Rare kaon measurements with NA62/NA48 minimum bias data

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On behalf of the NA62 collaboration

NA62 experiment
History milestones

- NA48
    - 1990 (proposal) - 2007 (most recent paper)
    - Main goal: $\operatorname{Re}\left(\dfrac{\epsilon'}{\epsilon}\right) \sim \dfrac{1}{6}\left\{1 - \dfrac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)}\Big/\dfrac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}\right\}$
- NA48/1
    - 1999 (proposal) - 2010 (most recent paper)
    - Goals: $\operatorname{BR}(K_S \to \pi^0 e^+ e^-)$, Ξ^0 decays
- NA48/2
    - 2000 (proposal) - ... (several analysis are on going)
    - Goals:
        - search for direct CP violation in $K^\pm \to \pi^\pm\pi^\pm\pi^\mp, K^\pm \to \pi^0\pi^0\pi^\pm$ decays
        - precise study of $K^\pm \to \pi^\pm\pi^\mp l^\pm \nu(\tilde{\nu})$ (Ke4) decays
        - measurements of rare and radiative decays $K^\pm \to \pi^\pm\pi^0\gamma, K^\pm \to \pi^\pm\gamma\gamma, K^\pm \to e^\pm\nu\gamma$
        - precise determination of $K^\pm \to \pi^0 l^\pm \nu$ (Kl3) form factors
- ~~NA48/3~~ NA62
    - 2005 (proposal) - ...
    - Goals:
        - observation of 80 events of the process $K^+ \to \pi^+\nu\bar{\nu}$
        - testing lepton universality with Ke2/Kmu2 decays
        - ....

NA62/NA48 experiment
Location

Jura mountains

NA48/2: primary beam: 400 GeV protons, $\sim 10^{12}$ per 4.8s, secondary: 60 GeV K^+/K^- (simultaneous)
NA62: primary beam: 400 GeV protons, $\sim 10^{12}$ per 4.8s, secondary: 74 GeV K^+/K^- (simultaneous/not simultaneous)
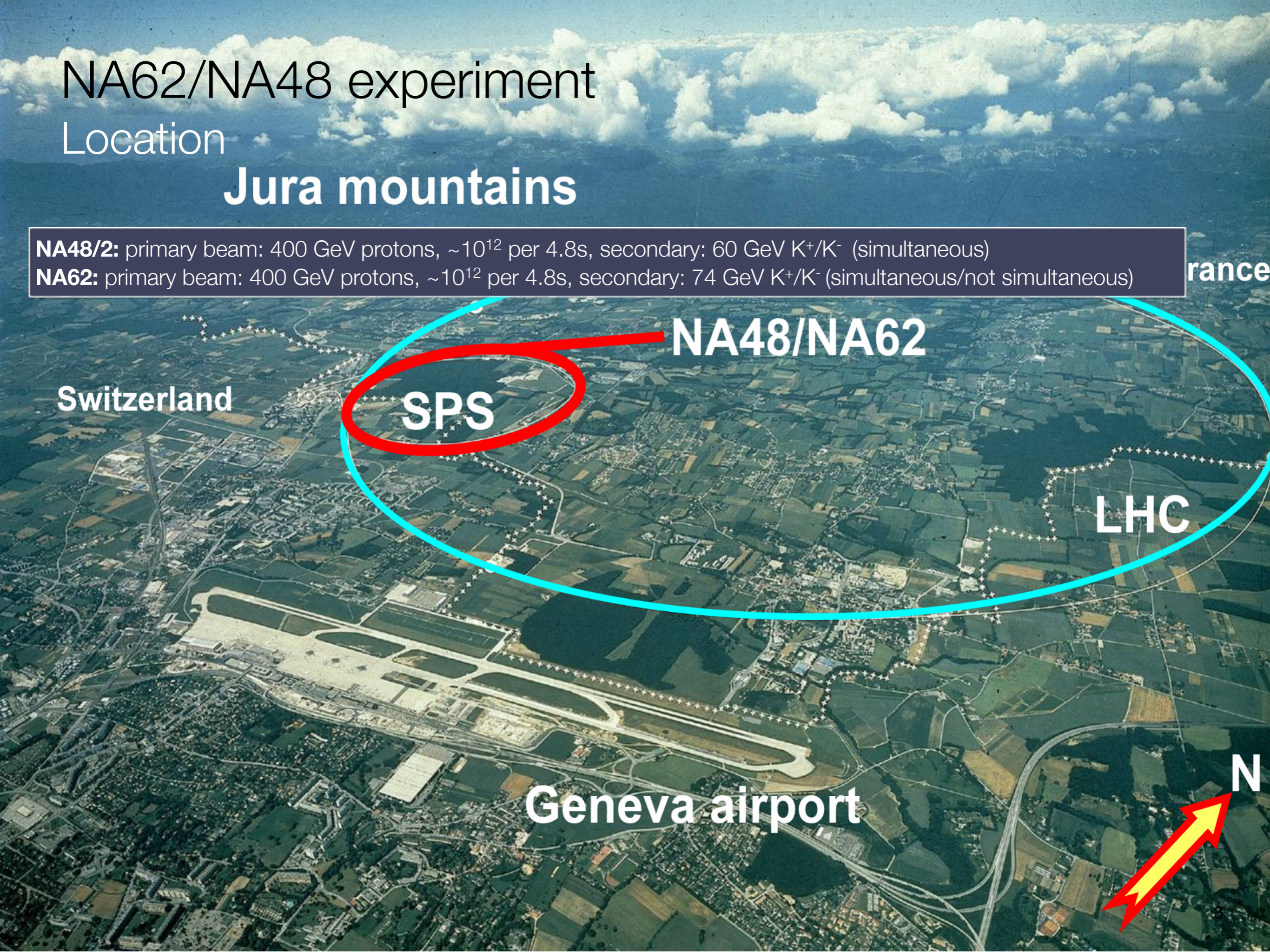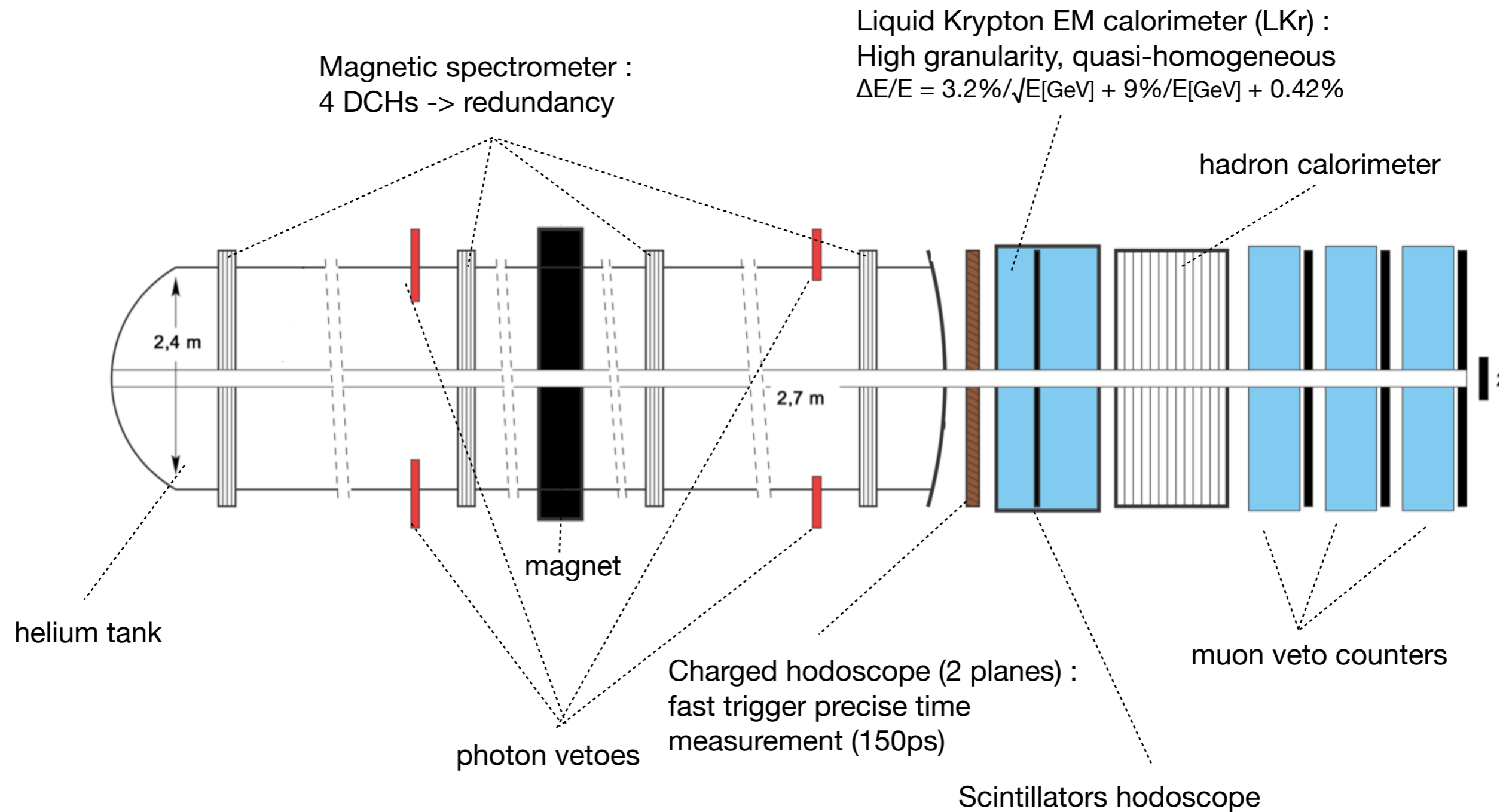
France

NA48/NA62

SPS

Switzerland

LHC

N

Geneva airport

NA62/NA48 experiment
NA48/2 setup

Magnetic spectrometer :
4 DCHs -> redundancy

Liquid Krypton EM calorimeter (LKr) :
High granularity, quasi-homogeneous
$\Delta E/E = 3.2\%/\sqrt{E[GeV]} + 9\%/E[GeV] + 0.42\%$

hadron calorimeter

2,4 m

2,7 m

magnet

helium tank

photon vetoes

Charged hodoscope (2 planes) :
fast trigger precise time
measurement (150ps)

muon veto counters

Scintillators hodoscope

NA62/NA48 experiment
Beam time

2003/04 - K$^{\pm}$ high intensity runs

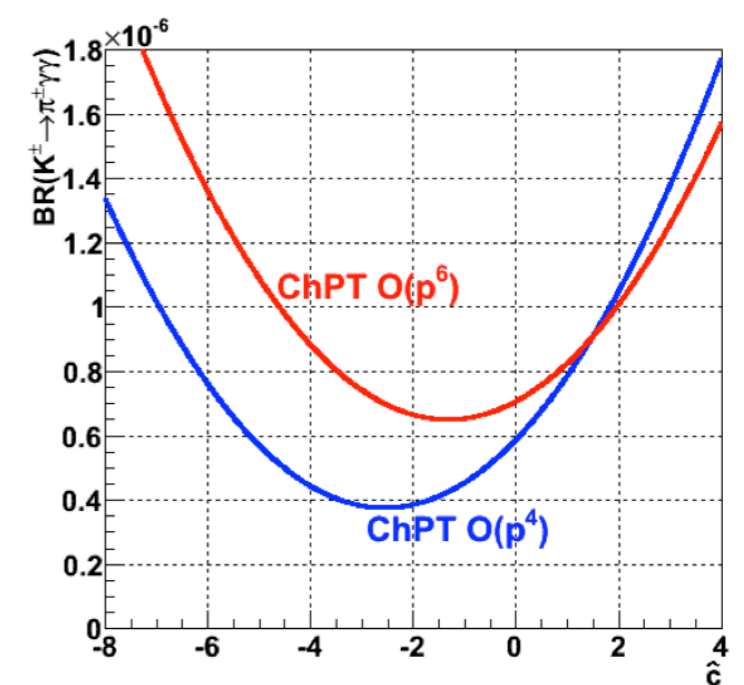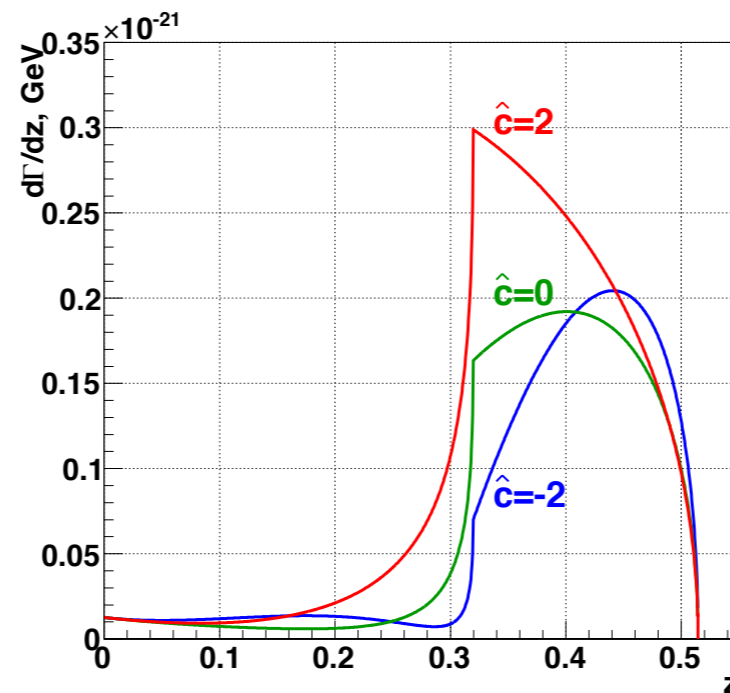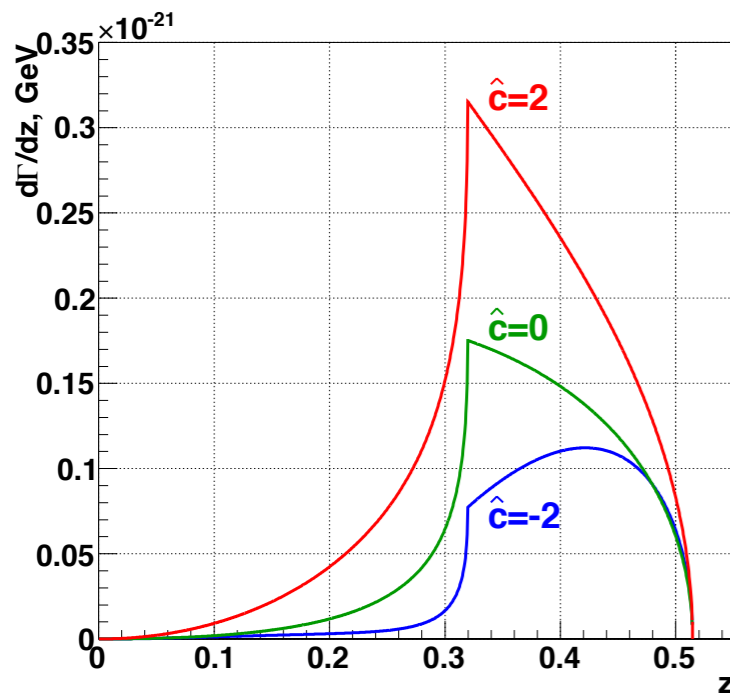2007/08 - $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ runs

2007-2012 - R&D

2012 - Integration of the available sub-detectors

~2014 - Physics runs after the end of LHC long shutdown

The K$^\pm\rightarrow\pi^\pm\gamma\gamma$ process
Motivation

Rate and spectrum ($z=(m_{\gamma\gamma}/m_K)^2$) depend on single unknown parameter $\hat{c}$

$O(p^4)$ Loop diagrams
(Ecker, Pich, de Rafael, NPB303 (1988) 665))
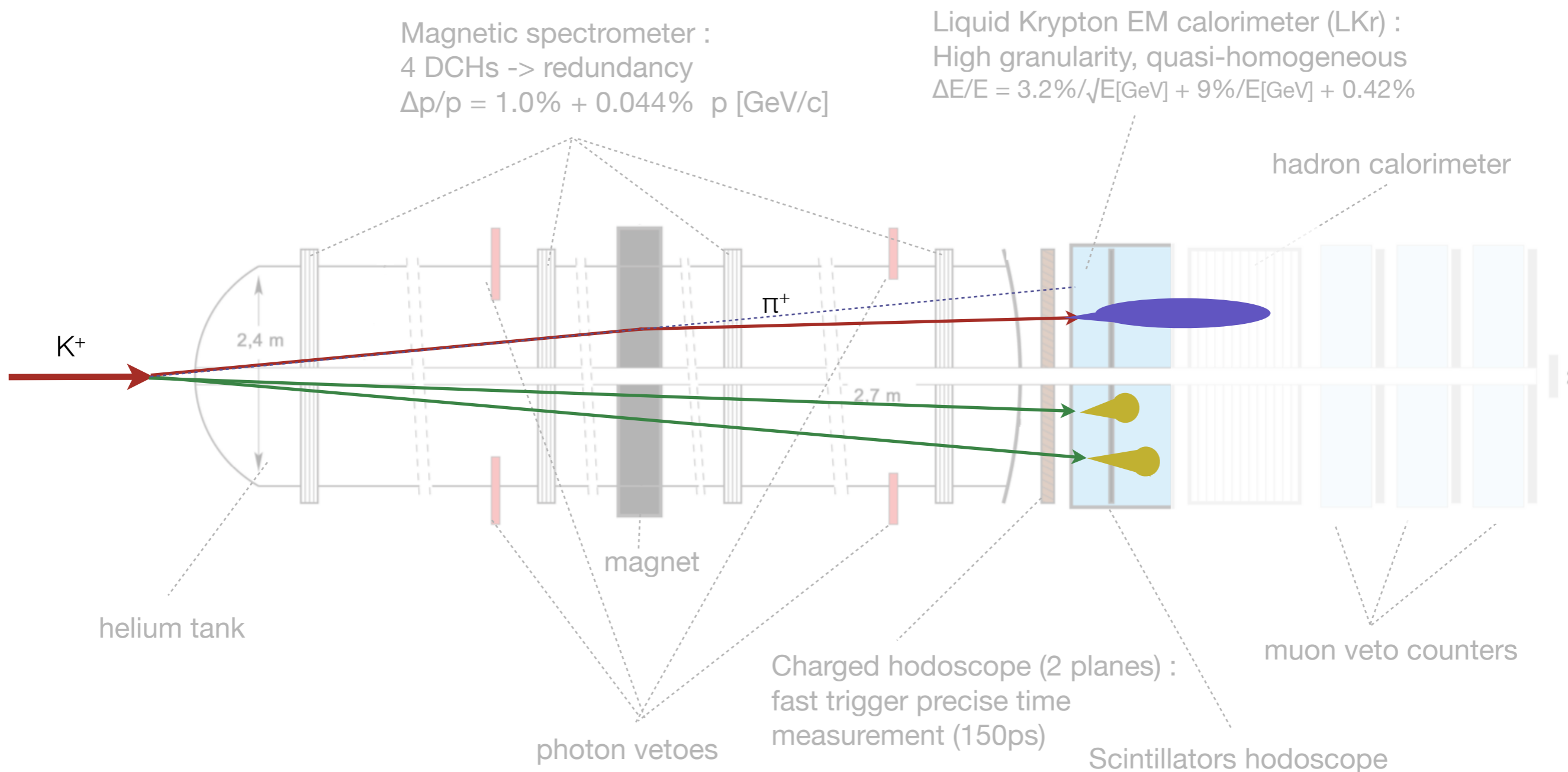
$O(p^6)$ Unitarity corrections
(D'Ambrosio, Portoles,
PLB386(1996)403))

Distributions of z related to different $\hat{c}$ values

BR(K$^\pm\rightarrow\pi^\pm\gamma\gamma$) vs $\hat{c}$

The K$^\pm \rightarrow \pi^\pm \gamma\gamma$ process
Detection principle

Magnetic spectrometer :
4 DCHs -> redundancy
$\Delta p/p = 1.0\% + 0.044\%$ p [GeV/c]

Liquid Krypton EM calorimeter (LKr) :
High granularity, quasi-homogeneous
$\Delta E/E = 3.2\%/\sqrt{E_{[GeV]}} + 9\%/E_{[GeV]} + 0.42\%$

hadron calorimeter

K$^+$

π^+

2,4 m

2,7 m

magnet

helium tank

muon veto counters

Charged hodoscope (2 planes) :
fast trigger precise time
measurement (150ps)

photon vetoes

Scintillators hodoscope

$\pi^\pm$ track position, direction $\Rightarrow$ Z$_{vertex}$

The $K^\pm \to \pi^\pm \gamma\gamma$ process
Background sources

Decay mode	Potentiality of misidentification
$K^\pm \to \pi^\pm \pi^0$	Mass misreconstruction
$K^\pm \to \pi^\pm \pi^0 \pi^0$	Losing additional γ('s) in veto (incl. LKr)
$K^\pm \to \pi^\pm \pi^0 \gamma$ (IB)	
$K^\pm \to \pi^\pm \pi^0 \gamma$ (DE)	
$K^\pm \to \pi^\pm \pi^0 \gamma$ (INT)	

contribution significantly depends on concrete kinematics and BR of channel

The K$^\pm \to \pi^\pm \gamma\gamma$ process
Experimental status

1997 - BNL E787, first observation
 Br(K$^\pm \to \pi^\pm \gamma\gamma$, 100 MeV/c < $p_{\pi^+}^{CM}$ < 180 MeV/c)= (6.0±1.5$_{stat}$ ±0.7$_{sys}$)×10^{-7}
 Candidates: 31, background: (5.1±3.3)

 Fit results: ĉ= 1.6±0.6; BR = (1.10±0.32)×10^{-6}

[P. Kitching et al. Observation of the decay K$^\pm \to \pi^\pm \gamma\gamma$. Phys. Rev. Lett., 79:4079, 1997.]

2005 - Search for the decay K+ → π+γγ in the π+ momentum region P > 213MeV/c
 Br(K$^\pm \to \pi^\pm \gamma\gamma$, P>213 MeV/c) < 8.3 x 10^{-9} (under the assumption of chiral perturbation
 theory including next-to-leading order "unitarity" corrections)
 Candidates: 0

[Phys. Lett. B 623, 192 (2005), arXiv:hep-ex/0505069, BNL-73917-2005-JA]

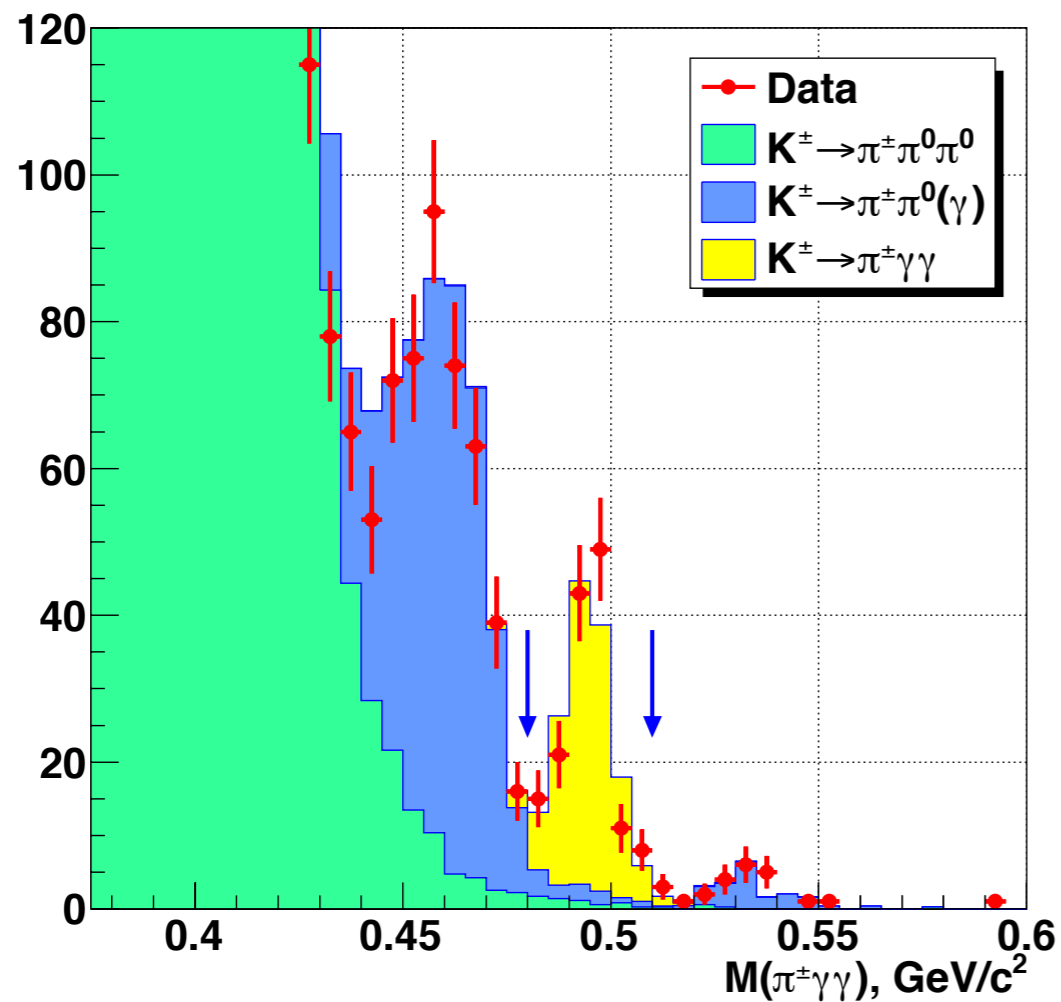# The $K^\pm \to \pi^\pm \gamma\gamma$ process
Statistics

- Minimum bias trigger samples, ~52h of data taking in 2004

- Downscaled (control) triggers, 120d of data taking in 2007

- Different acceptances, different beam momentum
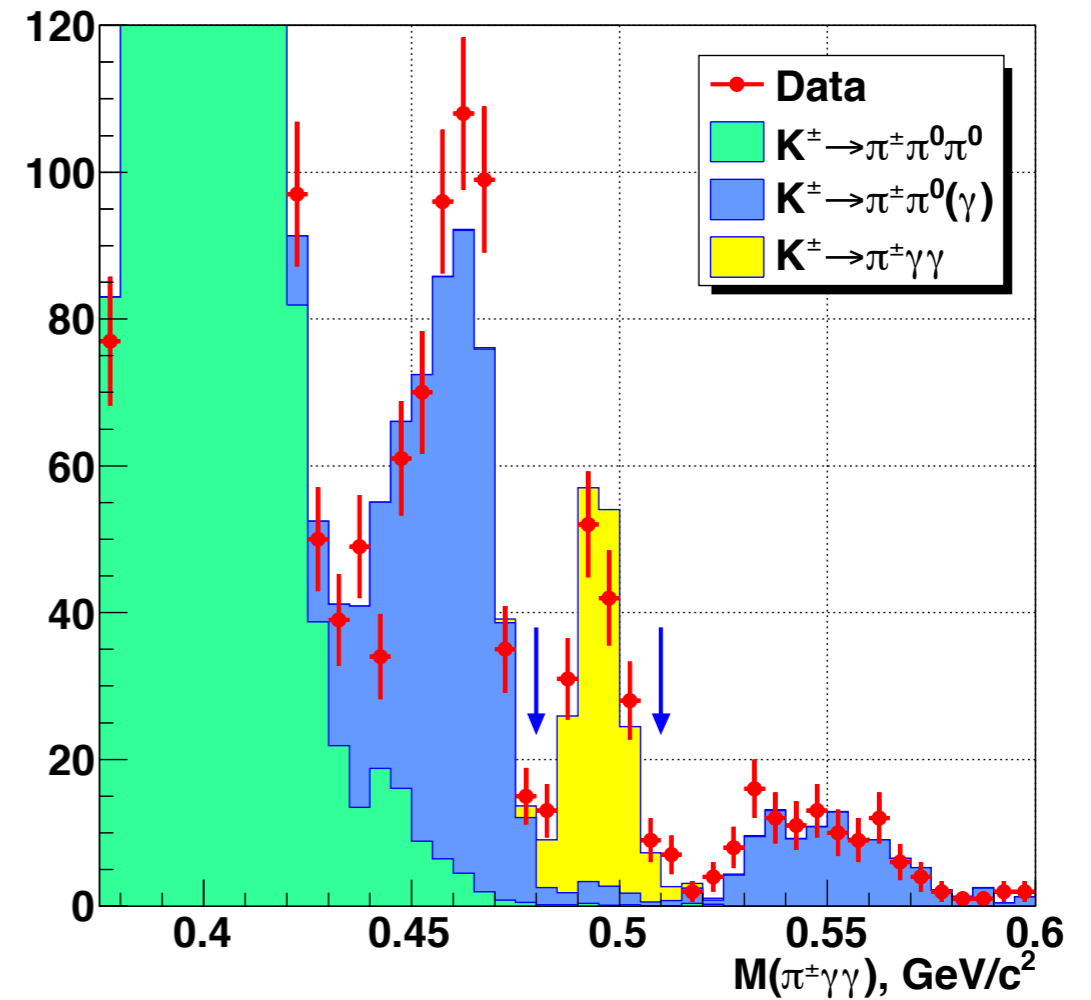
- Separate analysis

- Combine results

The K$^{\pm}{\to}\pi^{\pm}\gamma\gamma$ process
Results. Signal plots

2004 data

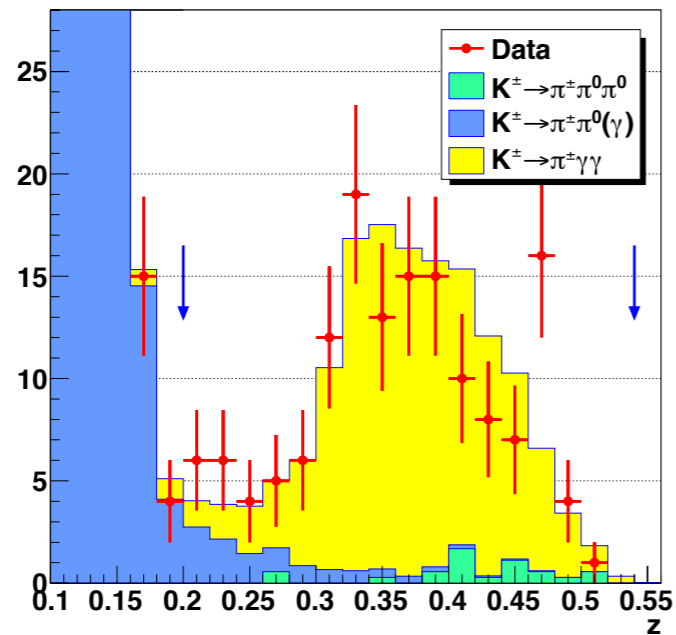### 2007 data

K$^{\pm}{\to}\pi^{\pm}\gamma\gamma$ candidates:	147
K$^{\pm}{\to}\pi^{\pm}\pi^0(\gamma)$ contribution:	11.0 ± 0.8
K$^{\pm}{\to}\pi^{\pm}\pi^0\pi^0$ contribution:	5.9 ± 0.7
K$^{\pm}{\to}\pi^{\pm}\gamma\gamma$ signal:	**130 ± 12**

K$^{\pm}{\to}\pi^{\pm}\gamma\gamma$ candidates:	175
K$^{\pm}{\to}\pi^{\pm}\pi^0(\gamma)$ contribution:	11.1 ± 1.8
K$^{\pm}{\to}\pi^{\pm}\pi^0\pi^0$ contribution:	1.3 ± 0.3
K$^{\pm}{\to}\pi^{\pm}\gamma\gamma$ signal:	**163 ± 13**

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The K$^\pm \to \pi^\pm \gamma\gamma$ process
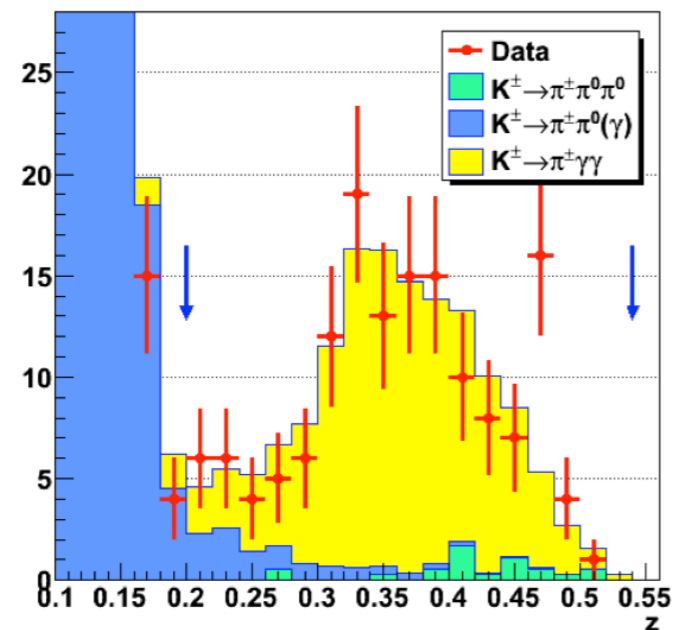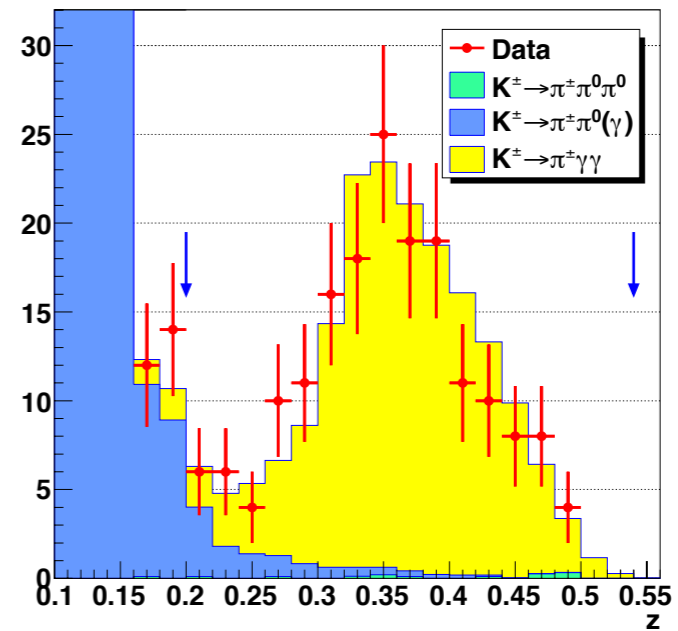## Results. ChPT fits
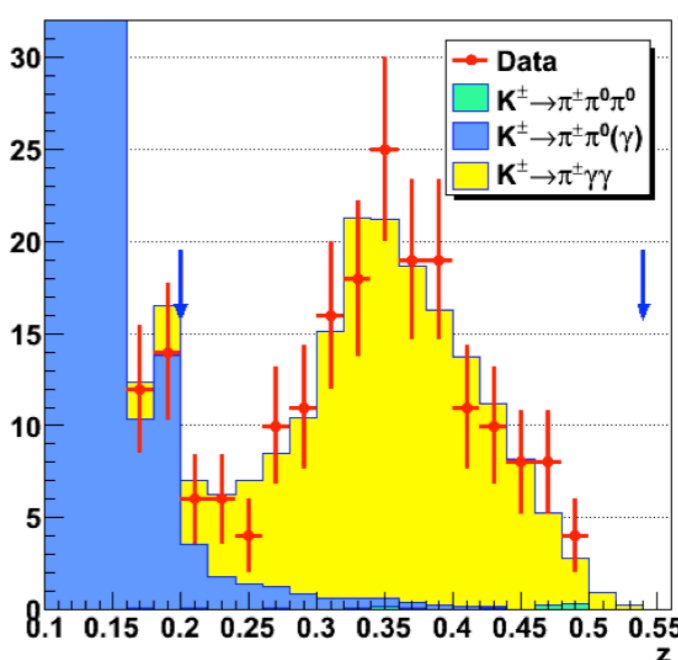
2004's data   ChPT O(p6)   2007's data

ChPT O(p4)

$z = (m_{\gamma\gamma}/m_K)^2$

The $K^\pm \rightarrow \pi^\pm \gamma\gamma$ process
Combined Results

	NA48/2 (2004)	NA62 (2007)	Combined
$\hat{c}$, O(p6)	$1.67\pm0.39_{stat}\pm0.09_{syst}$ = 1.67 ± 0.40	$2.21\pm0.31_{stat}\pm0.08_{syst}$ = 2.21 ± 0.32	**$2.00\pm0.24_{stat}\pm0.09_{syst}$ = 2.00 ± 0.26**
$\hat{c}$, O(p4)	$1.36\pm0.33_{stat}\pm0.07_{syst}$ = 1.36 ± 0.34	$1.71\pm0.29_{stat}\pm0.06_{syst}$ = 1.71 ± 0.30	**$1.56\pm0.22_{stat}\pm0.07_{syst}$ = 1.56 ± 0.23**

ChPT **O(p6) combined BR fit (full kinematic region): BR($K^\pm \rightarrow \pi^\pm \gamma\gamma$) = (1.01 $\pm$ 0.06)$\times 10^{-6}$**

preliminary

The K$^{\pm} \to \pi^{\pm} \gamma\gamma$ process
Future
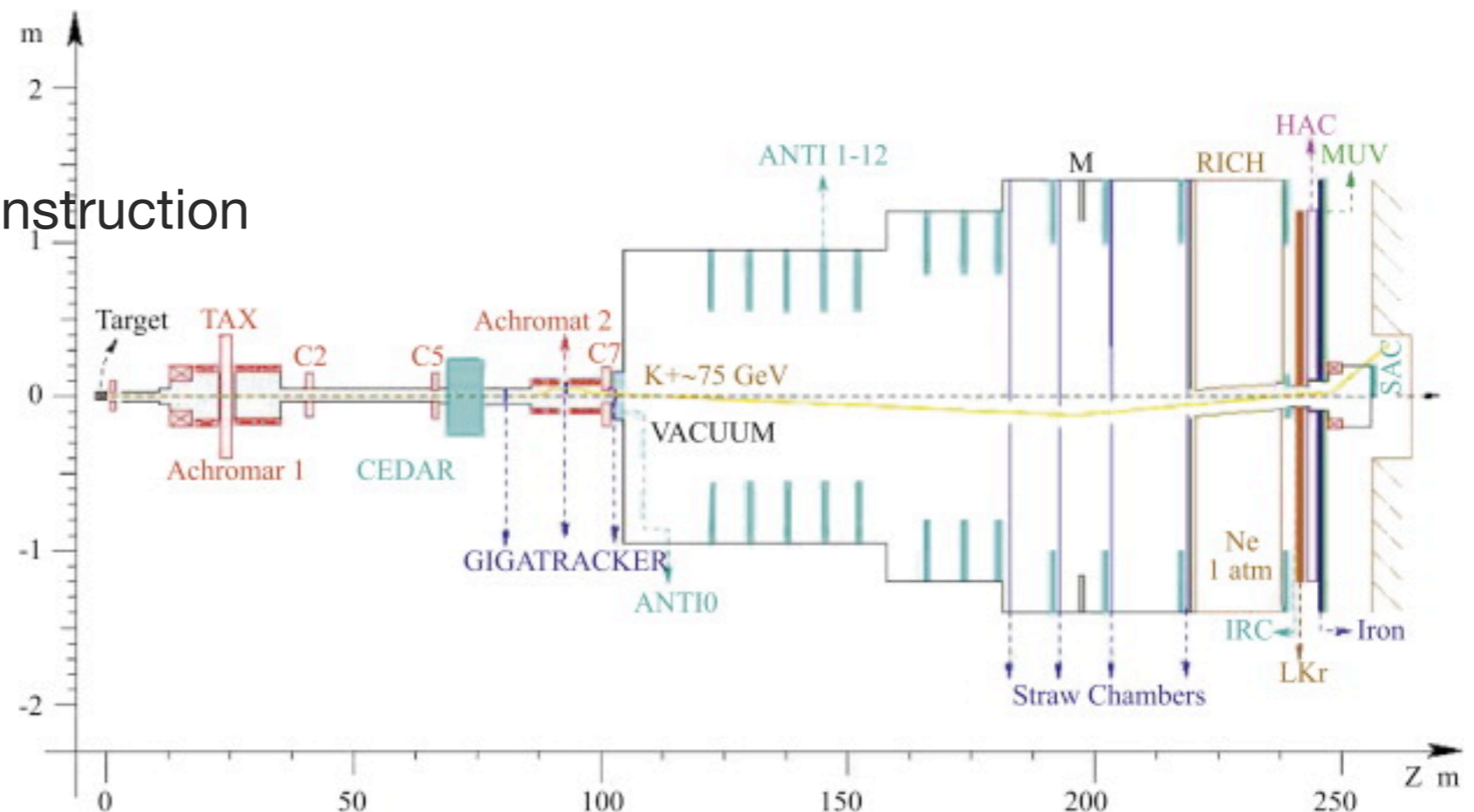
- Beam

  - Special data collection is foreseen. Target is to collect at least one order more K$^+ \to \pi^+ \gamma\gamma$ decays than has been ever achieved

- Setup

  - A new setup is under construction

- Analysis procedure

  - New approaches could be implemented

Summary on the $K^{\pm} \to \pi^{\pm} \gamma \gamma$ process

- Sample of $K^{+} \to \pi^{+} \gamma \gamma$ events recorded with a minimum bias trigger has been analyzed

- A set of 130±12 (for NA48/2) and 163±13 (for NA62) signal events of $K^{\pm} \to \pi^{\pm} \gamma \gamma$ decay was reconstructed (preliminary)

- The new value of model dependent ChPT O(p6) combined BR fit:

$$BR(K^{\pm} \to \pi^{\pm} \gamma \gamma) = (1.01 \pm 0.06) \times 10^{-6} \text{ was achieved}$$

- Improvement of precision of the $K^{+} \to \pi^{+} \gamma \gamma$ process could be achieved in the next few years

The K⁺→e⁺νγ process
Motivation

- SD (Structure Dependent term) of the decay matrix element is sensitive to observables of the K⁺→e⁺νγ process and gives dominant contribution to the decay rate

- Set of predictions for form-factors are given (ChPT O(4), ChPT O(6), LFQM)

- Differential decay rate in term of vector and axial form factors V (x) and A(x):

$$\frac{d^2\Gamma(K^+ \to e^+\nu\gamma, SD^+)}{dxdy} = \frac{G_F^2\ |V_{us}|^2\ M_K^5\ \alpha}{64\ \pi^2} (V(x) + A(x))^2\ (1-x)(x+y-1)^2$$
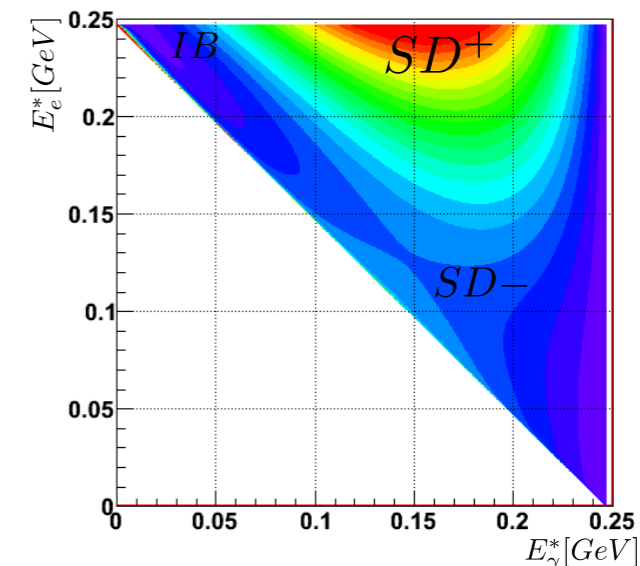
$$x = \frac{2E_\gamma^{cm}}{M_K}, y = \frac{2E_e^{cm}}{M_K}$$

From PDG(2012): BR = (9.4 ± 0.4) x 10⁻⁶
[KLOE, EPJ C64 (2009) 627, 1484 ± 63 events, 10 < E*γ < 250 MeV, pe* > 200 MeV/c]
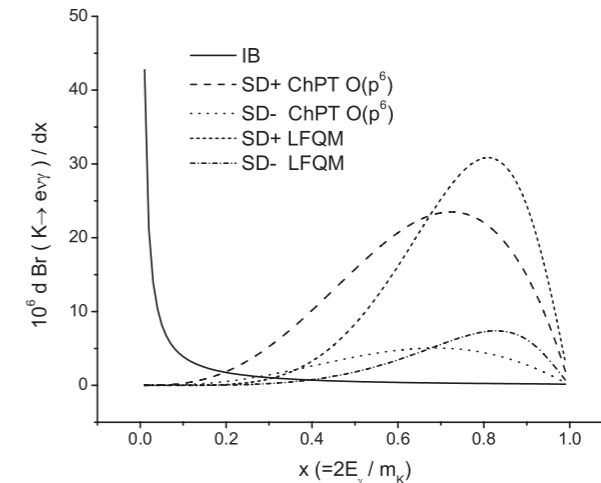
CHUAN-HUNG CHEN, CHAO-QIANG GENG, AND CHONG-CHUNG LIH, PHYSICAL REVIEW D **77,** 014004 (2008)

SD⁺ is the main contribution
x > 0.2 to reduce the IB background
y > 0.95 dictated by the main background coming from Ke3

The $K^+ \to e^+\nu\gamma$ process
Preliminary results

- ~10000 events was selected, K^- samples will be included into analysis
- normalization was performed with $K^+ \to \pi^0 e^+\nu$ decay mode
- acceptance ~7%, background 5%
- systematic uncertainties dominated by background subtraction
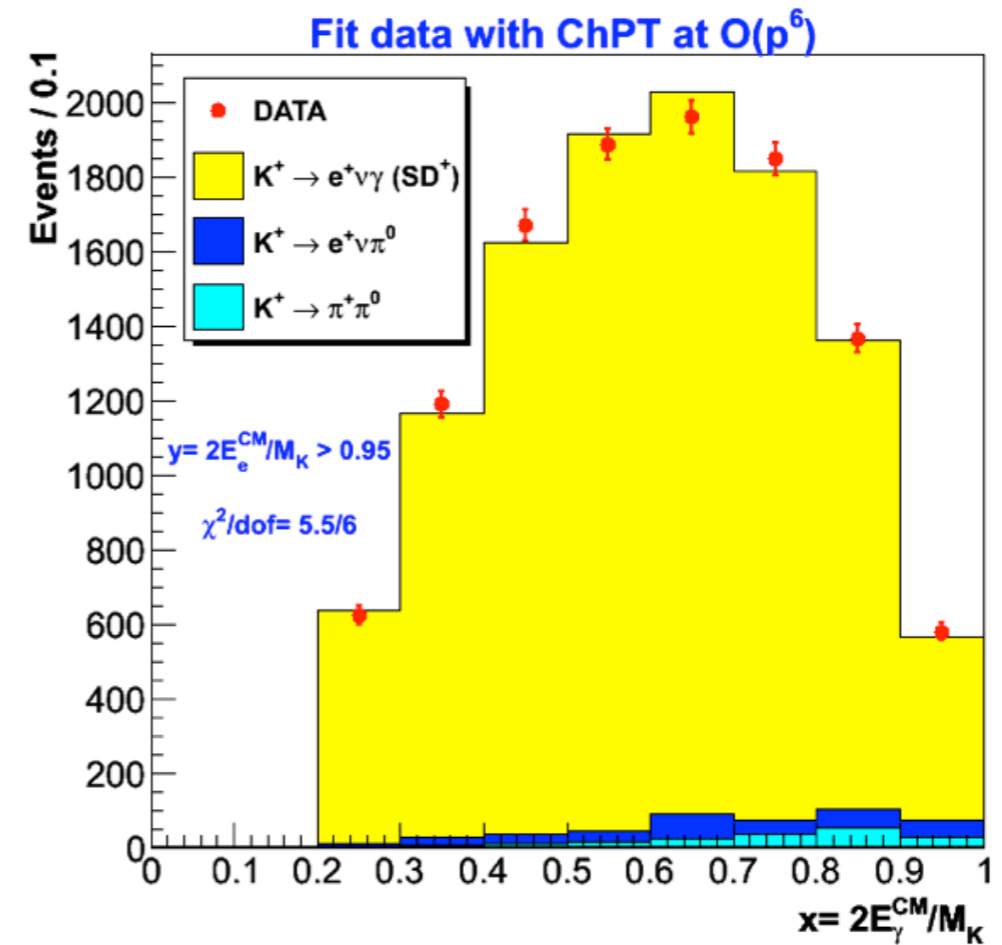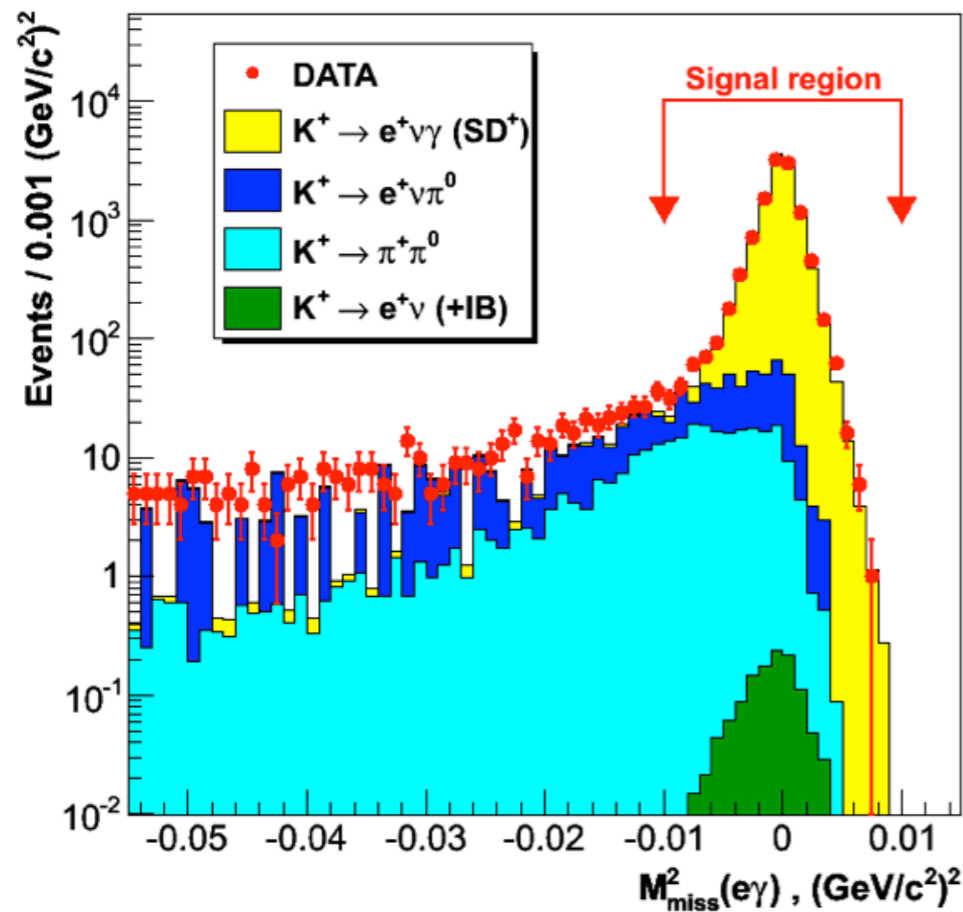
aim is to achieve 10 time more statistics than predecessor (KLOE)

Conclusion

Analysis is going on, in short term new results for the $K^+ \to e^+ \nu \gamma$ and $K^\pm \to \pi^\pm \gamma \gamma$ processes are expected

The collaboration is preparing the new setup and measurement of the $K^+ \to \pi^+ \gamma \gamma$ process could be possible in the next few years

Backup slides
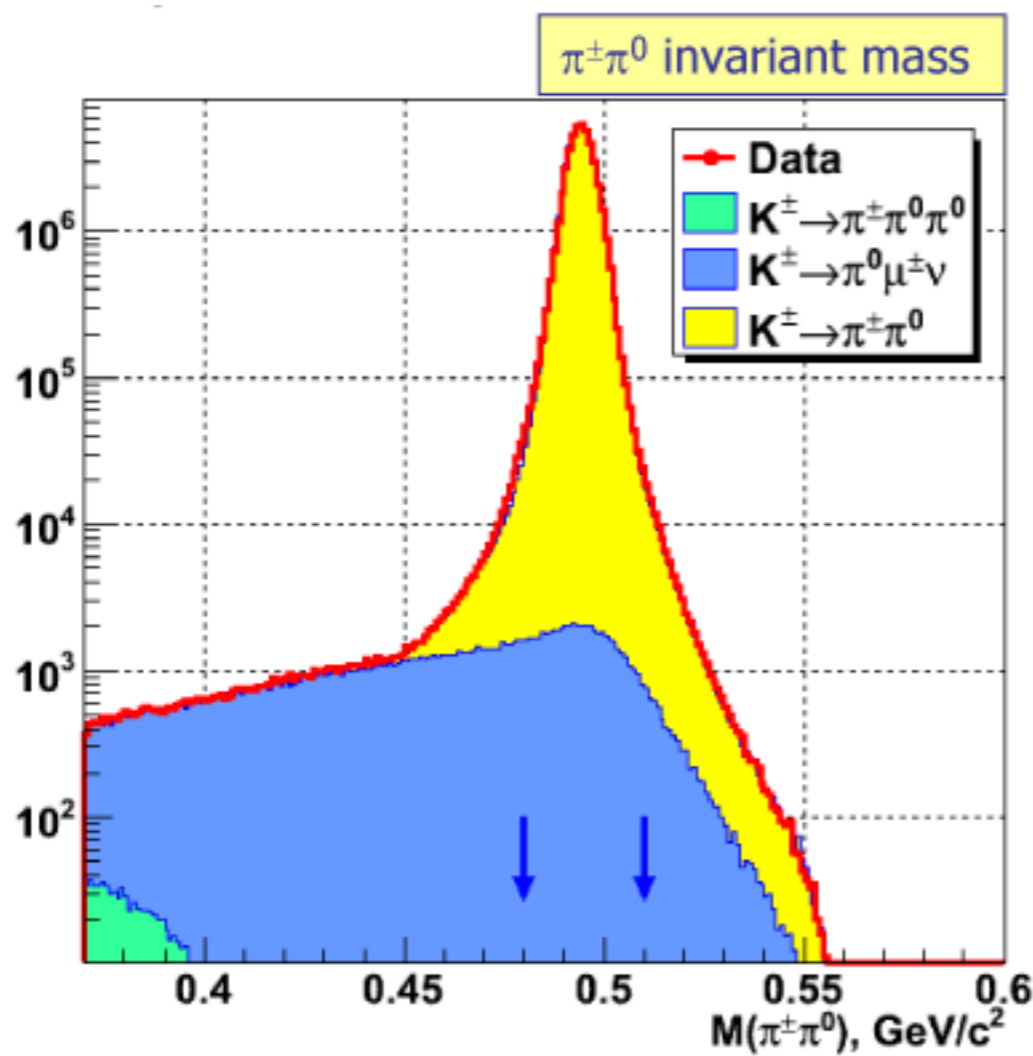
Data samples

Downscaling factors of the control triggers in 2007

Trigger	P1	P2,3	P4	P5,6
K_{e2} main: $Q_1*E_{LKR}(*1TRK)*L3\_autopass/D$	50	50	50	50
$K_{\mu2}$ main: $Q_1(*1TRK)/D$	50	50	150	150
Q_1/D	–	5000	5000	600
Q_1*E_{LKR}	225[*)]	–	–	100
NHOD	25[*)]	50	50	150
Overall downscaling	**11.399**	**17.539**	**22.782**	**22.979**
K decay flux $\times 10^9$ (−18m<z<80m)	2.28	6.25	4.51	10.14

Normalization

$\pi^\pm\pi^0$ invariant mass

Data
$K^\pm \to \pi^\pm\pi^0\pi^0$
$K^\pm \to \pi^0\mu^\pm\nu$
$K^\pm \to \pi^\pm\pi^0$

$M(\pi^\pm\pi^0)$, GeV/c^2

Mass resolution: $\sigma_{2\pi} = 3.3$ MeV/c^2.

The signal region (480; 510) MeV/c^2 corresponds to ~4.5σ.

$K_{2\pi\gamma}$ (IB) process fully included in MC simulation.

$K_{2\pi}$ candidates: 44.327M
$K_{\mu3}$ background: 50.4K (0.11%)

Acceptance: 16.85%
K decay flux: 1.287×10^9

Fitting

The expected number of reconstructed signal events in bin:

$$\lambda_j^{signal}(\hat{c}) = (\Phi_K/(\hbar/\tau_K)) \sum_i \mathcal{I}_i A_{ij} ,$$

$\mathcal{I}_i = \int\int d\Gamma(\hat{c},z)dydz$ over the i-th bin.

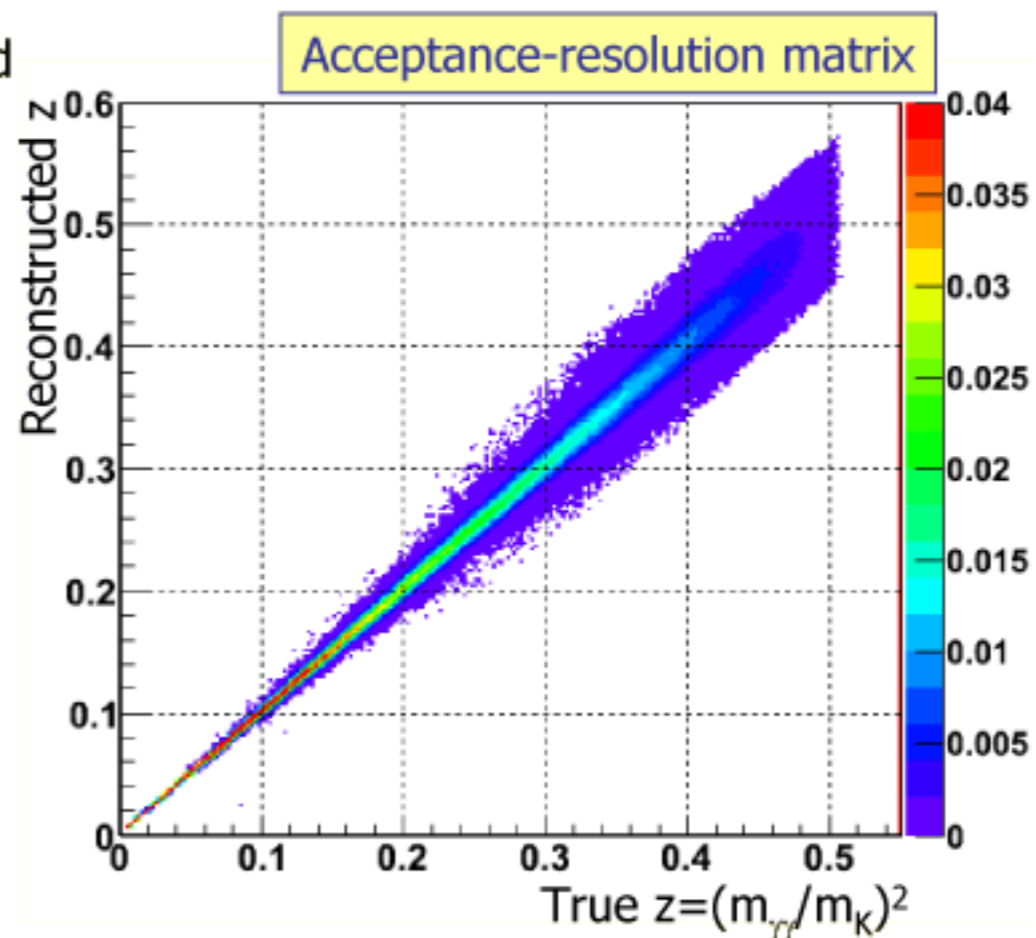The resulting $\lambda_j^{signal}(\hat{c})$ are then re-binned to standard $\Delta z=0.02$ bins.

Maximize the log-likelihood:
$$\ln\mathcal{L} = \sum_{z\ bins} (k_j \ln\lambda_j - \lambda_j - \ln(k_j!))$$

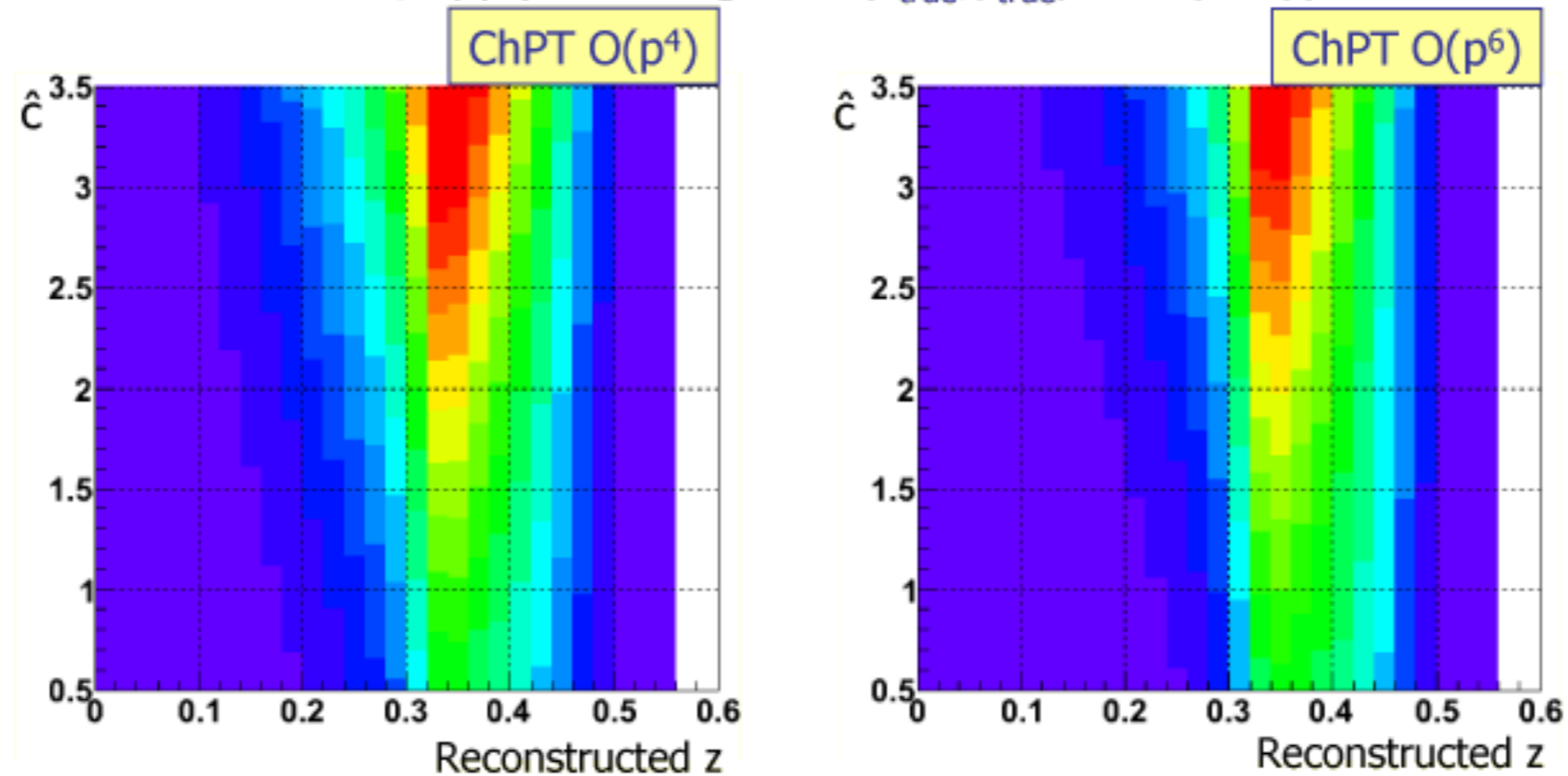$\lambda_j(\hat{c}) = \lambda_j^{signal}(\hat{c}) + \lambda^{bkg}$: expected number of events in bin j;

k_j: observed number of events in bin j.

Acceptance-resolution matrix
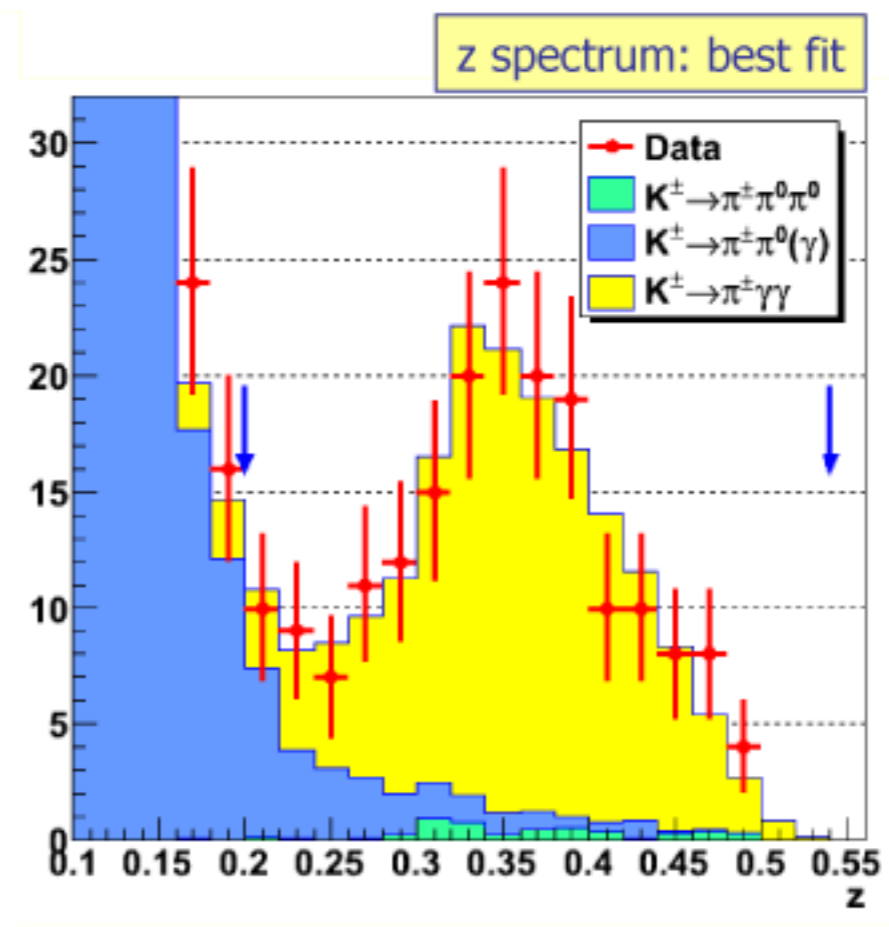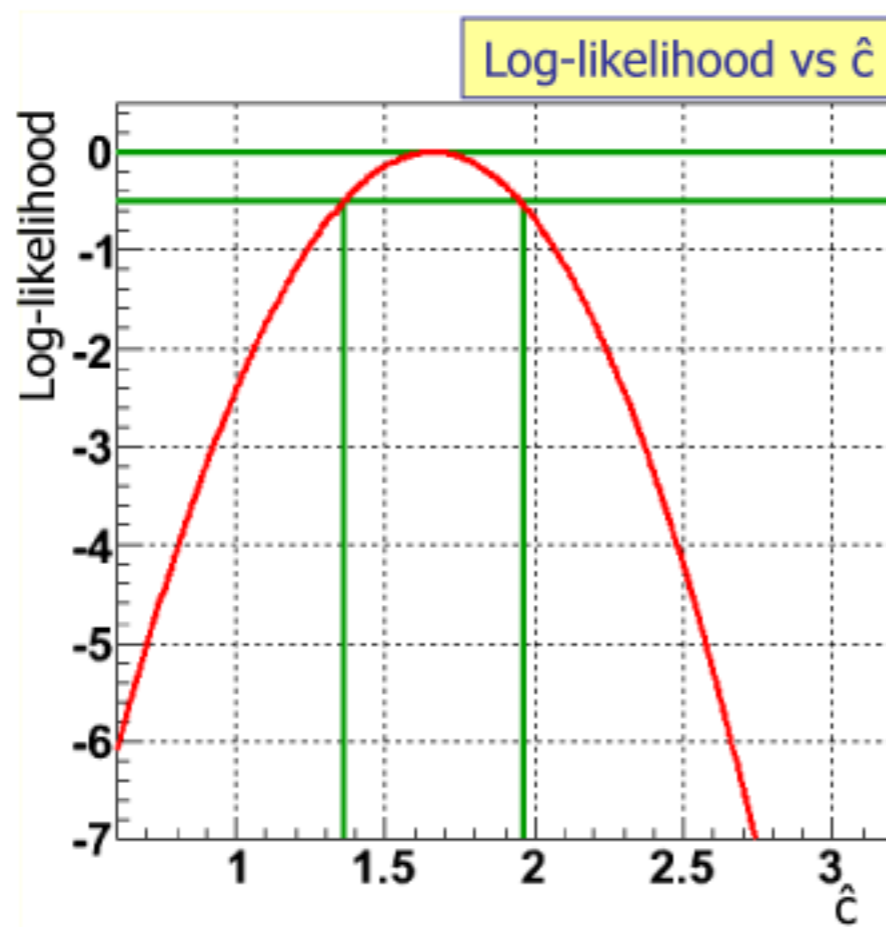

Reconstructed z vs True $z=(m_{\gamma\gamma}/m_K)^2$

Fitting

Run over a MC sample with a uniform phase space distribution.
For a set of $\hat{c}$ values, apply the weights $w(z_{true}, y_{true}) = d\Gamma/(dzdy)$ to the events.

ChPT O(p^4)

ChPT O(p^6)

For each $\hat{c}$, the expected reconstructed z spectrum is extracted from the histograms above, scaled by $\mathcal{I}_{PS}\Phi_K / (\hbar/\tau_K) / N_{gen}$, where $\mathcal{I}_{PS} = \int\int dydz = 0.147429$ is the phase space integral.

Log-likelihood is then maximized as in the previous method.

Fitting

Fitting