GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Kaon physics at CERN - Recent results from the NA48/2 and NA62 experiments

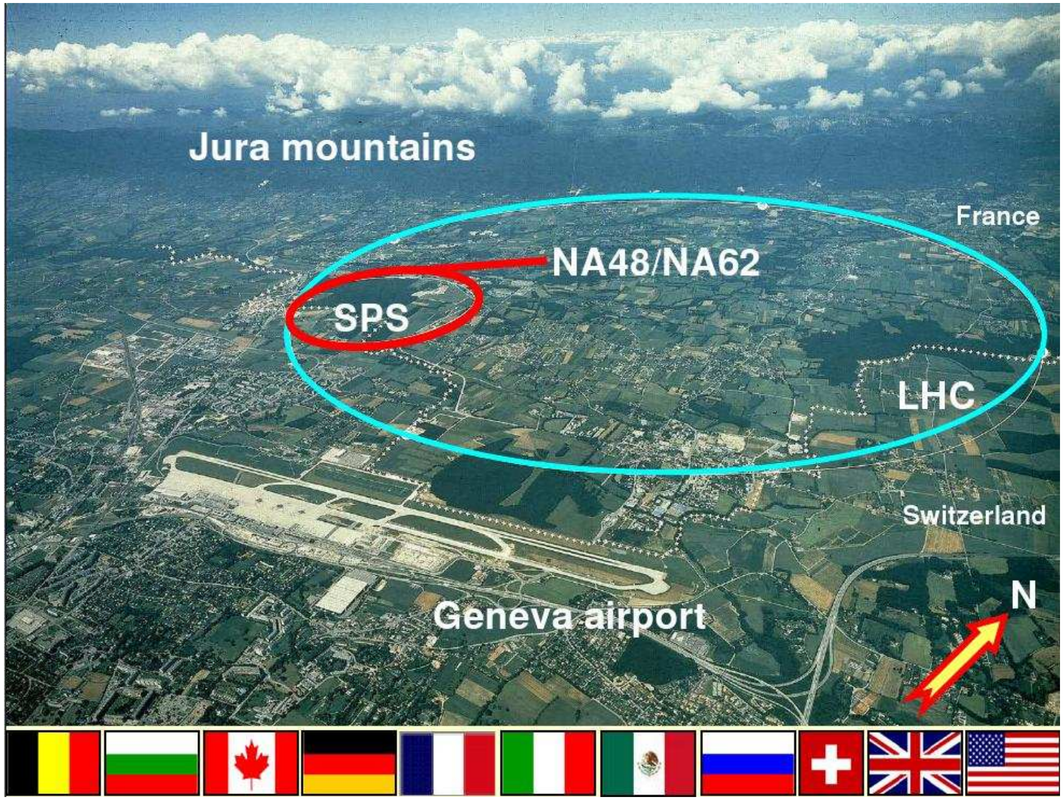
Andreas Winhart

Institut für Physik, Universität Mainz

for the NA48/2 and NA62 collaborations

Meson 2012, Cracow

NA48/NA62 at CERN



Ancestor: NA31

NA48
- **1997** ε'/ε run $K_L + K_S$
- **1998** ε'/ε run $K_L + K_S$
- **1999** ε'/ε run $K_L + K_S$ | K_S Hi. Int.
- **2000** K_L only | K_S High Intensity — *NO Spectrometer*
- **2001** ε'/ε run $K_L + K_S$ | K_S High Int.

NA48/1
- **2002** K_S High Intensity

NA48/2
- **2003** $K^{\pm}$ High Intensity
- **2004** $K^{\pm}$ High Intensity

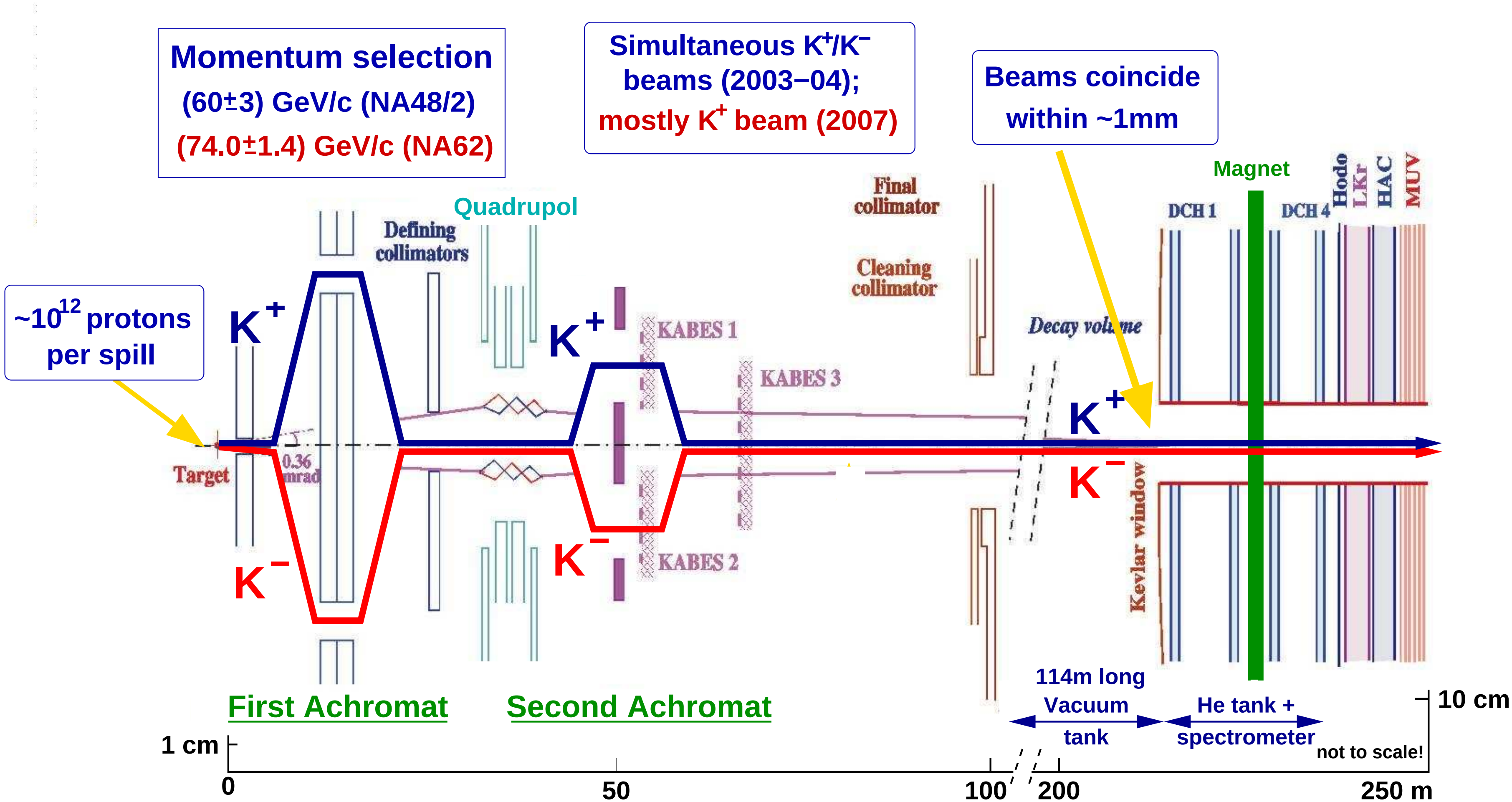
NA62 (Rk phase)
- **2007/08:** $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ runs

NA62
- **2007−2013:** R&D
- **2012:** Start $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

Topics covered in this talk:

- $K^{\pm}_{l3}$ form factors measurement at NA48/2.
- ChPT test: New measurement of $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$.
- Precision lepton flavour universality test: $K^{\pm} \rightarrow l^{\pm}\nu$.
- NA62: The ultra-rare decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$.

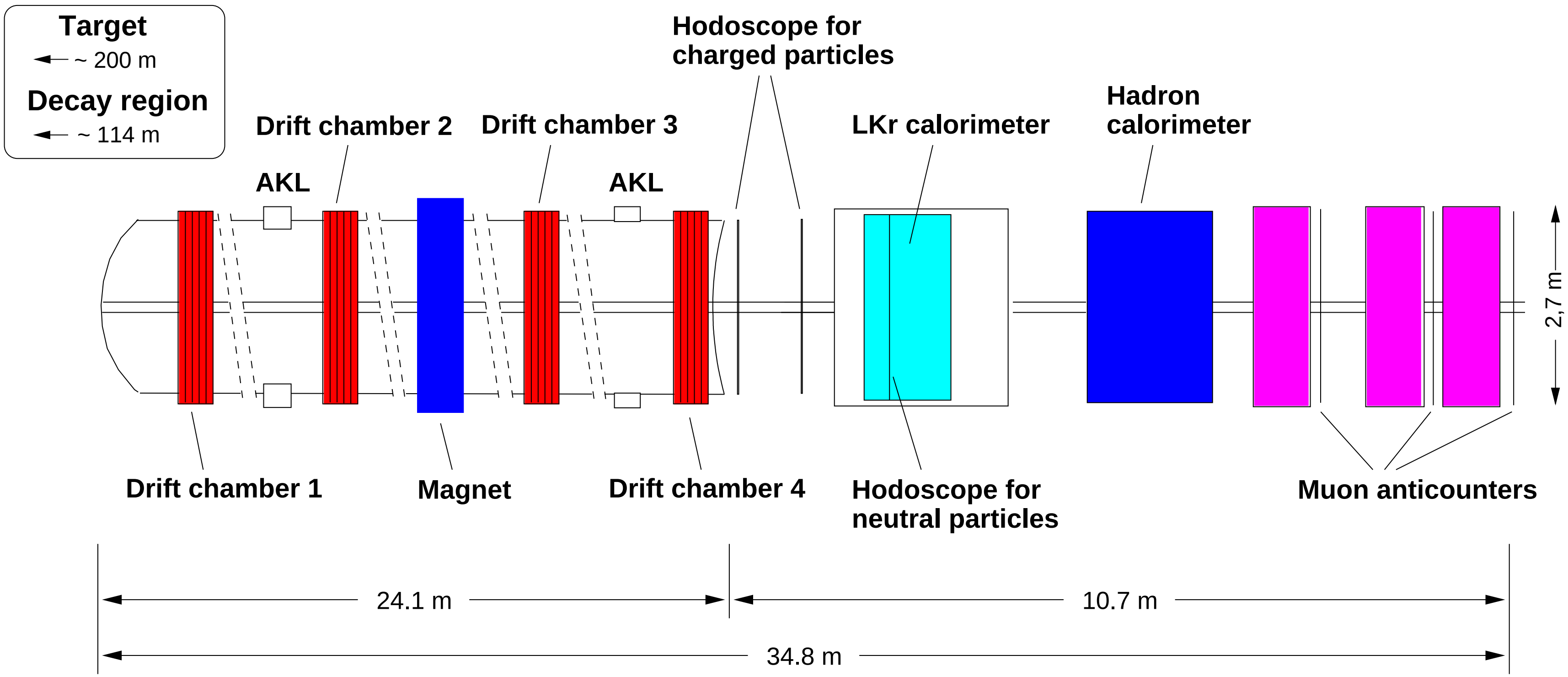
The NA48/2 and NA62 (R_K) beam line



The analyses presented in this talk are based on two data taking periods with minimum bias trigger configurations:

NA48/2: a special three days run in 2004 / NA62: four months in 2007.

The NA48 detector



Magnetic spectrometer

- 4 drift chambers with central dipole magnet
- 4 views/chamber: redundancy $\rightarrow$ efficiency
- Magnet polarity periodically reversed

NA48/2: $\Delta p/p = 1.00\,\% \oplus 0.044\,\% \times p$

NA62: $\Delta p/p = 0.47\,\% \oplus 0.020\,\% \times p$

Liquid Krypton EM calorimeter (LKr)

- High granularity (13248 cells of $2 \times 2\,$cm^2)
- Quasi-homogeneous, $\sim$7 m^3 liquid krypton as active medium (27 X_0 deep) $\rightarrow$ fully contains γ's up to 100 GeV
- $\sigma_E/E = 3.2\,\%/\sqrt{E} \oplus 9\%\,/\,E \oplus 0.42\%$ [GeV]
- Spatial resolution $\sim 1\,$mm (at 20 GeV)

Precision measurement of $K^{\pm}_{l3}$ form factors

The kaon semileptonic decays

$K \to \pi l \nu \ (K_{l3})$ decays provide the **most accurate** and **theoretically cleanest** way to access |Vus|:

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^l(\lambda_{+0})(1 + \delta_{SU(2)}^l + \delta_{EM}^l)^2$$

Experimental inputs:

- $\Gamma(K_{l3(\gamma)})$ Branching ratios and kaon lifetimes.
- $I_K^l(\lambda_{+0})$ Phase space integral depending on the form factors.

Theory inputs:

- S_{EW} Universal short distance EW corrections (1.0232 ± 0.0003).
- $f_+(0)$ Form factor at zero momentum transfer.
- $\delta_{SU(2)}^l$ Form factor correction for isospin breaking (charged mode only).
- δ_{EM}^l Long distance EM effects.

K_{l3} form factors: Introduction

K_{l3} decays are described by **two form factors** $\mathbf{f_{\pm}(t)}$, and the **matrix element** can be written as:

$$M = \frac{G_F}{2} V_{us}(f_+(t)(P_K + P_\pi)^\mu \bar{u}_l \gamma_\mu (1+\gamma_5) u_\nu + f_-(t) m_l \bar{u}_l (1+\gamma_5) u_\nu)$$

$t = q^2$ is the square of the four-momentum transfer to the lepton-neutrino system.

$f_-(t)$ can only be measured in $\mathrm{K}_{\mu 3}$ decays because of $m_e << m_\mu$.

Usually form factors are re-formulated to express the vector and scalar exchange contributions:

$f_+(t)$ is the **vector form factor**.

$f_0(t)$ is the **scalar form factor** which can be described as a linear combination of $f_\pm(t)$

$$f_0(t) = f_+(t) + \frac{t}{(m_K^2 - m_\pi^2)} f_-(t).$$

$f_+(0)$ cannot be measured directly $\Rightarrow$ the form factors are normalized to it:

$$\bar{f}_+(t) = \frac{f_+(t)}{f_+(0)}, \qquad \bar{f}_0(t) = \frac{f_0(t)}{f_+(0)}.$$

Form factor parametrizations

1) Parametrizations using **physical quantities** are called **class 1** parametrizations.
They depend on free parameters with a physical meaning.

Pole parametrization:

Assumes the exchange of vector and scalar resonances K^* with spin parity $1^-/0^+$ and masses m_V/m_S.

$f_+(t)$ can be described by $\mathrm{K}^*(892)$, while for $f_0(t)$ no obvious dominance is seen:

$$\bar{f}_{+,0}(t) = \frac{m^2_{V,S}}{m^2_{V,S} - t}$$

---

2) Parametrizations **without a physical meaning** are called **class 2** parametrizations.
They require more free parameters and are extensions in the momentum transfer t.

Linear and quadratic parametrizations:

$$\bar{f}_{+,0}(t) = \left[1 + \lambda_{+,0}\frac{t}{m^2_\pi}\right] \qquad \textbf{Linear}$$

$$\bar{f}_{+,0}(t) = \left[1 + \lambda'_{+,0}\frac{t}{m^2_\pi} + \frac{1}{2}\lambda''_{+,0}\left(\frac{t}{m^2_\pi}\right)^2\right] \qquad \textbf{Quadratic}$$

More free parameters to be determined $\quad\rightarrow\quad$ **Correlations!**

No sensitivity to determine $\boldsymbol{\lambda''_0}$ with current experiments $\quad\rightarrow\quad$ $\boldsymbol{\bar{f}_+}$ quadratic / $\boldsymbol{\bar{f}_0}$ linear.

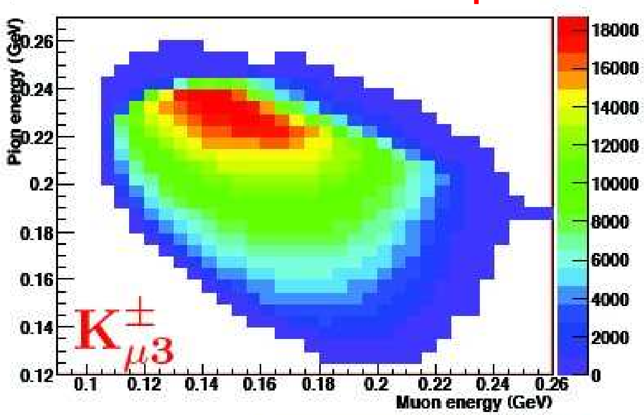
K_{l3} Dalitz plots + corrections

Data recorded 2004 in a special three days run with minimum bias trigger.

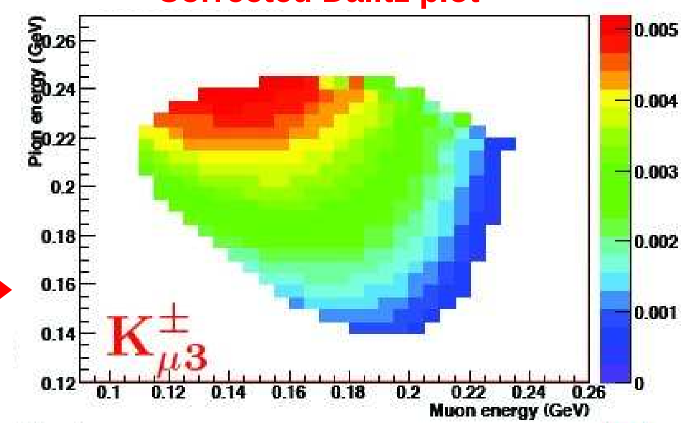
2.5×10^6 $K^{\pm}_{\mu 3}$ candidates selected
4.0×10^6 $K^{\pm}_{e3}$ candidates selected

Very low background for both channels at per-mil level !

Reconstructed data Dalitz plot

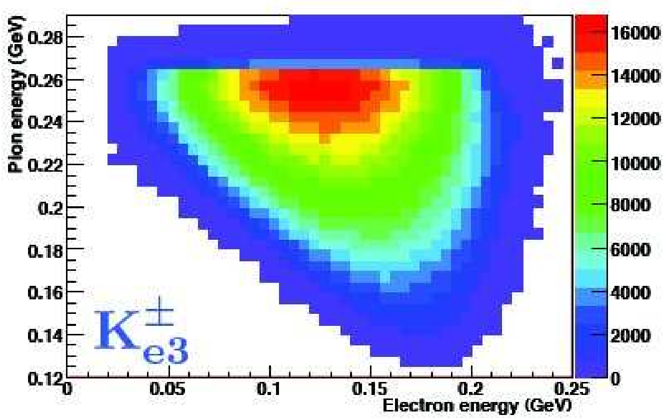


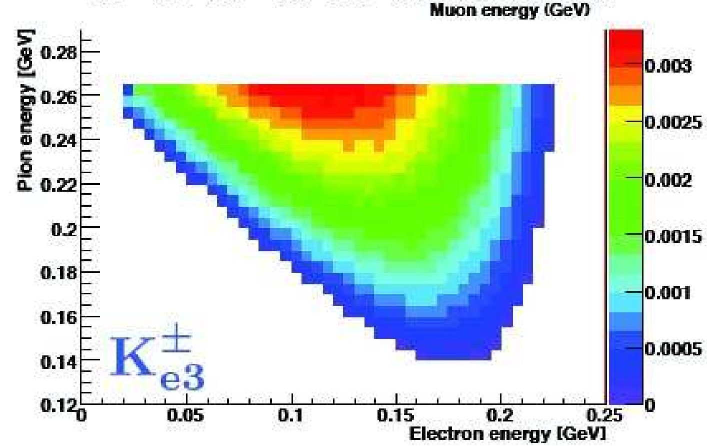
Corrected Dalitz plot



Applied corrections:

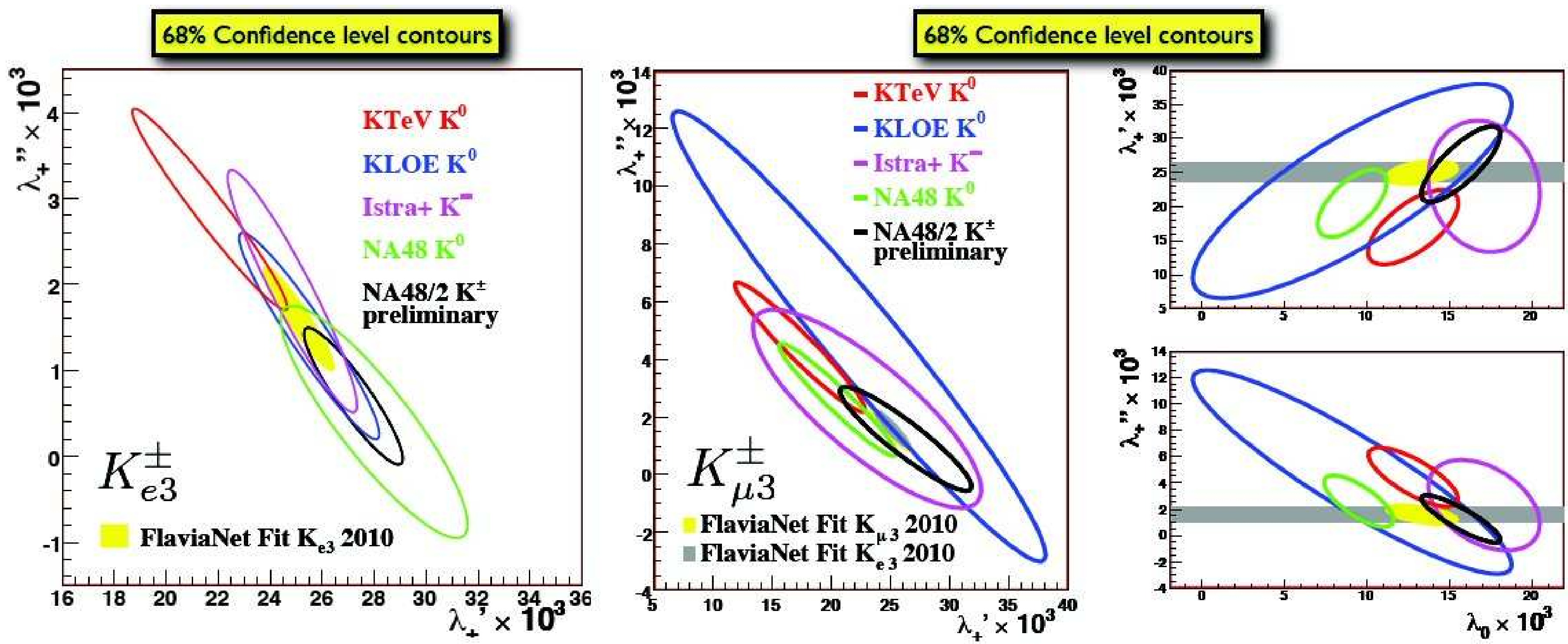
Background subtraction
Acceptance
Radiative corrections





Preliminary results (1)

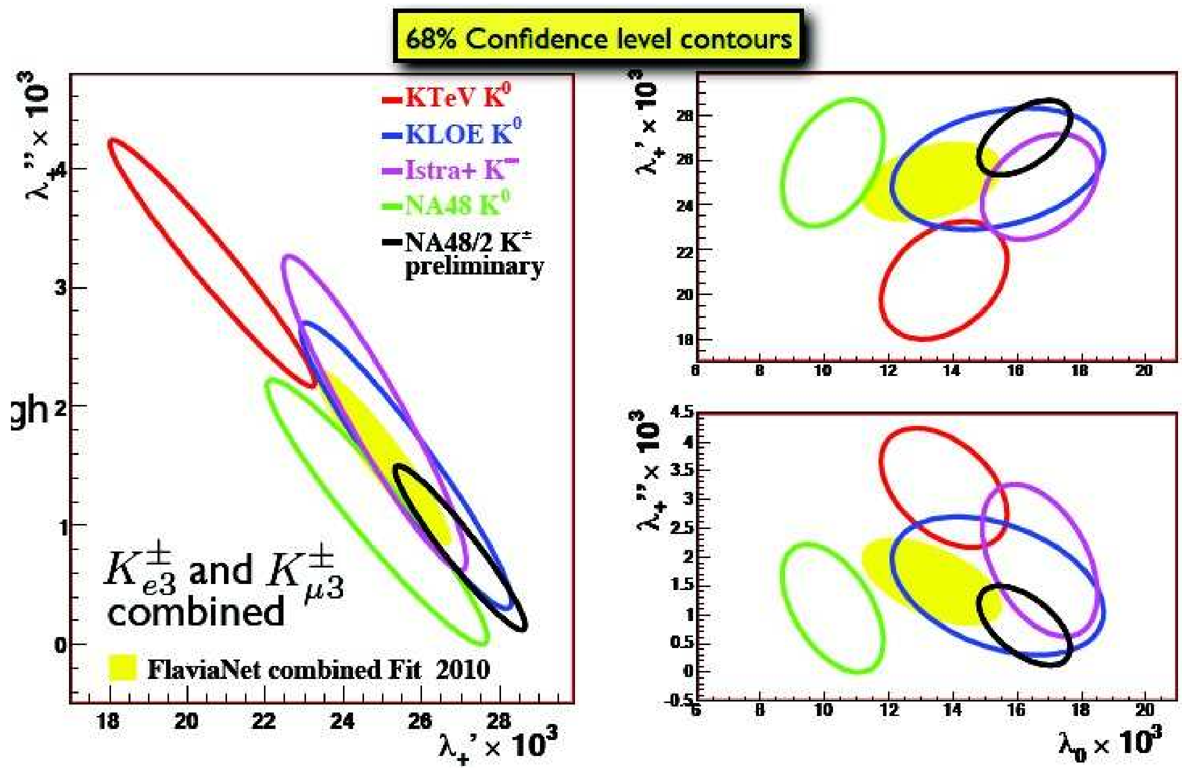
Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ_0
$K^\pm_{\mu 3}$	$26.3 \pm 3.0_{\rm stat} \pm 2.2_{\rm syst}$	$1.2 \pm 1.1_{\rm stat} \pm 1.1_{\rm syst}$	$15.7 \pm 1.4_{\rm stat} \pm 1.0_{\rm syst}$
$K^\pm_{e3}$	$27.2 \pm 0.7_{\rm stat} \pm 1.1_{\rm syst}$	$0.7 \pm 0.3_{\rm stat} \pm 0.4_{\rm syst}$	
Pole (MeV/c^2)	m_V		m_S
$K^\pm_{\mu 3}$	$873 \pm 8_{\rm stat} \pm 9_{\rm syst}$		$1183 \pm 31_{\rm stat} \pm 16_{\rm syst}$
$K^\pm_{e3}$	$879 \pm 3_{\rm stat} \pm 7_{\rm syst}$		



Preliminary results (2)

Quadratic $(\times 10^{-3})$	λ'_+	λ''_+	λ_0
$K^\pm_{\mu 3} K^\pm_{e3}$ combined	26.98 ± 1.11	0.81 ± 0.46	16.23 ± 0.95
Pole (MeV/c^2)	m_V		m_S
$K^\pm_{\mu 3} K^\pm_{e3}$ combined	877 ± 6		1176 ± 31

- **NA48/2** is the first experiment which measured both $\mathrm{K}^\pm_{\mathrm{e}3}$ and $\mathrm{K}^\pm_{\mu 3}$.
- Results for $\mathrm{K}^\pm_{\mathrm{e}3}$ and $\mathrm{K}^\pm_{\mu 3}$ from NA48/2 in good agreement.
- **NA48/2 preliminary result** with high precision, fully competitive to other measurements. Offers the combined result with the smallest error.



ChPT tests:

A new measurement of

$K^{\pm} \to \pi^{\pm}\gamma\gamma$ decays

$K^\pm \to \pi^\pm\gamma\gamma$: Introduction

ChPT description:

$\mathcal{O}(\mathrm{p}^4)$ Loop diagrams

$\to$ **cusp** at $\pi^+\pi^-$ threshold: $\boldsymbol{m_{\gamma\gamma} = 2m_{\pi^+}}$
(or $z = (m_{\gamma\gamma}/m_K)^2 \approx 0.32$).

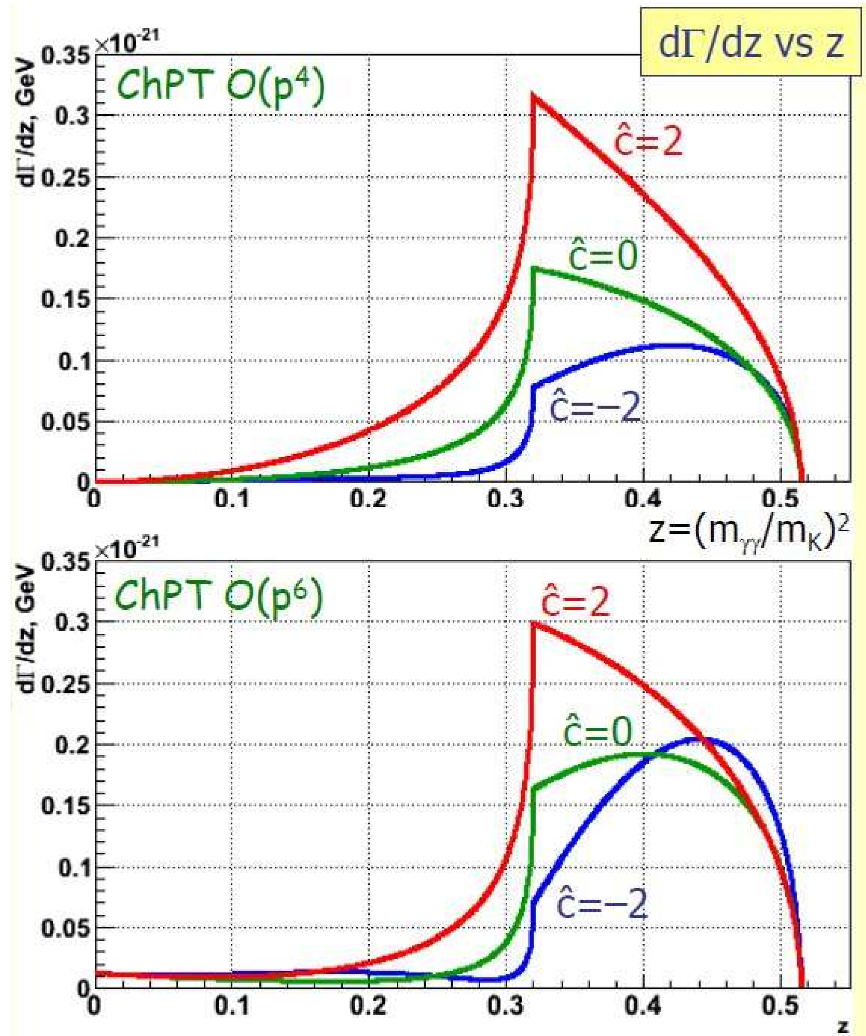
[Ecker, Pich, de Rafael, NPB303 (1988) 665]

Rate and spectrum depend on a single unknown $\mathcal{O}(1)$ parameter $\hat{c}$.

$\mathcal{O}(\mathrm{p}^6)$

'Unitarity corrections' increase BR at low $\hat{c}$ and result in a non-zero rate at $m_{\gamma\gamma} \to 0$.

[D'Ambrosio, Portoles, PLB386 (1996) 403]



Experimental status:

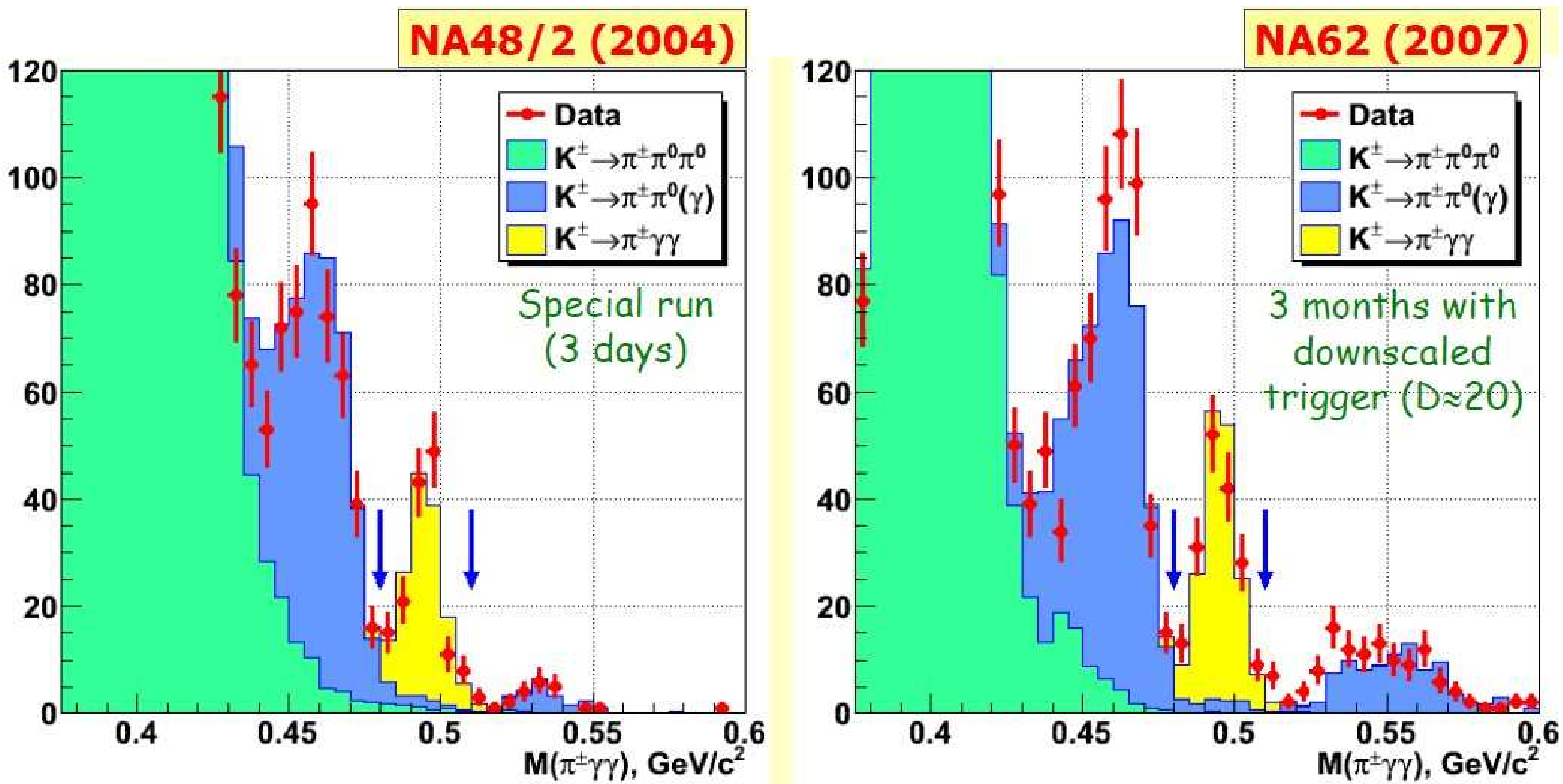
BNL 787: 31 candidates with 5 bkg. events, $\mathrm{BR} = (1.10 \pm 0.32) \times 10^{-6}$.

[PRL79 (1997) 4079]

NA48/2 main data set: measurement hindered by trigger efficiency.

$\to$ New strategy: use minimum bias trigger samples from NA48/2 and NA62.

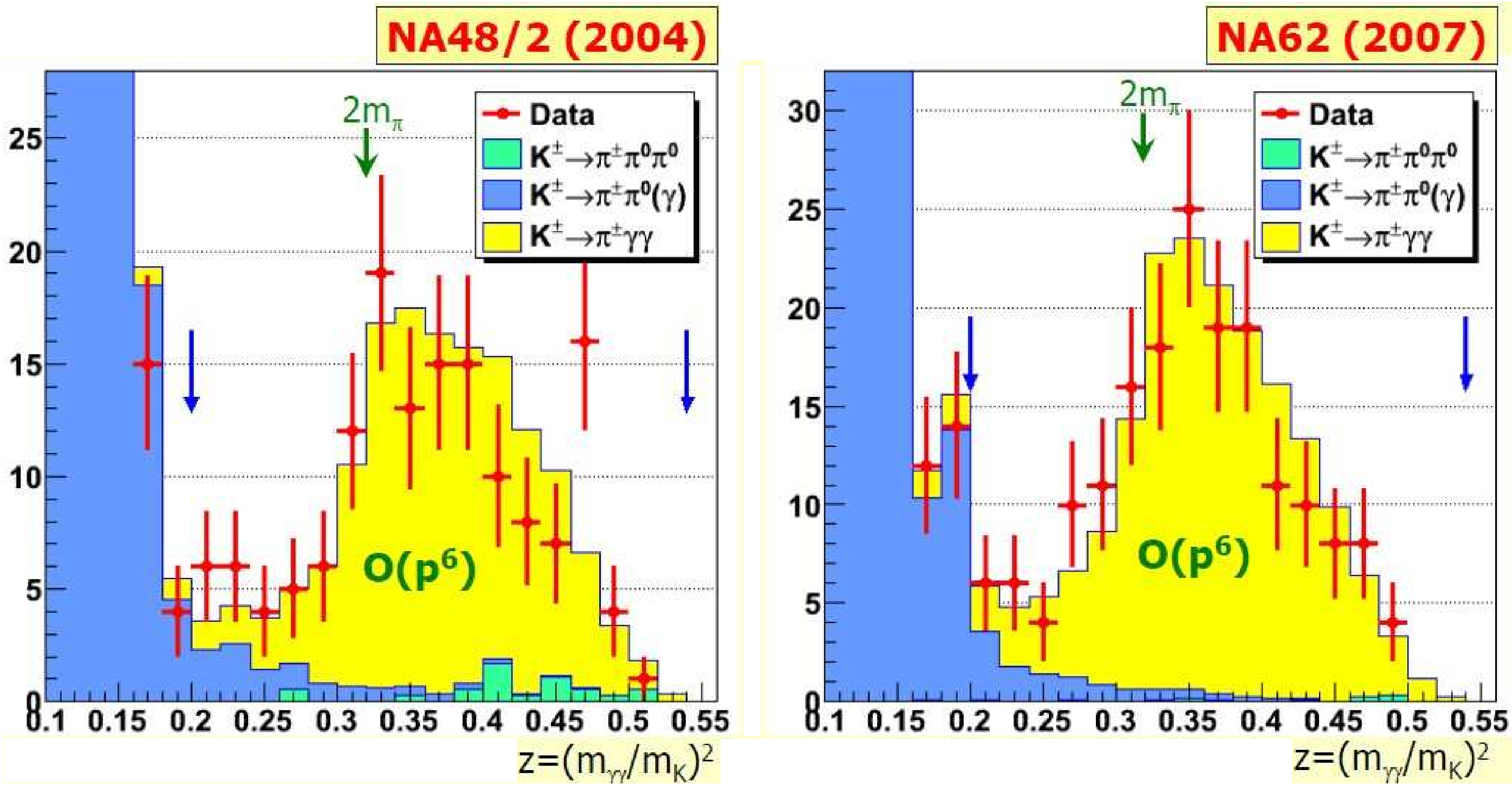
Minimum bias data samples 2004+2007



$K_{\pi\gamma\gamma}$ candidates	147
$K_{2\pi(\gamma)}$ background	11.0 ± 0.8
$K_{3\pi}$ background	5.9 ± 0.7
$K_{\pi\gamma\gamma}$ signal	130 ± 12

$K_{\pi\gamma\gamma}$ candidates	175
$K_{2\pi(\gamma)}$ background	11.1 ± 1.0
$K_{3\pi}$ background	1.3 ± 0.3
$K_{\pi\gamma\gamma}$ signal	163 ± 13

$K^{\pm} \to \pi^{\pm}\gamma\gamma$: ChPT fits



- Visible region is above the $K^+ \to \pi^+\pi^0$ peak with $m_{\gamma\gamma} = m_{\pi^0}$: $z > 0.2$ or $m_{\gamma\gamma} > 220$ MeV/c^2.
- Cusp-like behaviour at $2m_\pi$ ($z \approx 0.32$) is clearly observed.

$K^{\pm} \to \pi^{\pm}\gamma\gamma$: Preliminary fit results

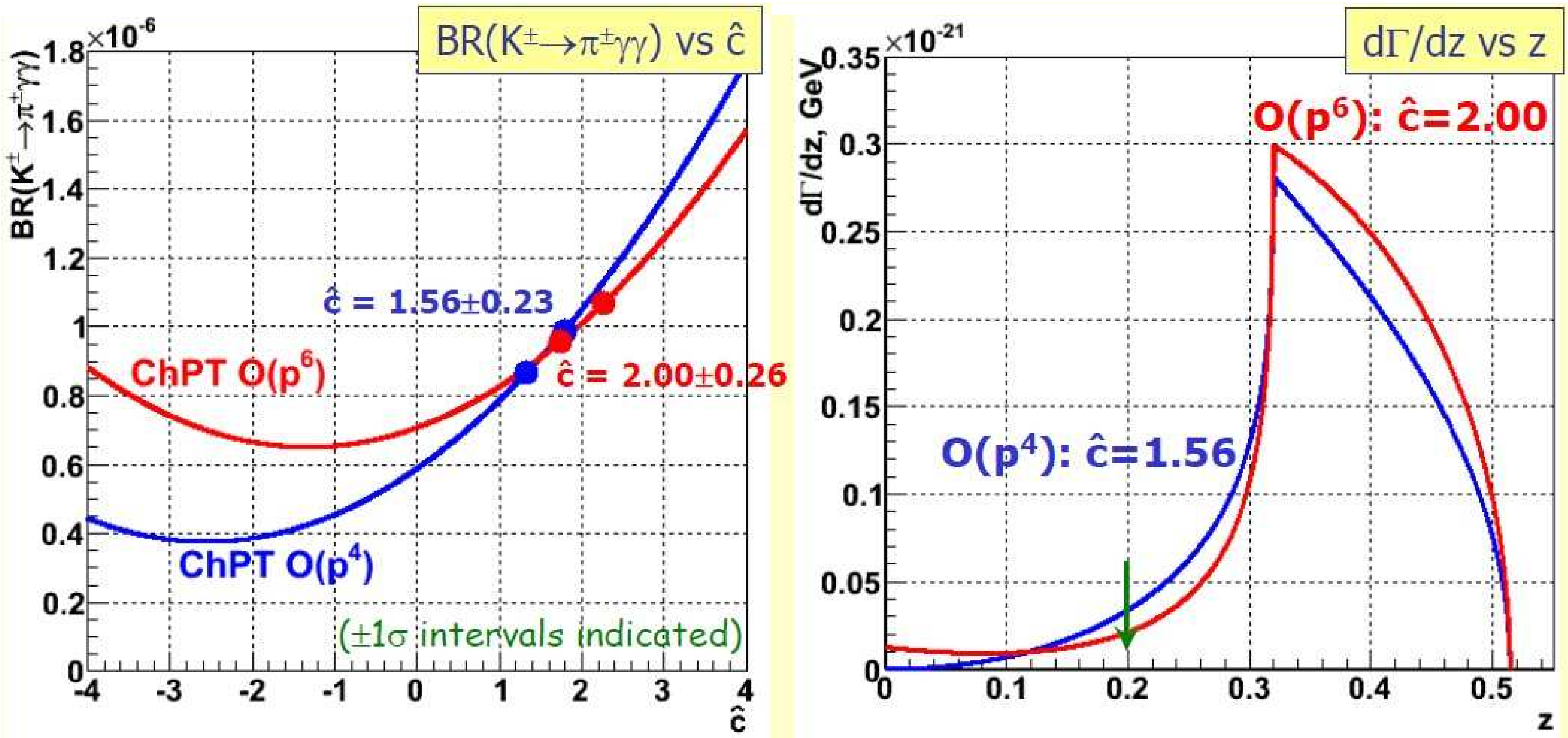
Fit results for parameter $\hat{c}$

$\hat{c} =$	$\mathcal{O}(p^4)$	$\mathcal{O}(p^6)$	Combined
NA48/2 2004	$1.36 \pm 0.33_{stat} \pm 0.07_{syst} = 1.36 \pm 0.34$	$1.67 \pm 0.39_{stat} \pm 0.09_{syst} = 1.67 \pm 0.40$	$1.56 \pm 0.22_{stat} \pm 0.07_{syst} = 1.56 \pm 0.23$
NA62 2007	$1.71 \pm 0.29_{stat} \pm 0.06_{syst} = 1.71 \pm 0.30$	$2.21 \pm 0.31_{stat} \pm 0.08_{syst} = 2.21 \pm 0.32$	$2.00 \pm 0.24_{stat} \pm 0.09_{syst} = 2.00 \pm 0.26$

ChPT $\mathcal{O}(p^6)$ combined BR fit: $\mathrm{BR} = (1.01 \pm 0.06) \times 10^{-6}$.

- All results presented here are preliminary! (E. Goudzovski @ FPCP, May 2012)
- The combined 2004+2007 results contain correlated uncertainties.
- PDG (= BNL E787): $\mathrm{BR} = (1.10 \pm 0.32) \times 10^{-6}$.
- In good agreement with NA48/2 preliminary result.
  (based on partial (40%) data sample with 1164 $K^{\pm} \to \pi^{\pm}\gamma\gamma$ candidates)
  (Cristina Morales-Morales @ Moriond QCD 2008)

$K^{\pm} \to \pi^{\pm}\gamma\gamma$: Fit results + conclusions



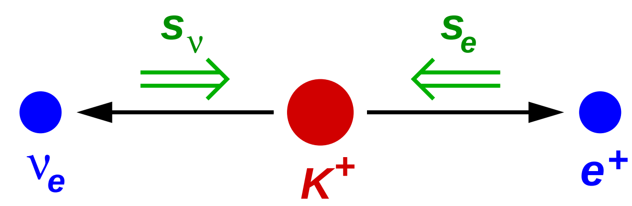
- Total number of candidates (from NA48/2 + NA62) = 322.
- Background contamination: $(9 \pm 1)\%$ due to $K^+ \to \pi^+\pi^0(\pi^0)(\gamma)$ with photon fusion.
- Very low systematic uncertainties.
- ChPT $\mathcal{O}(p^4)$ vs $\mathcal{O}(p^6)$ models cannot be discriminated.

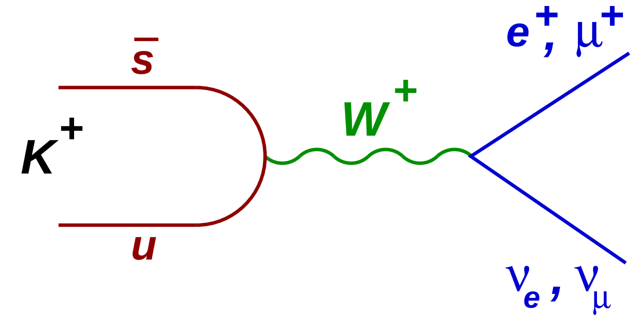
Precision lepton universality test through the ratio

$$\Gamma(\mathrm{K}^{\pm} \to \mathrm{e}^{\pm}\nu)/\Gamma(\mathrm{K}^{\pm} \to \mu^{\pm}\nu)$$

$\mathrm{R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)}$ in the SM

- **Precision tests** $\to$ search for deviations from the SM in rare or forbidden processes
- **Leptonic meson decays:** $\mathbf{P^+ \to l^+ \nu}$
  Angular momentum conservation leads to helicity suppression of SM contribution
- Excellent sub-per-mil accuracy of SM prediction due to cancellation of hadronic uncertainties in the ratio $\mathrm{R_K = K_{e2}/K_{\mu 2}}$
  (similarly, $\mathrm{R_\pi}$ in the pion sector)





$$\mathrm{R_K} = \frac{\Gamma(\mathbf{K}^\pm \to \mathbf{e}^\pm \nu)}{\Gamma(\mathbf{K}^\pm \to \mu^\pm \nu)} = \frac{\mathbf{m_e^2}}{\mathbf{m_\mu^2}} \cdot \left(\frac{\mathbf{m_K^2 - m_e^2}}{\mathbf{m_K^2 - m_\mu^2}} \right)^{\mathbf{2}} \cdot (\mathbf{1} + \delta \mathbf{R_K^{\mathrm{rad.corr.}}})$$

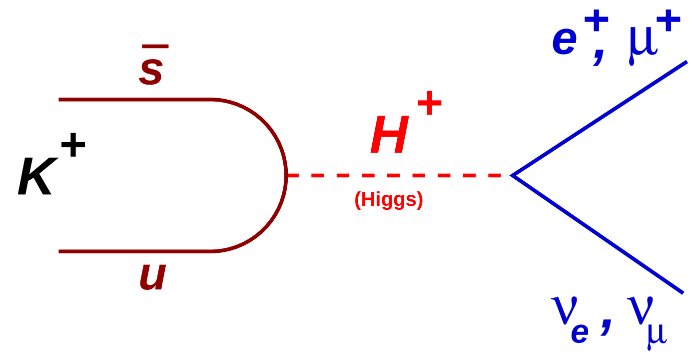
$$= (2.477 \pm 0.001) \times 10^{-5}$$ [Cirigliano, Rosell, PRL99 (2007) 231801]

- Radiative corrections $\delta R_K^{\mathrm{rad.corr.}}$ (few %) due to the IB part of the radiative $\mathrm{K \to e\nu\gamma}$ process (by definition included in $\mathrm{R_K}$)
- Measurements of $\mathrm{R_K}$ and $\mathrm{R_\pi}$ have long been considered as tests of lepton universality
- Strong helicity suppression of $\mathrm{R_P}$ enhances sensitivity to non-SM effects

$R_K = K_{e2}/K_{\mu 2}$ beyond the SM

2HDM (incl. SUSY) - tree level:

$K^+ \to l^+\nu$ can proceed via exchange of charged Higgs H^+ instead of W^+
$\to$ ratio R_K remains unchanged

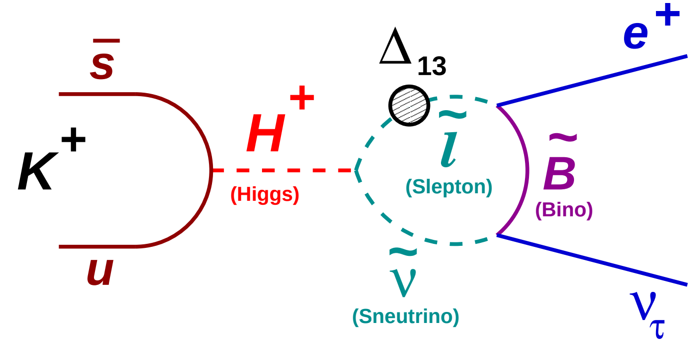


Possible scenario, one loop level:

[Masiero, Paradisi, Petronzio, PRD 74 (2006) 011701]

'Loop effects are predicted to lead to **lepton flavour violating (LFV) couplings** $lH^+\nu_\tau$ which give dominant contribution to ΔR_K'

$$\mathbf{R_K^{\mathsf{LFV}}} \approx \mathbf{R_K^{\mathsf{SM}}} \left[\mathbf{1} + \left(\frac{\mathbf{m_K^4}}{\mathbf{M^4_{H^\pm}}}\right)\left(\frac{\mathbf{m_\tau^2}}{\mathbf{M_e^2}}\right)|\mathbf{\Delta_{13}}|^{\mathbf{2}}\tan^{\mathbf{6}}\beta\right]$$



Up to $\sim$1 % effect possible in large (not extreme) $\tan\beta$ regime with relatively massive charged Higgs $\to$ experimentally accessible !

Example:

$\mathbf{\Delta_{13}} = 5\times10^{-4}$, $M_H = 500\,\mathrm{GeV}$, $\tan\beta = 40$:
$R_K^{\mathsf{LFV}} \approx R_K^{\mathsf{SM}}(1+0.013)$

Analogous SUSY effects in pion decay are suppressed by factor $(m_\pi/M_K)^4 \approx 6\times10^{-3}$

However, large effects expected in B decays due to $(M_B/M_K)^4 \sim 10^4$

Measurement method

K_{e2} and $K_{\mu 2}$ candidates collected simultaneously

- Measurement independent of kaon flux.
- A number of systematic effects cancel at first order in the ratio R_K (e.g. reconstruction/trigger efficiencies, time-dependent effects).

A counting experiment in 10 independent bins of lepton momentum

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{A(K_{\mu 2}) \times f_\mu \times \epsilon(K_{\mu 2})}{A(K_{e2}) \times f_e \times \epsilon(K_{e2})} \cdot \frac{1}{f_{LKr}}$$

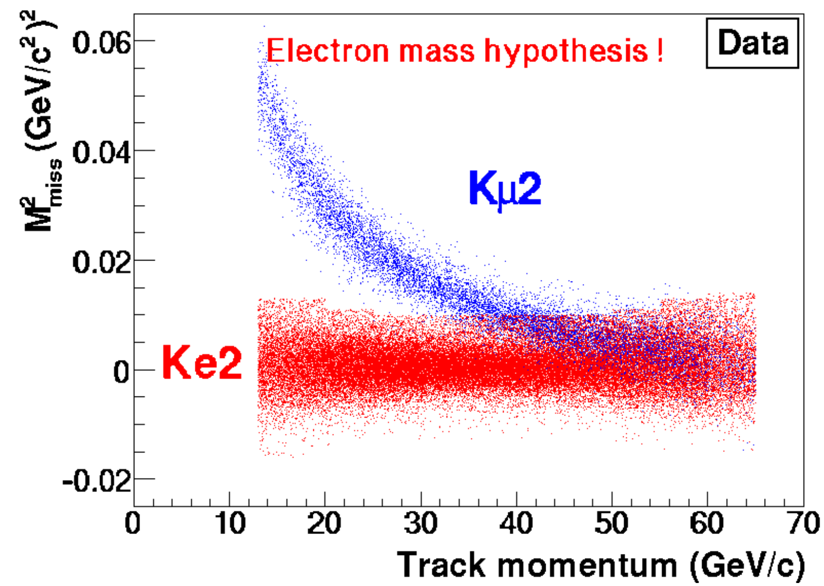
$N(K_{e2}), N(K_{\mu 2})$:	numbers of selected K_{l2} candidates
$N_B(K_{e2}), N_B(K_{\mu 2})$:	numbers of background events
$A(K_{e2}), A(K_{\mu 2})$:	geometric acceptances (from MC)
f_e, f_μ:	measured particle ID efficiencies (from data)
$\epsilon(K_{e2})/\epsilon(K_{\mu 2}) > 99.9\,\%$:	E_{LKr} trigger efficiency
$f_{LKr} = 0.9980\,(3)$:	global LKr readout efficiency
$D = 150$:	downscaling factor of the $K_{\mu 2}$ trigger

Main source of systematic uncertainty: $N_B(K_{e2})$.

K_{e2} and $K_{\mu 2}$ selection

Large common part (topological similarity)

- One reconstructed track
- Geometrical acceptance cuts
- Decay vertex defined as closest distance of approach of track + nominal kaon axis
- Track momentum 13 - 65 GeV/c



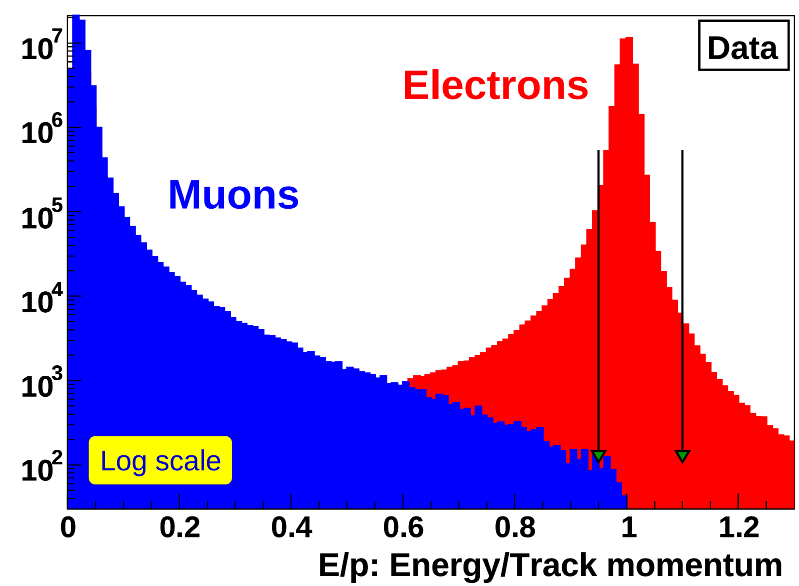
Kinematic separation

Missing mass $\boxed{M^2_{miss} = (P_K - P_l)^2}$

$\mathbf{P_K}$ average measured with $\mathbf{K^{\pm} \to 3\pi}$ decays

$\Rightarrow$ Sufficient $\mathbf{K_{e2}/K_{\mu 2}}$ separation only for lepton momenta < 30 GeV/c

Particle identification



E/p LKr energy deposit / track momentum

< 0.85 for muons, electrons: (0.90-0.95) < E/p < 1.10

$\rightarrow$ powerful $\mu^{\pm}$ suppression in $\mathrm{e}^{\pm}$ sample ($\sim \mathbf{10^6}$)

$\mathrm{K}_{\mu 2}$ background in K_{e2} sample

Problem:

'Catastrophic' energy loss of muons in LKr $\Rightarrow$ Muons with E/p > 0.95 identified as electrons ($\mathrm{P}_{\mu e} \sim 3 \times 10^{-6}$ and momentum-dependent).

$\mathrm{P}_{\mu e} / \mathrm{R}_{\mathrm{K}} \sim 10\,\%$ $\Rightarrow$ $\mathrm{K}_{\mu 2}$ decays represent the major background

Solution: **Direct measurement of $\mathrm{P}_{\mu e}$**

$\Rightarrow$ Lead wall ($9.2\,X_0$) in front of LKr: suppression of electron contamination from μ-e decay.

$\Rightarrow$ Tracks traversing Pb with p > 30GeV/c + E/p > 0.95 $\rightarrow$ pure μ samples with catastrophic bremsstrahlung (electron contamination $< 10^{-8}$).

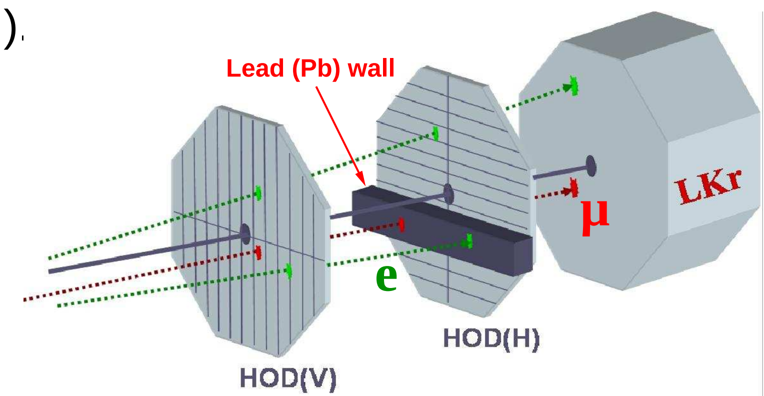
$\mathrm{P}_{\mu e}$ is modified by the Pb wall (ionization losses + bremsstrahlung)

$\Rightarrow$ The correction is evaluated with a dedicated Geant4-based simulation.

Due to the Pb wall affecting the acceptances and the different background conditions

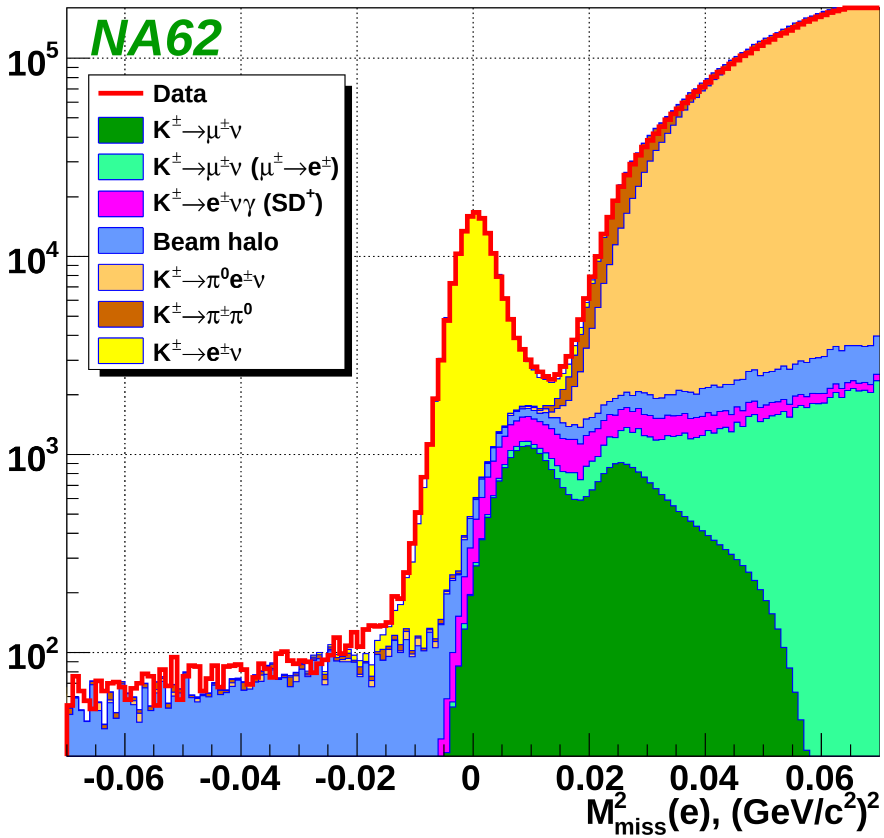
$\rightarrow$ Divide the data addtionally into 4 samples:

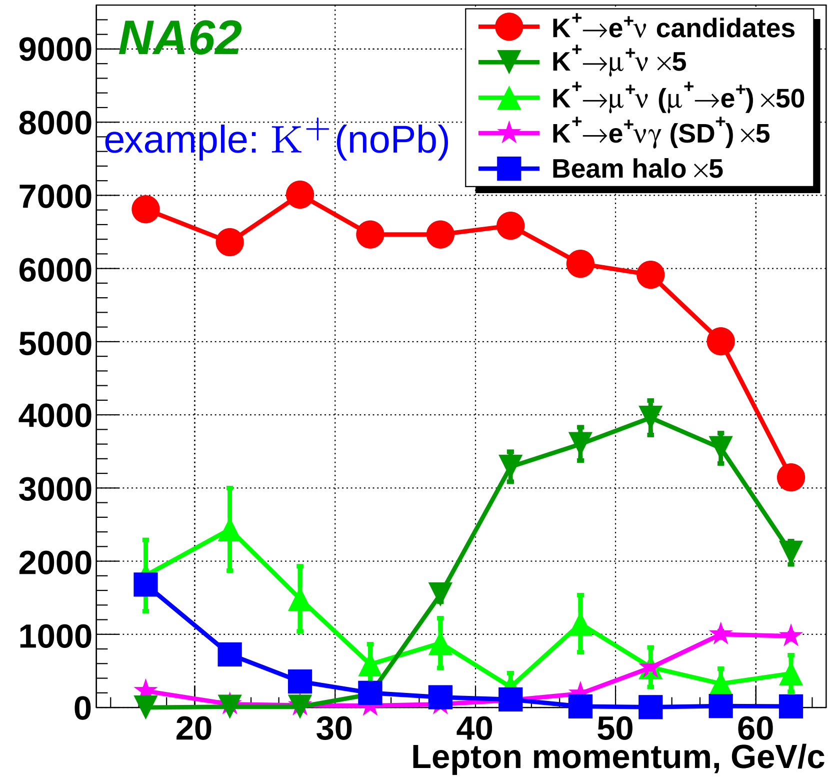
K^+(Pb), K^+(noPb) / K^-(Pb), K^-(noPb)



Thickness:	$\sim 10\,X_0$ (Pb + Fe)
Width:	240 cm (= HOD size)
Height:	18 cm (= 3 counters)
Area:	$\sim 20\,\%$ of HOD area
Duration:	$\sim 50\,\%$ of R_{K} data taking

K_{e2} candidates and background





145,958 $K^{\pm} \to e^{\pm}\nu$ candidates

$(99.28 \pm 0.05)\,\%$ electron ID efficiency

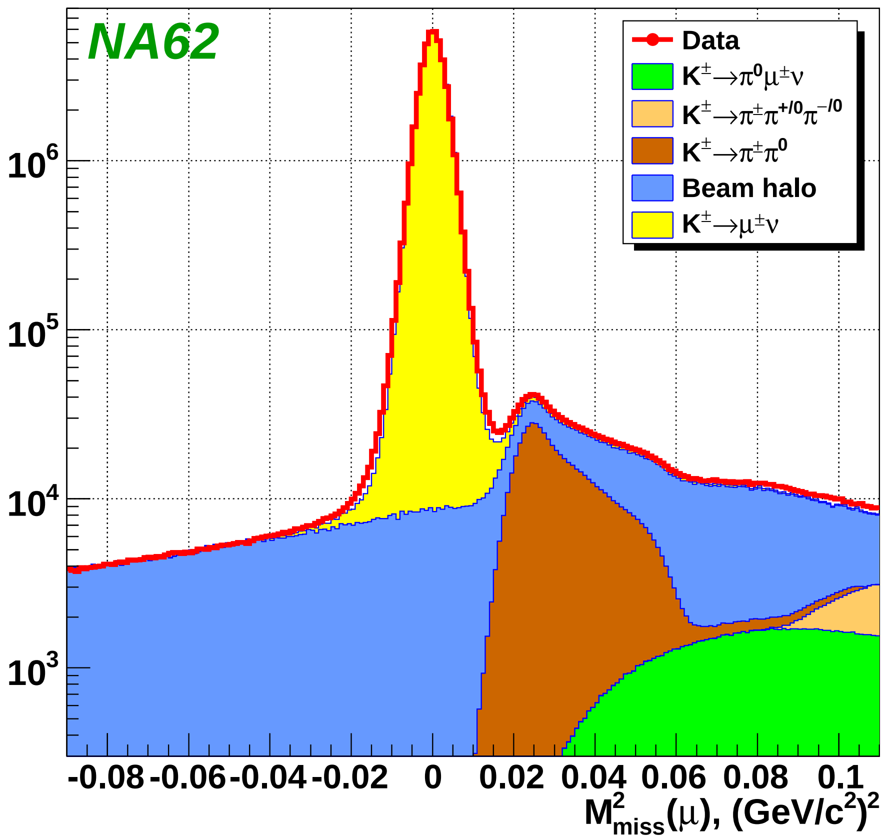
B/(S+B) $= (10.95 \pm 0.27)\,\%$

cf. KLOE: 13.8k candidates,

$\sim 90\,\%$ electron ID efficiency, $16\,\%$ bkg.

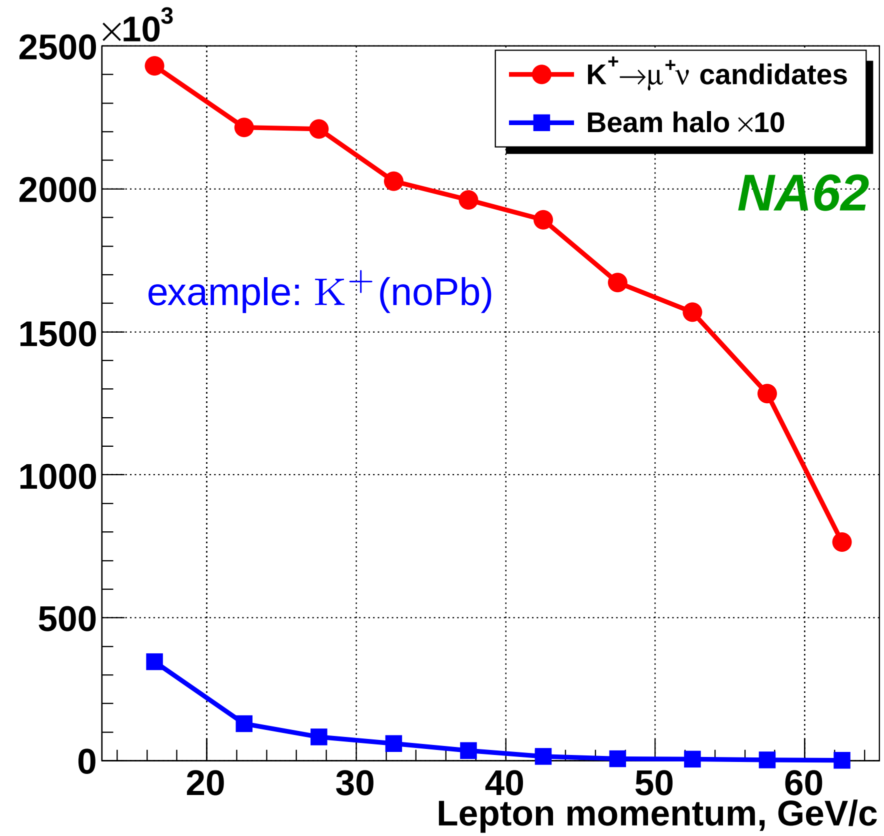
Main Sources	B/(S+B)
$K_{\mu 2}$	$(5.64 \pm 0.20)\,\%$
$K_{\mu 2}(\mu \to e)$	$(0.26 \pm 0.03)\,\%$
$K_{e2\gamma}(SD^+)$	$(2.60 \pm 0.11)\,\%$
Beam halo	$(2.11 \pm 0.09)\,\%$

$K_{\mu2}$ candidates and backgrounds



42.817M $K^{\pm}\to\mu^{\pm}\nu$ candidates
with very low background
B/(S+B) $= (0.50 \pm 0.01)\,\%$

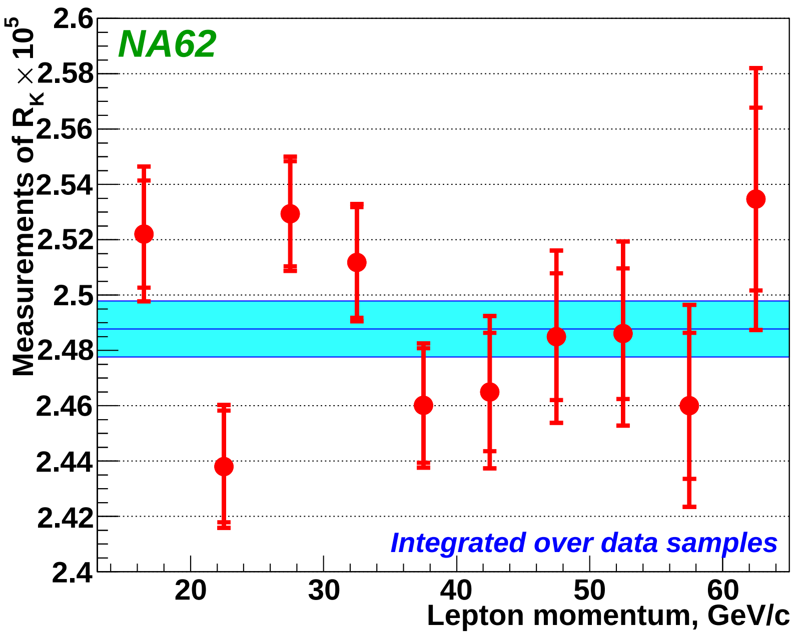
($K_{\mu2}$ trigger was pre-scaled by D = 150)

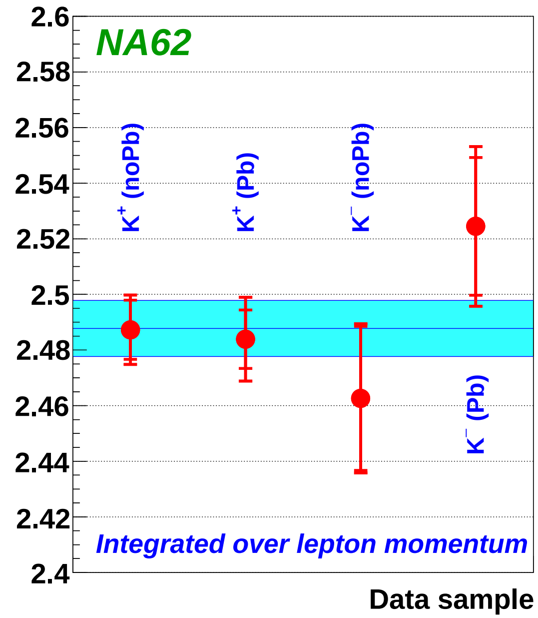


The only significant background source is the beam halo.

NA62 final result

Fit over 40 measurements (4 data samples x 10 momentum bins) including correlations: χ^2/ndf = 47/39.





$$\mathbf{R_K} = (2.488 \pm 0.007_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}) \times 10^{-5}$$
$$= (2.488 \pm 0.010) \times 10^{-5} \quad (0.40\,\%\ \textbf{precision !})$$

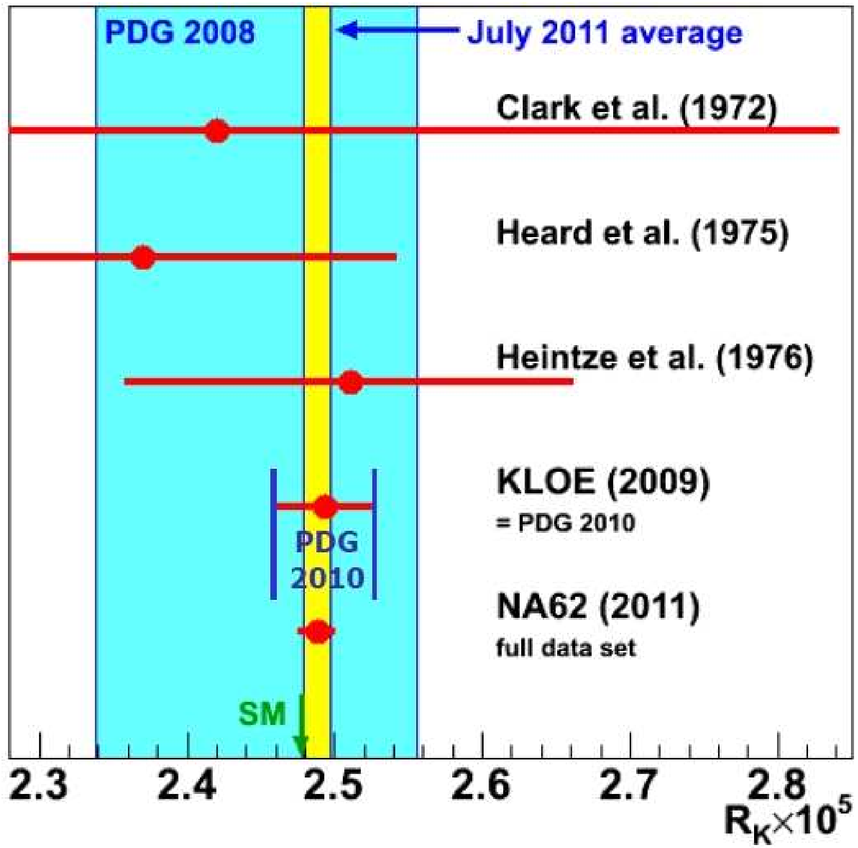
NA62 publications:

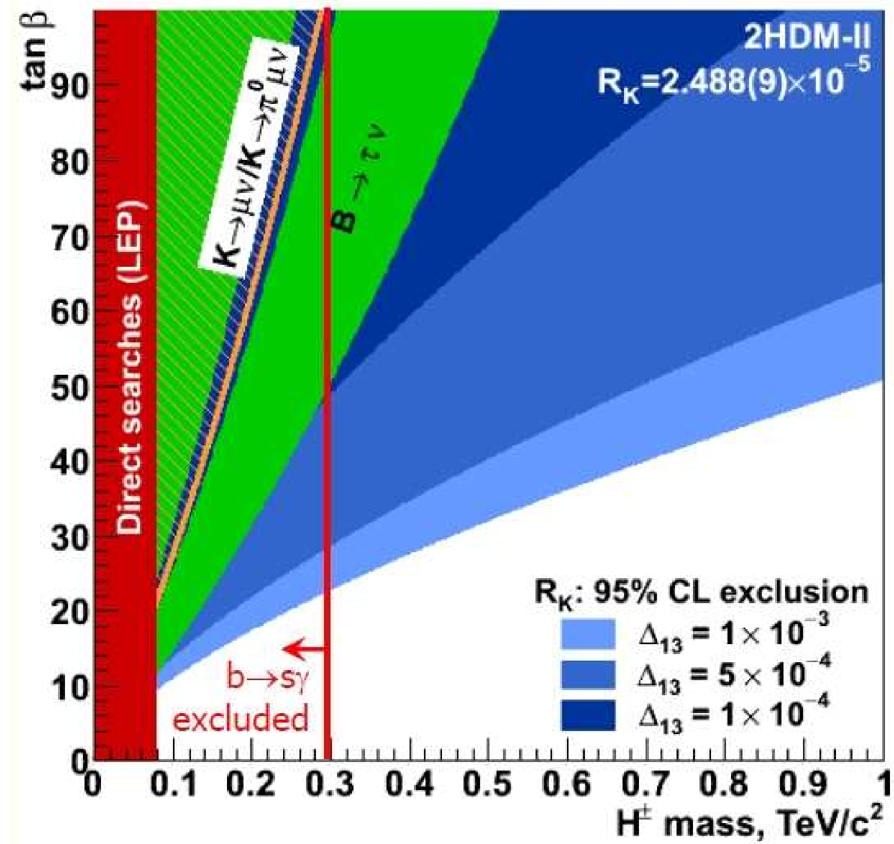
- Partial ($40\,\%$) data set: PLB 698 (2011) 105.
- Full data set: paper to be submitted in summer 2012.

Uncertainties summary

Source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$	0.004
$K_{e2\gamma}(SD^+)$	0.002
$K_{e3}, K_{2\pi}$	0.003
Beam halo	0.002
Matter composition	0.003
Acceptance corr.	0.002
Electron ID	0.001
DCH alignment	0.001
1TRK trigger eff.	0.001
LKr readout eff.	0.001
Total	0.010

$\mathrm{R_K}$: world average and New Physics limits





World average	$\mathrm{R_K} \times 10^5$	Precision
PDG 2008	2.447 ± 0.109	$4.5\,\%$
PDG 2010	2.493 ± 0.031	$1.3\,\%$
July 2011	2.488 ± 0.009	$0.4\,\%$

- KLOE and NA62 have significantly improved the precision in $\mathrm{R_K}$.
- In agreement with SM expectation, but $\sim 1\sigma$ above $\to$ motivation for further precision $\mathrm{R_K}$ measurements.

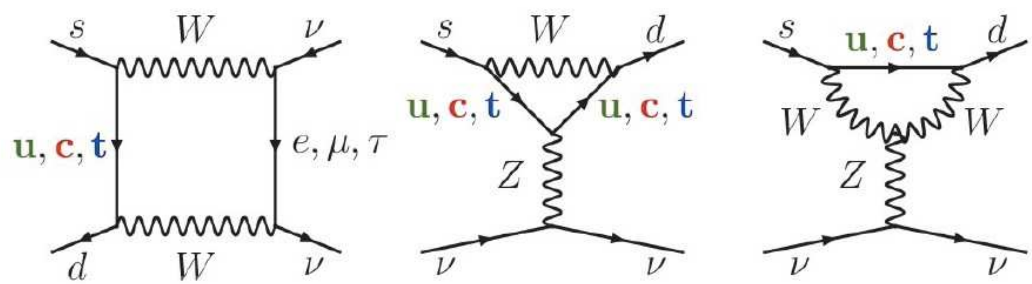
The Holy Grail:
NA62 and the ultra-rare decay
$K^+ \to \pi^+ \nu\bar{\nu}$

$\mathrm{K} \to \pi\nu\bar{\nu}$ - The golden modes for kaons

Why $\mathbf{K} \to \pi\nu\bar{\nu}$ **decays** are among the few golden channels to search for New Physics:

1) They are extremely rare !

Loop-induced **FCNC processes**, transition described by **Z-penguin** and **box diagrams**:



2) The SM prediction is exceptionally precise !

$$\mathbf{BR(K^0 \to \pi^0\nu\bar{\nu}) = \kappa_L Im(V_{ts}^* V_{td})^2 X(m_t, m_W)/|V_{us}|^5}$$

$$\mathbf{BR(K^+ \to \pi^+\nu\bar{\nu}) = \kappa_+ (V_{ts}^* V_{td})^2 X(m_t, m_W)/|V_{us}|^5}$$ **+ charm contr.**

The hadronic matrix element can be extracted from the precisely measured $\mathrm{K} \to \pi e \nu$ decay.

Charm contribitions in charged mode only, precision recently reduced by NNLO calculation.

$$\mathbf{BR(K^0 \to \pi^0\nu\bar{\nu}) = (2.43 \pm 0.39) \times 10^{-11}}$$

$$\mathbf{BR(K^+ \to \pi^+\nu\bar{\nu}) = (7.81 \pm 0.80) \times 10^{-11}}$$

The SM prediction is tiny !

(Brod et al., PRD83 (2011) 034030)

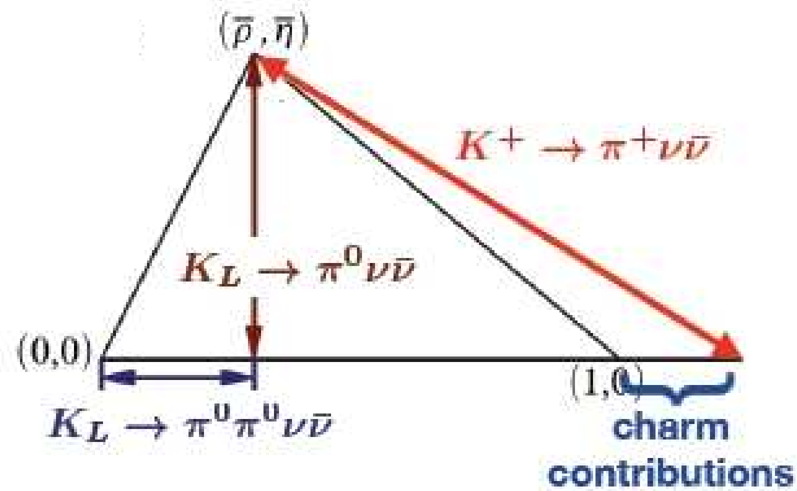
Uncertainty almost only from knowledge on $|V_{ts}|$!

3) In extensions of the SM, the decay remains similarly predictive !

$\mathrm{K} \to \pi\nu\bar{\nu}$ - The golden modes for kaons

Furthermore, **$\mathbf{K}^+ \to \pi^+\nu\bar{\nu}$ allows the measurement of $|V_{td}|$** complementary to those from $\mathrm{B}-\bar{\mathrm{B}}$ mixing and $\mathrm{B} \to \rho\gamma$ (and without requiring input from lattice QCD).

A precision in the branching ratio $\delta\mathrm{BR}/\mathrm{BR} = 10\%$ would lead to $\delta|V_{td}|/|V_{td}| = 7\%$.



Experimental situation - far from theory precision

$\mathrm{BR}(\mathrm{K}^0 \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8} (90\%\mathrm{CL})$ **E931a (KEK)** (PRD 81 (2010) 072004)

$\mathrm{BR}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ **E787/E949 (BNL)** (PRL 101 (2008) 191802)

- BNL result based on **7 $\mathbf{K}^+ \to \pi^+\nu\bar{\nu}$ candidates** (2.6 expected bkg.).
- Incoming **kaons stopped in target**

$\to$ low signal efficiency ($\sim 1\%$) and significant background ($\sim 30\%$) due to π scattering.

NA62@CERN aims to collect $\mathcal{O}(100)$ $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ decays with $\sim 10\%$ background in 2 years of data taking using a novel decay-in-flight-technique.

Principles of NA62 (1)

- $\mathbf{K^+}$ **decay-in-flight-technique** to avoid the scattering and the backgrounds introduced by the stopping target.
  $\rightarrow$ long decay region
- **High momentum** to improve the background rejection.
  $\rightarrow$ unseparated hadron beam

Statistics:

To measure a 10^{-11} BR, you need a huge amount of kaon decays ($\mathcal{O}(10^{13})$ in total).

$\longrightarrow$ **Very high kaon intensity and good signal efficiency**.

Systematics:

$\geq 10^{12}$ background rejection (i.e. $\sim 10\%$ precision bkg. measurement)

$\longrightarrow$ **Signal purity and detector redundancy.**

Signal signature:

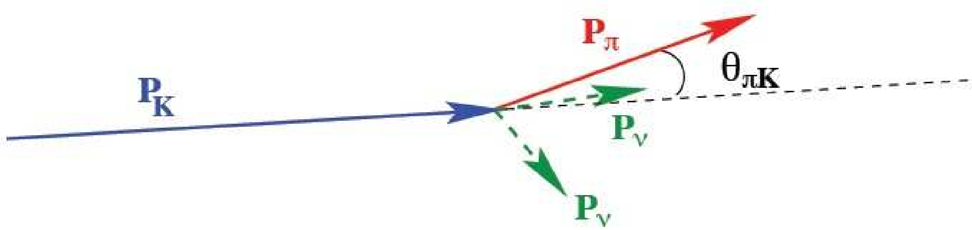
Only one charged track identified as a pion + nothing.

Background:

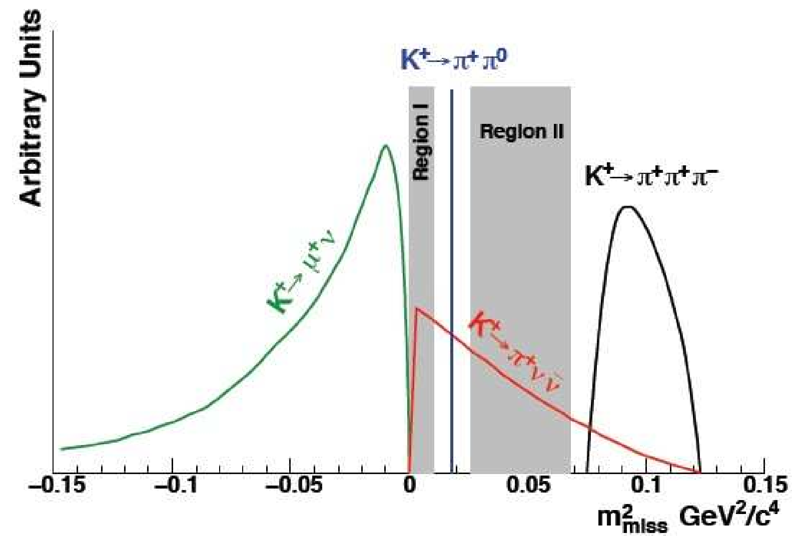
All the $\mathbf{K^+}$ decay modes !

Kinematical background rejection

Reconstruction of missing mass:



$$m^2_{\text{miss}} \approx m^2_K\left(1-\frac{p_\pi}{p_K}\right) + m^2_\pi\left(1-\frac{p_K}{p_\pi}\right) - p_K\, p_\pi\, \vartheta^2_{\pi K}$$



92% of total background kinematically **constrained**:

$\rightarrow$ Definition of the signal region

$\rightarrow$ $K^+ \rightarrow \pi^+\pi^0$ 'needle' forces to split it into two parts (Region I + Region II).

Kinematic rejection power:

$\sim 10^4$ ($K^\pm \rightarrow \pi^\pm\pi^0$), $\sim 10^5$ ($K^\pm \rightarrow \mu^\pm\nu$).

$\rightarrow$ Two signal regions with low background.

8% of total background **not** kinematically **constrained**:

$\rightarrow$ Radiative decays or decays with neutrino in final state.

$\rightarrow$ Span across the signal region.

$\rightarrow$ Rejection relies on excellent vetoes + PID.

Experimental requirements

1) Precise timing to associate the decay to the correct incoming parent particle **(K^+)** in a ~ 800 MHz hadron beam.

$\rightarrow$ **Beam tracker with $\sigma_t \sim 100$ ps. (GigaTracker GTK: three Si pixel stations)**

2) Kinematical rejection

$\rightarrow$ **low mass / high resolution spectrometers operating in vacuum.**

$K^+ \rightarrow$ GTK / $\pi^+ \rightarrow$ Straw spectrometer

3) Excellent high efficiency vetoes

γ veto: Mandatory to veto γ's from $K^+ \rightarrow \pi^+\pi^0$

With p(K^+) = 75 GeV/c and low momentum π^+ (p(π^+): 15-35 GeV/c)

$\rightarrow$ p(π^0) > 40 GeV/c $\rightarrow$ cannot be missed at full angular coverage (**$\sim 10^8$ rejection !**)

Components: **LargeAngleVeto (LAV, reusing OPAL lead glass blocks), NA48 LKr, SAV.**

μ veto: **Extreme μ suppression of 10^{11}** required (to kill main decay $K_{\mu 2}$).

$\rightarrow$ No single detector can do this, several detector components must work together.

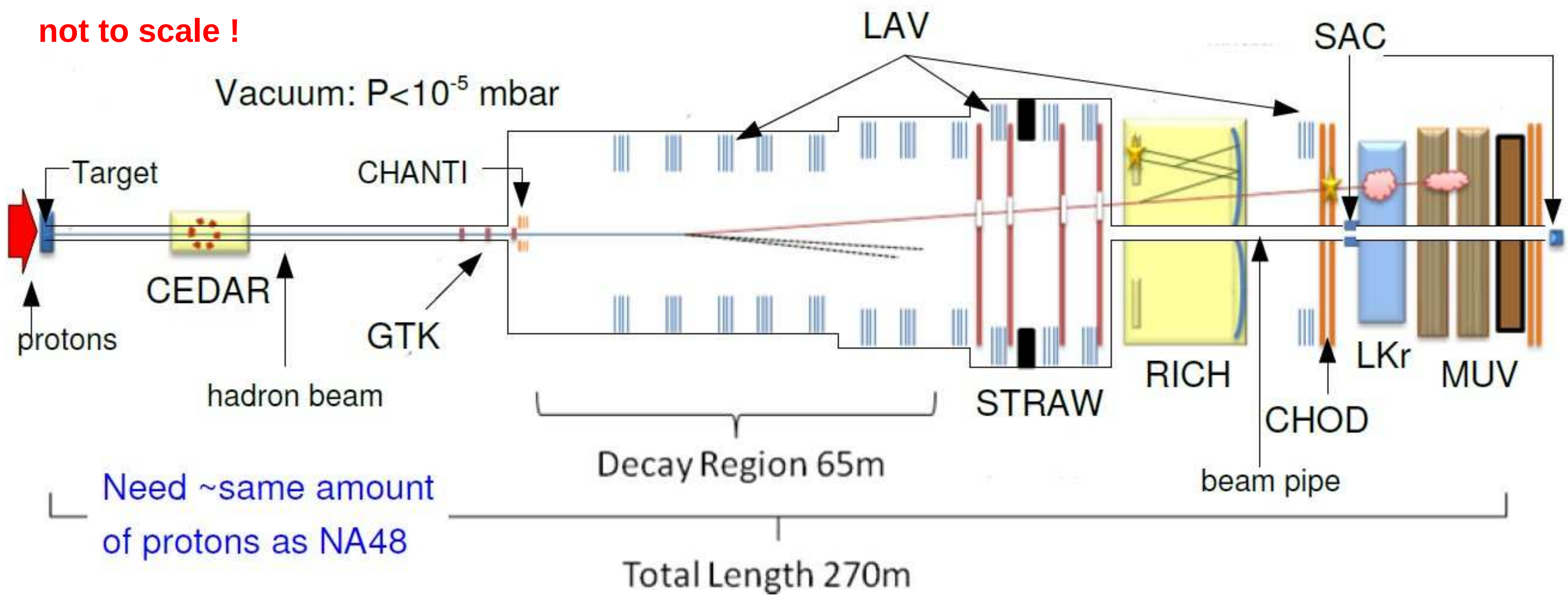
4) Particle identification

$\rightarrow$ **K/π (CEDAR: Cherenkov kaon tagger).**

$\rightarrow$ **π/μ (RICH: 17m long, excellent time resolution of $\sim$70ps (defines event time)).**

The NA62 detector for $K^+ \to \pi^+ \nu \bar{\nu}$

- SPS primary protons @ 400 GeV/c.
- 75 GeV/c unseparated hadron beam (p/π/K), ($\Delta p/p \sim 1\%$).
- 750 MHz $\to$ 50 MHz kaons (6%) $\to$ 6 MHz decays.
- 4.8×10^{12} kaon decays per year.



NA62 timeline:

- First technical run in autumn 2012 including many parts of the experiment.
- 2013: Complete detector installation.
- 2014-?: Data taking with full detector (driven by CERN accelerator schedule).