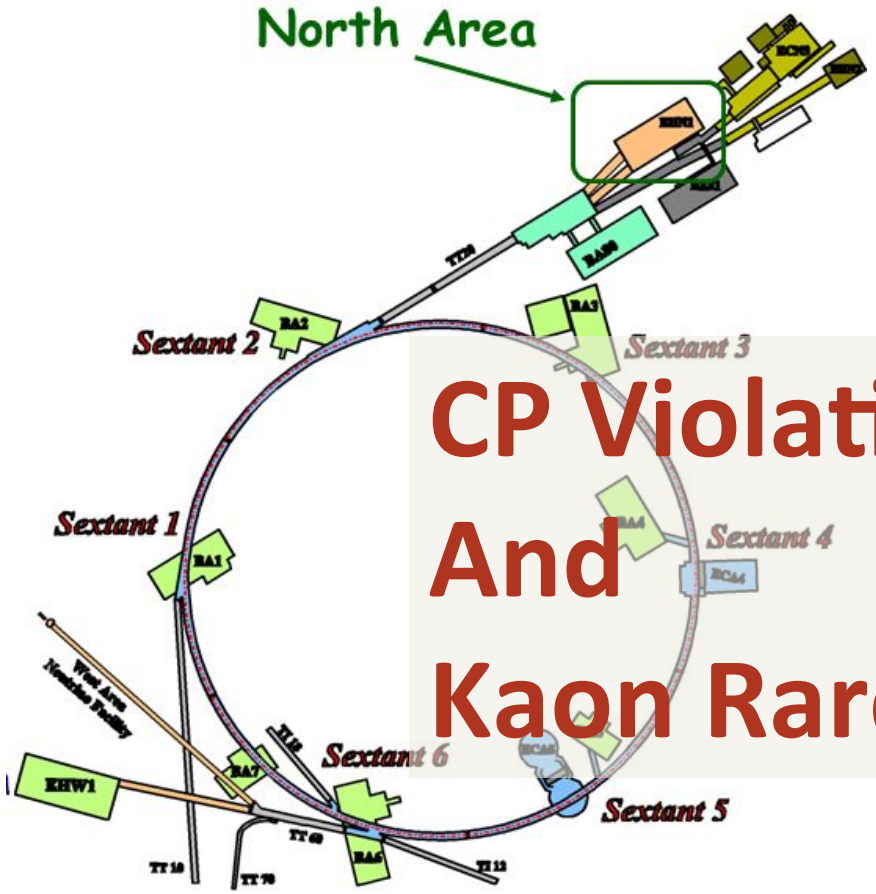
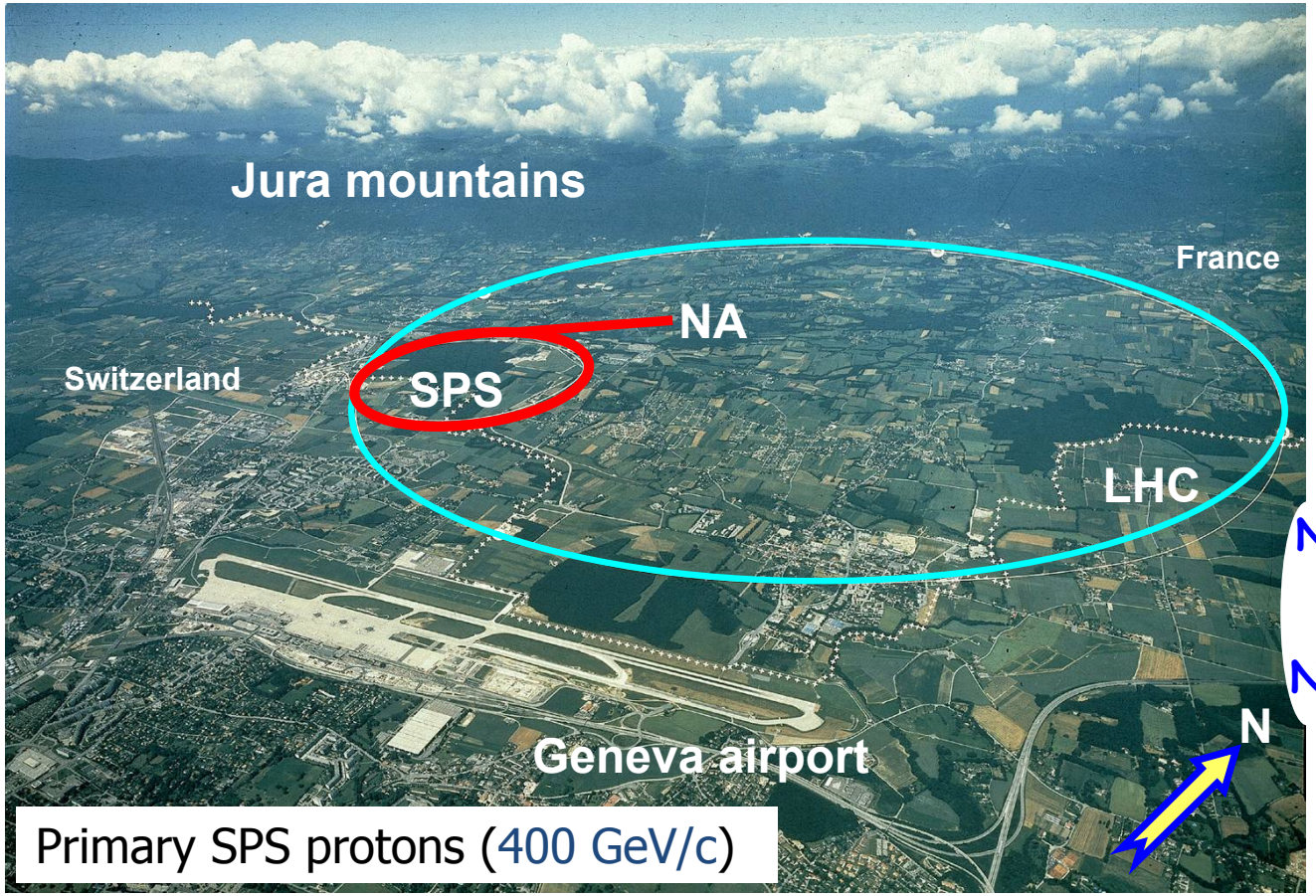


CP Violation And Kaon Rare Decays

Cristina Lazzeroni
University of Birmingham

40 years SPS NA Physics Celebration, CERN, 3 April 2019

Kaon experiments at CERN North Area



NA31	1986-89: ε'/ε: K_L+K_S	
NA48 direct CPV	1997-98: ε'/ε: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 (R_K)	2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	
	2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	
NA62	2007–2014: design & construction 2014-2015: Commissioning 2016-2018: phys data	

A story of innovation in physics and technology

CP violation in Kaon system

CP eigenstates:

$$K_1^0 = \frac{K^0 + \overline{K}^0}{\sqrt{2}} \qquad K_2^0 = \frac{K^0 - \overline{K}^0}{\sqrt{2}}$$

$CP(K_1) = +1 \rightarrow 2\pi$

$CP(K_2) = -1 \rightarrow 3\pi$

Mass eigenstates:

$$K_S = \frac{K_1 + \tilde{\varepsilon}\, K_2}{\sqrt{1 + |\tilde{\varepsilon}|^2}} \qquad K_L = \frac{K_2 + \tilde{\varepsilon}\, K_1}{\sqrt{1 + |\tilde{\varepsilon}|^2}}$$

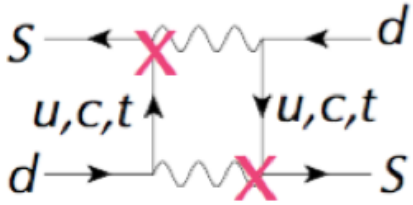
$K_L \rightarrow \pi\pi$ because of mixing

Indirect CPV

$H_{\Delta S=2}$

Indirect CP violation

Kaon oscillation



Superweak model (Wolfenstein 1964):

Mixing only source of CPV, transition matrix is CP conserving:

$$< 2\pi|T|K_2 >= 0 \qquad \eta_{+-} = \eta_{00} = \frac{< 2\pi|T|K_L >}{< 2\pi|T|K_S >} = \varepsilon \qquad \epsilon \sim \mathcal{O}(10^{-3})$$

CP violation in Kaon system

General case: $< 2\pi|T|\mathrm{K}_2 > \neq 0$

$$\varepsilon' = \frac{A(\mathrm{K}_2 \to 2\pi, I=2)}{A(\mathrm{K}_1 \to 2\pi, I=0)}$$

I=isospin

$$\eta_{00} = \varepsilon - 2\varepsilon'$$

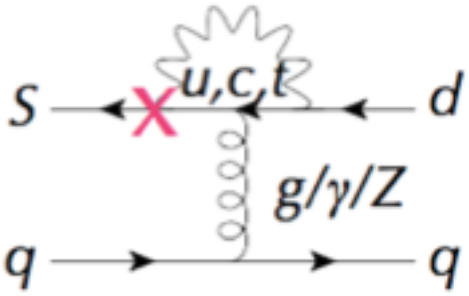
$$\eta_{+-} = \varepsilon + \varepsilon'$$

$$\epsilon' \sim \mathcal{O}(10^{-6})$$

$H_{\Delta S=1}$

Direct CP Violation

Penguin



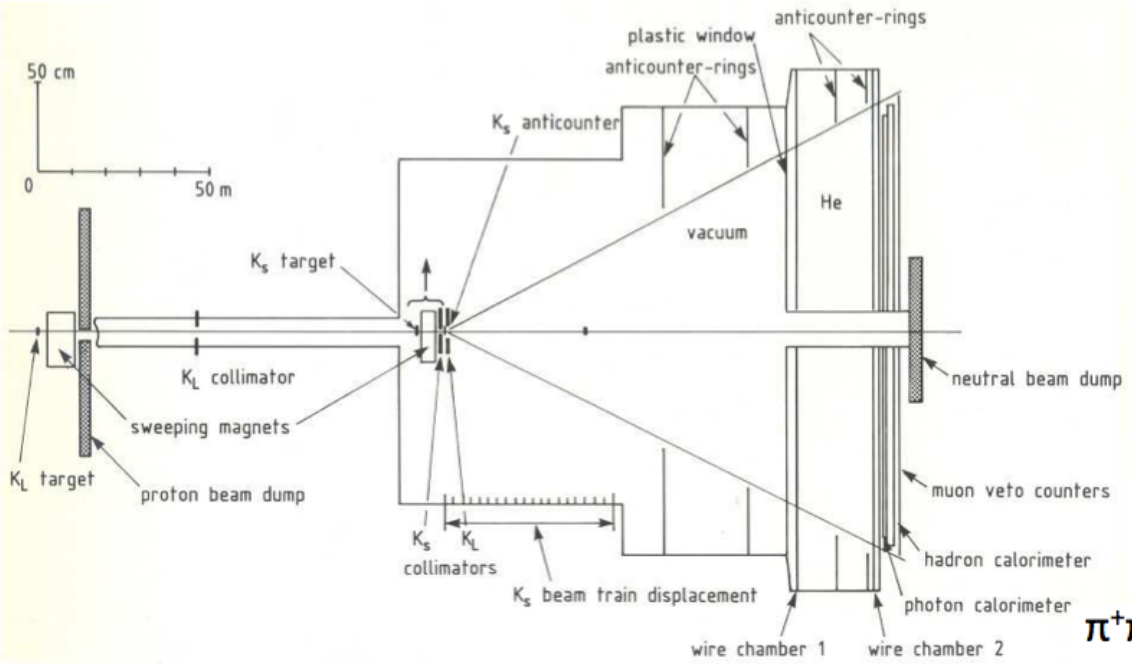
$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^+\pi^-)} \approx 1 - 6\,\varepsilon'/\varepsilon$$

Double Ratio R

'80-'90: theory prediction reached (10^{-4} - 16 10^{-4})

Need 10^{-4} precision experiments

The NA31 experiment



Liquid Argon Calorimeter

$\pi^0\pi^0$: High energy and position precision LAr calorimetry

$\pi^+\pi^-$: No magnet. Two drift chambers with 4 wire planes each.

Beam designed and tuned: Doble, Garfstrom

Isolate very rare K_L to 2π decays

Handle the very different K_S, K_L lifetimes

Alternate K_S and K_L beams, make K_S spectra similar to K_L

Detect concurrently charged and neutral decays

Particles accompanying the beam can cause gain or loss of good event,

Different from K_S and K_L: overlay method

[Lydia Iconomidou-Fayard, CERN 60 years Fest]

NA31 result and the landscape

1988:

$Re(\varepsilon'/\varepsilon)=(3.30+-1.09)10^{-3}$

[Phys Lett B206 (1988) 169]

1993:

$Re(\varepsilon'/\varepsilon)=(2.03+-0.67)10^{-3}$

[Physics Letters B 317 (1993) 233]

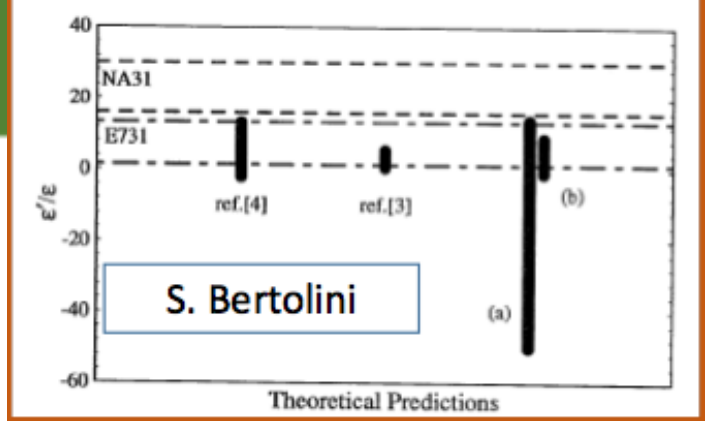
Combined NA31 : $(23.0+6.5)\ 10^{-4}$ 3.5σ

E731 Collaboration - FermiLab
L.K.Gibbons et al., Phys.Rev.Lett. 70 (1993) 1203.

Our final result is

$$Re(\varepsilon'/\varepsilon) = [7.4 \pm 5.2(stat) \pm 2.9(syst)] \times 10^{-4}.$$

Most theory schools favoured
➔The « very small ε'/ε» region

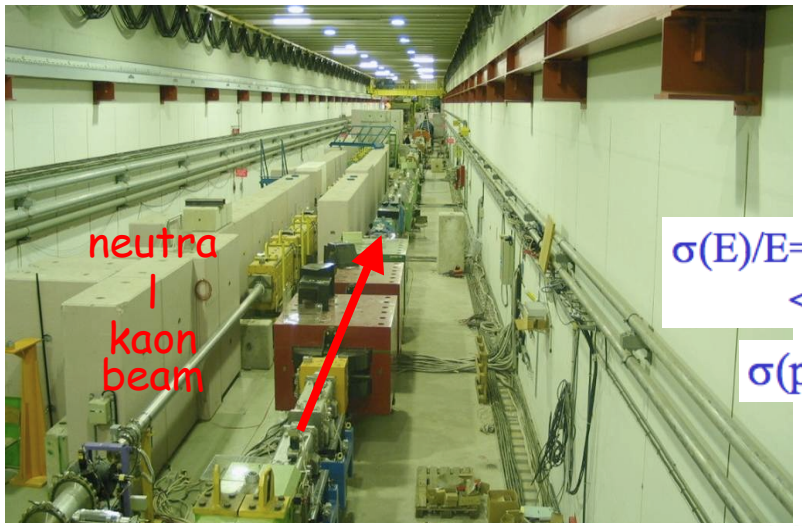


Kaon Conference, Orsay 1996

Need to improve precision
to resolve the tension: NA48 and KTeV

[Lydia Iconomidou-Fayard, CERN 60 years Fest]

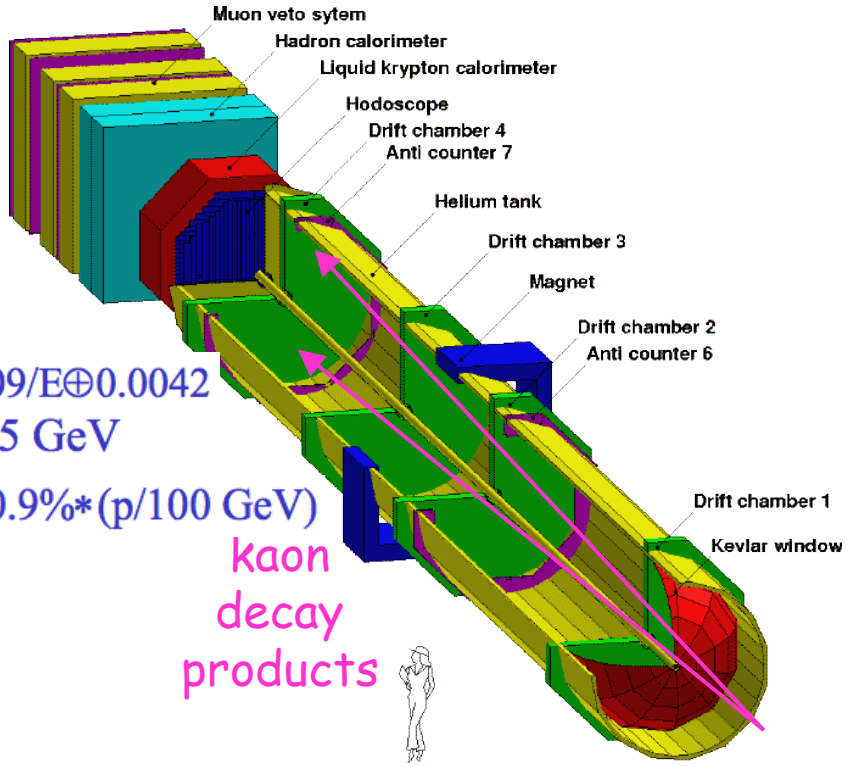
The NA48 experiment

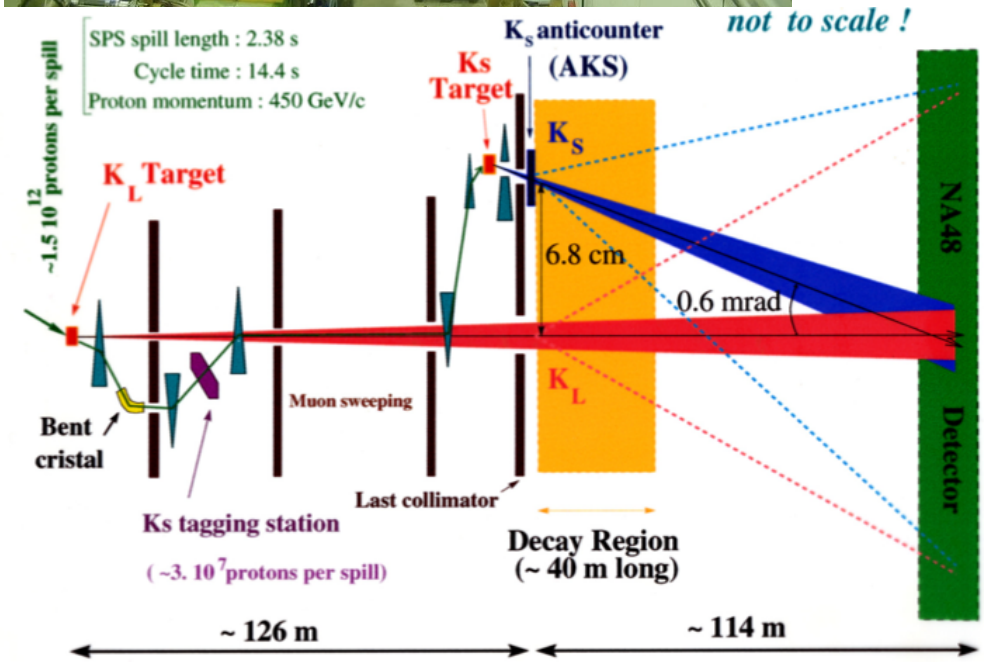


$\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$

$< 1\%$ for $E = 25$ GeV

$\sigma(p)/p = 0.5\% \oplus 0.9\% * (p/100\ \text{GeV})$





1. At least 10× the statistics of present experiments
2. Reduction of systematic uncertainties by a factor 3

Principal elements:

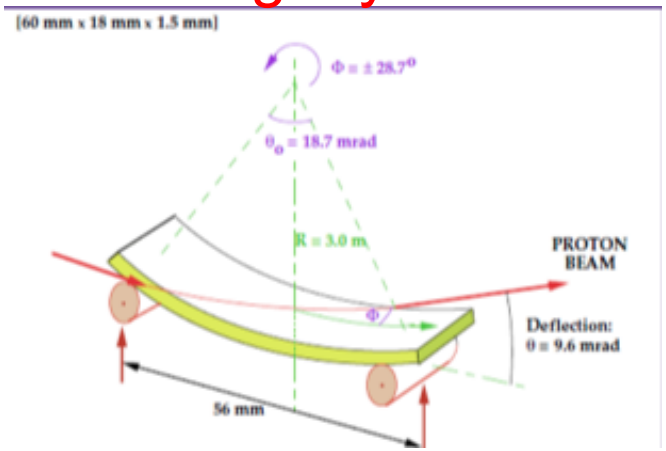
1. Concurrent detection of all 4 decay modes in the same detector
2. Tagging of K_S and K_L: coll. beams
3. Fast LKr calorimeter 2.4 m ϕ for photon detection
4. Magnet spectrometer for $\pi^+\pi^-$ to reduce background to 10^{-3} level
5. New method of analysis to reduce systematic error ($K_L : K_S$ weighting)

Heinrich Wahl HEP2005

Beam designed and tuned: Doble, Garfstrom, Gatignon

NA48: some “masterpieces”

Bending crystal

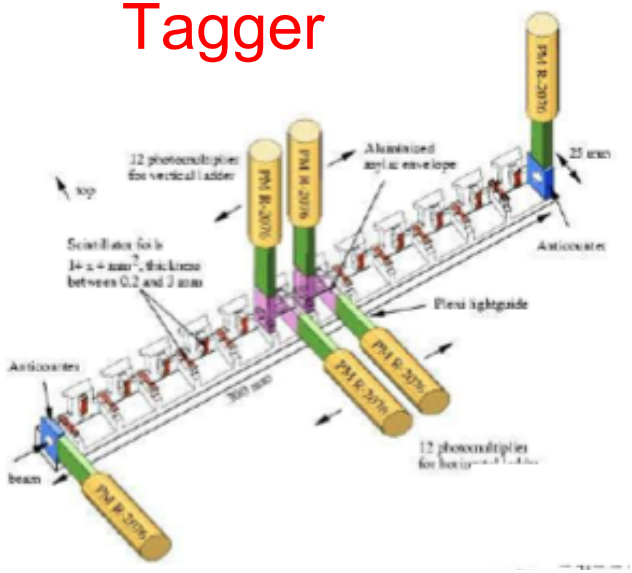


Silicon mono-crystal mounted on a motorized goniometer.
Selects 10^{-5} of the incident proton beam and deflects them towards the K_S target

LKr Calorimeter

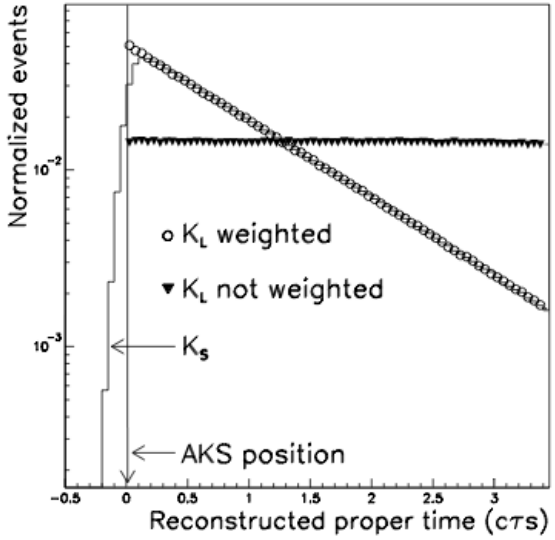
$K_L \rightarrow \pi^0\pi^0$ most difficult
Crucial to have:
Good energy resolution
small syst on energy scale and linearity
Should keep noise and constant terms to minimum

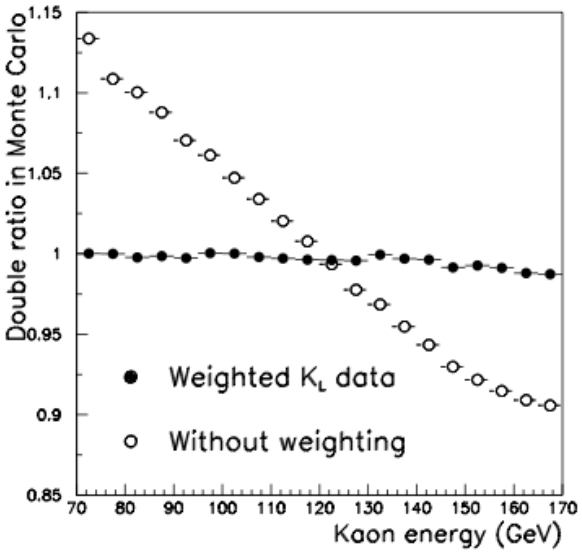
Tagger

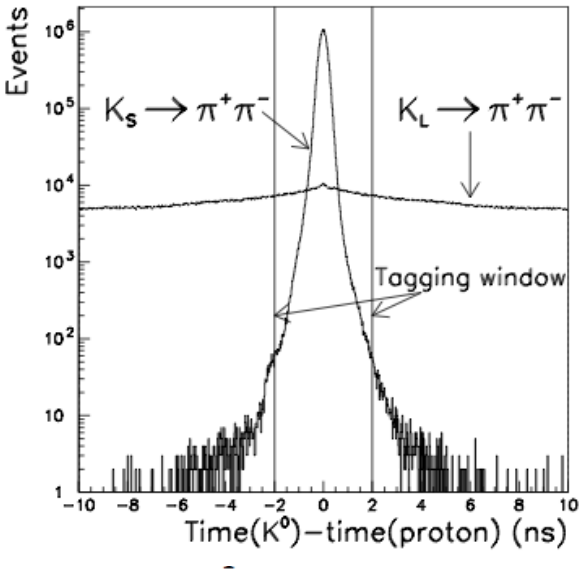


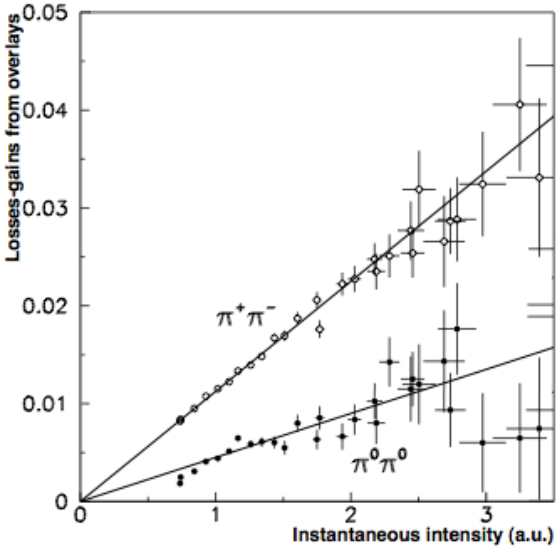
Scintillators with alternating vertical and horizontal orientations
Traversed ONLY by K_S protons
Gives the proton time ~150ps

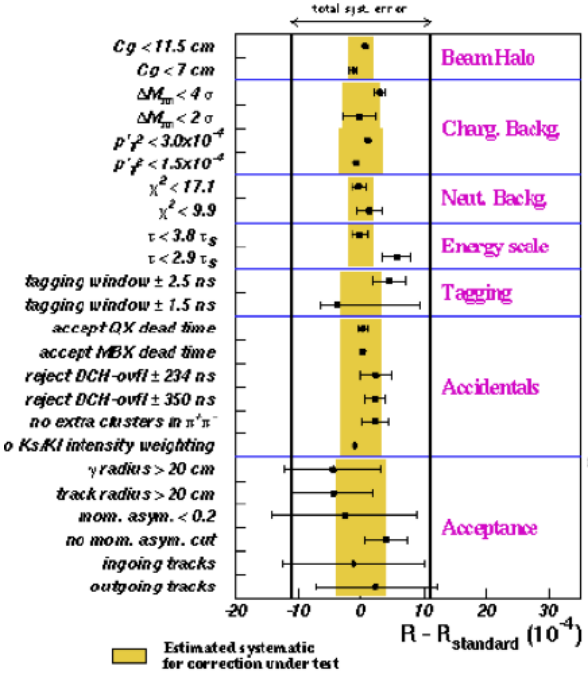
NA48: the art of precision - and checks

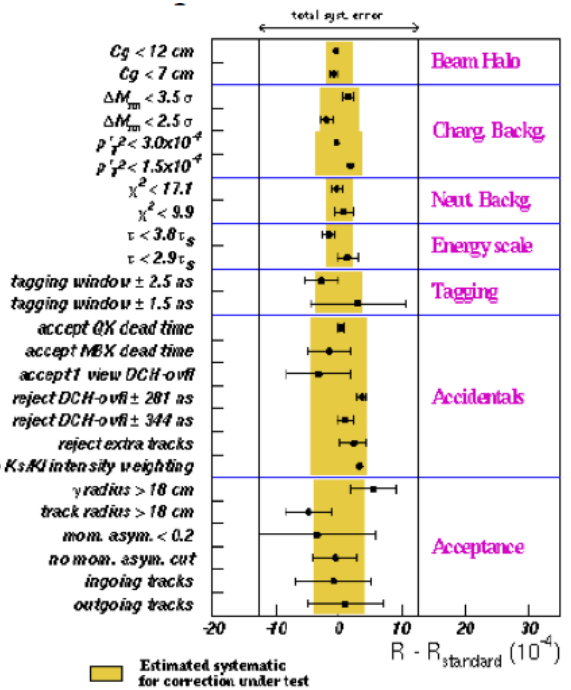




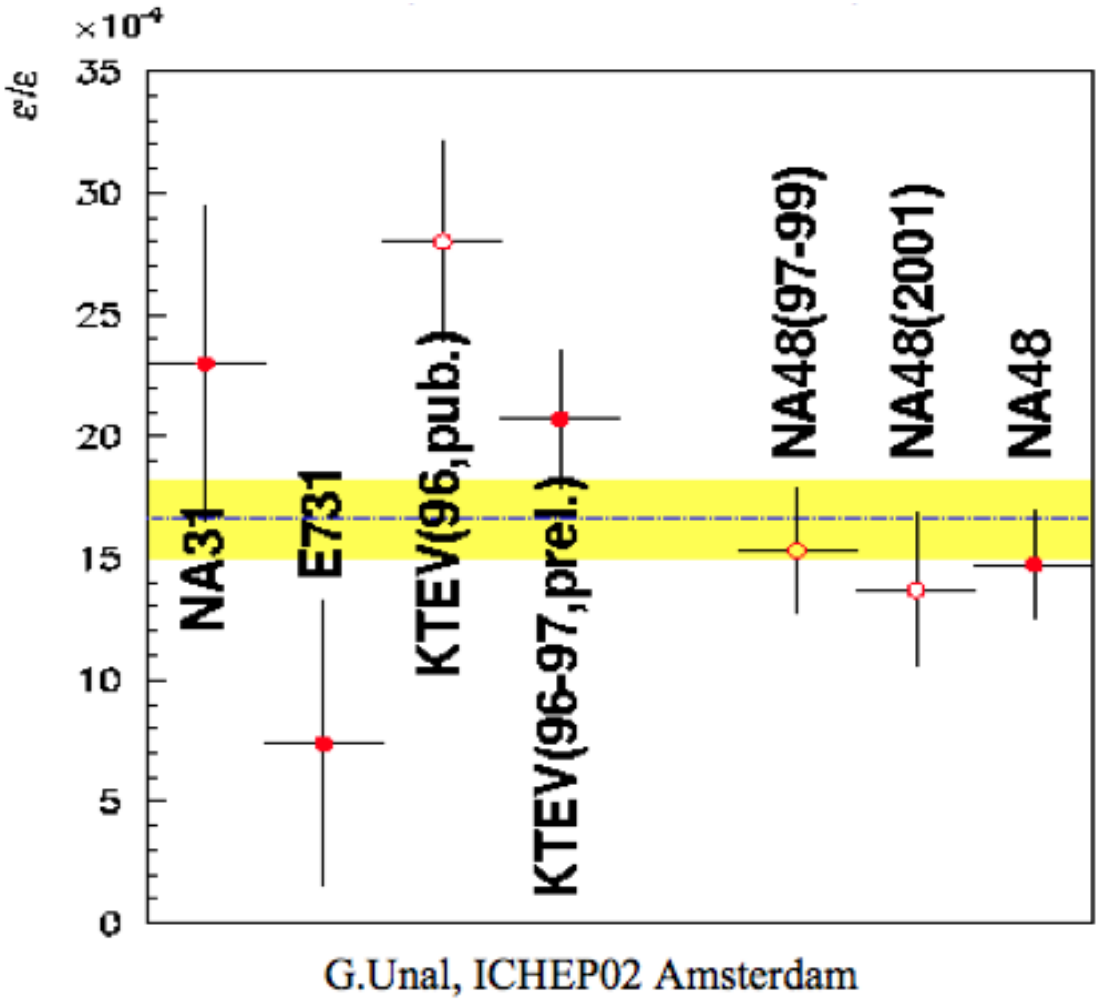








NA48: the final result



NA48 final measurement:

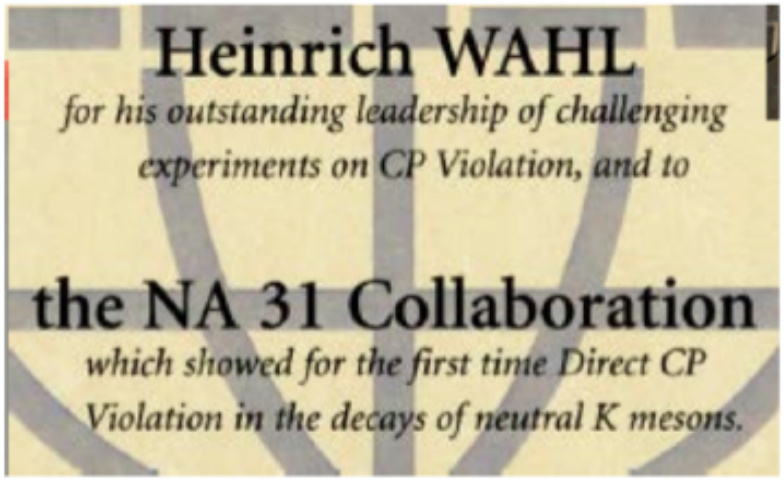
$$\varepsilon'/\varepsilon = (14.7 \pm 2.2)\ 10^{-4}$$

Confirmation of
"large" direct CPV

[Phys.Lett. B465 (1999)
Eur.Phys.Jour. C22 (2001)
Phys.Lett. B544 (2002)
Phys.Rev.D83 092001 (2011)]

Prizes

2005 EPS Prize to Heinrich Wahl and NA31



EPS 2003 (Young Physicist) to Guillaume Unal

for his contribution to the analysis of NA48 data, whereby direct CP violation in K decays was established.

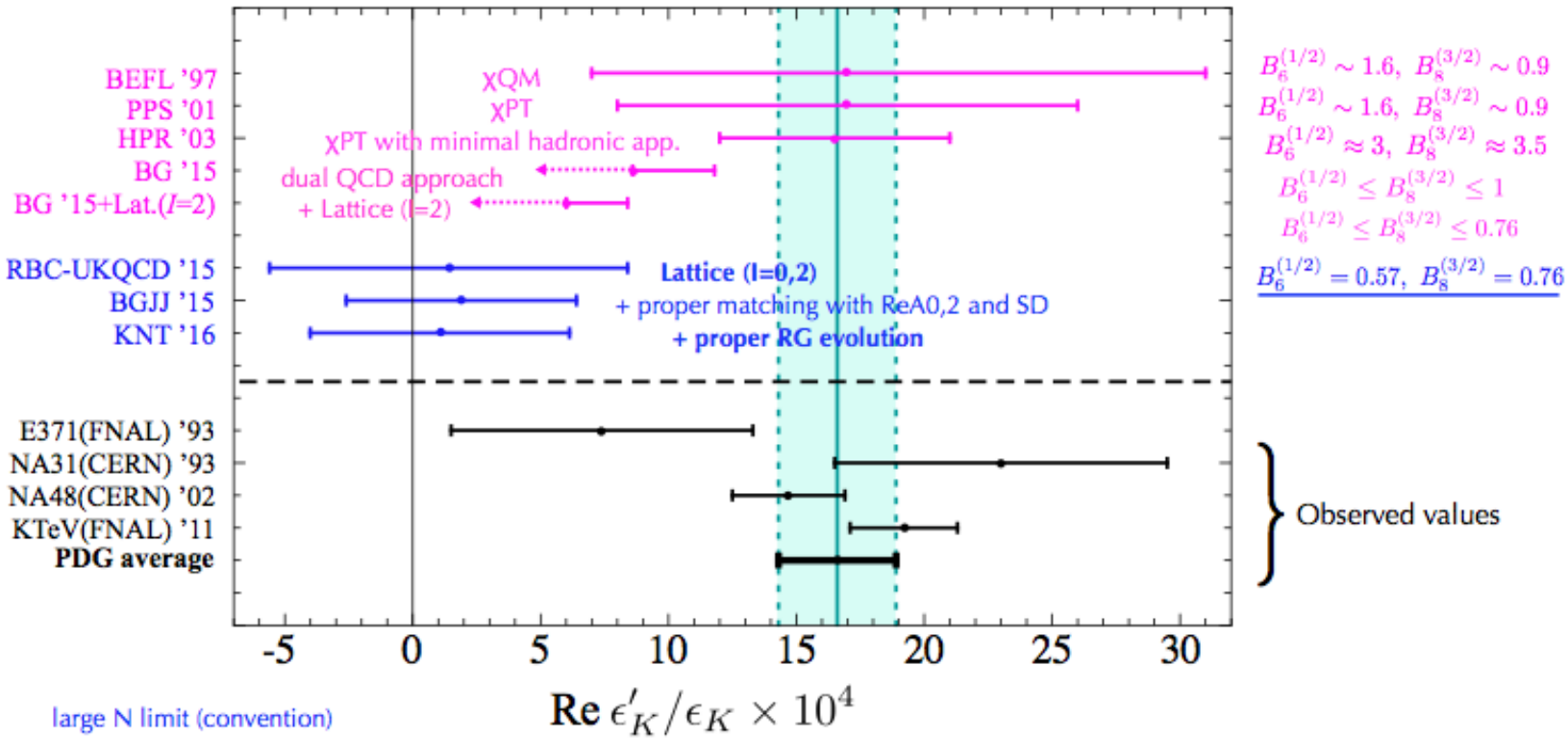
2007 Panofsky Prize to Italo Mannelli, Heinrich Wahl and Bruce Winstein

For leadership in the series of experiments that resulted in a multitude of precision measurements of properties of neutral K mesons, most notably the discovery of direct CPV

APS physics

ε'/ε continues to puzzle

Current situation of $\epsilon'_K/\epsilon_K \propto \mathrm{Im}A_0 - \left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right)\mathrm{Im}A_2$



large N limit (convention)

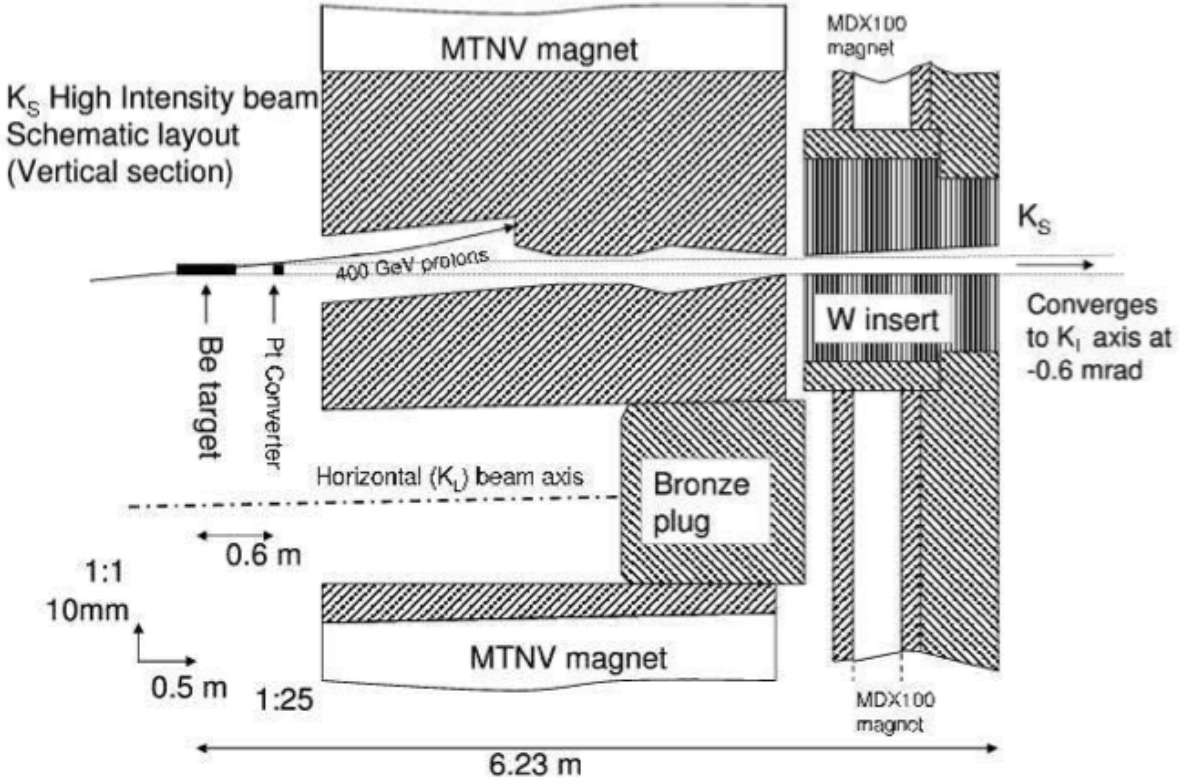
$B_6^{(1/2)} = B_8^{(3/2)} = 1$

dual QCD prediction

$B_6^{(1/2)} \leq B_8^{(3/2)} < 1,\ B_8^{(3/2)} = 0.8$

$\left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right)$	Exp.	χPT	dual QCD	Lattice (I=0,2)
	22.45 ± 0.05	~ 14	16.0 ± 1.5	31.0 ± 11.1

NA48/1: K_S rare decays



+ NA48 Detector

Beam:
designed and
tuned by
Niels Doble and
Lau Gatignon

$$B(K_S \to \pi^0 e^+ e^-) \simeq 5.2 \times 10^{-9}\, a_S^2$$

$$BR(K_L \to \pi^0 e^+ e^-) = \left(15.3 a_S^2 \pm 6.8 a_S \left(\frac{\mathrm{Im}(\lambda_t)}{10^{-4}} \right) + 2.8 \left(\frac{\mathrm{Im}(\lambda_t)}{10^{-4}} \right)^2 \right) \cdot 10^{-12}$$

Indirect CP violating contribution:
$BR(K_L \to \pi^0 e^+ e^-)_{IND} = BR(K_S \to \pi^0 e^+ e^-)/330$

Direct CP violating component

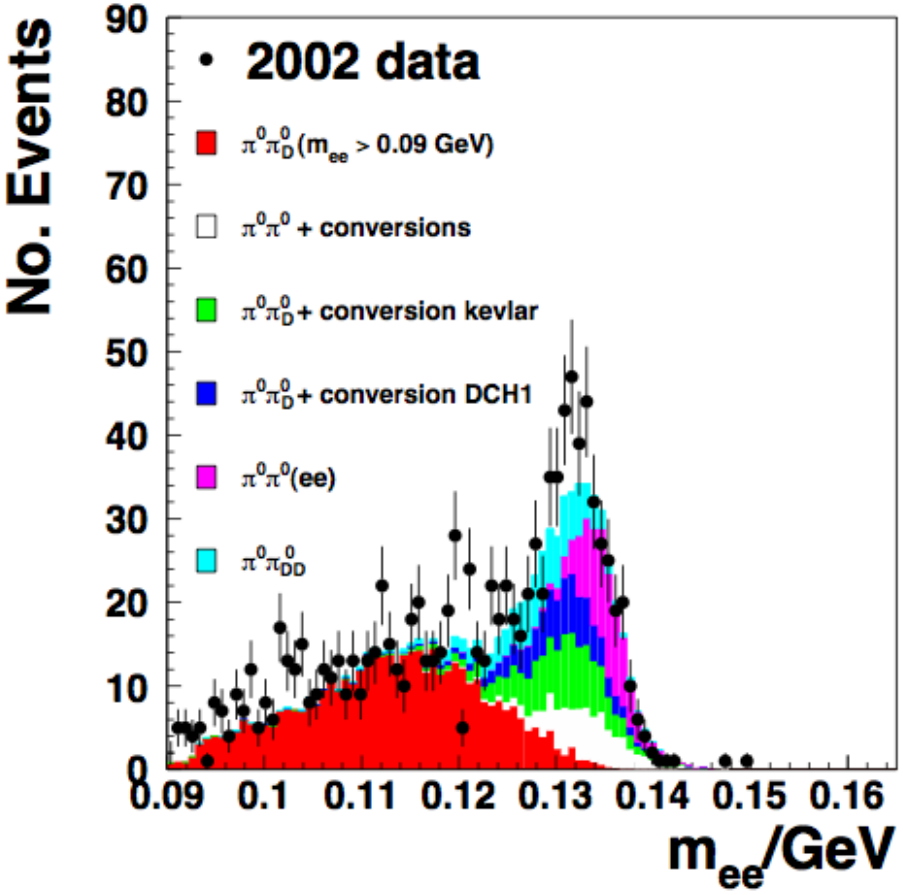
Interference sensitive to $\mathrm{Im}(\lambda_t) = \mathrm{Im}(V_{td} V_{ts}^*)$

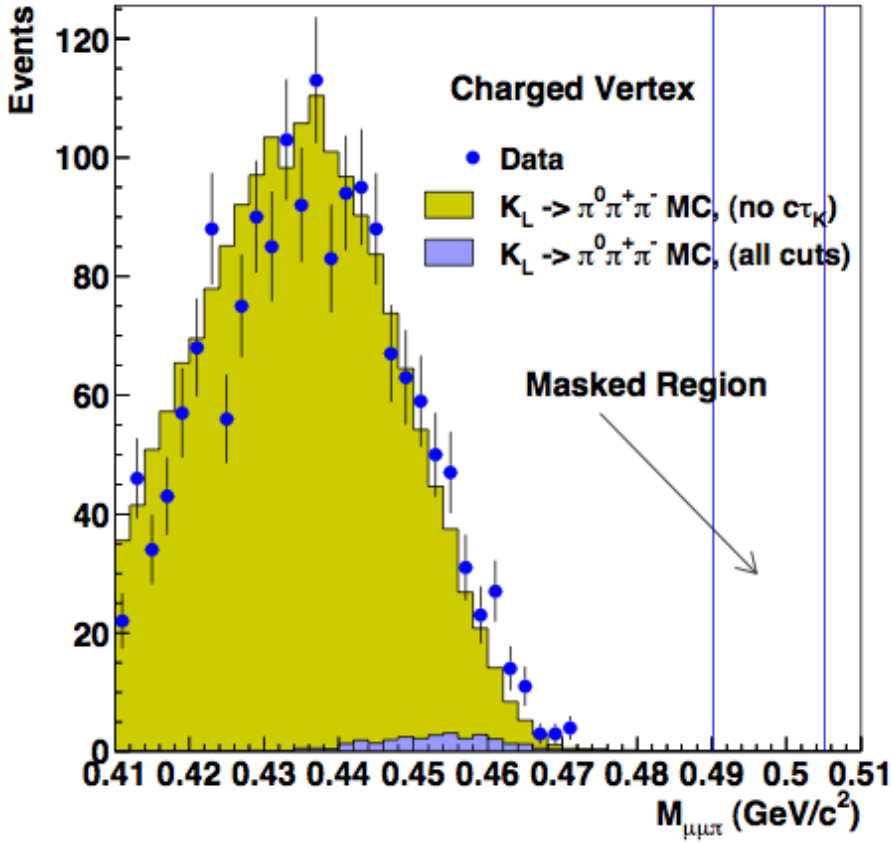
$K_S \to \pi^0 l^+ l^-$: the first NA48 blind analysis

$|M_{\pi 0 rec} - M_{\pi 0}| < 2.5\sigma_{M\pi 0}$ * $|M_{K rec} - M_K| < 2.5\sigma_{MK}$ Signal region

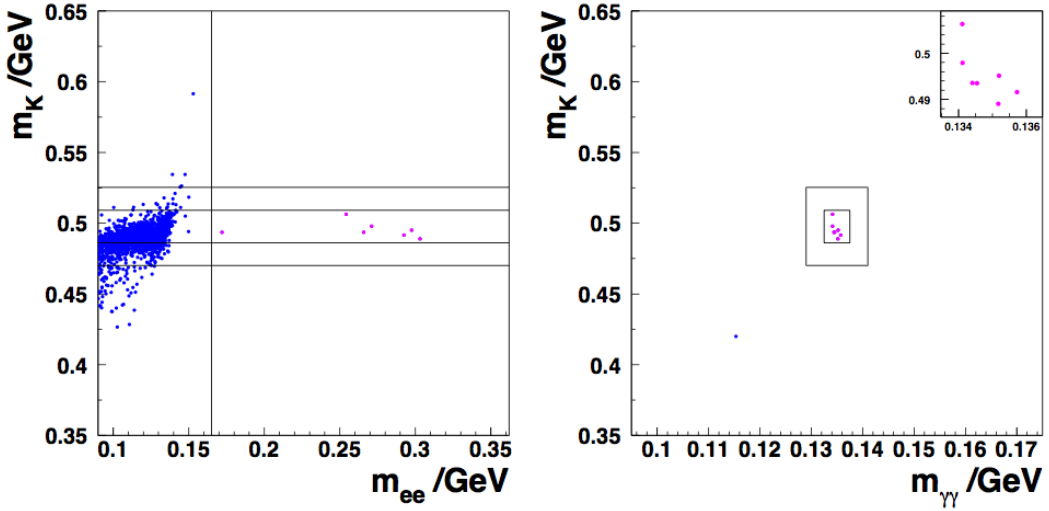
$|M_{\pi 0 rec} - M_{\pi 0}| < 6\sigma_{M\pi 0}$ * $|M_{K rec} - M_K| < 6\sigma_{MK}$ Control region

Large number of backgs studied (kaons, hyperons, time fragments)





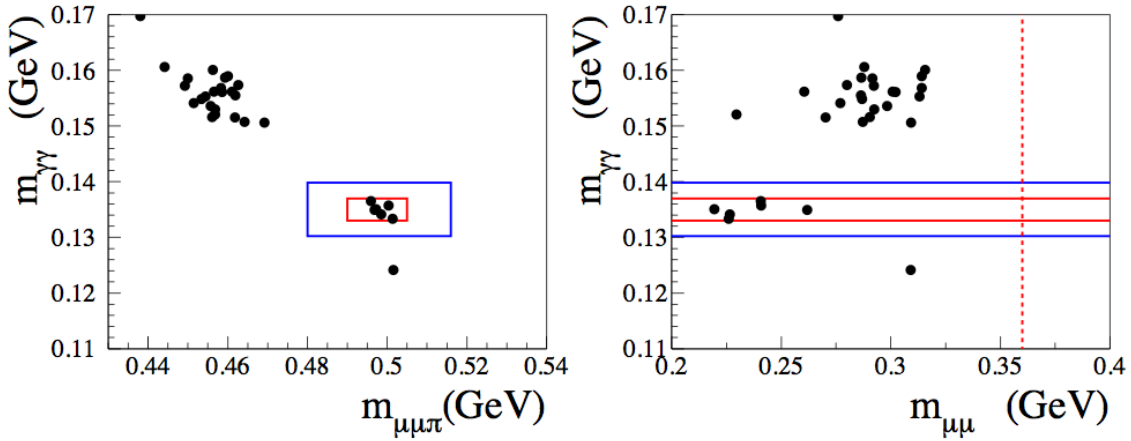
First observation of $K_S \to \pi^0 l^+ l^-$



7 events

Bckg: $0.15^{+0.10}_{-0.04}$

$$BR(K_S \to \pi^0 e^+ e^-,\ m_{ee} > 0.165\ \mathrm{GeV}/c^2) = (3.0^{+1.5}_{-1.2}(\mathrm{stat}) \pm 0.2(\mathrm{syst})) \times 10^{-9}$$



6 events

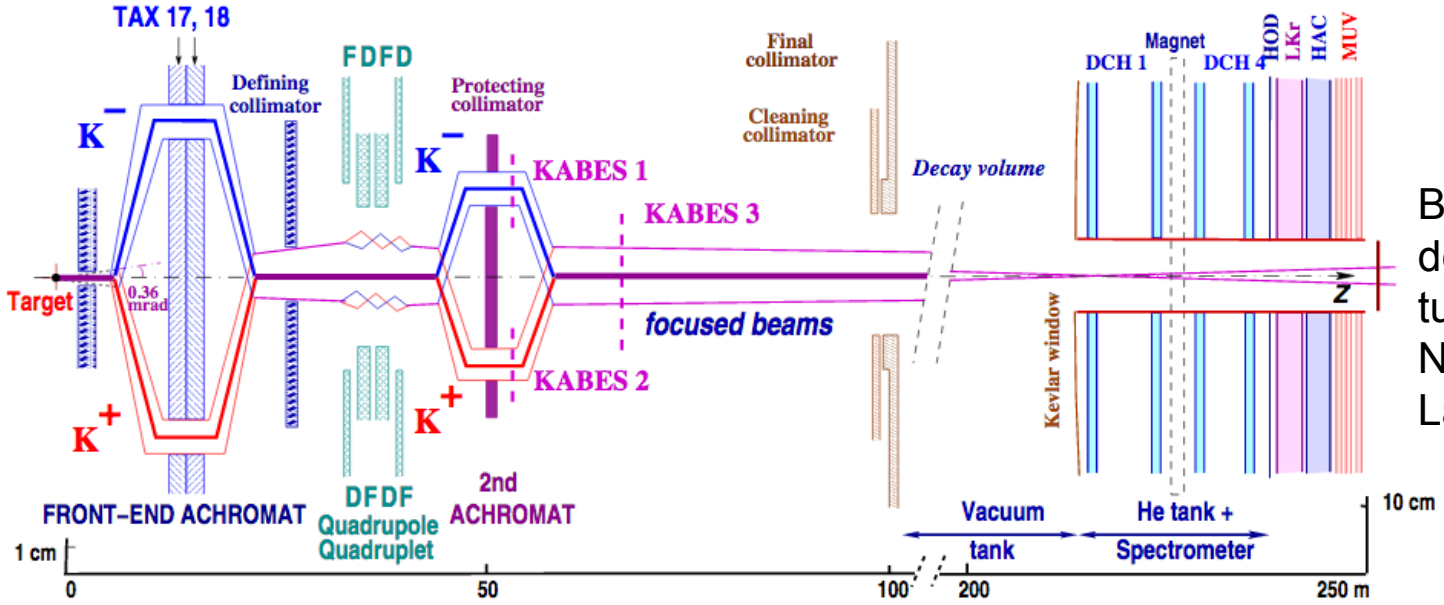
Bckg: $0.22^{+0.18}_{-0.11}$

$$B(K_S \to \pi^0 \mu^+ \mu^-) = [2.9^{+1.5}_{-1.2}(stat) \pm 0.2(syst)] \times 10^{-9}$$

Rarest K_S decays ever observed

[Physics Letter B576 (2003) 43
Phys.Letter B599 (2004) 197]

NA48/2: matter-antimatter asymmetry with K^+



Beam: designed and tuned by Niels Doble and Lau Gatignon

$$|A(K\to 3\pi)| \propto 1+gY+jX+hY^2+kX^2+\ldots$$

$$Y=(s_3-s_0)/M_\pi^2$$

$$X=(s_1-s_2)/M_\pi^2$$

$$A_g=(g^+-g^-)/(g^++g^-) \quad \neq 0 \Rightarrow \text{CPV}$$

$A_g\ (\pi^\pm\pi^+\pi^-) = (-1.5 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.3_{syst})\ 10^{-4}$

$A_g\ (\pi^\pm\pi^0\pi^0) = (1.8 \pm 1.7_{stat} \pm 0.6_{syst})\ 10^{-4}$

[Eur.Phys. J. C52 (2007) 875–891]

Limited mainly by the size of the data sample

Many other physics outputs including cusp effect…

R_K: μ-e universality in $K^{\pm}\to l^{\pm}\nu$

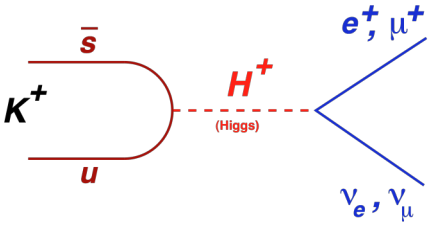
$$R_K = \frac{\Gamma(K^{\pm}\to e^{\pm}\nu)}{\Gamma(K^{\pm}\to \mu^{\pm}\nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}}_{\text{Helicity suppression: f}\sim 10^{-5}} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \underbrace{(1+\delta R_K^{\text{rad.corr.}})}_{\text{Radiative correction (few \%) due to } K^+\to e^+\nu\gamma \text{ (IB) process, by definition included into } R_K} \quad \text{SM}$$

$R_K^{SM} = (2.477\pm0.001)\times10^{-5}$

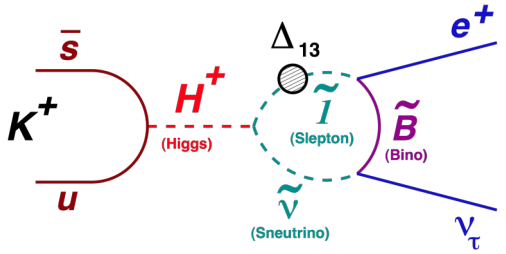
Phys. Lett. 99 (2007) 231801

[V.Cirigliano, I.Rosell JHEP 0710:005 (2007)]

Expect violation of universality at the 1% level in models involving BSM physics with charged Higgs



Tree level



One-loop level

PRD 74 (2006) 011701,JHEP 0811 (2008) 042

Use same NA48/2 detector and a 74 GeV beam

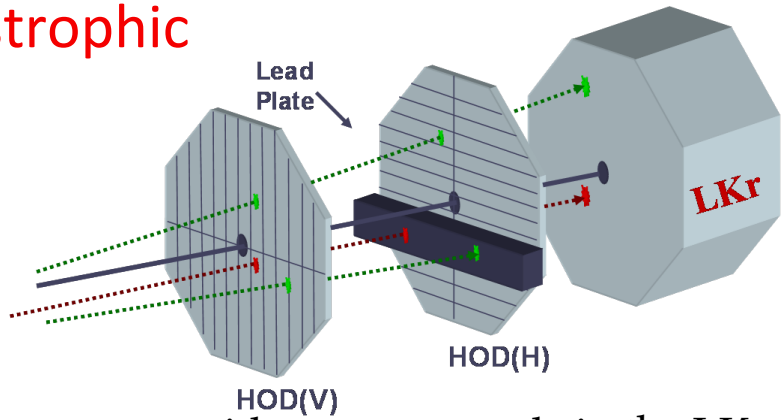
Challenge: control systematic effects

Ke2/Kμ2 candidates collected concurrently, efficiencies measured directly from data

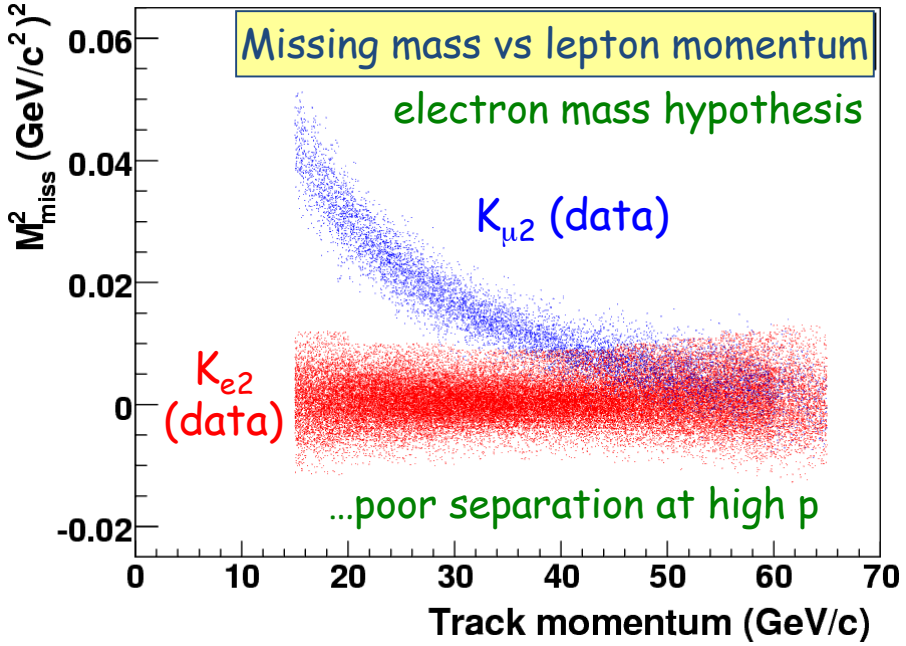
Measuring R_K

Lepton identification based on the ratio E/p (energy deposited in the LKr /track momentum measured by the magnetic spectrometer

Small fraction of muons undergoing catastrophic bremsstrahlung in the calorimeter

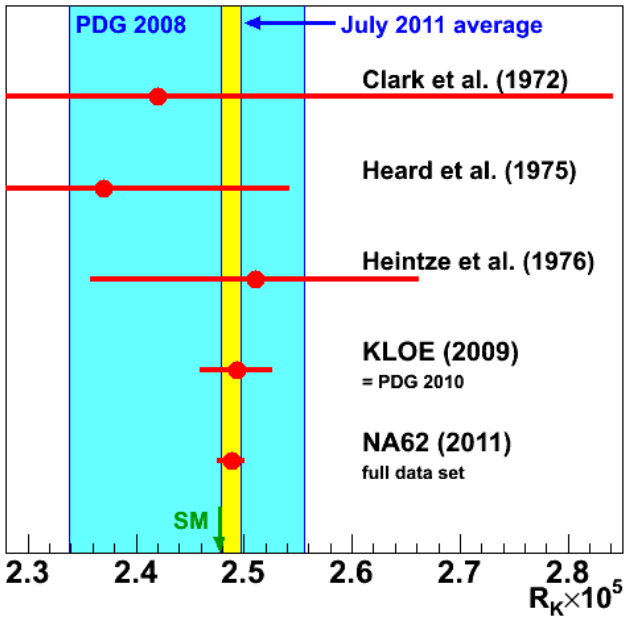


provide pure μ sample in the LKr



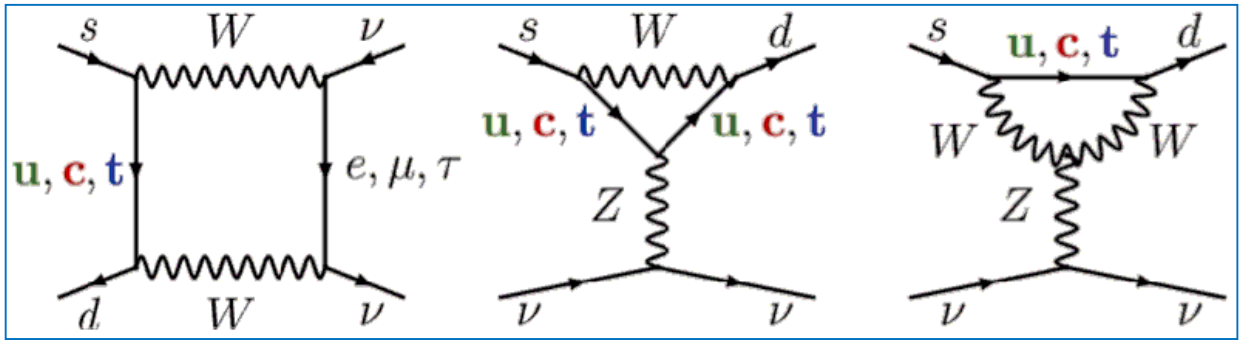
$R_K = (2.488 \pm 0.010) \times 10^{-5}$

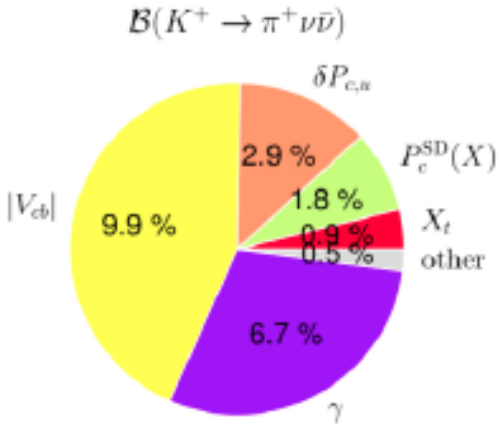
[Phys. Lett. B 719 (2013) 326]



NA62 main physics goal

SM: box and penguin diagrams





Theoretical error budget

Buras. et. al., JHEP11(2015)033

Ultra-rare decays with
the highest CKM suppression:

$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$

Hadronic matrix element related
to a measured quantity ($K^+ \to \pi^0 e^+ \nu$).

Exceptional SM precision.
Free from hadronic uncertainties.

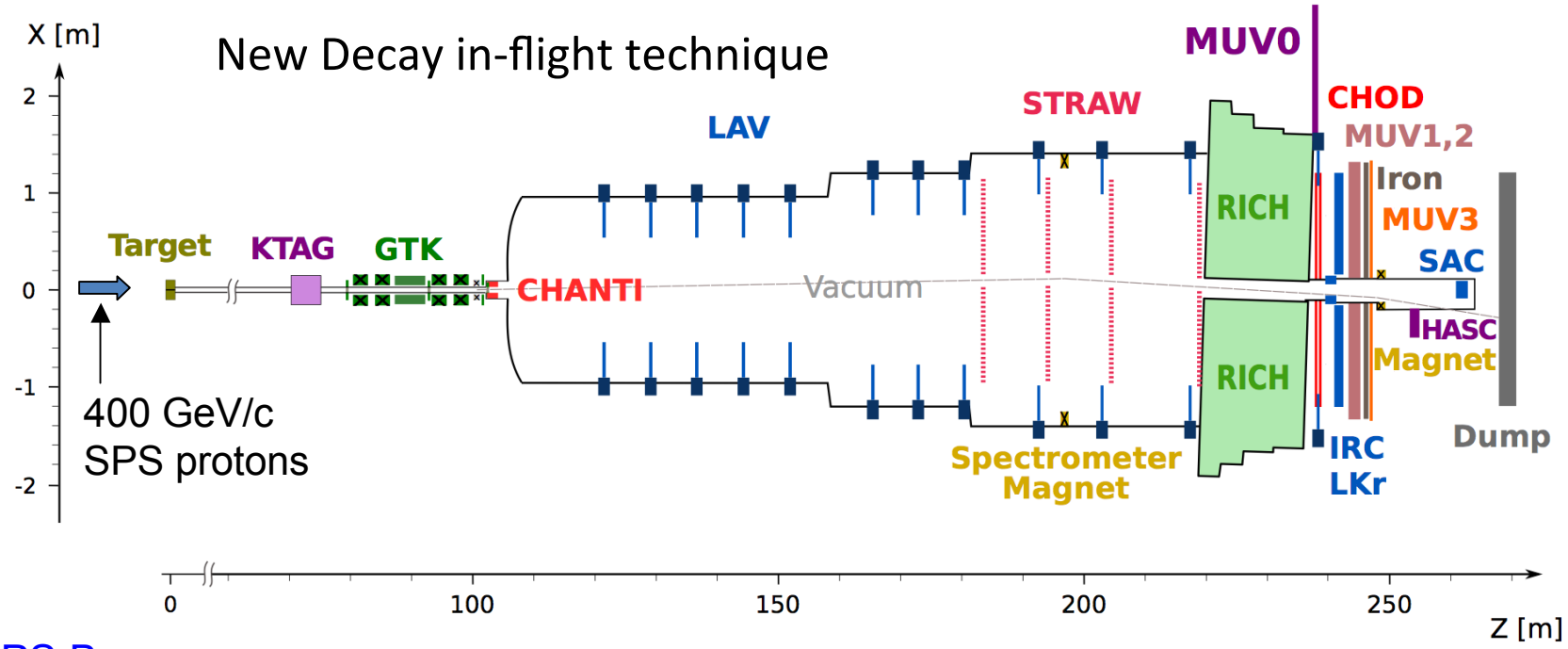
SM branching ratios

Buras et al., JHEP 1511 (2015) 033

Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\nu(\gamma)$	8.4±1.0
$K_L \to \pi^0 \nu\nu$	3.00±0.31

Theoretically clean, almost unexplored.
Sensitive to new physics and the Zepto Universe.

NA62: new beam and detector



SPS Beam:

400 GeV/c protons

2.10^{12} protons/spill

5s spill [3s eff.] / ~16 s

Beam: Neils Doble and Lau Gatignon

Secondary positive Beam:

75 GeV/c momentum, 1 % bite

100 μrad divergence (RMS)

60x30 mm^2 transverse size

$K^+(6\%)/\pi^+(70\%)/p(24\%)$

For $33x10^{11}$ ppp on T10

→ 750 MHz at GTK3

Decay Region:

60 m long fiducial region

~ 5 MHz K^+ decay rate

Vacuum ~ $O(10^{-6})$ mbar

Data taking so far:

2014: Pilot run

2015: Commissioning

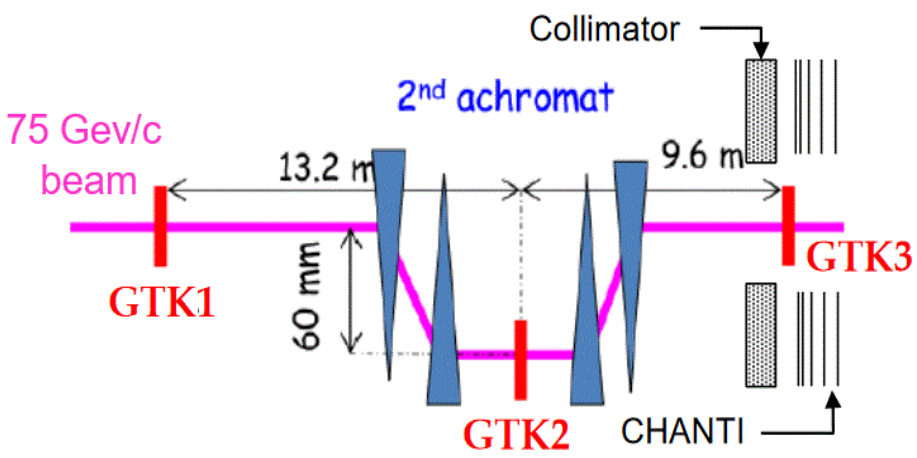
2016: Commissioning + Physics Run (30 days)

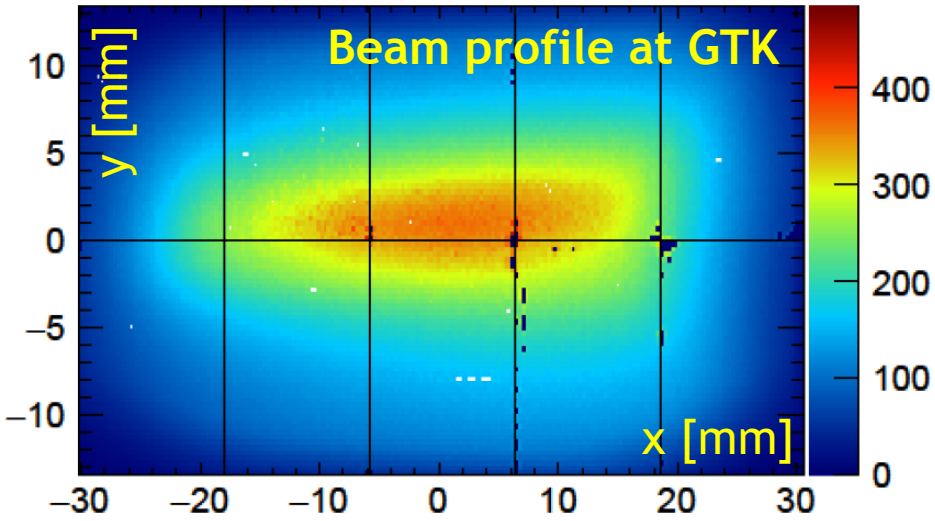
2017: Physics Run (161 days)

2018: Physics Run (217 days)

[JINST 12 (2017) P05025]

NA62 Beam tracker: the Gigatracker





Tracker design:

Three Si pixel stations in the beam.

Operation at beam rate **750 MHz**, 100 MHz/cm^2

In total, **54k** pixels (**300×300 μm^2**).

Thickness: **~0.5% X_0** per station.

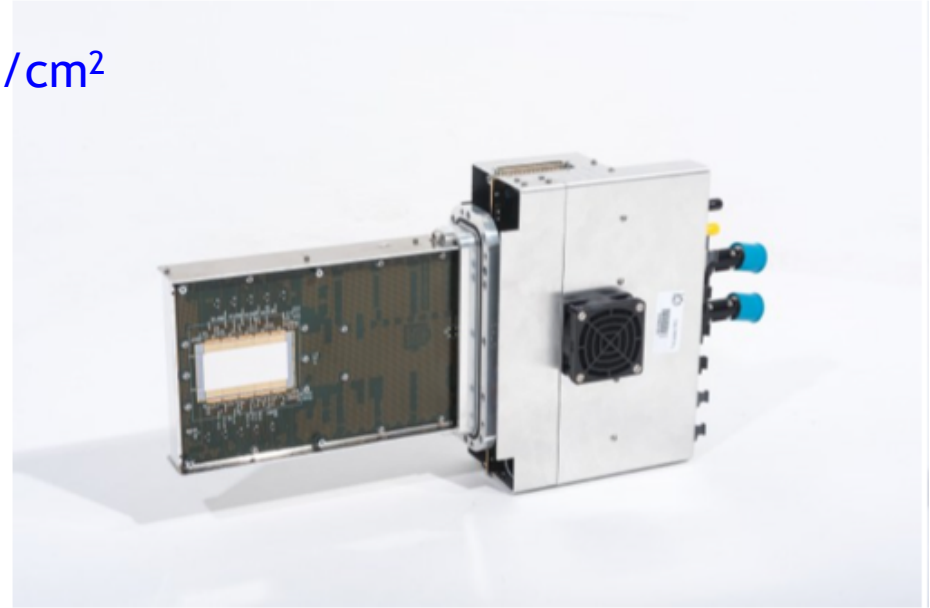
Performance:

Station efficiency: **97%.**

Time resolution **$\sigma(t_{BeamTrack}) \approx 100$ ps**

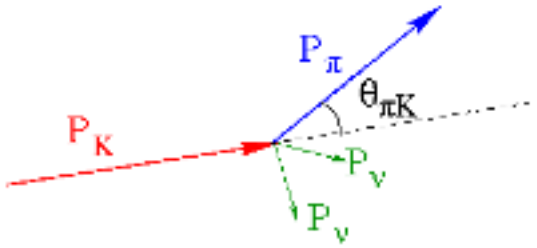
Momentum resolution **0.2%**

Space resolution σ_{xy} ~100 μm



Decay in flight technique @NA62

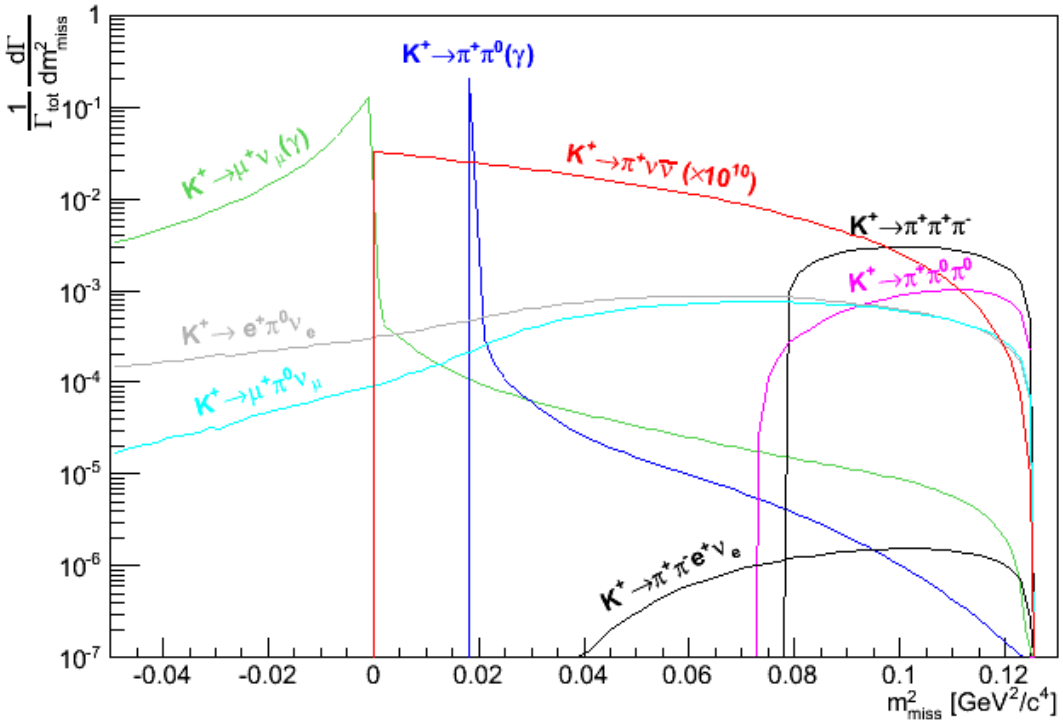
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$



15 < P(π+) < 35 GeV/c

+ Particle ID (calorimeters + Cherenkov + muonID)

Photon veto



Background rejection:

O(100 ps) timing between sub-detectors

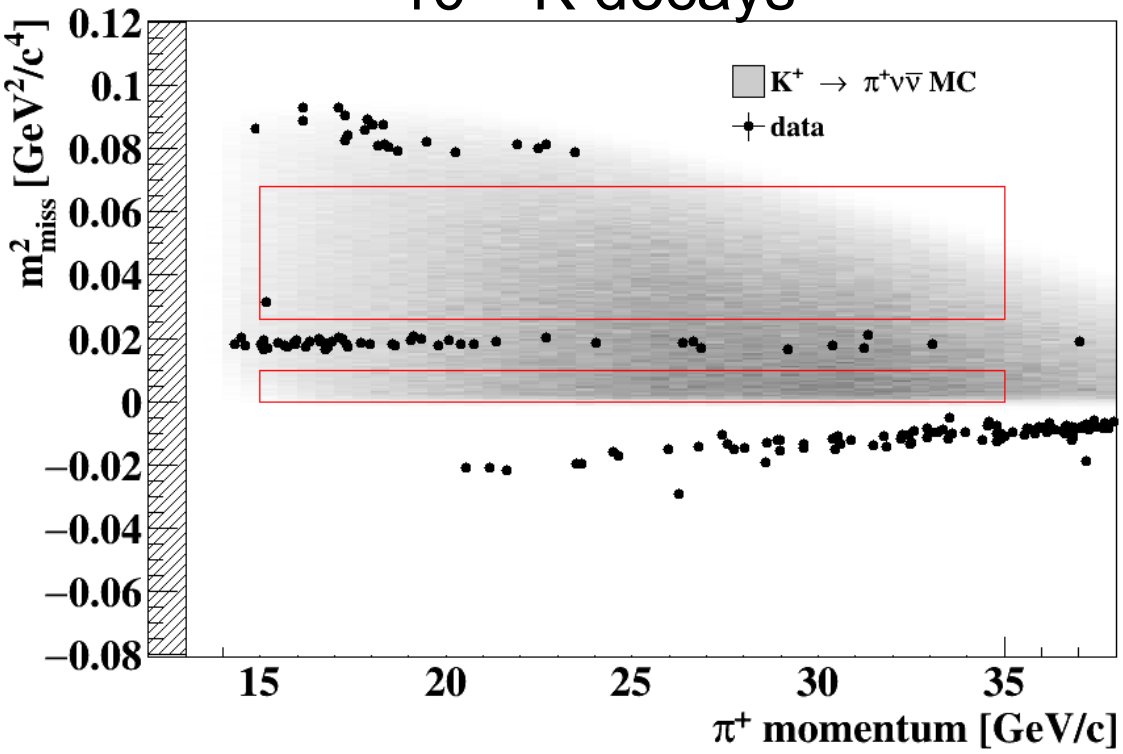
O(10^4) background suppression from kinematic

>10^7 muon suppression

>10^7 π^0 suppression (from $K^+ \to \pi^+\pi^0$)

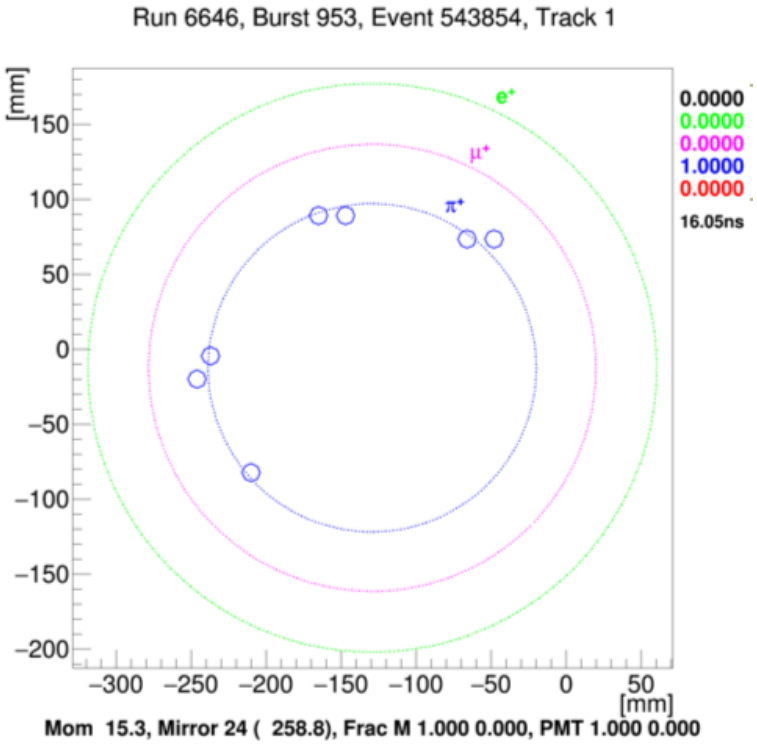
NA62 2016 Data Result

~ 10^{11} K decays



[Phys. Lett. B791 (2019) 156]

0.27 SM Signal events
and 0.15 Backg expected



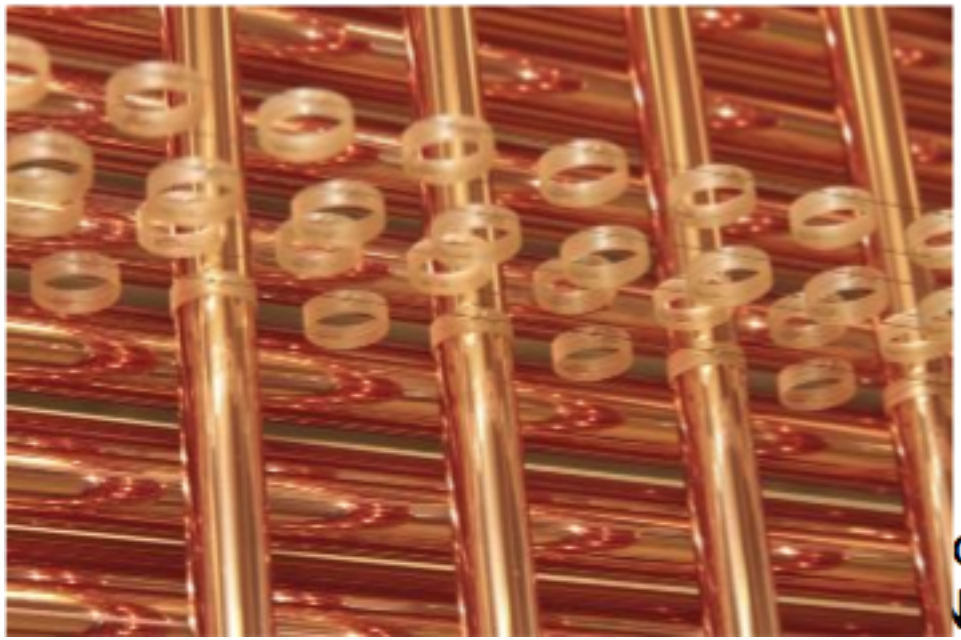
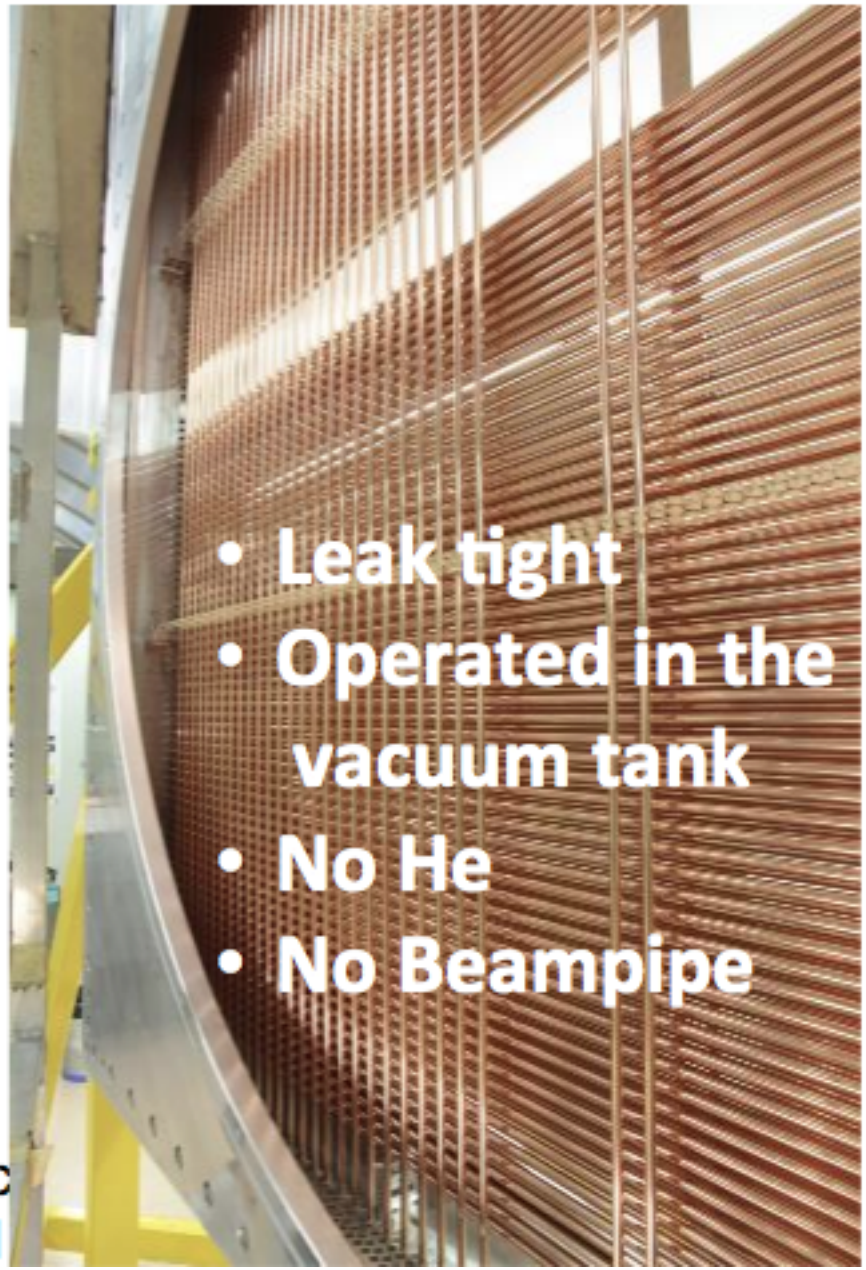
2017 data analysis in progress

Conclusions and Prospects

The observation of direct CP violation and ultra-rare kaon decays was and is a huge portal for physics and physicists

Both continue to challenge the Standard Model

The discovery of direct CP and the observation of ultra-rare kaon decays demanded and still demand challenging experiments
Several pioneering techniques and methods

The future includes (see following session):
NA62 in “dump mode”
High-intensity Kaon Factory for $K \rightarrow \pi\nu\nu$
and more

NA62 Straws tracker