Study of $K \to \pi\gamma\gamma$ decay at the NA62 experiment

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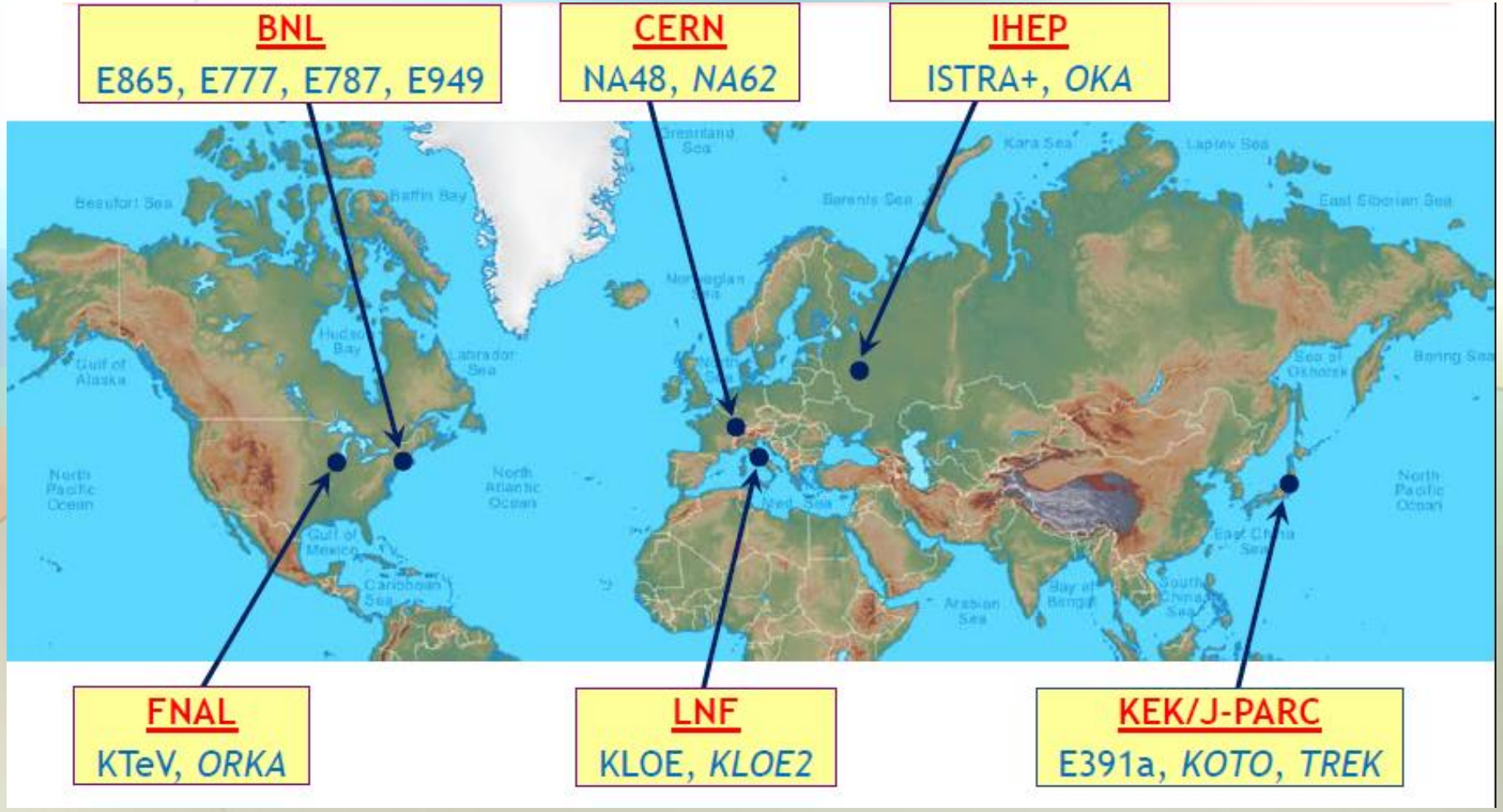
For the NA62 collaboration

plan

- $K \rightarrow \pi\gamma\gamma$ decay
- NA62 experiment at CERN
- Results of 2007 run
- Combined NA48/2 and NA62 results
- NA62 current status
- Conclusions

Kaon map of the world

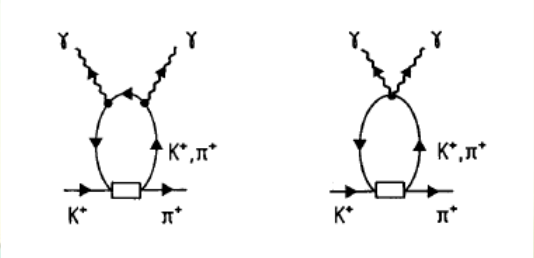


$K \to \pi \gamma \gamma$ decay: theory

In the ChPT framework the differential rate of the decay $K^{\pm}(p) \to \pi^{\pm}(p_3)\gamma(q_1)\gamma(q_2)$ process (no $O(p^2)$ contribution) is:

$$\frac{\partial\Gamma}{\partial y \partial z}(\hat{c}, y, z) = \frac{m_K}{2^9\pi^3}\left[z^2\left(|A(\hat{c}, z, y^2) + B(z)|^2 + |C(z)|^2\right) + \left(y^2 - \frac{1}{4}\lambda(1, r_\pi^2, z)\right)^2 |B(z)|^2\right]$$

$$y = \frac{p(q_1 - q_2)}{m_K^2}, \quad z = \frac{(q_1 + q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2$$



$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ca)$$

ChPT $O(p^4)$:

✓Leading contribution from $A(z, \hat{c})$, responsible for a cusp at $m_{\gamma\gamma} = 2m_\pi$

✓$C \sim 0.1A$ *[Ecker, Pich, de Rafael, Nucl. Phys. B303 (1988), 665]*

✓$B=0$, $D=0$

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

$$\hat{c} = \frac{128\pi^2}{3}\left[3(L_9 + L_{10}) + (N_{14} - N_{15} - 2N_{18})\right]$$

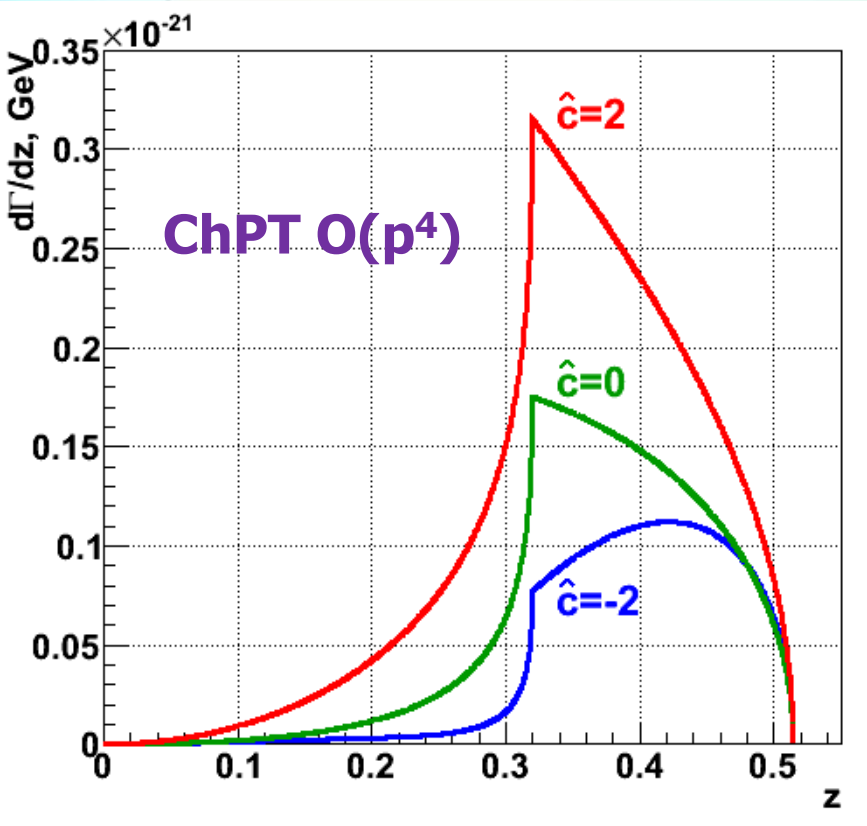
Weak Chiral Lagrangian

Strong loop and counterterms

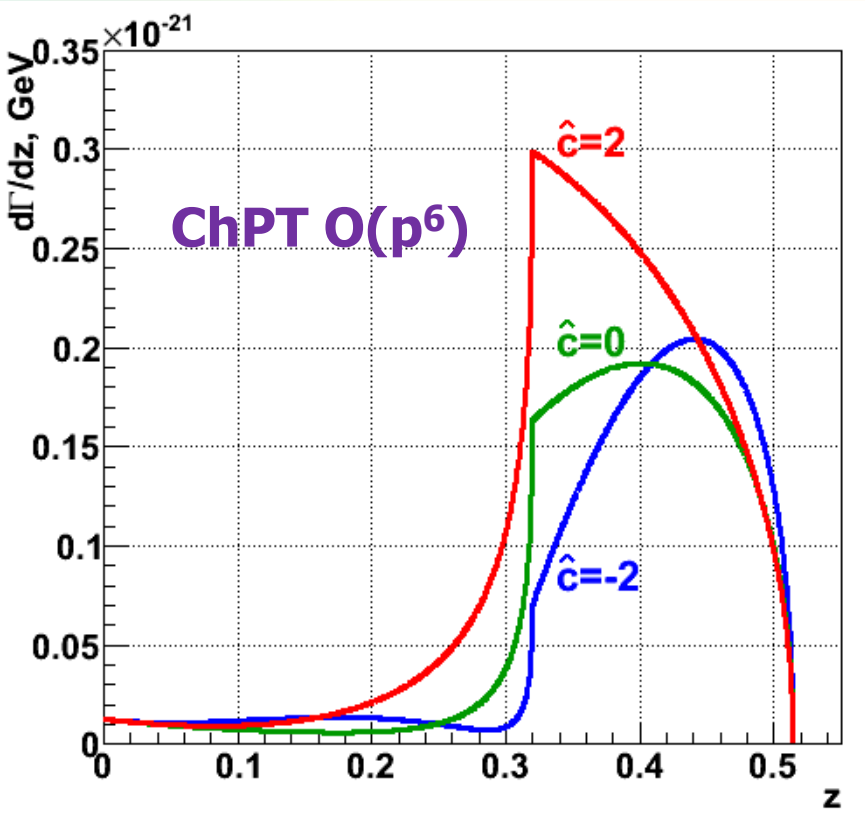
$K \to \pi\gamma\gamma$ decay: theory

$$z = \frac{(q_1+q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2$$

- ✓ Spectrum determined by $\hat{c}$
- ✓ Cusp can be seen at $z = (2m_\pi/m_K)2$
- ✓ Non-zero rate at $z = 0$ (generated by B amplitude) for ChPT $O(p^6)$



$O(p^4)$ loop
[Ecker, Pich, de Rafael, NPB303 (1988) 665]



$O(p^6)$ unitary corrections
[D'Ambrosio, Portoles, PLB386 (1996) 403]

$K \to \pi \gamma \gamma$ decay: experimental status

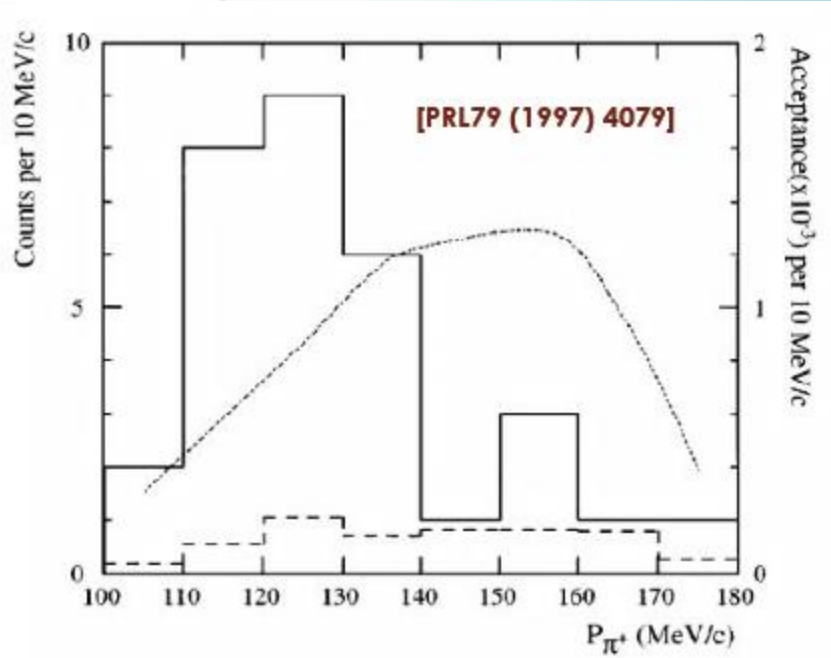


FIG. 1. π^+ momentum distribution for 31 $K^+ \to \pi^+ \gamma\gamma$ candidates (solid) and for estimated background events (dashed). The acceptance is given by the dotted line.

E787 (1997):

BR = (11 ± 3 ± 1) x 10^{-7}

31 candidates, ~5 bkg events

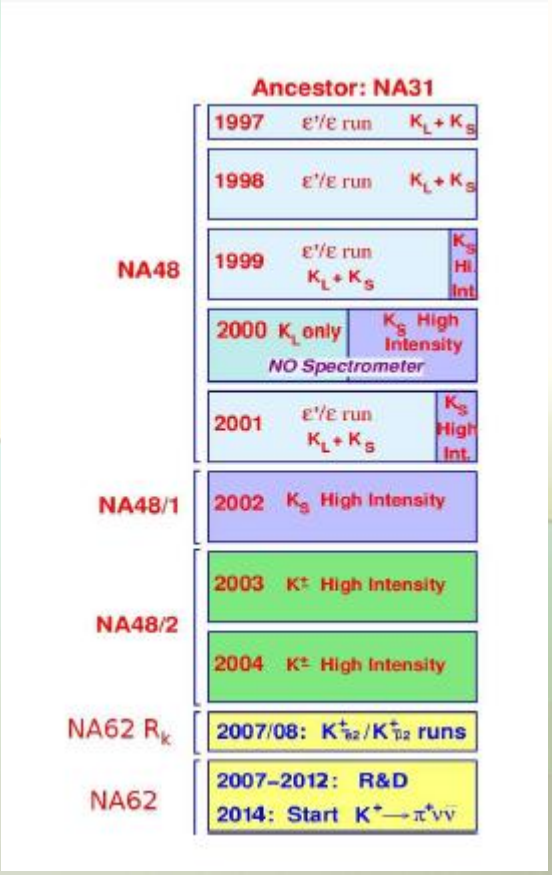
Extracted $\hat{c}$ values:

$O(p^4)$: $\hat{c} = 1.6 \pm 0.6$

$O(p^6)$: $\hat{c} = 1.8 \pm 0.6$

[PRL79 (1997) 4079]

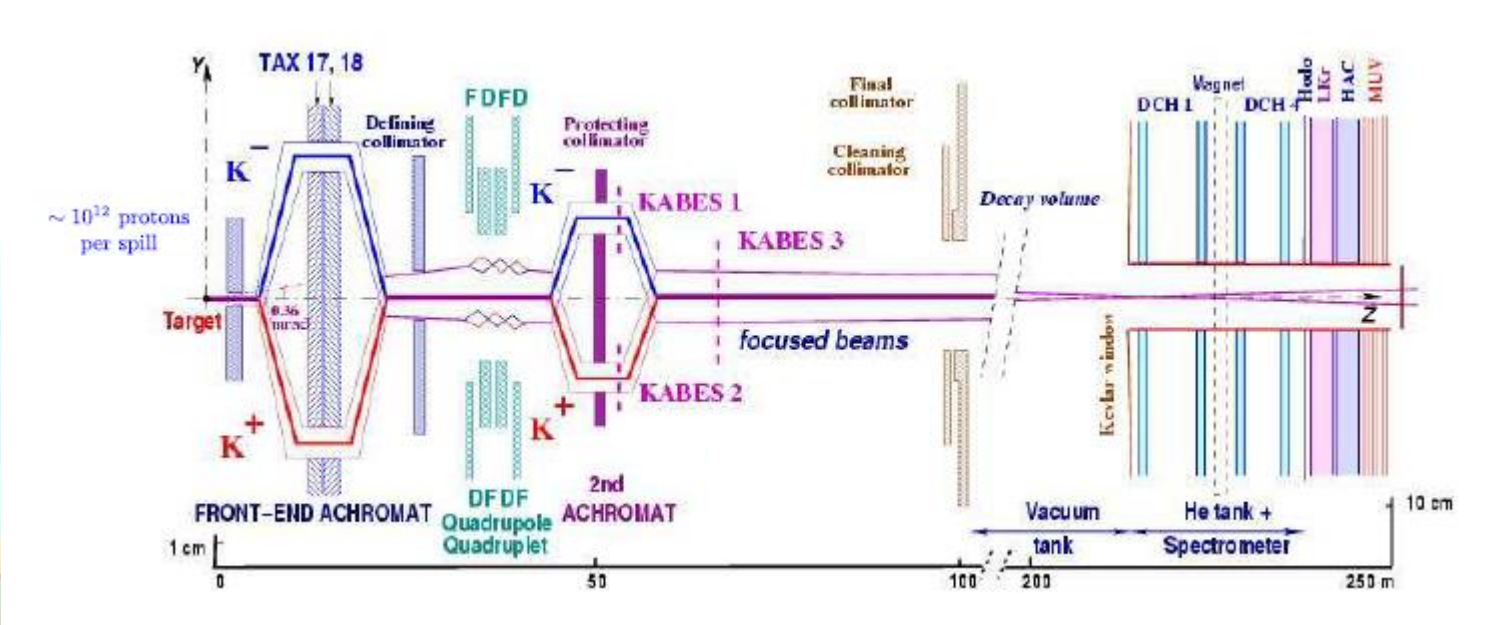
NA62 experiment



NA62 main goal:
measure $K^+ \to \pi^+ \nu\nu$ decay
(~100 events with S/B~10)

NA62 collaboration:
Birmingham, Bratislava, Bristol, CERN, JINR Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, IHEP Protvino, INR Moscow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Naples, Padua, Perugia, Pisa, Prague, Rome I, Rome II, San Luis Potosí, Sofia, Stanford, Turin

NA48/2 and NA62 beamline



NA48/2 Data taking:

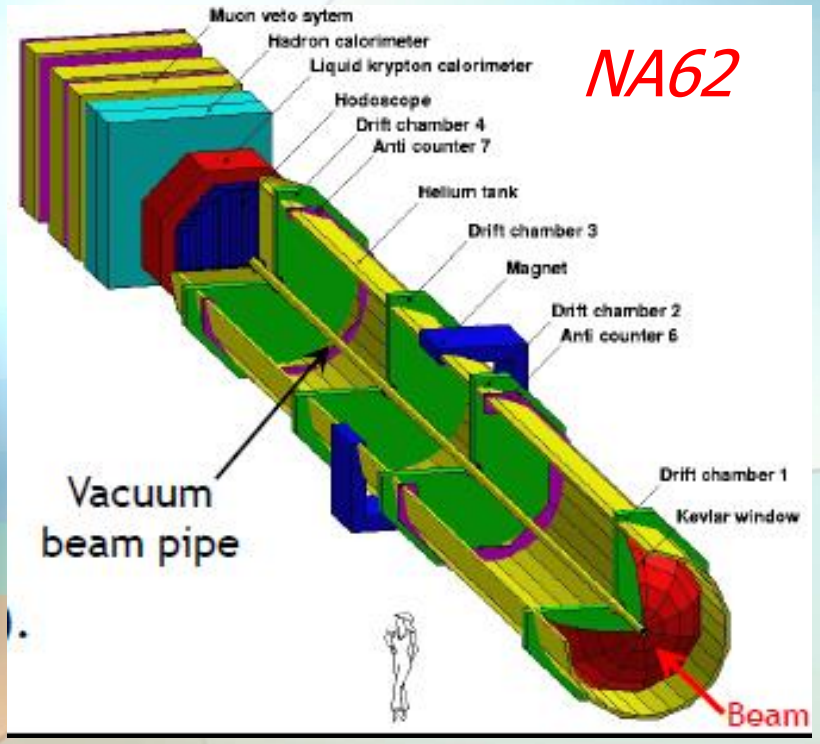
- 4 months in 2003 ($K^{\pm}$)
- 4 months in 2004 ($K^{\pm}$)

NA62-RK Data taking:

- 2007 mostly K^{+}

Kaon beam momentum [GeV/c]	
NA48/2 (2003-4)	60.0 ± 2.2
NA62 (2007)	74.0 ± 1.4
NA62 (2014)	75.0 ± 0.8

NA48/2 and NA62 detector



Main detectors:

- ✓ Magnetic spectrometer
- ✓ Scintillator hodoscope
- ✓ Liquid Krypton EM calorimeter (LKr)

Magnetic spectrometer:

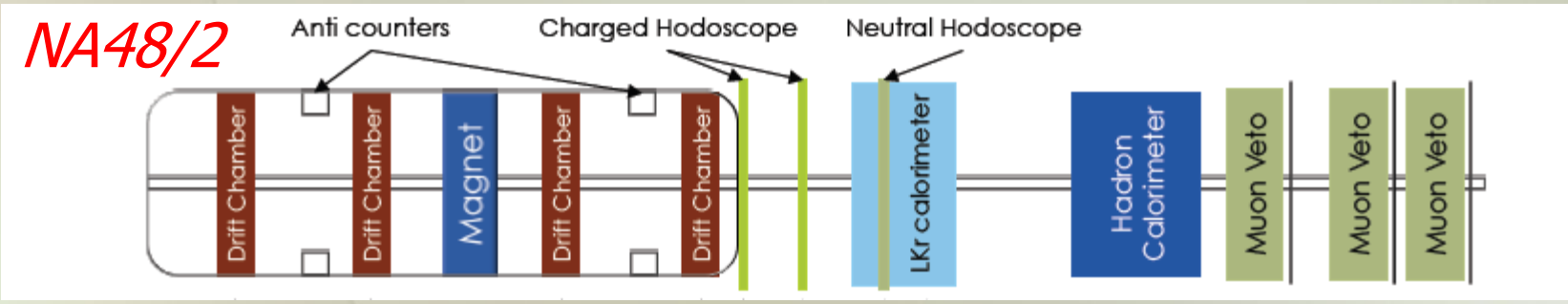
- ✓ 4 drift chambers (DCH)
- ✓ 4 views per DCH
- ✓ $\delta p/p = 0.48\% + 0.009\% p$ [GeV/c]

Scintillator hodoscope:

- ✓ Good time resolution (150ps)
- ✓ Fast trigger

LKr:

- ✓ High granularity (13248 cells, 2x2 cm^2)
- ✓ Quasi-homogenious, 7m^3 liquid Kr (27X_0)
- ✓ $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ [GeV]



Analysis strategy

- ✓ Select signal events $K \to \pi\gamma\gamma$
- ✓ Select events corresponding to the normalization decay $K \to \pi\pi^0$ ($\pi^0 \to \gamma\gamma$)
- ✓ Calculate model-independent BR
- ✓ Calculate $\hat{c}$ from the fit of z-spectrum ($\hat{c}$ is model-dependent)
- ✓ Calculate BR (model-dependent) from $\hat{c}$
- ✓ Compare BR measurement with previous results

Main variable for the signal observation: $M(\pi\gamma\gamma)$
Main variable for the signal study: $z = (m_{\gamma\gamma}/m_K)^2$

Event selection

Identical cuts for signal and normalization:

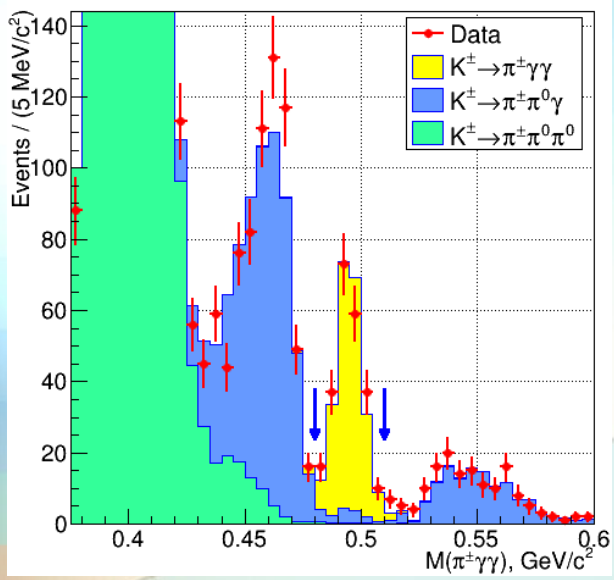
- ✓ One secondary track (pion)
- ✓ Reconstructed vertex inside 98m fiducial volume
- ✓ Track momentum: $8 < p < 50$ GeV/c
- ✓ $E/p < 0.85$ (pion ID)
- ✓ 2 isolated clusters in LKr with $E > 3$GeV
- ✓ $0.48 < M(\pi\gamma\gamma) < 0.51$ GeV/c^2

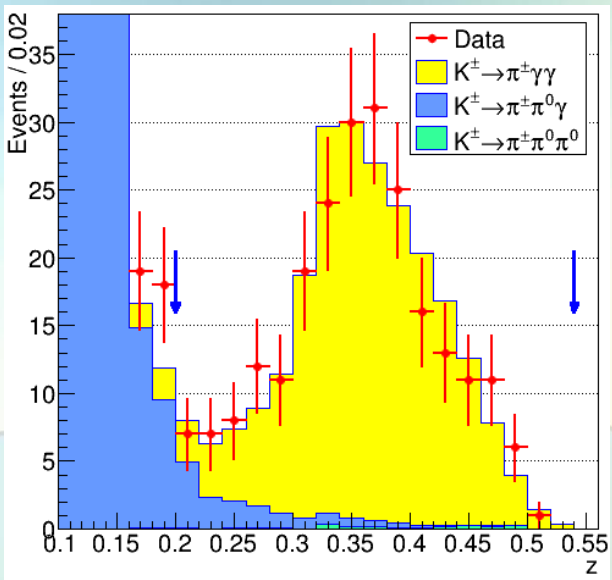
Different cuts for signal and normalization:

- ✓ $z > 0.2$ for signal (to suppress backgrounds)
- ✓ $0.064 < z < 0.086$ for normalization ($z \sim 0.075$ corresponds to the $m_{\gamma\gamma} \sim m_{\pi 0}$)

Main variable for the signal observation: $M(\pi\gamma\gamma)$
Main variable for the signal study: $z = (m_{\gamma\gamma}/m_K)^2$

Signal observation





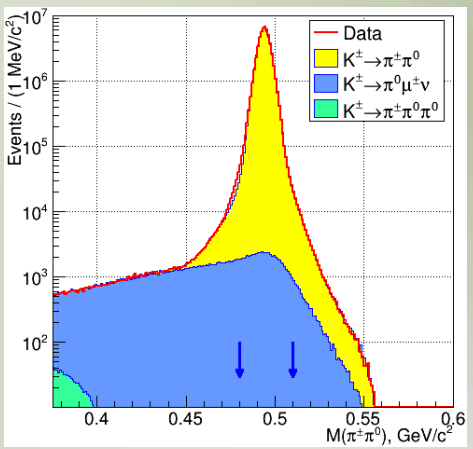
large z:
pion at rest, goes into the beam tube

232 signal candidates

$K \to \pi\pi^0\gamma$ bkg: 15.3 ± 1.1 events

$K \to \pi\pi^0\pi^0$ bkg: 2.1 ± 0.3 events

Main bkg source: cluster merging in LKr



5.488×10^7 normalization candidates

bkg contamination 0.115%

Model-independent (MI) BR

z range	N_j	N_j^B	A_j	$\mathcal{B}_j \times 10^6$
0.20–0.24	13	4.89	0.194	0.045 ± 0.020
0.24–0.28	9	2.73	0.198	0.034 ± 0.016
0.28–0.32	18	2.33	0.194	0.087 ± 0.024
0.32–0.36	33	1.30	0.190	0.180 ± 0.033
0.36–0.40	31	0.98	0.184	0.177 ± 0.033
0.40–0.44	18	1.61	0.173	0.103 ± 0.027
0.44–0.48	23	1.21	0.135	0.175 ± 0.038
$z > 0.48$	4	0.52	0.049	0.076 ± 0.044

$$B_j = (N_j - N_j^B)/(N_K A_j)$$

events — N_j; background — N_j^B; acceptance — A_j; Total K decays — N_K

- ✓ z-range divided into small bins (acceptance in a bin independent of kinematics)
- ✓ Bin content dependence on y is weak (<10%)
- ✓ ChPT Γ-dependence on y is ~10%

Final NA62 result:

$$B_{MI}(z > 0.2) = \sum_{j=1}^{8} B_j = (1.088 \pm 0.093_{stat}) \times 10^{-6}$$

MI BR: NA48/2 and NA62 combined results

Bin z range	$B_j \times 10^6$
0.20-0.24	0.030 ± 0.011
0.24-0.28	0.046 ± 0.011
0.28-0.32	0.097 ± 0.015
0.32-0.36	0.194 ± 0.022
0.36-0.40	0.207 ± 0.023
0.40-0.44	0.123 ± 0.019
0.44-0.48	0.164 ± 0.025
z>0.48	0.104 ± 0.036

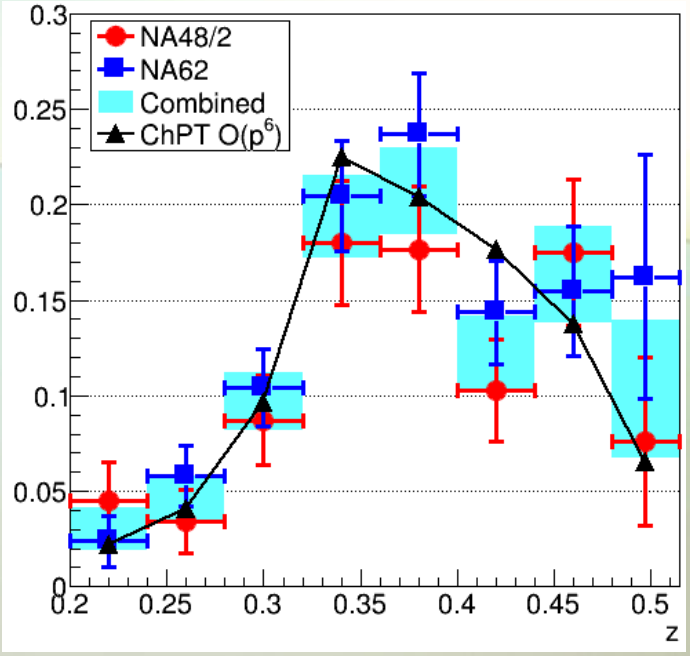
$$B_j = (N_j - N_j^B) / (N_K A_j)$$

events

background

acceptance

Total K decays

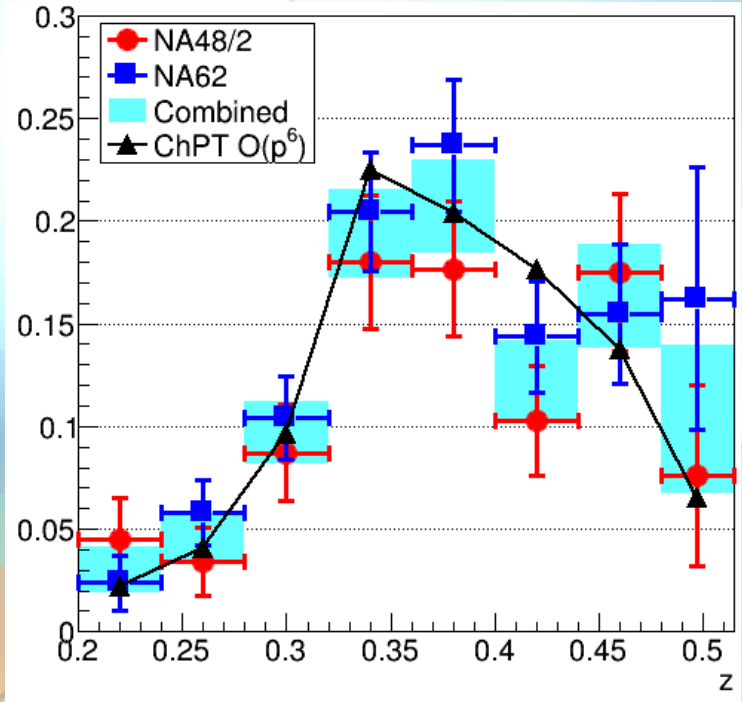


Final combined NA48/2 and NA62 result:

381 candidates

$$BR_{MI}(z>0.2) = (0.965 \pm 0.061 \pm 0.014) \times 10^{-6}$$

Fit of the z-spectrum



NA62 (2007) ChPT O(p⁴) fit:

$\hat{c}_4 = 1.93 \pm 0.26_{stat} \pm 0.08_{syst}$

NA62 (2007) ChPT O(p⁶) fit:

$\hat{c}_6 = 2.10 \pm 0.28_{stat} \pm 0.18_{syst}$

NA62 (2007) and NA48/2 combined ChPT O(p⁴) fit:

$\hat{c}_4 = 1.72 \pm 0.20_{stat} \pm 0.06_{syst}$

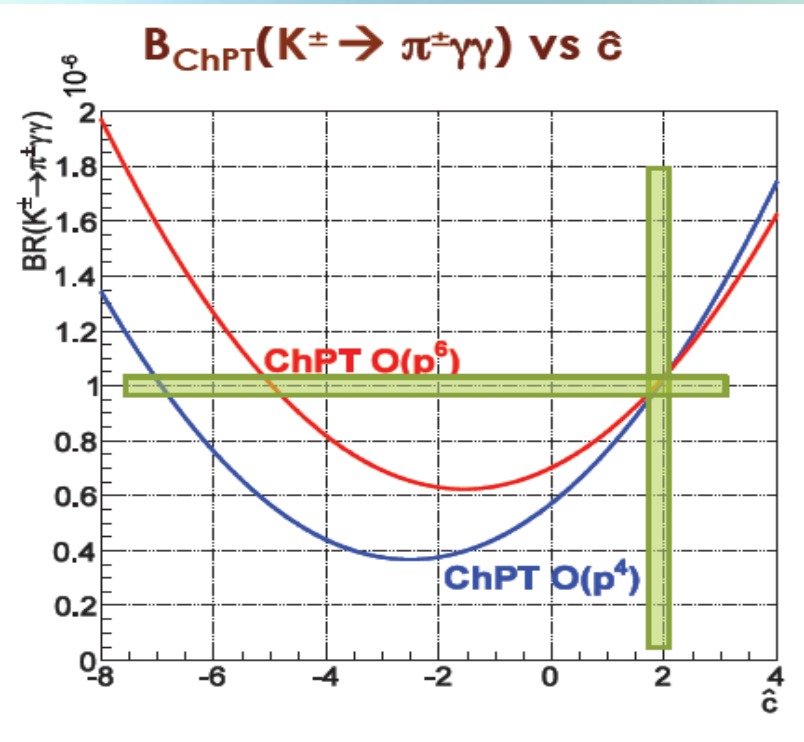
NA62 (2007) and NA48/2 combined ChPT O(p⁶) fit:

$\hat{c}_6 = 1.86 \pm 0.23_{stat} \pm 0.11_{syst}$

Using ChPT formulation: D'Ambrosio, Portolés, PLB386 (1996) 403

- ✓ Cusp structure confirmed by the data
- ✓ Data consistent with both ChPT $O(p^4)$ and $O(p^6)$
- ✓ Systematic uncertainty dominates by the precision of the bkg estimate

Model-dependent BR from ĉ



Combined Model Dependent BR in full phase space:

$$BR_{Op6} = (1.003 \pm 0.051_{stat} \pm 0.024_{syst}) \times 10^{-6}$$

To be compared with PDG(BNL E787): $BR_6 = (1.1 \pm 0.3 \pm 0.1)\times10^{-6}$

Publications:

NA48/2: [Phys. Lett. B730 (2014) 141]

NA62 (2007) and combined results: [Phys. Lett. B732 (2014) 65]

Current status of the NA62 experiment

NA62 experiment at CERN

Rare kaon decays:

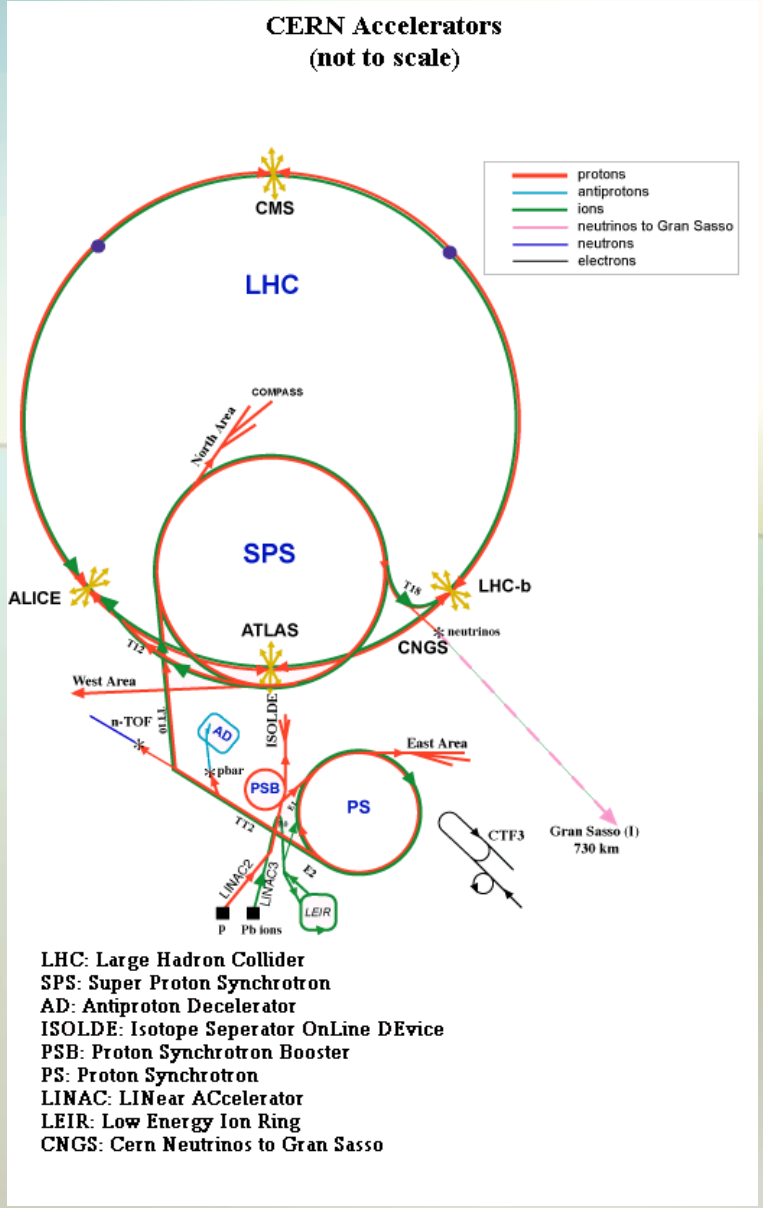
- ✓ Indirect searches for New Physics (NP) beyond Standard Model (SM)
- ✓ Complementary to LHC

NA62 at SPS CERN:

- ✓ Last generation **kaon experiment**
- ✓ Main goal: measurement of the $K^+ \to \pi^+ \nu\nu$ decay with ~10% precision (~100 events in 2 years of data taking)

$K^+ \to \pi^+ \nu\nu$ decay:

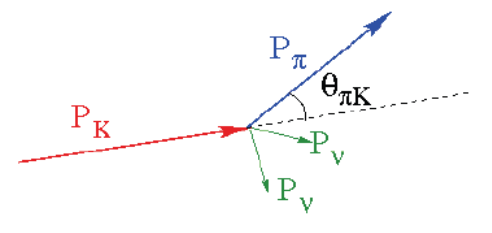
- ✓ Theoretically clean:
  $BR_{SM} = (7.81 \pm 0.75 \pm 0.29) \cdot 10^{-11}$
- ✓ Strongly suppressed in SM (FCNC)
- ✓ Sensitive to NP



NA62 experimental setup

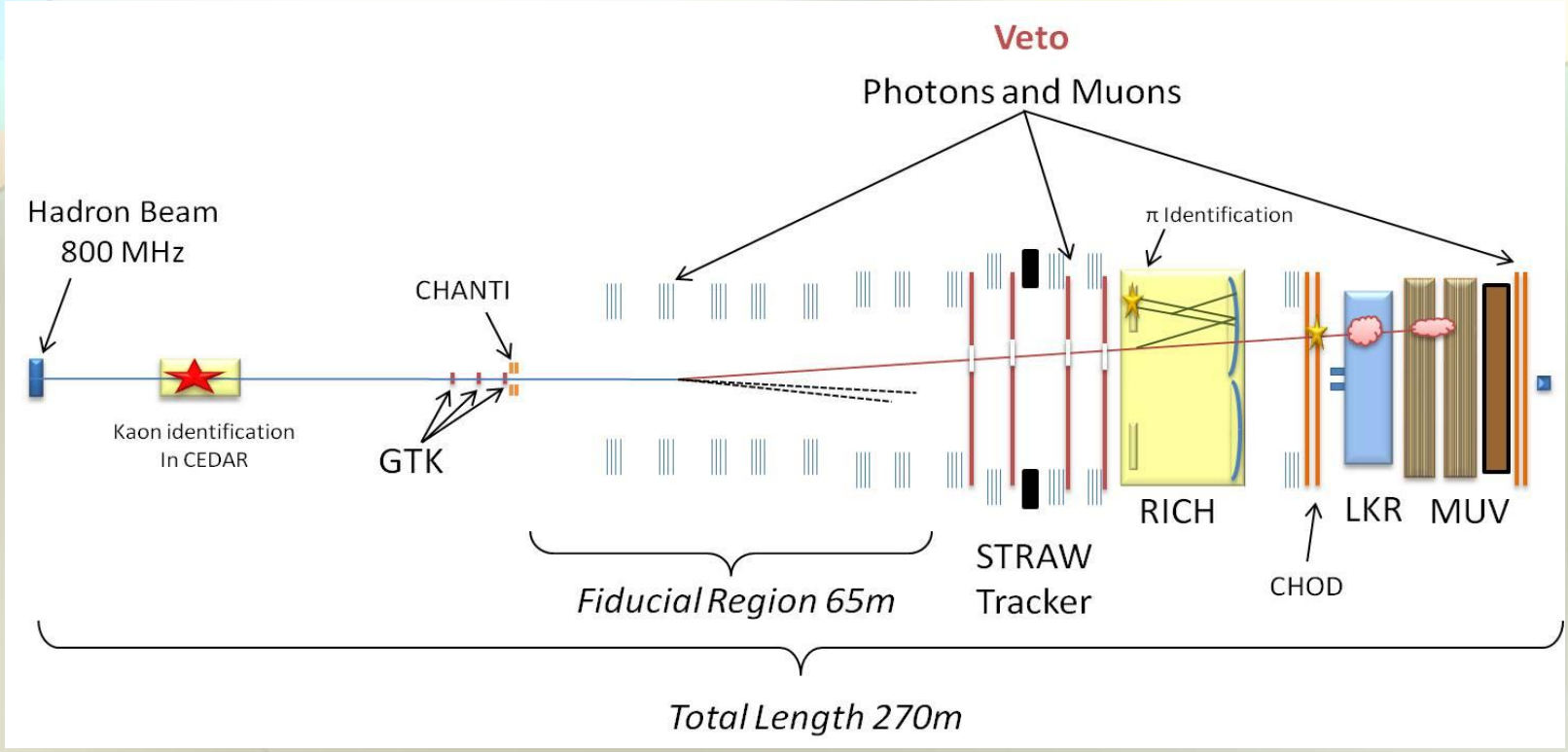
From SPS to NA62:

- ✓ SPS primary beam: 400 GeV/c, ~$5\cdot10^{12}$ppp
- ✓ Secondary hadron beam: 75 GeV/c, ~6% of K^+
- ✓ ~$4.8\cdot10^{12}$ kaon decays per year
- ✓ ~10% signal efficiency
- ✓ ~50 signal events per year



NA62 setup:

- ✓ Decays-in-flight technique
- ✓ Detect K^+ and π^+



NA62 basic principles

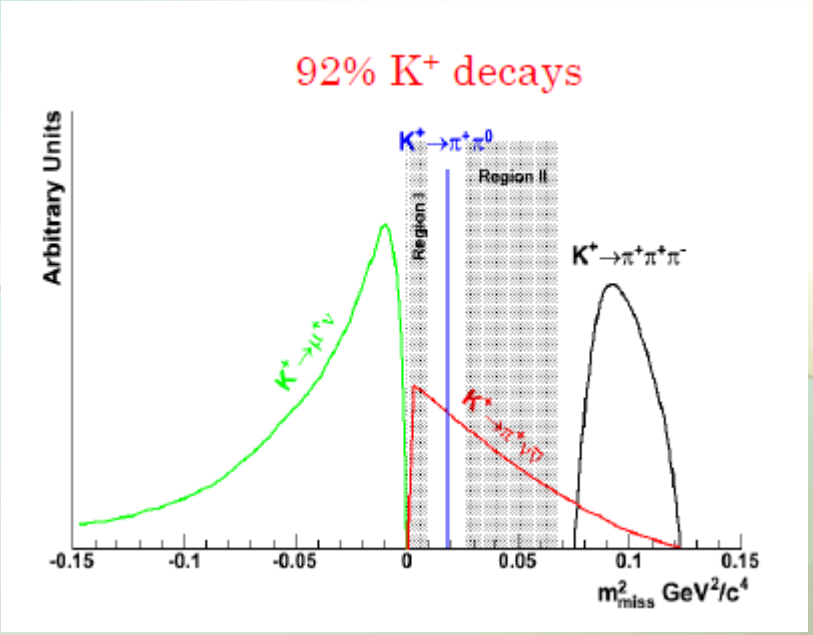
$BR(K^+ \to \pi^+ \nu\nu) \sim 8 \cdot 10^{-11}$

Main backgrounds:

$BR(K^+ \to \mu^+ \nu_\mu) = 0.64$

$BR(K^+ \to \pi^+ \pi^0) = 0.21$

Main variable for the kinematic selection: $M^2_{miss} = (P_K - P_\pi)^2$



NA62 basic principles:

- ✓ High intensity + fast timing
- ✓ Kinematic selection
- ✓ Particle ID
- ✓ Photon rejection

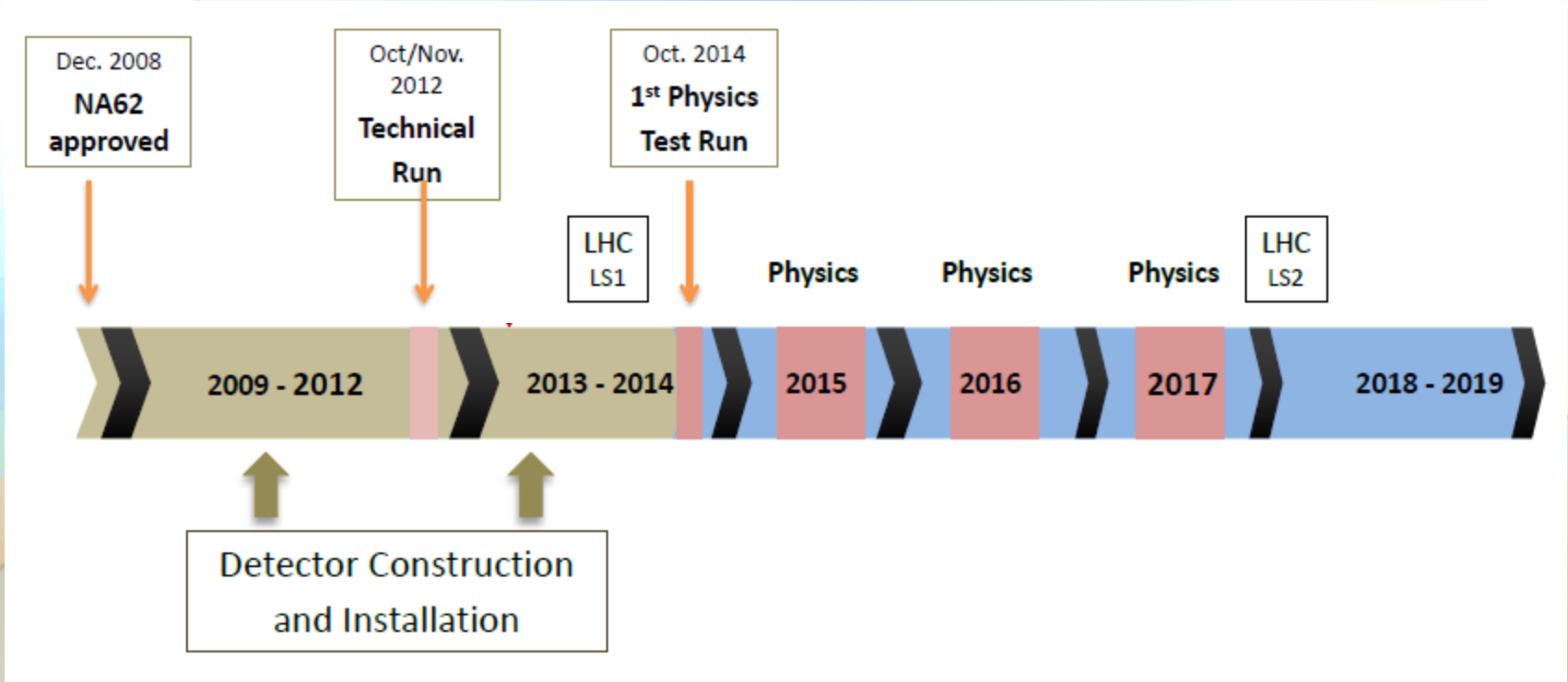
Main Backgrounds Rejection:

	$\pi^+\nu\nu$	$\mu^+\nu$	$\pi^+\pi^0$
BR	8×10^{-11}	63%	21%
m_{miss}	14.4%	8×10^{-6}	1.2×10^{-4}
γ rejection	-	-	3.5×10^{-8}
μ veto	-	10^{-5}	-
RICH	-	5×10^{-3}	-
Total	1.15×10^{-11}	2.5×10^{-13}	8.8×10^{-13}
Ratio	1	2.2%	7.5%

Beyond the baseline:

$\sim 10^5$ $K \to \pi\gamma\gamma$ decays per year

Timeline of the NA62 experiment



- 5 years of construction interleaved with a Technical Run in fall 2012
- In 2014 a first Run with full detector
- Plan 3 years of Physics data taking before LHC Long Shutdown 2 (LS2)

conclusions

- ✓ $K \to \pi\gamma\gamma$ decay has been studied at the NA62 experiment (2007 run), 232 candidates selected (bkg ~17 events)
- ✓ Results for the combined data samples

(NA48/2 and NA62, 381 candidates):

- Model-independent BR measured:

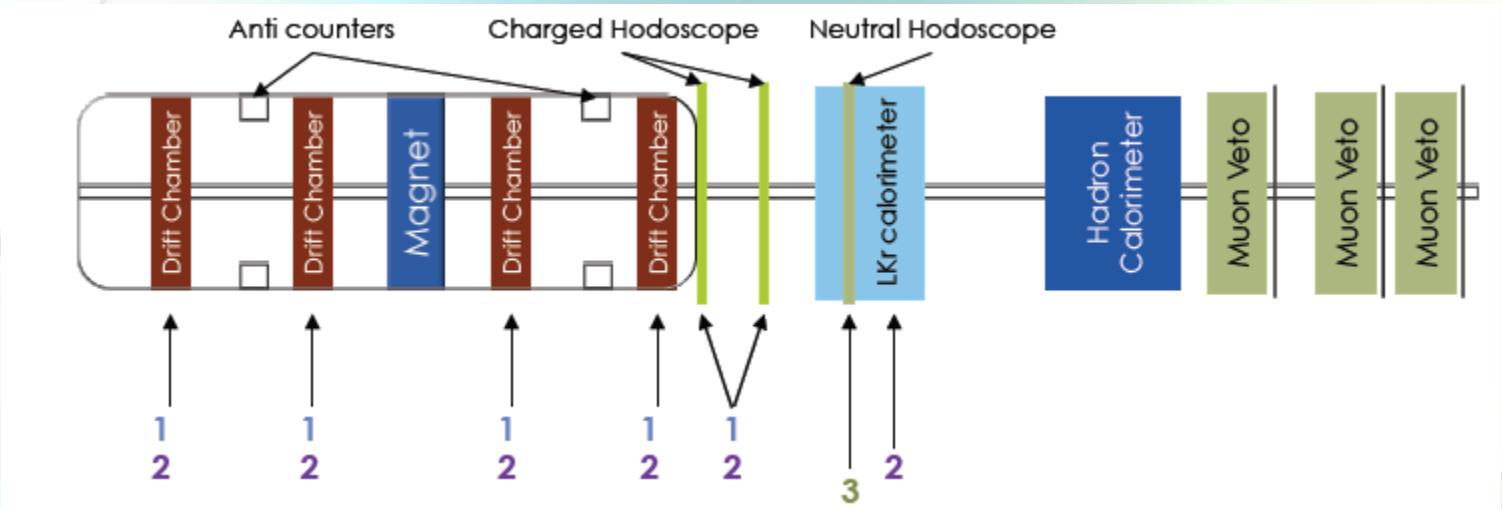
  $BR_{MI} = (0.965 \pm 0.061 \pm 0.014) \times 10^{-6}$
- ChPT fits are performed for the z-spectrum, $\hat{c}$ extracted:

  $\hat{c}_4 = 1.72 \pm 0.20 \pm 0.06$; $\hat{c}_6 = 1.86 \pm 0.23 \pm 0.11$
- Model-dependent BR calculated from $\hat{c}$:

  $BR(O(p^6), \text{full range}) = (1.003 \pm 0.056) \times 10^{-6}$
- NA62 starts main data taking soon (October 2014: first run)

spares

Trigger conditions



1. Time coincidence in the two CHOD planes AND loose condition on Drift Chambers hiti multiplicity (20%)
2. Previous condition AND an energy realease > 10 Gev in the Liquid Kripton Calorimeter (60%)
3. A signal in the Neutral Hodoscope (20%)

The resulting data sample correspond to about 6% of the total beam flux.