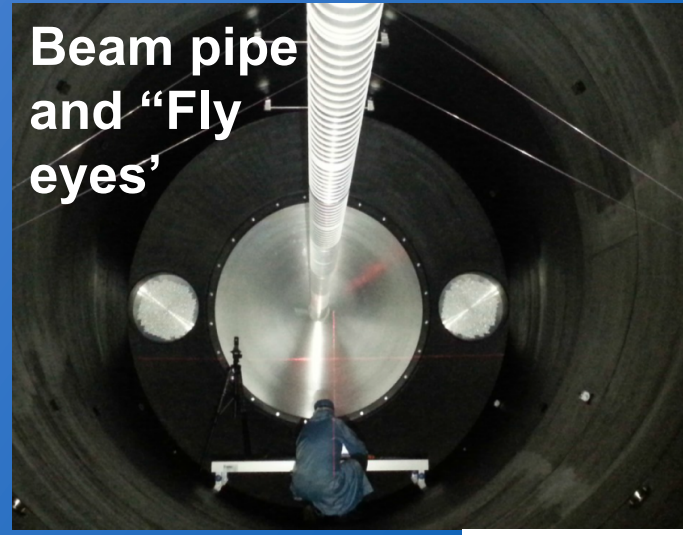
Timing

ABSTRACT

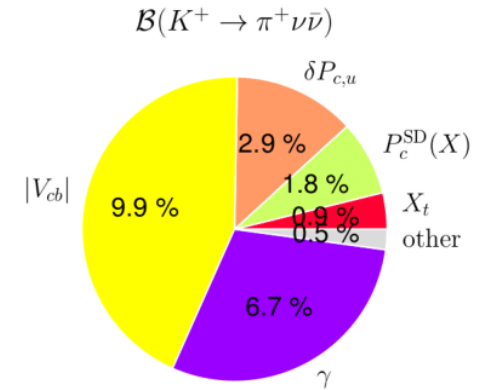
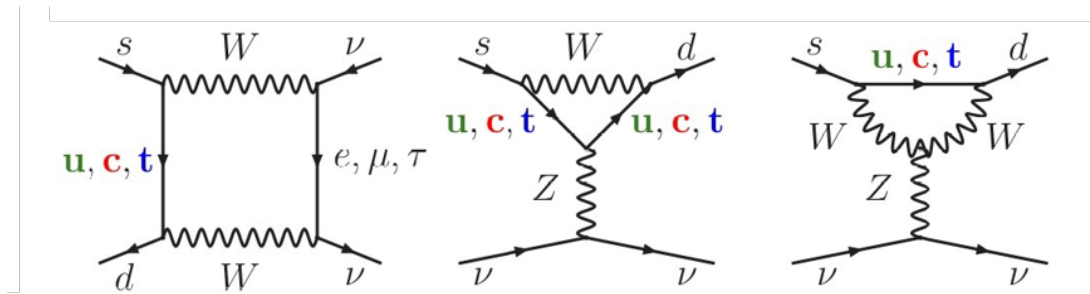
The NA62 experiment at CERN, aimed to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching fraction ($O(10^{-10})$), relies on a Neon based RICH detector for π/μ separation, time measurement and level 0 trigger. The experimental requirements for this detector are: a muon contamination in pion samples lower than 5×10^{-3} in the momentum range 15–35 GeV/c and a time resolution on the charged track better than 100 ps. A prototype of such a detector was built and tested in 2009; it consists of a full length (≈ 18 m) Ne filled vessel equipped with a spherical mirror and 414 PMs on its focal plane, located about 17 m upstream of the mirror. This prototype was tested at CERN SPS on a positive hadron beam, in the required momentum range, to measure the π/μ separation and to confirm the time resolution obtained with a previous prototype; the μ misidentification probability is about 0.7% and the time resolution is better than 100 ps in the whole momentum range.

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NA62 RICH



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



- FCNC loop processes: $s \rightarrow d$ la soppressione CKM piu' forte
- Teoricamente preciso: dominato da iterazione a corta distanza
- Incertezze adroniche normalizzate tramite I decadimenti K_{l3}
- Predizione teorica: [\[Brod, Gorbahn, Stamou, Phys. Rev.D 83, 034030 \(2011\), Buras. et. al., JHEP11\(2015\)033\]](#)

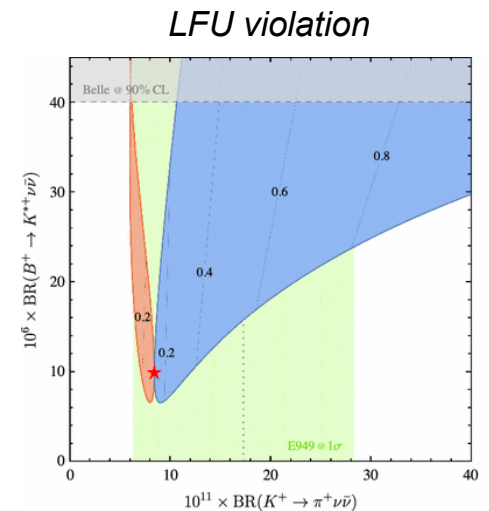
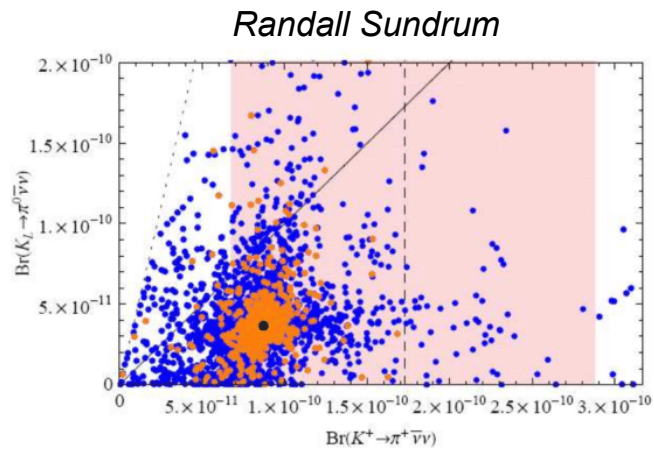
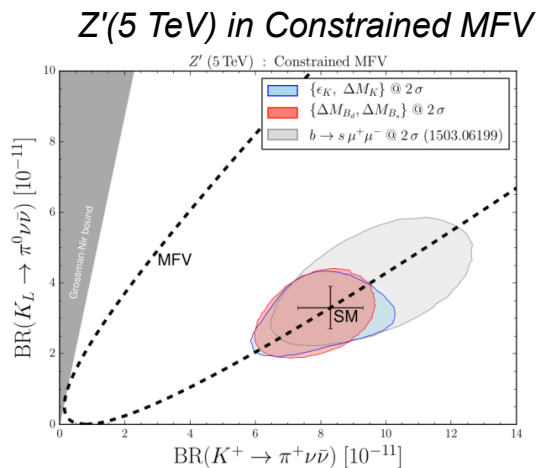
$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left(\frac{|V_{cb}|}{0.0407} \right)^{2.8} \left(\frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$$

- Risultati sperimentali: [\[Phys. Rev. D 79, 092004 \(2009\)\]](#)

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17.3_{-10.5}^{+11.5}) \times 10^{-11} \text{ (BNL, "kaon decays at rest")}$$

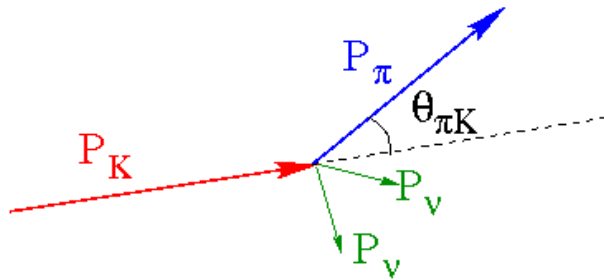
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ oltre il Modello Standard

- Custodial Randall-Sundrum [[Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 \(2009\) 108](#)]
- Analisi MSSM [[Blazek, Matak, Int.J.Mod.Phys. A29 \(2014\) no.27](#)],[[Isidori et al. JHEP 0608 \(2006\) 064](#)]
- Modelli semplificati Z, Z' [[Buras, Buttazzo, Kneijens, JHEP11\(2015\)166](#)]
- Littlest Higgs with T-parity [[Blanke, Buras, Recksiegel, Eur.Phys.J. C76 \(2016\) 182](#)]
- Violazione universalita' leptonica [[Isidori et al., Eur. Phys. J. C \(2017\) 77: 618](#)]
- Limiti da risultati esistenti:
 - Mescolamento quark, elementi CKM, decadimenti rari K e B, ricerche dirette al collider



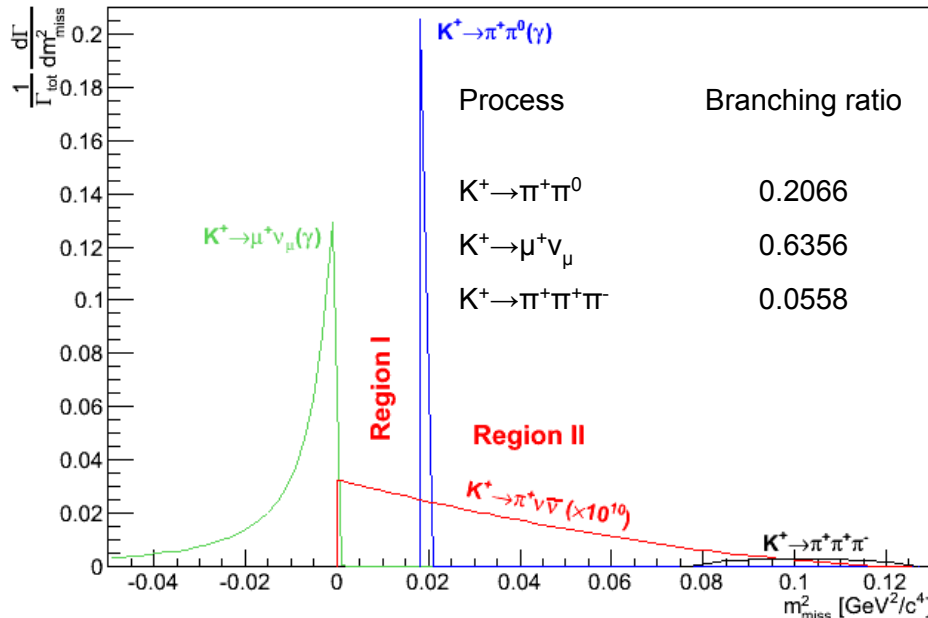
NUOVA TECNICA IN VOLO

Decay in flight technique $m_{miss}^2 = (P_K - P_{\pi^+})^2$



■ Pietre miliari:

- ★ Risoluzione temporale $\sim O(100 \text{ ps})$
- ★ Soppressione cinematica $\sim O(10^4)$
- ★ Soppressione $\mu > 10^7$
- ★ Soppressione π^0 (from $K^+ \rightarrow \pi^+ \pi^0$) $> 10^7$

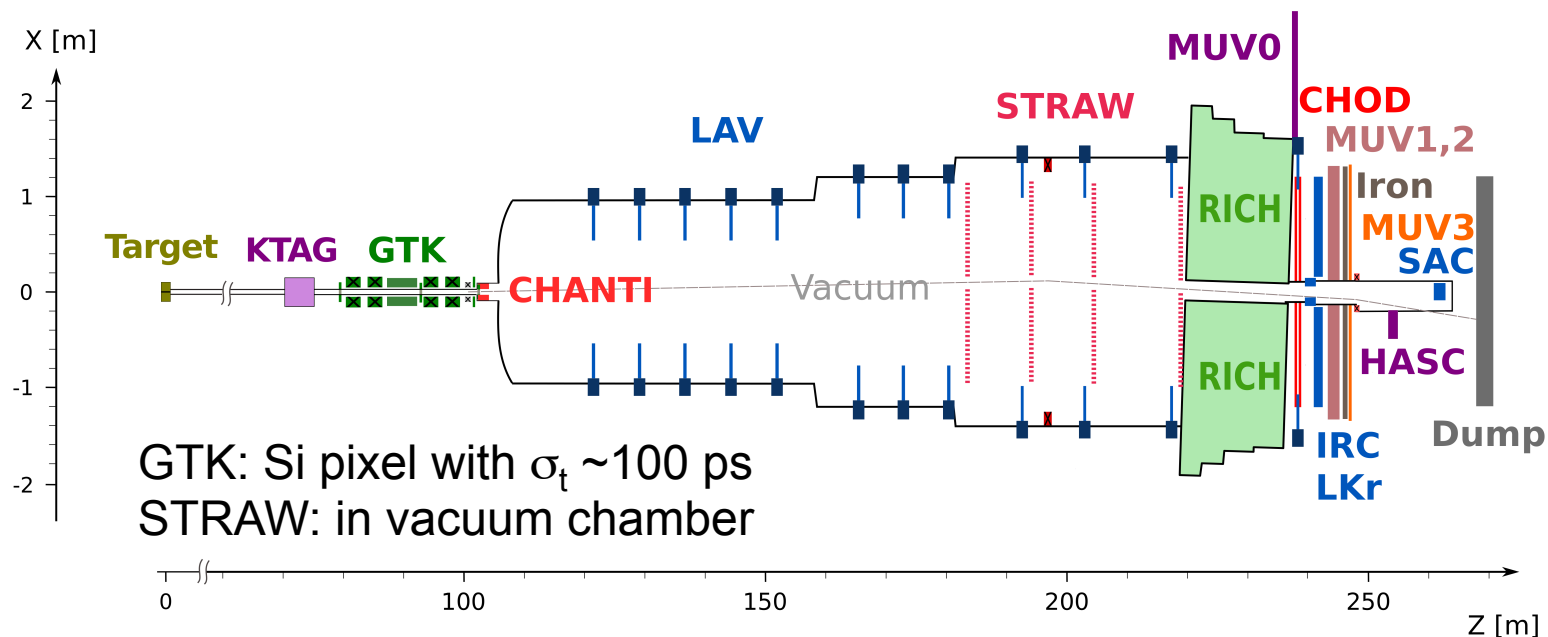


- +
- $15 < P_{\pi^+} < 35 \text{ GeV}/c$
- Identificazione di particelle:
1. Cherenkov detectors
 2. Calorimetri
 3. Veti per fotoni

NA62 beam and detector



NA62: Fascio & Rivelatore



■ SPS Beam:

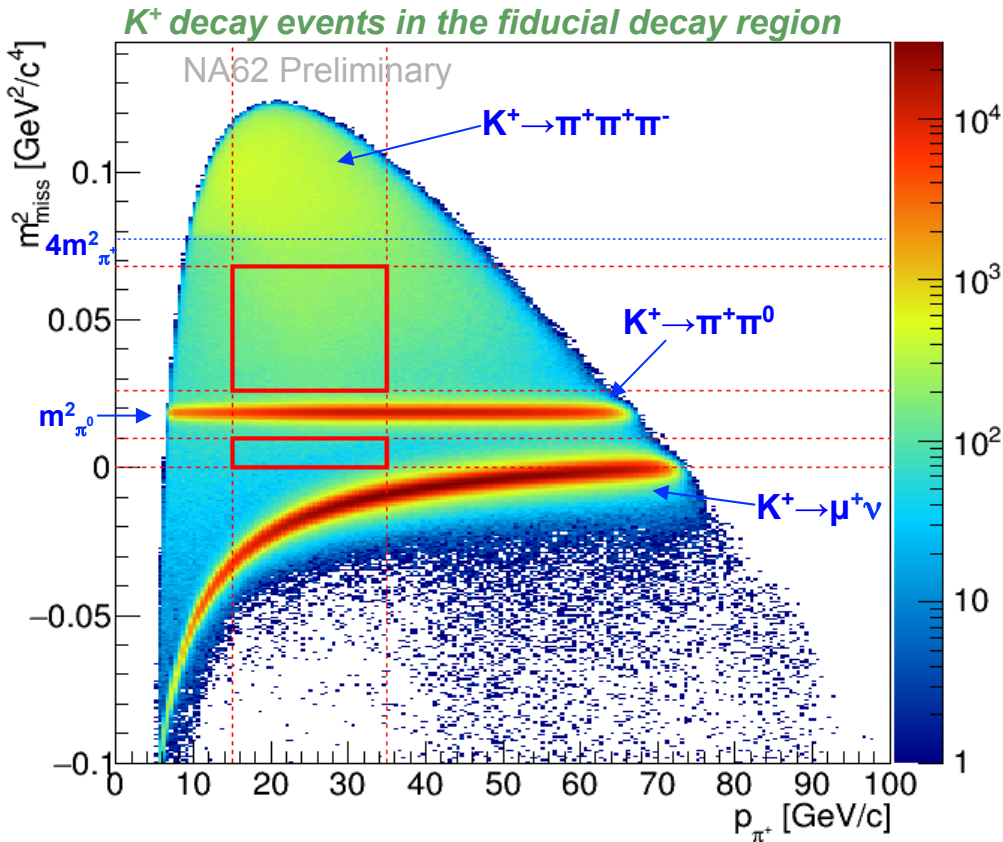
- ★ 400 GeV/c protons
- ★ $2 \cdot 10^{12}$ protons/spill
- ★ 3.5s spill

■ Secondary positive Beam:

- ★ 75 GeV/c momentum, 1 % bite
- ★ 100 μ rad divergence (RMS)
- ★ 60x30 mm² transverse size
- ★ $K^+(6\%)/\pi^+(70\%)/p(24\%)$
- ★ $33 \cdot 10^{11}$ ppp on T10 (750 MHz at GTK3)

■ Decay Region:

- ★ 60 m long fiducial region
- ★ ~ 5 MHz K^+ decay rate
- ★ Vacuum $\sim O(10^{-6})$ mbar



■ Selezione:

- ★ singola traccia
- ★ identificazione π^+
- ★ reiezione fotoni
- ★ reiezione molteplicita`

■ Performance

- ★ $\epsilon_{\mu^+} = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
- ★ $\epsilon_{\pi^0} = 3 \cdot 10^{-8}$
- ★ $\sigma(m^2_{\text{miss}}) = 1 \cdot 10^{-3} \text{ GeV}^2/c^4$
- ★ $\sigma_T \sim O(100 \text{ ps})$

Primi Risultati

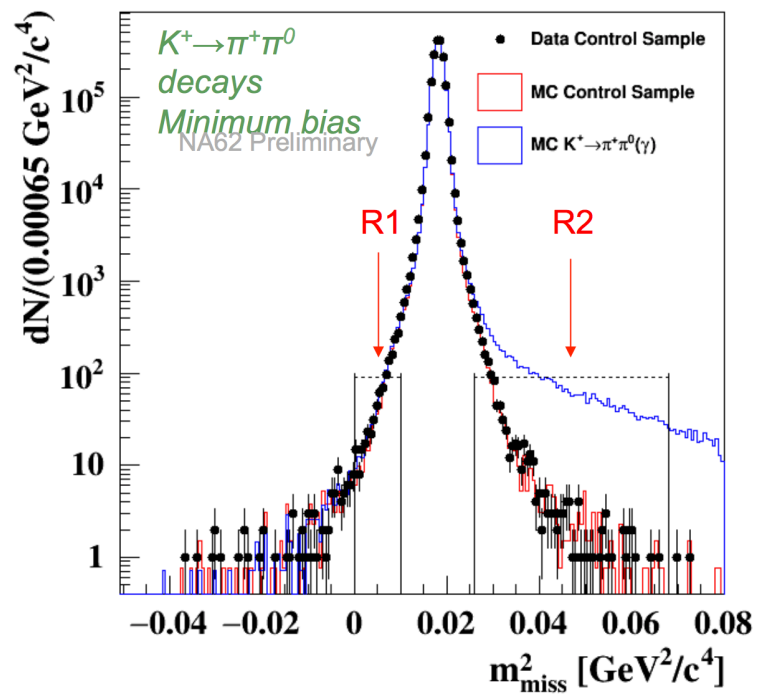


$N_K \sim 1.2 \cdot 10^{11}$ (2016, $\sim 0.5\%$ statistica totale attesa di NA62)

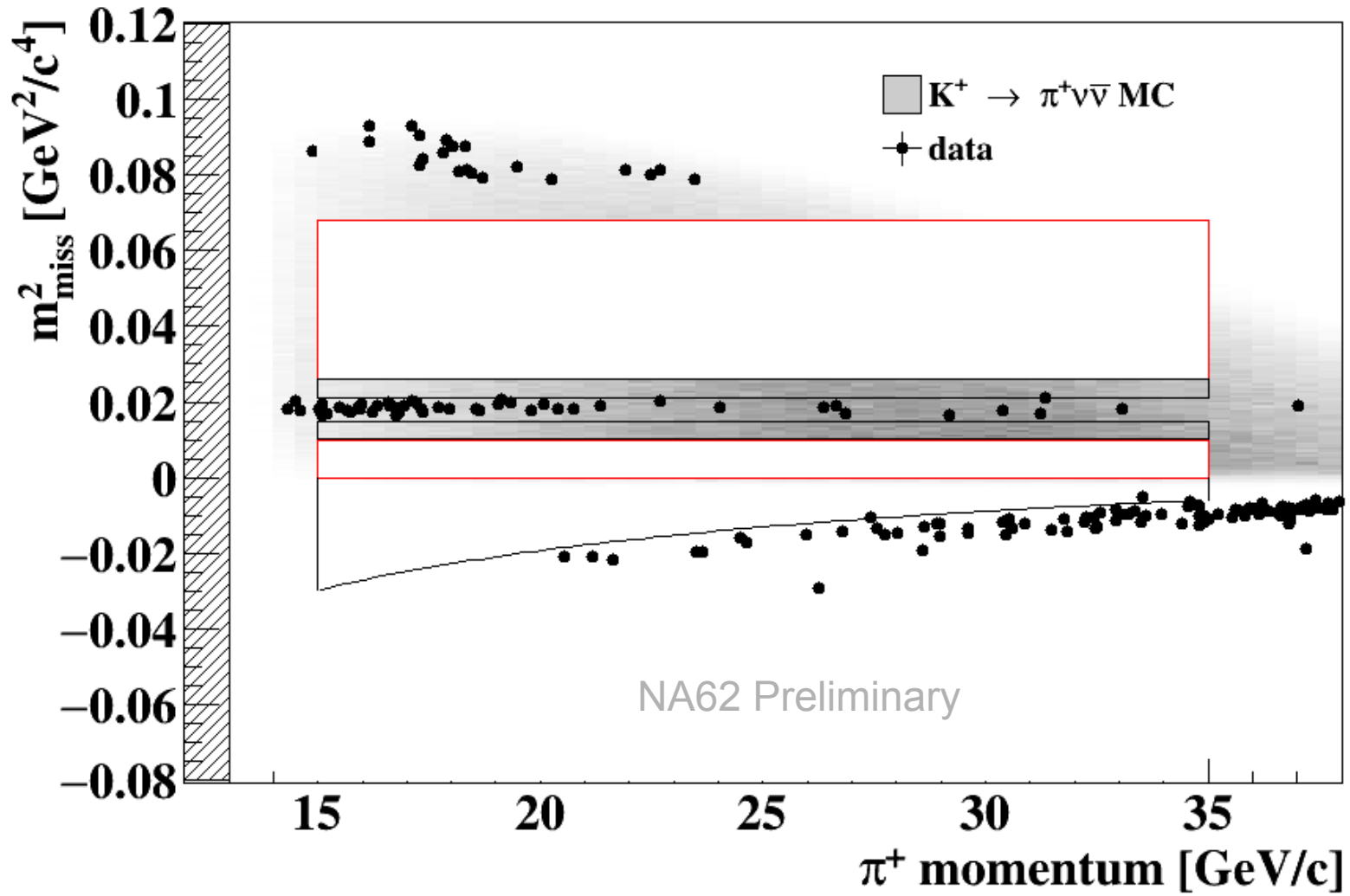
Accettanza*Efficienza (4%)

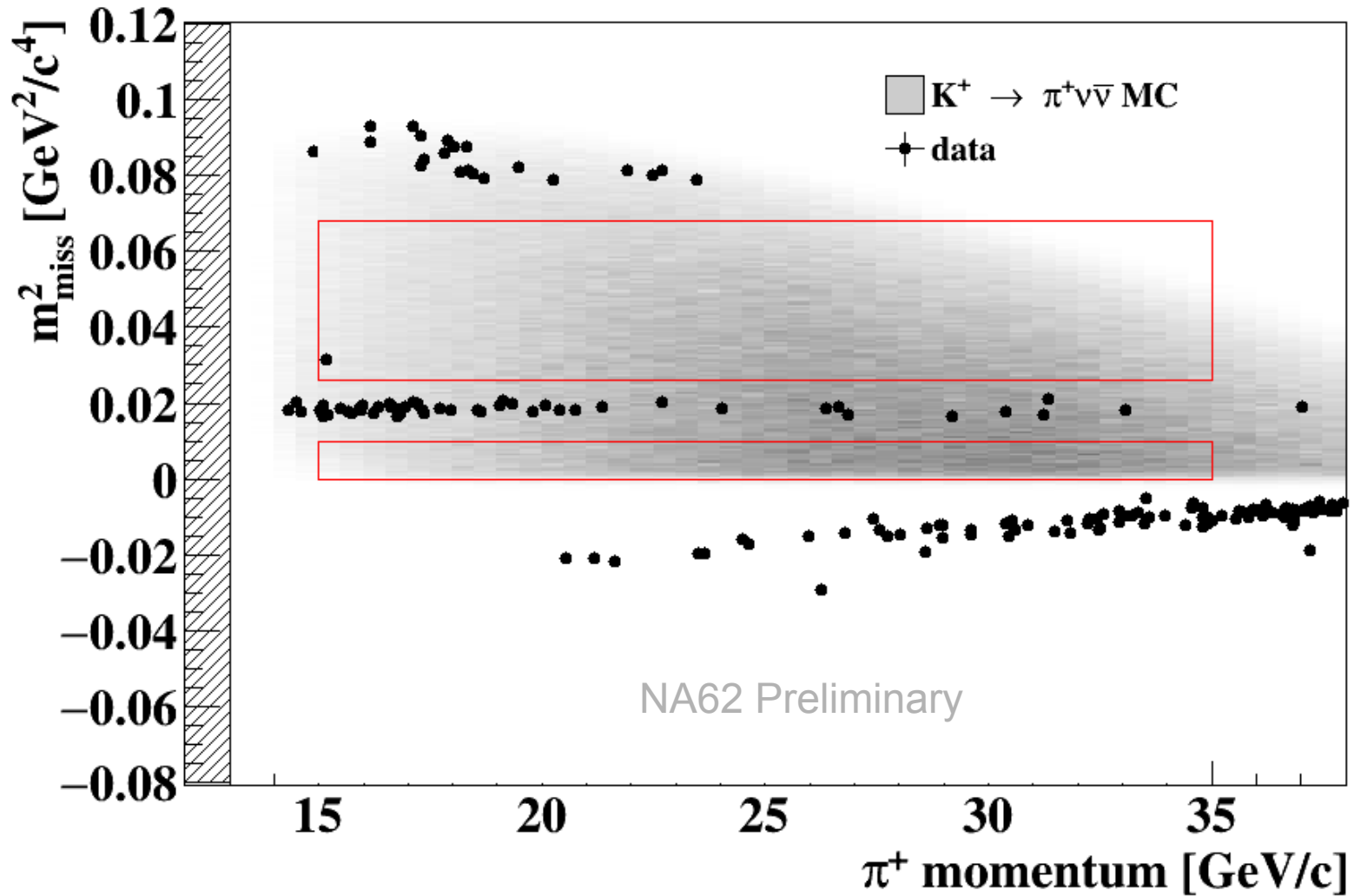
SES $\sim 3.15 \cdot 10^{-10}$

Process	Expected events in R1+R2
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
$K^+ \rightarrow \pi^+ \pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \rightarrow \mu^+ \nu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$0.018^{+0.024}_{-0.017} _{stat} \pm 0.009_{syst}$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream Background	$0.050^{+0.090}_{-0.030} _{stat}$



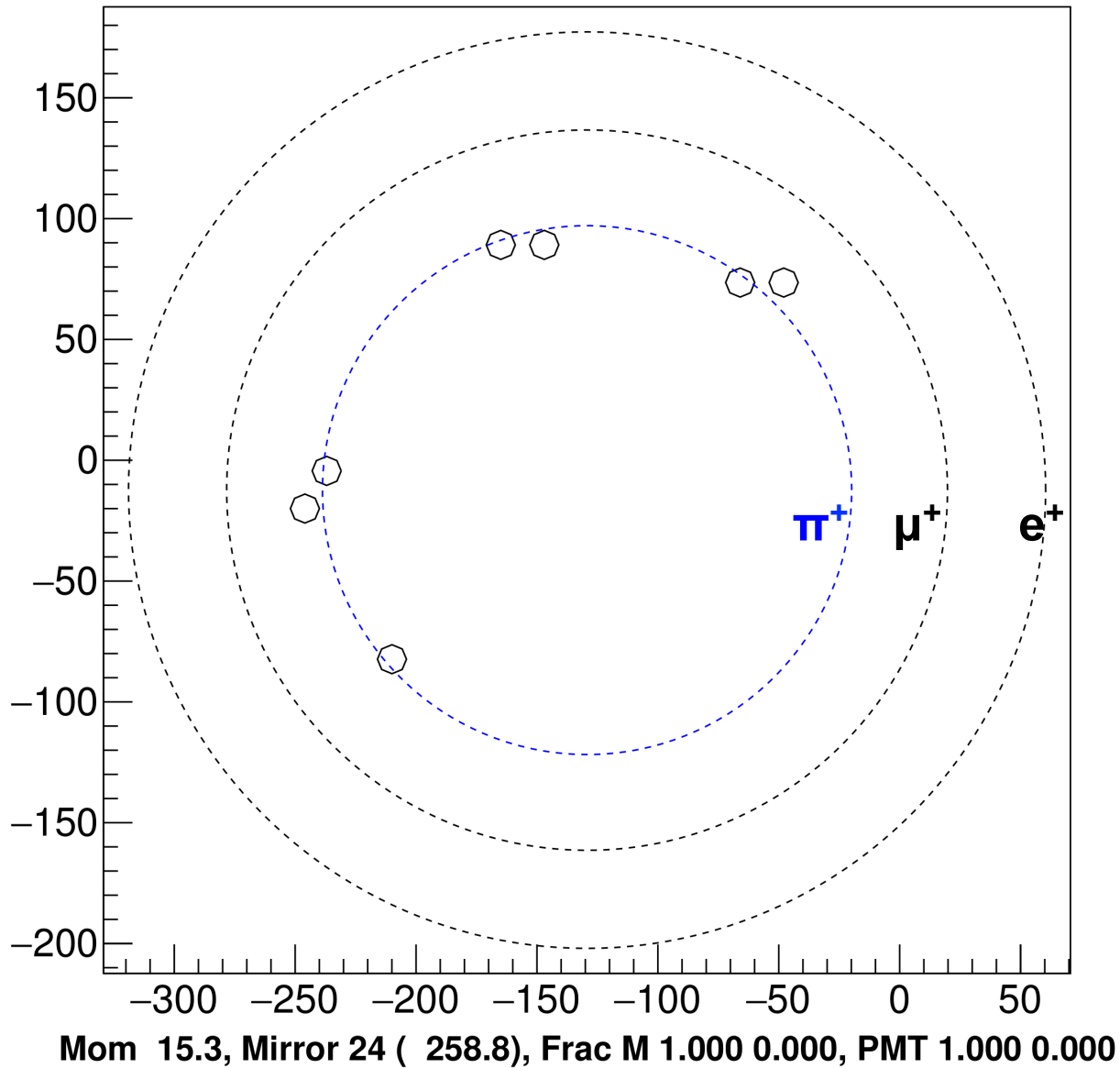
Primi Risultati





One event observed

RICH: Il primo candidato



$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 11 \times 10^{-10} \text{ @ } 90\% \text{ CL}$$

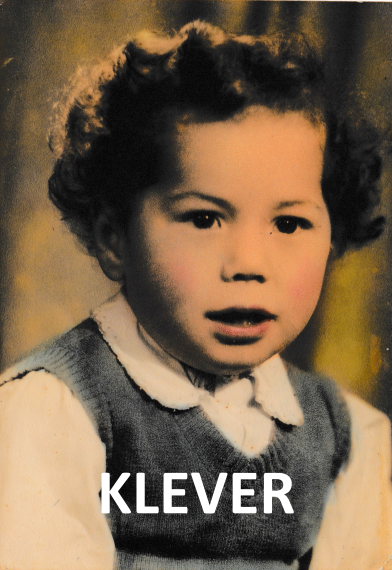
$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10} \text{ @ } 95\% \text{ CL}$$

- Osservato un candidato in regione 2, compatibile con SM
- Per confronto:

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 28_{-23}^{+44} \times 10^{-11} \text{ @ } 68\% \text{ CL}$$

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$$

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{exp} = (17.3_{-10.5}^{+11.5}) \times 10^{-11} \text{ (BNL, "kaon decays at rest")}$$



Enrico origina KLEVER

To:
Prof. Alberto Tesi
Magnifico Rettore
Università degli Studi di Firenze
Piazza San Marco, 4 – 50121 – Firenze - Italy

In compliance with the Italian call for proposals PRIN 2010-2011, foreign institutions cannot receive financial support. All costs and expenses paid directly by CERN concerning the implementation of all activities related to the above mentioned association will be at no charge for the PRIN project.

LETTER OF INTENT

I, the undersigned Sergio Bertolucci, CERN (European Center for Nuclear Research) Director for Research, confirms the will of CERN to participate as “Associate organization” to the 3 year research project *“Development of very high efficiency and excellent time resolution detectors, and related experimental techniques, for studying flavor physics and looking for 'new physics' in ultra-rare neutral kaon decays through the upgrade of the NA62 apparatus at CERN.”* submitted according to the call for proposals PRIN 2010-2011 managed by the Italian Ministry of Education, University and Research (Ministero dell’Università, dell’Istruzione e della Ricerca).

All intellectual property rights arising from the research activities shall be the property of the Party carrying the work generating that research result(s). The results will be owned by the Party who has directly contributed to its creation, in terms of inventive and creative contribution.

In case of joint ownership of the result leading to a patentable invention, the partners will conclude specific agreements to regulate the joint ownership and exploitation of the results. In this case any publication and/or scientific presentation in congress need to be compliant will necessary procedures to ensure the protection of any patentable results.

The Project is under the scientific responsibility of Prof. Enrico IACOPINI, Florence University, coordinating 8 research units from the Physics Departements of the Universities of Ferrara, Firenze, Napoli, Perugia, Pisa, Roma II, Torino and the INFN National Laboratory of Frascati.

Yours sincerely
Sergio Bertolucci

Signature.....

Stamp of the institution.....

Date

The Physics Dept. of CERN will collaborate with the research unit of the Physics Dept. of Florence University lead by Prof. Enrico Iacopini, also responsible of the local research team.

21.06.2018

Mario, Enrico & i mesoni K

Mario ed Enrico: **K**apitani coraggiosi

- E un grande onore per me essere qui oggi per celebrare i contributi di **Mario Calvetti ed Enrico Iacopini** alla fisica dei K
- Mario già era coinvolto con i K quando io ancora non ero ancora scientificamente nato, mi sono limitato a riassumere solo alcuni dei suoi contributi a **NA48**, l'esperimento del CERN che ha misurato la violazione diretta di CP nei mesoni K neutri
- Mario aveva già avuto un impatto importante sul precedente esperimento, **NA31**, che fu il primo a mettere in evidenza questa violazione
- Fu Mario ad attirare Enrico ad NA48, le implicazioni sono state numerose, per riassumere il tutto in una parola: **NA62**
- Senza Enrico non ci sarebbe NA62, così come senza Mario non ci sarebbe stato NA48
- E non finisce qui: grazie ad un PRIN Enrico ha lanciato **KLEVER**, il prossimo capitolo **di una lunga storia...**

**GRAZIE A MASSIMO PER QUESTA
OPPORTUNITA!**