Kaons @ CERN:
Recent Results and Propects

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on behalf of the NA62 and NA48/2 Collaborations

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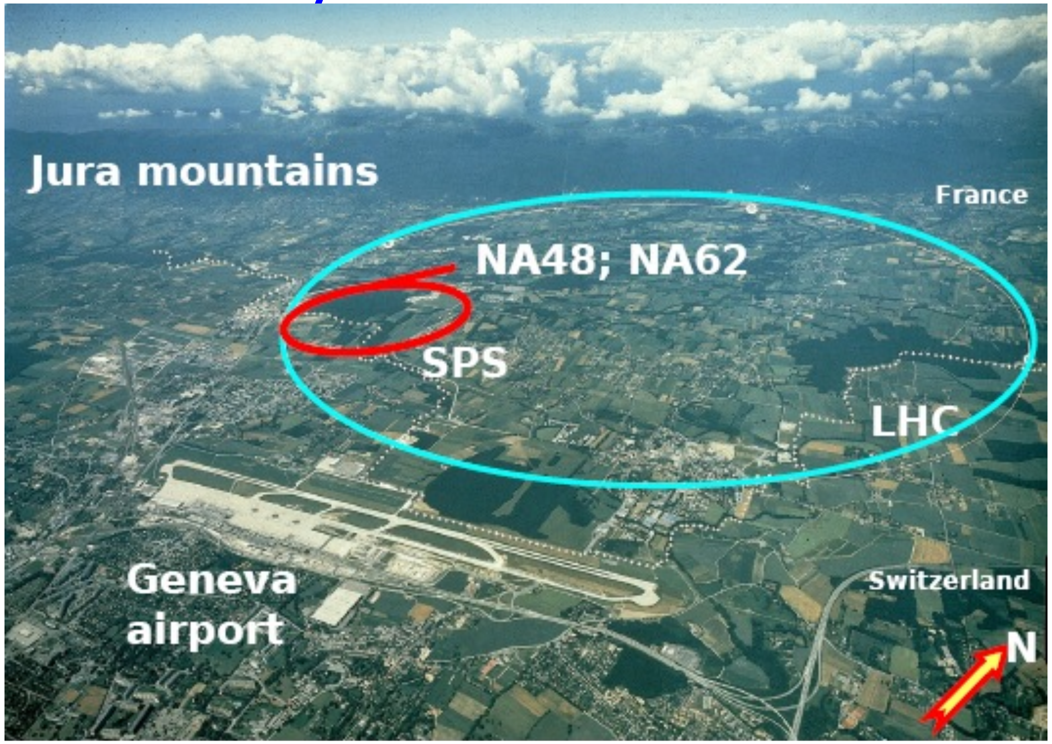
Outline

- Kaon physics at CERN → NA48/n & NA62 brief history
- This talk → two main topics:
- Chiral Perturbation Theory tests
  - $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ decay **NEW result**
- Tests of SM and search for New Physics
  - The $K^{+} \rightarrow \pi^{+}\nu\bar{\nu}$ decay
- Summary and Outlook

The NA62 Collaboration:
Birmingham, Bratislava, Bristol, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Glasgow, Liverpool, Louvain, Mainz, Merced, Moskow, Napoli, Perugia, Pisa, Protvino, Roma I, Roma II, San Luis Potosi, SLAC, Sofia, Torino

The NA48/2 Collaboration:
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna



NA48/n history

NA48
Main goal: Search for direct CPV
Measurement of ε′/ε
Beams: $K_L + K_S$

NA48/1
Main goal: Rare K_S decays and hyperon decays, CPV tests
Beams: K_S

1997
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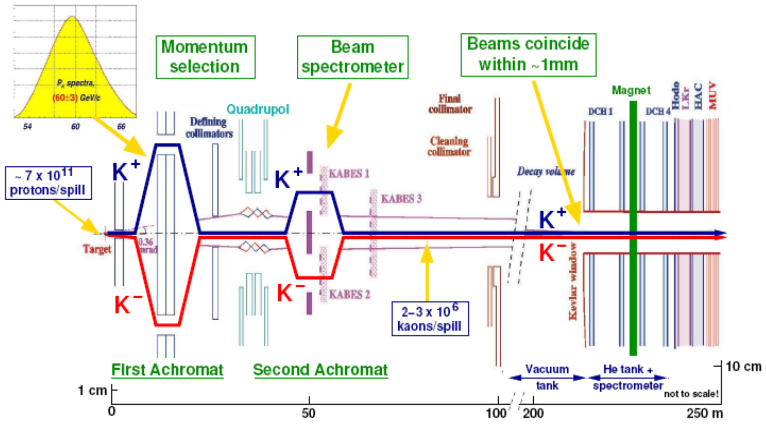
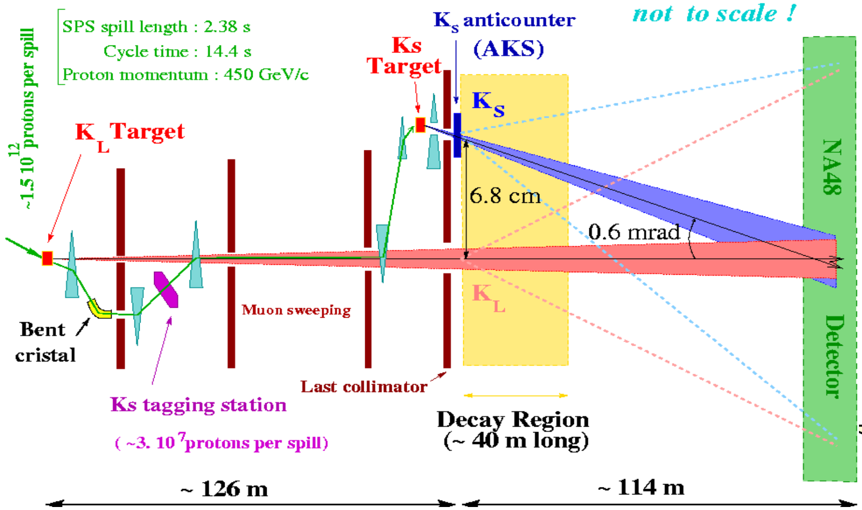


NA48/2
Main goal: Search for direct CPV
Charge asymmetry measurement
Beams: $K^+ + K^-$

NA62

NA62
Main goal: Measurement of the decay $K^+ \to \pi^+ \nu \bar{\nu}$
Beam: K^+



High energy scales

Flavour sector → probing extremely high energy scales:

precision frontier *complementary* to LHC energy frontier

Study processes suppressed in SM, sensitive to New Physics

RARE DECAYS

Four main reasons

1) study explicit Violations of SM, such as LFV
2) probe the flavour sector by means of FCNC
3) test of fundamental symmetries such as CP and CPT
4) study of strong interaction at low energy in exclusive processes

NEW

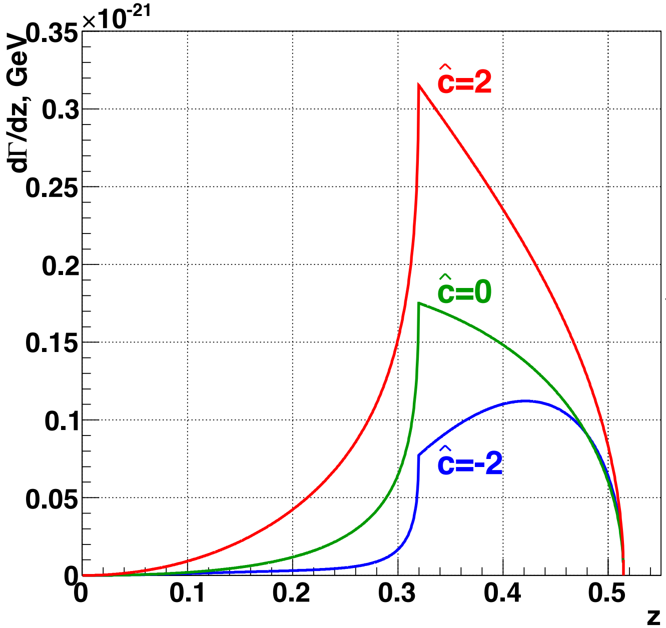
NA48/2 and NA62
Chiral Perturbation Theory tests

$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$

$K^\pm \to \pi^\pm \gamma\gamma$ - introduction

- Decay spectrum and rate strongly depend on the single $\hat{c}$ parameter O(1)
- The $M_{\gamma\gamma}$ spectrum has a pronounced cusp-like behaviour at $2m_\pi$ threshold

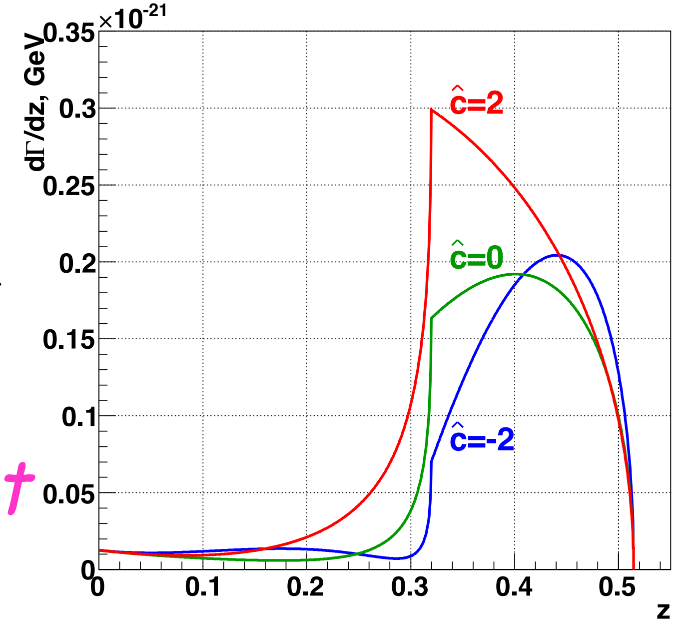
- Unitarity corrections effects can increase the BR at low $\hat{c}$ with a non-zero rate at $m_{\gamma\gamma} \to 0$



[Ecker, Pich, de Rafael, Phys. NPB 303 (1988), 665]

$O(p^4)$ $O(p^6)$

Stringent test of ChPT



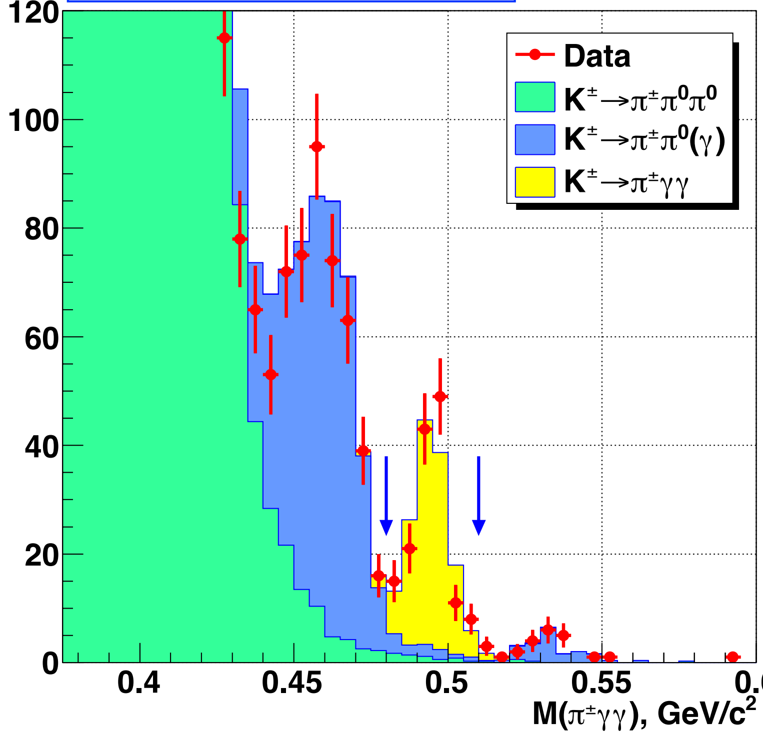
[D'Ambrosio and Portolés, PLB 386 (1996), 403]

Experimental status

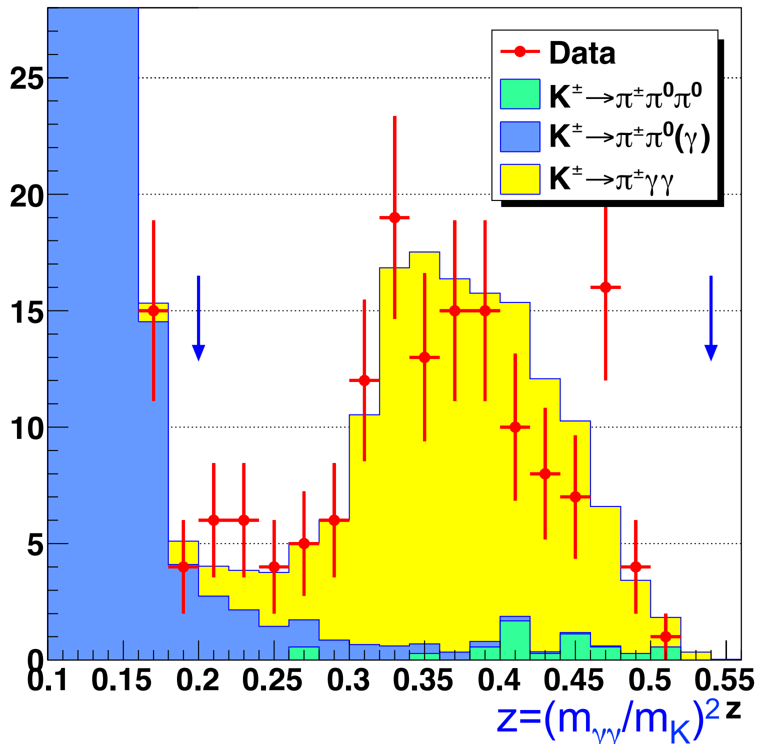
- BNL E787: 31 candidates, BR=$(1.10\pm0.32)\times10^{-6}$ (full kinematic range) [PRL79 (1997) 4079]
- New measurement → NA48/2 and NA62

NA48/2 Data set - 2004 (3 days)

mass spectrum



ChPT O(p^6) fit



$K_{\pi\gamma\gamma}$ 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

preliminary

ChPT O(p^4):

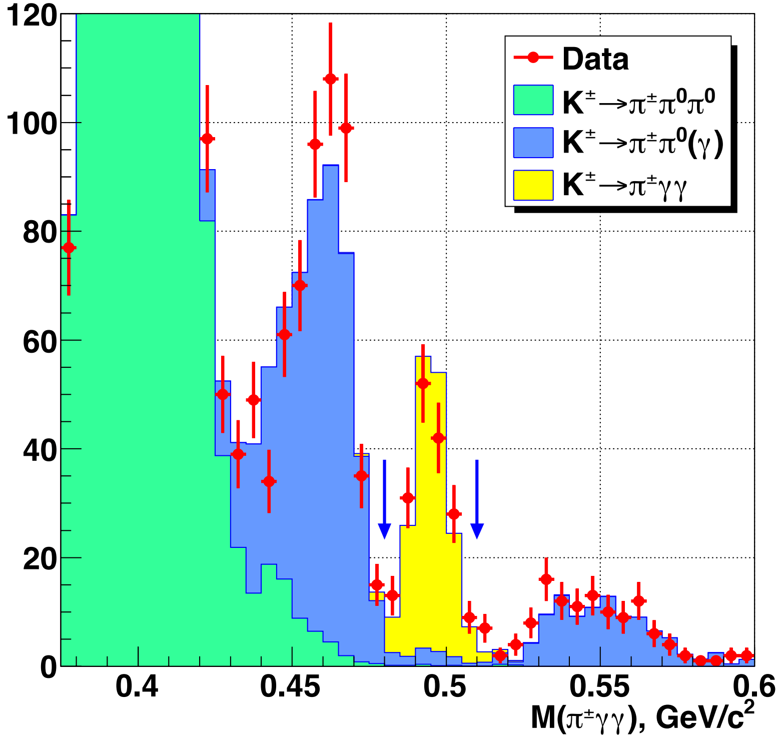
$\hat{c} = 1.36 \pm 0.33_{stat} \pm 0.07_{syst} = 1.36 \pm 0.34$

ChPT O(p^6):

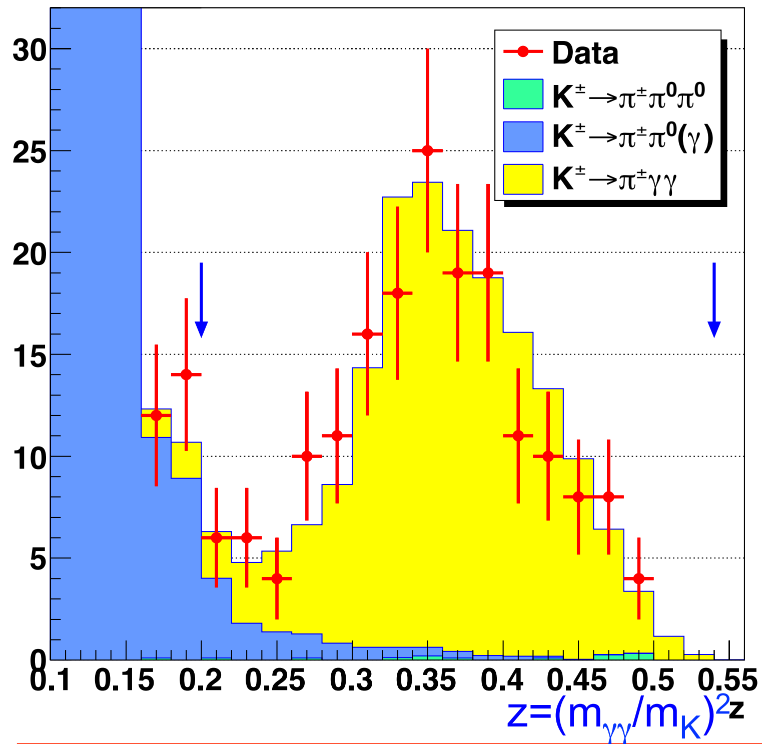
$\hat{c} = 1.67 \pm 0.39_{stat} \pm 0.09_{syst} = 1.67 \pm 0.40$

NA62 Data set - 2007 *(3 months / downscaled trigger)*

mass spectrum



ChPT O(p^6) fit



$K_{\pi\gamma\gamma}$ 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

preliminary

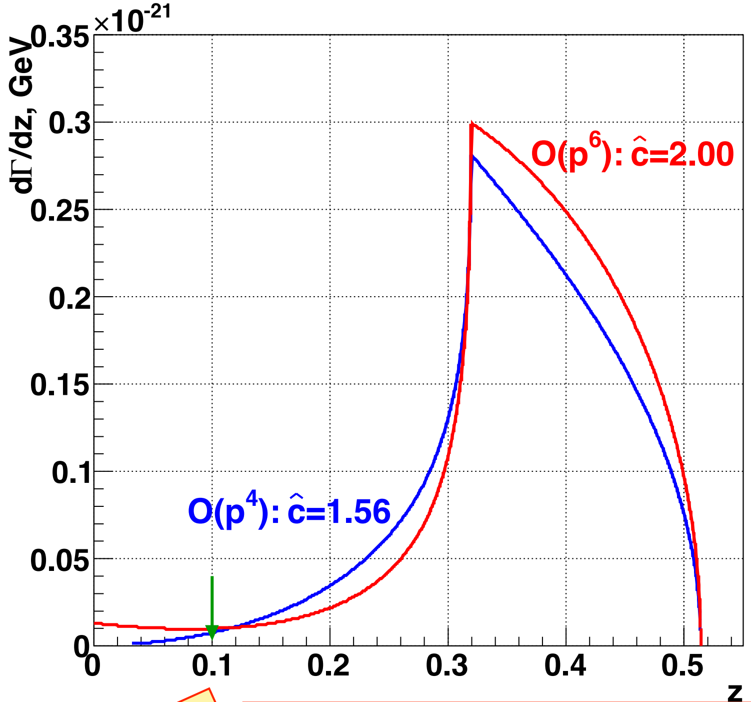
ChPT O(p^4):

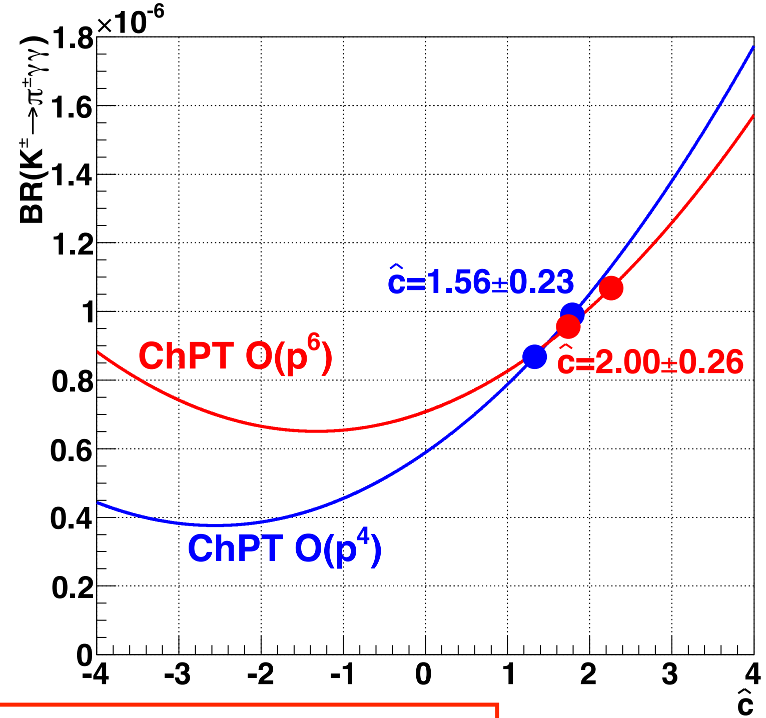
$\hat{c} = 1.71 \pm 0.29_{stat} \pm 0.06_{syst} = 1.71 \pm 0.30$

ChPT O(p^6):

$\hat{c} = 2.21 \pm 0.31_{stat} \pm 0.08_{syst} = 2.21 \pm 0.32$

Combined 2004 & 2007 - Fit results





preliminary

ChPT O(p^4): $\hat{c} = 1.56 \pm 0.22_{stat} \pm 0.07_{syst} = 1.56 \pm 0.23$

ChPT O(p^6): $\hat{c} = 2.00 \pm 0.24_{stat} \pm 0.09_{syst} = 2.00 \pm 0.26$

$BR = (1.01 \pm 0.06) \times 10^{-6}$ model dependent

- ➔ very low systematic uncertainties
- ➔ ChPT O(p^4) vs O(p^6) models cannot be discriminated within the current experimental sensitivity

From NA48/2……….

✓ Precision measurement of $K^{\pm} \to \pi^0 l^{\pm} \nu$ (K_{l3}) form factors

- provide the most accurate and theoretically cleanest way to access |Vus|

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

preliminary

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

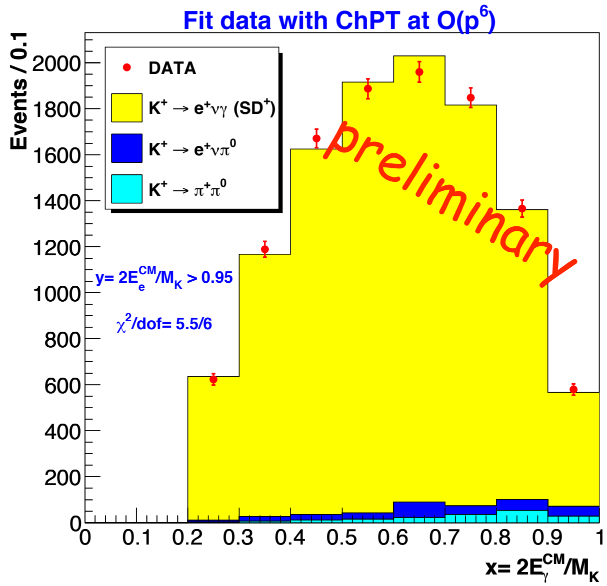
- NA48/2 is the first experiment which measured both Ke3 and Kμ3.
- high precision preliminary results, competitive with other measurements
- Results for Ke3 and Kμ3 from NA48/2 in good agreement.

✓ First observation of the decay $K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-$

- Sensitivity to CPV and NP,
- ~ 4500 events in the signal region

✓ Measurement of the $K^+ \to e^+ \nu \gamma$ (SD+) decay

- ChPT test to NLO in ChPT [O(p4) and O(p6)]
- Model-independent form factor extraction allows comparison with theoretical predictons
- $K^+ \to e^+ \nu \gamma$(SD+) candidates ~ 10000



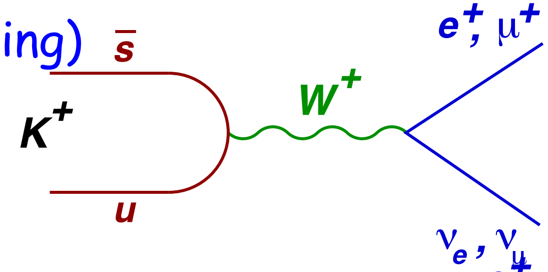
..........towards NA62

NA62 (R_K phase - 2007) Test of μ-e universality

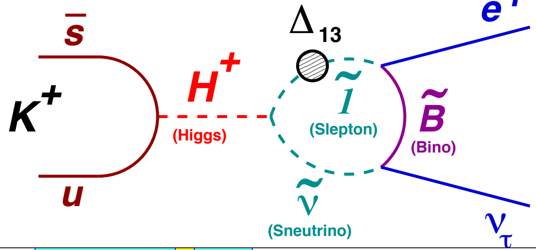
- In the SM K_{e2} strongly helicity suppressed (V-A coupling)
- measure:

$$R_K = \frac{\Gamma\left(K^\pm \to e^\pm \nu_e\right)}{\Gamma\left(K^\pm \to \mu^\pm \nu_\mu\right)} = \left(2.477 \pm 0.001\right) \cdot 10^{-5}$$

[V. Cirigliano and I. Rosell, PRL99 (2007) 231801]



- Beyond the SM the presence of LFV terms, charged Higgs mediated, introduces extra contribution to the SM amplitude, enhancing the decay rate
  [Masiero, Paradisi, Petronzio, PRD 74 (2006) 011701]



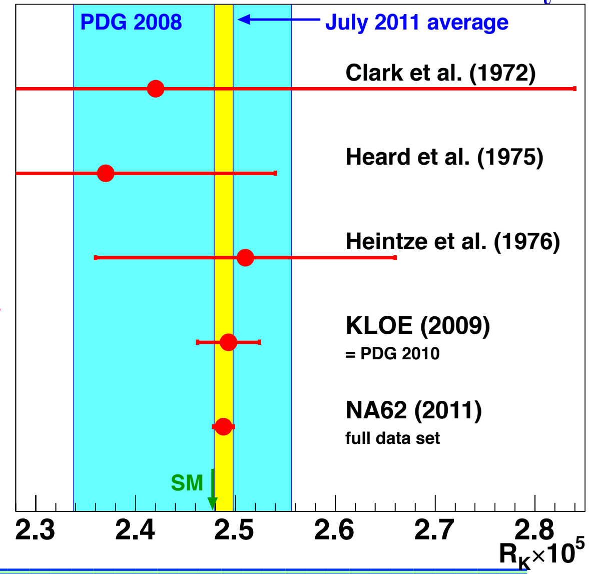
NA62 final result

$$R_K = \left(2.488 \pm 0.010\right) \cdot 10^{-5}, \delta R_K / R_K = 0.40\%$$

World Ke2 statistics increased by 1 order of magnitude
In agreement with SM expectation, but ~ 1 σ above

⇒ further precision R_K measurements

- Partial data set (40%): PLB 698 (2011) 105
- Full data set: paper close to be submitted



NA62
Measurement of the ultra-rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Ultra-rare kaon decays & CKM

The Unitarity Triangle describes in the (ρ,η) plane the CKM matrix

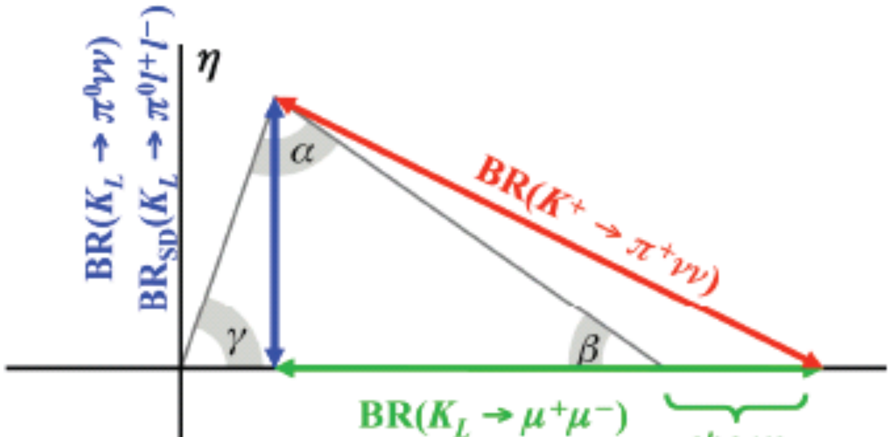
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The "Standard" Unitarity Triangle

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

The "Kaon" Unitarity Triangle

$$V_{us}^{*}V_{ud} + V_{cs}^{*}V_{cd} + V_{ts}^{*}V_{td} = 0$$



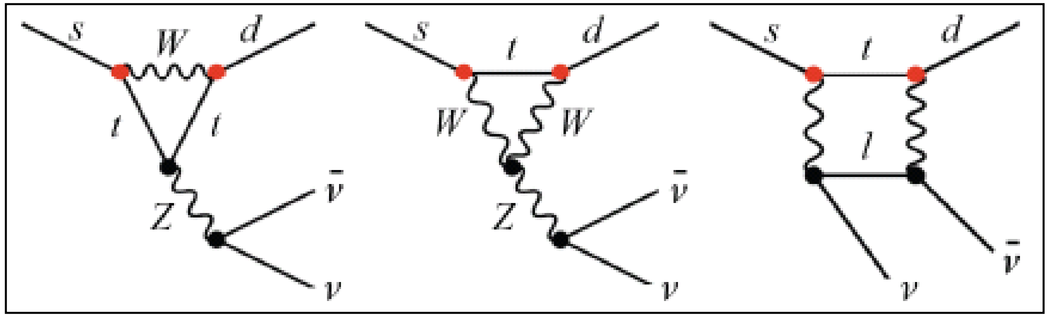
$K^+ \to \pi^+ \nu\bar\nu$	$\lvert V^*_{ts} V_{td}\rvert$
$K_L \to \pi^0 \nu\bar\nu$	$\mathrm{Im}\,(V^*_{ts} V_{td}) \propto \eta$

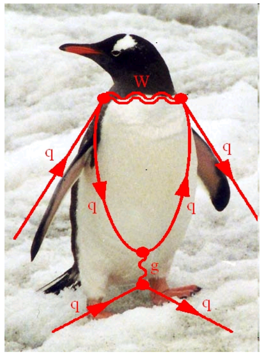
the holy grail

Alternative way to measure the Unitarity Triangle parameters with smaller theoretical uncertainty

$K \rightarrow \pi\nu\nu$ in the SM . . .

- FCNC process forbidden at tree level → room for NP up to 10xSM
- Short distance contribution dominated by Z penguin and W box diagrams
- "Super-clean" theoretically
  - hadronic matrix element can be extracted from measured quantities(Ke3)
- Very small BR due to the CKM top coupling
  - $A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \approx \lambda^5$
- Measurement of $|V_{td}|$ complementary to those from B-B mixing and $B \rightarrow \rho\gamma$
- $\delta BR/BR = 10\%$ → $\delta|V_{td}|/|V_{td}| = 7\%$.





BR × 10^{10}	SM Prediction	Experiments
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	0.781 ± 0.075 ± 0.029 [1]	$1.73^{+1.15}_{-1.05}$ [2]
$K^0 \rightarrow \pi^0 \nu \bar{\nu}$	0.243 ± 0.039 ± 0.006 [1]	< 260 (@90% CL) [3]

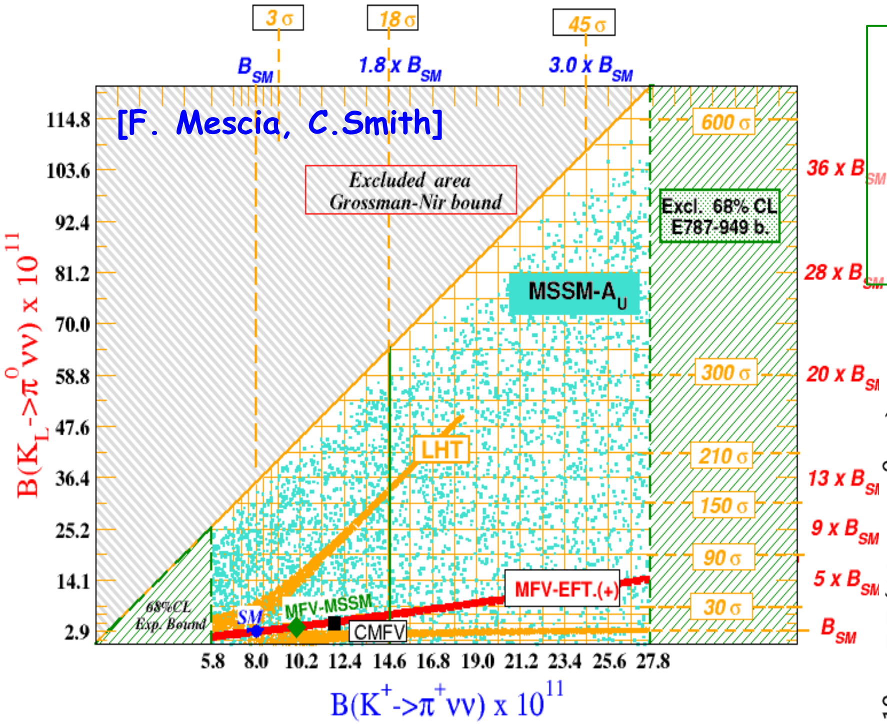
7 events: twice as large as, but still consistent with SM expectation

[1] Brod, Gorbahn, Stamou: PRD83(2011) 034030, arXiv 1009.0947
[2] BNL E787/E949: PRL101 (2008) 191802, arXiv 0808.2459
[3] KEK E391a: PR D81 (2010) 072004, arXiv 0911.4789

. . . and beyond the SM

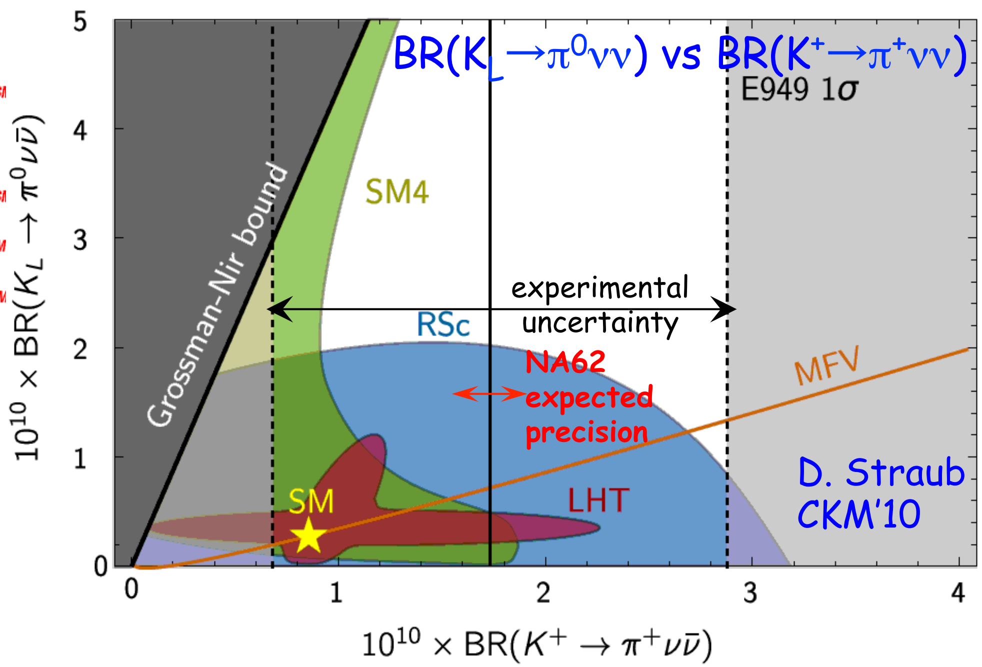
Several SM extensions predict sizable deviations for the BR

→ Possibility to distinguish among different models



Possibility to distinguish among different models

Chargino / H± loops (MSSM at low/large tanβ),
R-parity violation (non MFV), enhanced EW Penguins,
Little Higgs, extra dimensions, 4th generation, ...



(hep-ph/0906.5454, hep-ph/0812.3803,hep-ph/0604074)

Concrete NP models predicting high deviations from MFV

Randall-Sudrum,
Littlest Higgs with T-parity,
SM 4th generation

NA62 - Experimental principles

- Goal ➡ 10% precision Branching Ratio measurement
- O(100) $K^+ \to \pi^+ \nu\bar{\nu}$ events in two years of data taking

➔ Statistics
- BR(SM) ~ 7.8×10^{-11}
- Acceptance: 10%
- K decays: 10^{13}

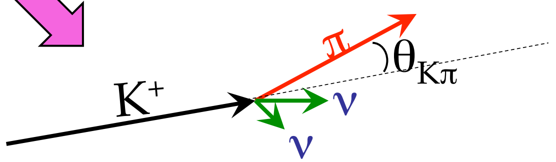
➔ Systematics
- $\geq 10^{12}$ background rejection
- $\leq$10% precision on background measurement

Kaon intensity & signal efficiency → High momentum K^+ beam

Signal purity & detector redudancy → Decay in-flight technique

Very challenging experiment

Weak signal signature



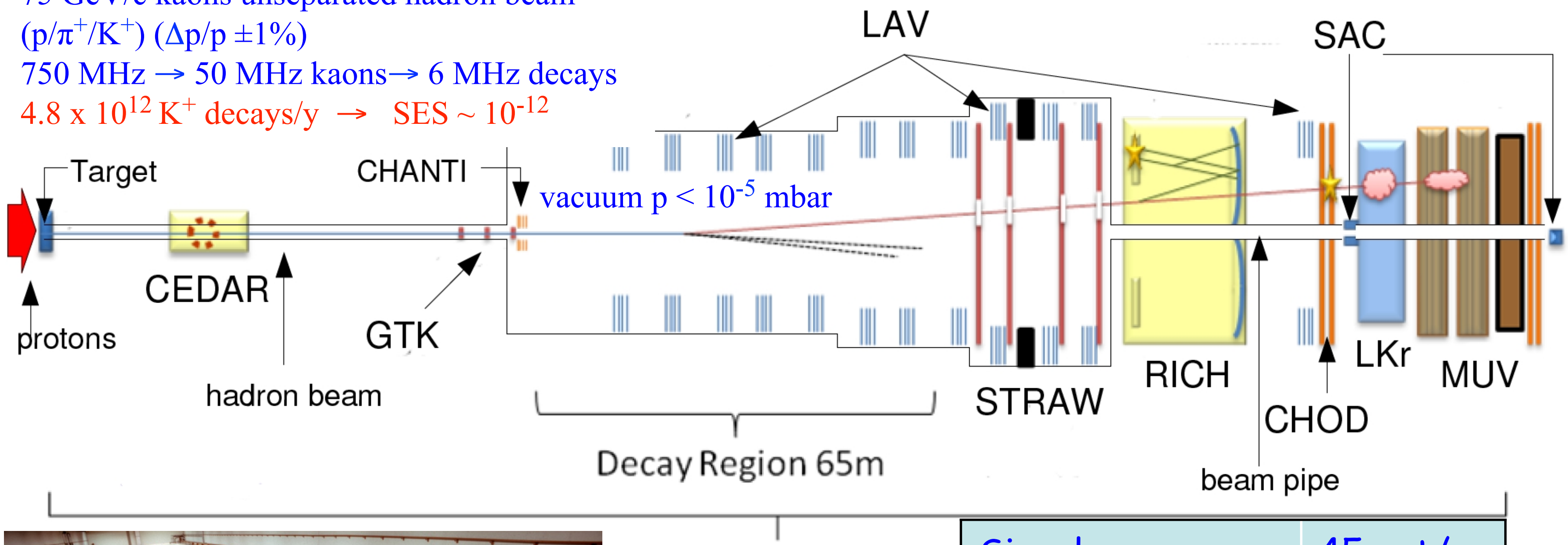
$m^2_{miss} = (P_K - P_\pi)^2$

Huge background

Decay	BR
$\mu^+\nu$ $(K_{\mu 2})$	63.5%
$\pi^+\pi^0$ $(K_{\pi 2})$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+\nu$ (K_{e3})	5.1%
$\pi^0\mu^+\nu$ $(K_{\mu 3})$	3.3%

Experiment layout & sensitivity

- 400 GeV/c SPS primary protons
- 75 GeV/c kaons unseparated hadron beam
- $(p/\pi^+/K^+)$ ($\Delta p/p$ ±1%)
- 750 MHz → 50 MHz kaons→ 6 MHz decays
- 4.8 x 10^{12} K^+ decays/y → SES ~ 10^{-12}



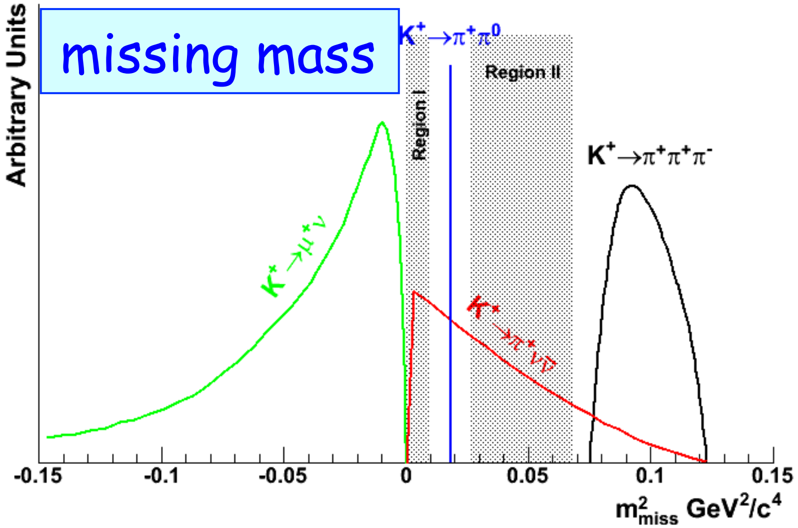
Signal	45 evt/y
$K^+ \to \pi^+\pi^0$	4.3%
$K^+ \to \mu^+\nu$	2.2%
$K^+ \to \pi^+\pi^+\pi^-$	< 4.5%
$K^+ \to \pi^+\pi^0\gamma$	~ 2%
$K^+ \to \mu^+\nu\gamma$	0.7%
total background	< 13.5%

Background and kinematics

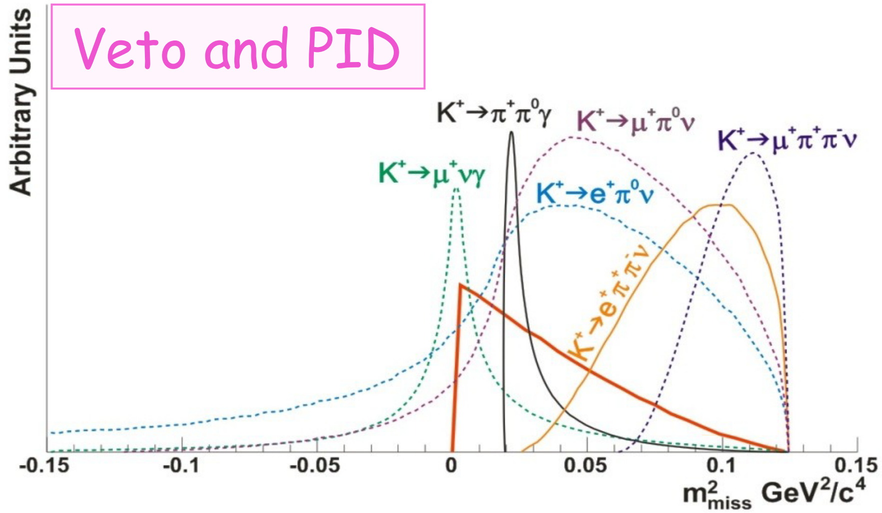
92% Bkg separated from signal by kinematic cuts

8% not separated

missing mass



Veto and PID



$m^2_{miss} = (P_K - P_\pi)^2$ defines low bkg signal regions separated by $K^+ \to \pi^+\pi^0$

extend in the signal region kinematics doesn't help

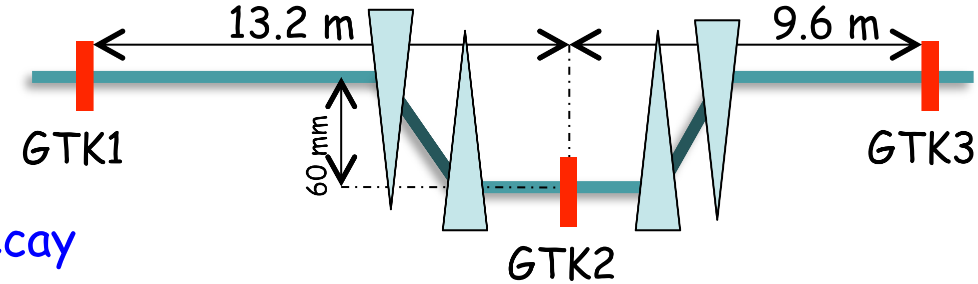
- ✓ high resolution m^2_{miss} reconstruction
- ✓ measure precisely kaon and pion momenta
- ✓ keep multiple scattering as low as possible

Gigatracker (Kaon)
Straw chambers (pion)

- ✓ Suppress $K^+ \to \pi^+\pi^0$ background
- ✓ Reject offline decays with γ
- ✓ K^+ identification in the had beam
- ✓ 10^{-3} π-μ separation

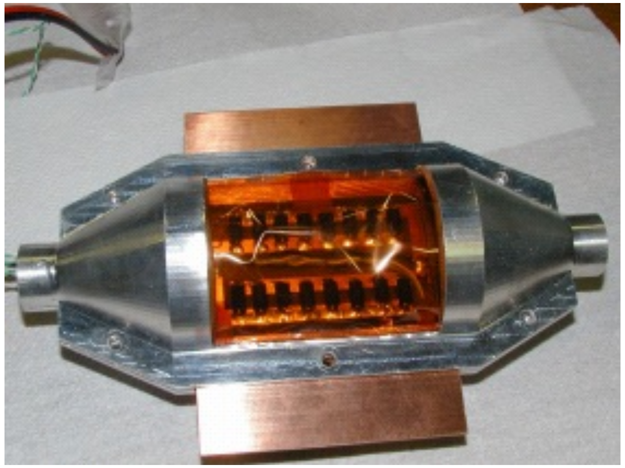
Photon veto system
Particle Identification

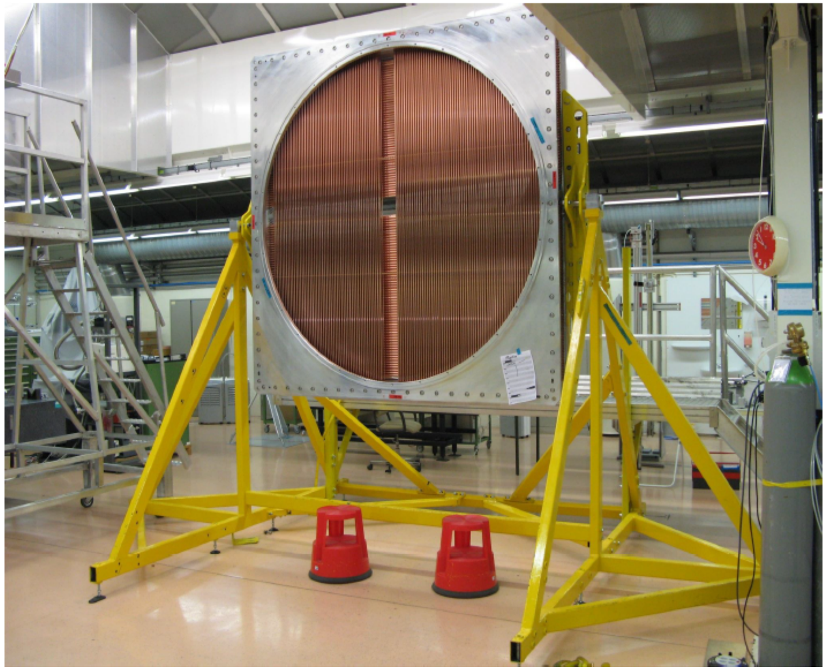
Tracking detectors



Gigatracker

- measurement of time, coordinates and momentum of individual particles
- three Si-pixel station before the decay volume
- $\sigma(t) \sim 150$ ps on single track (test beam)





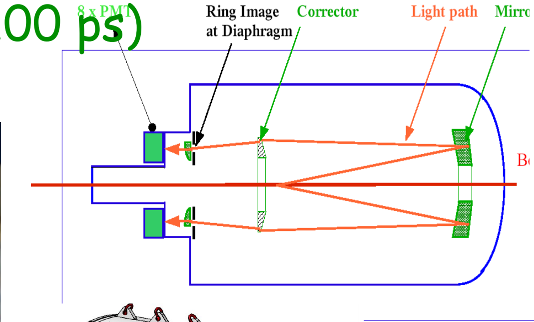
Straw chamber spectrometer

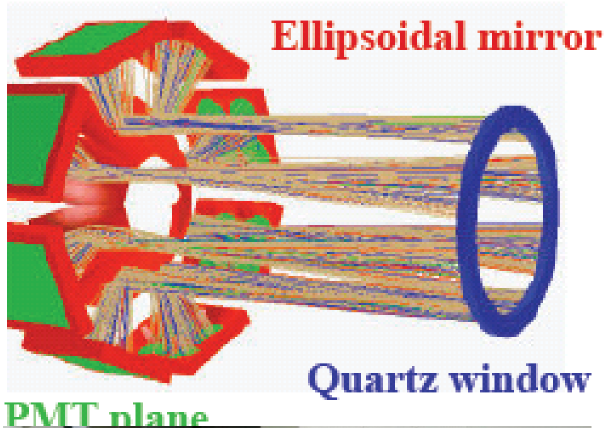
- measurement of coordinates and momentum of charged particles originating from decay
- 4 chambers + magnet
- $\sigma(P_\pi)/P_\pi \sim 0.3\% \oplus 0.007\% \times P_\pi$ (GeV/c)
- $\sigma(dX/dZ)/(dX/dZ) \sim 45\text{-}15\ \mu rad$

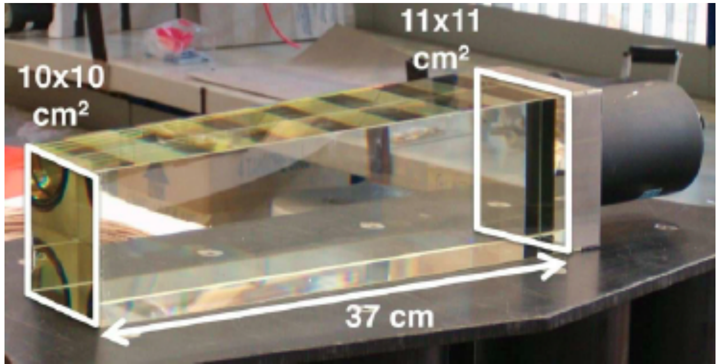
Veto & PID detectors/1

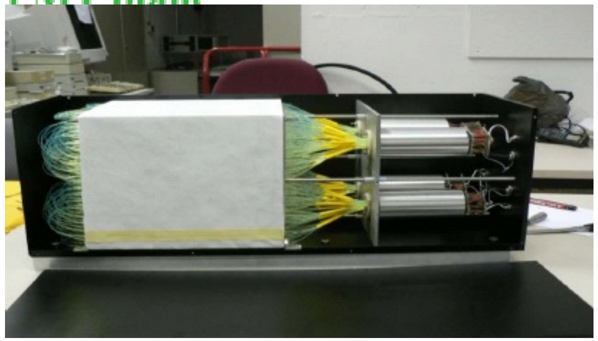
CEDAR - Differential Cherenkov counter

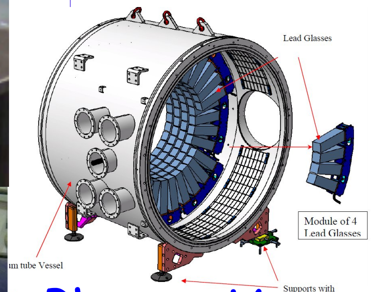
- Filled with Hydrogen gas
- Positive identification of Kaons in a 800 MHz hadron beam
- Excellent time resolution O(100 ps)
- Sustain rate O(MHz/mm^2)











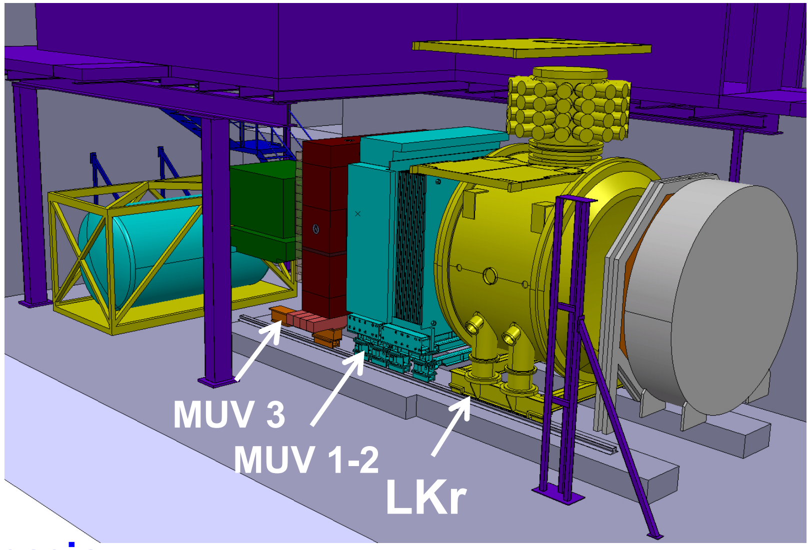
Photon Veto System

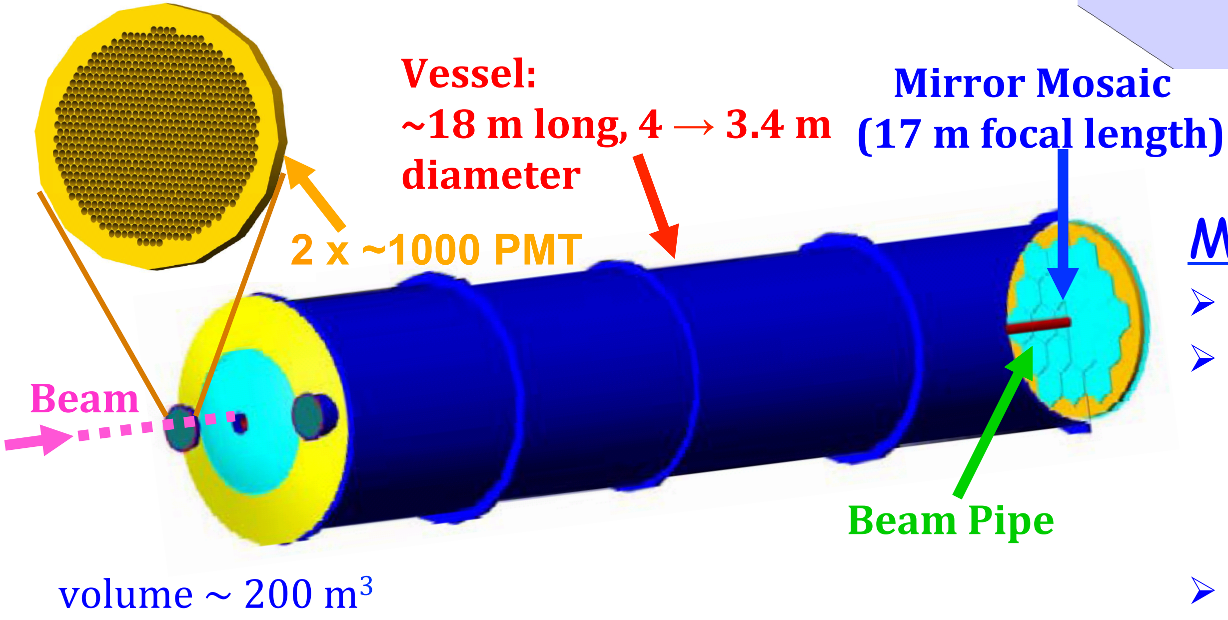
- several subsystems, among them:
- Large angle (8.5-50 mrad) Lead glass blocks
- Inefficiency $<10^{-4}$ for 100 MeV $< E_\gamma <$ 35 GeV
- Small angle (1-8 mrad) “shashlyk” calorimeters
- Inefficiency $<10^{-3}$ for $E_\gamma >$ 10 GeV

Veto & PID detectors/2

RICH – Ring Imaging Cherenkov counter

- Filled with Neon at atm pressure
- Separate π-μ in $15 < p < 35$ GeV/c with a μ suppression factor better than 5×10^{-3}
- Measure pion crossing time with a resolution < 100 ps
- Provide a L0 trigger for charged tracks





Muon detector

- 3 planes MUV 1,2,3 + iron
- MUV 1+MUV 2 reach a factor of 10^6 in muon rejection (combined with the RICH)
- MUV 3 for trigger purposes

Summary and outlook

Precision physics complementary to high-energy approach for NP search

- New measurement of the $K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$ from NA48/2 and NA62
  - ➔ new precise experimental data on ChPT parameters
  - ➔ ChPT $O(p^4)$ vs $O(p^6)$ models cannot be discriminated within the current experimental sensitivity
- The $K^{+}\rightarrow\pi^{+}\nu\bar{\nu}$ decay ➔ very challenging experiment
  - ➔ collect O(100) events & provide a 10% BR measurement
  - ➔ key points: excellent resolutions, hermetic coverage, PID
  - ➔ construction well advanced, first technical run in October 2012
  - ➔ 2013 – complete detector and installation
  - ➔ 2014 (?) data taking with full detector (CERN accelerator schedule)
  - ➔ The high performances of the detectors can also be the building blocks for a further physics program
- Many other results at the frontier of precision physics

A very rich program in the near future

NA62 Penguins at work