Measurements of Kaon Decays

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JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRiSMA Cluster of Excellence

Kaon Physics

Kaons have long time driven advances in physics:

- Discovery of CP violation in $K_L \to \pi^+\pi^-$.
- Suppression of $K_L \to \mu^+\mu^-$ leading to the GIM mechanism.
- Search for new physics in forbidden decays (e.g. $K^+ \to \pi^- e^+ e^+$).

Since 1990's heavy flavours (*B*, *D* mesons) mostly took over...

- Precise determination of CKM matrix elements.
- Measurements of CP violation.

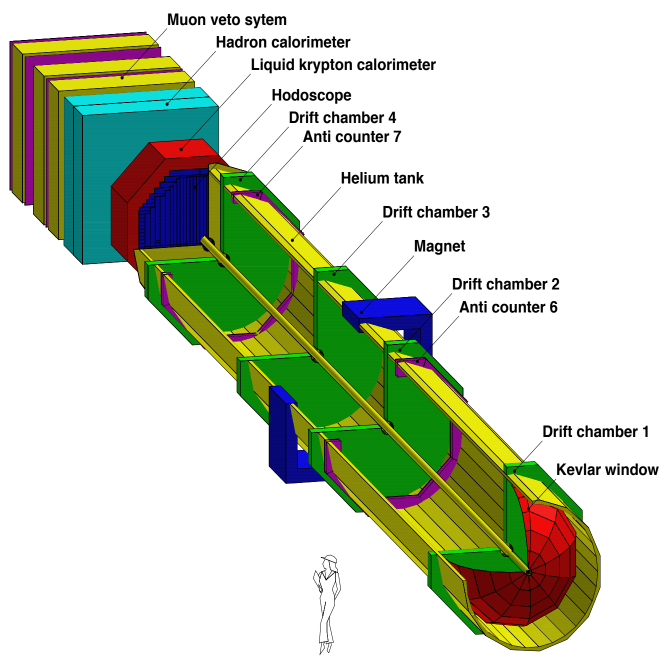
...but in the new century: ***the return of the Kaons***

- First discovery of direct CP violation.
- Precision determination of $|V_{us}|$.
- Precision measurements of Chiral Perturbation Theory.
- Measurement of **rare, very rare, and ultra-rare decays.**

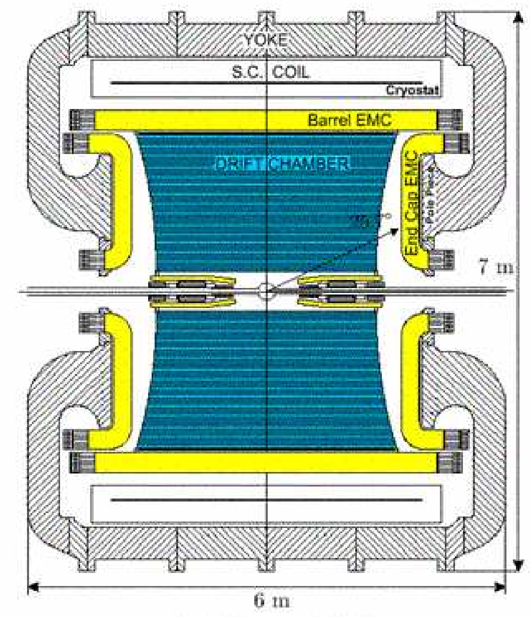
Kaon Experiments

Running from ~1997 - ~2007, all finished by now.

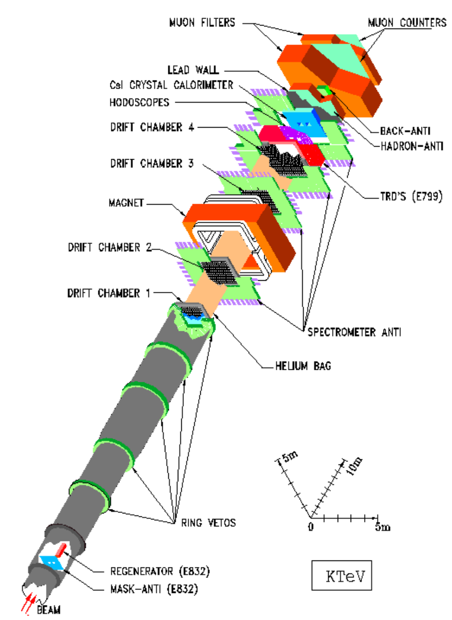
NA48



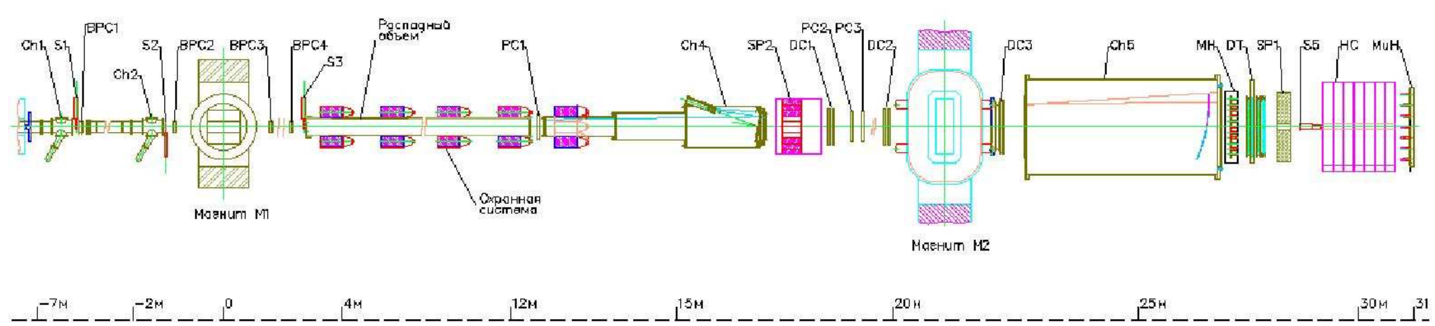
KLOE



KTeV



ISTRA+



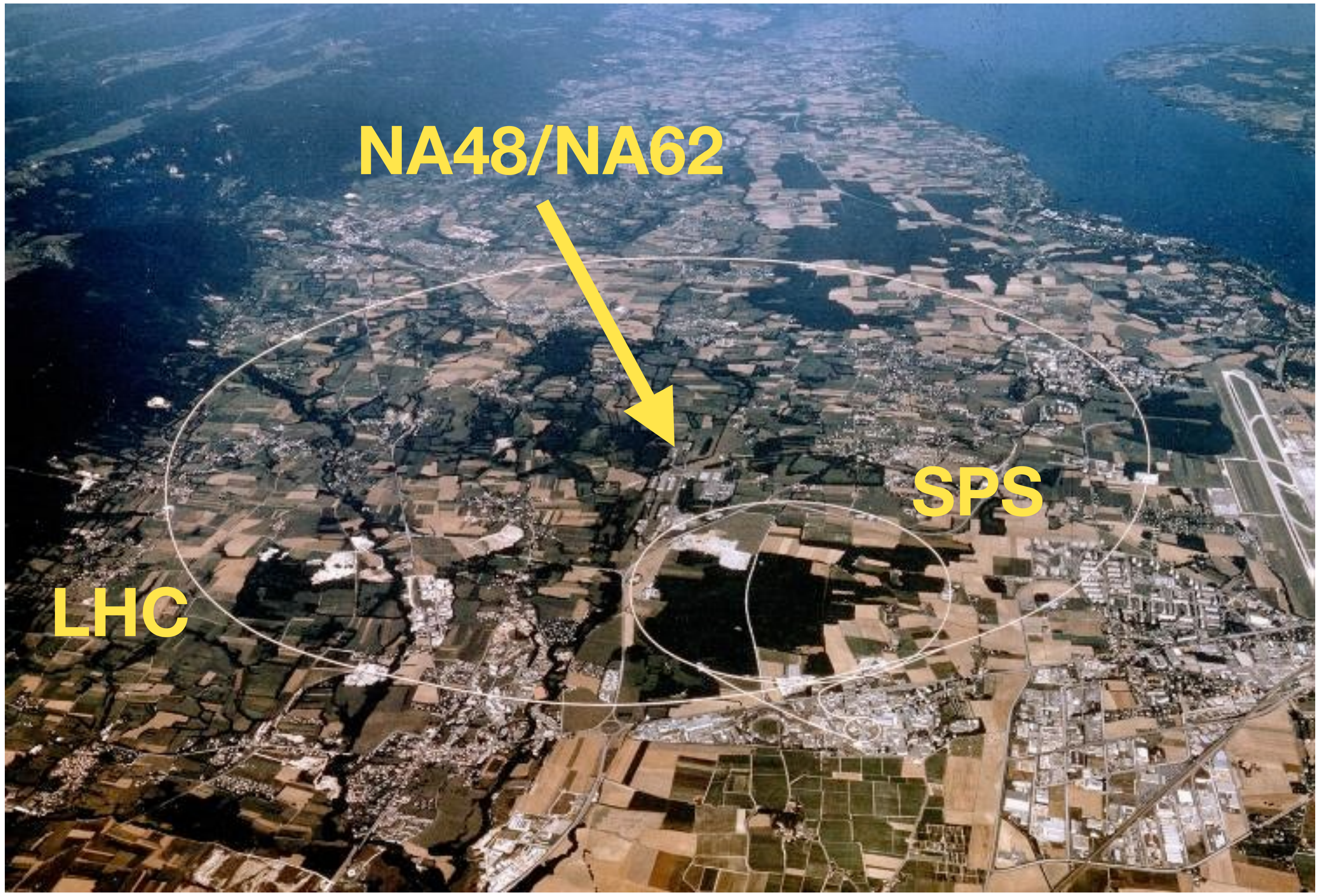
New experiments to come:

NA62
$K \to e\nu / K \to \mu\nu$
$K^+ \to \pi^+ \nu\bar{\nu}$

KOTO
$K_L \to \pi^0 \nu\bar{\nu}$

KLOE-2
all K decays

The NA48 and NA62 Experiments



- **NA48/62:** 48th/62nd experiment in the CERN North Area.
- Fixed-target experiments with 400 GeV/*c* proton beams from the SPS.

Earlier: ***NA31***

NA48	1997:	ε'/ε: K_L+K_S	
	1998:	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 phase	2007:	$K^\pm_{e2}/K^\pm_{\mu 2}$	tests
	2008:	$K^\pm_{e2}/K^\pm_{\mu 2}$	tests
NA62 $K^+\to\pi^+\nu\bar{\nu}$	2012:	technical run	
	2014:	1st $K^+\to\pi^+\nu\bar{\nu}$ run	

The NA48 and NA62 Experiments

- **NA48/2: (2003/2004)**
  - Simultaneous ***K*± beams** for CP violation search in $K^\pm \to \pi^\pm \pi \pi$
- **NA62 "R_K phase": (2007/2008)**
  - Still use of NA48/2 detector & beam.
  - Search for Lepton Flavour Violation in

$$R_K = \Gamma(K \to e\nu) / \Gamma(K \to \mu\nu)$$

- **New NA62 experiment: (≥ 2014)**
  - Completely new detector.
  - 100 SM-events of the very rare decay

$$K^+ \to \pi^+ \nu \bar{\nu}$$

Further rare K⁺ decays

	1997:	ε'/ε: K_L+K_S	
	1998:	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
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NA48/2	2003:	K^+/K^-	
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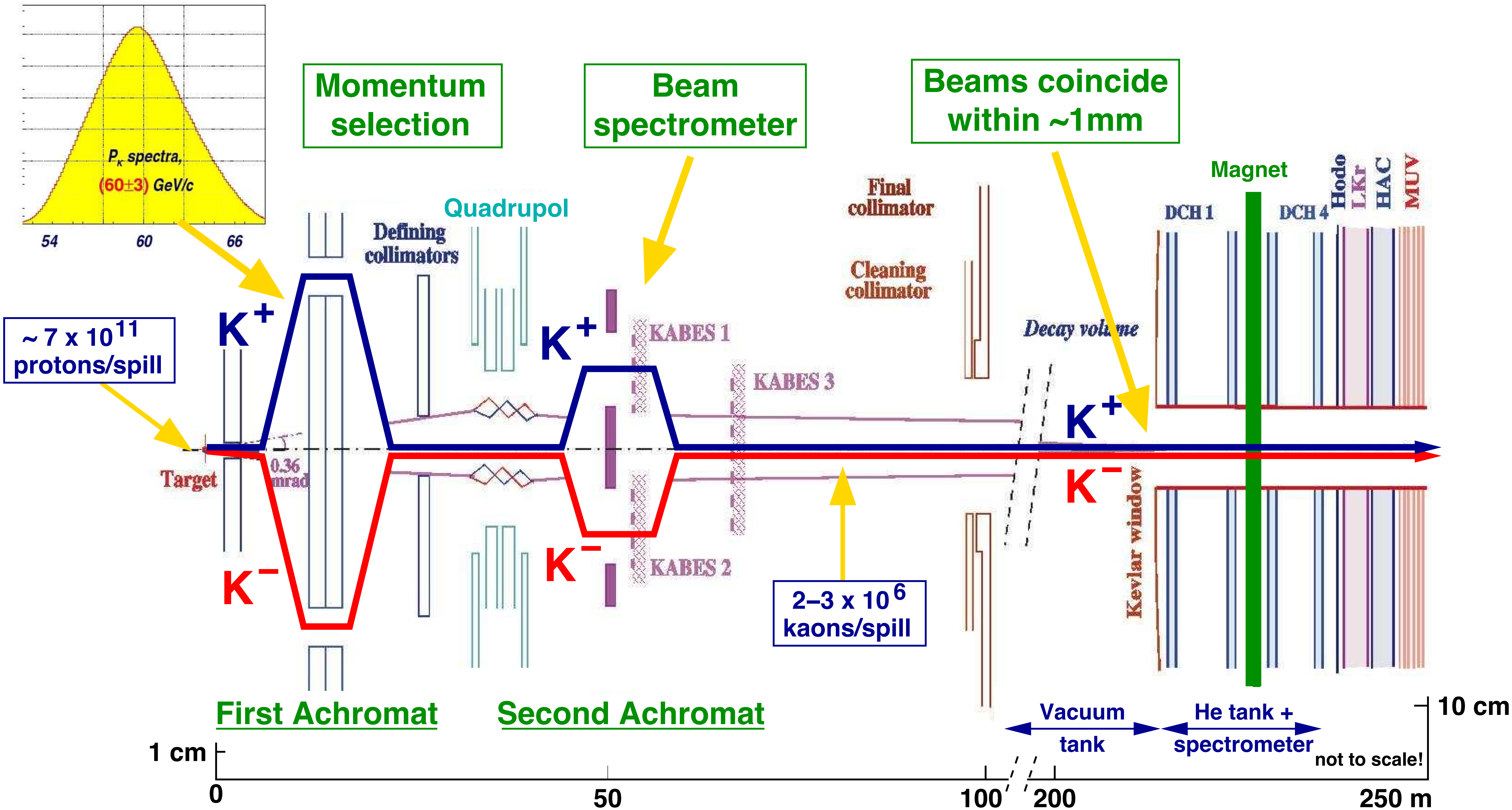
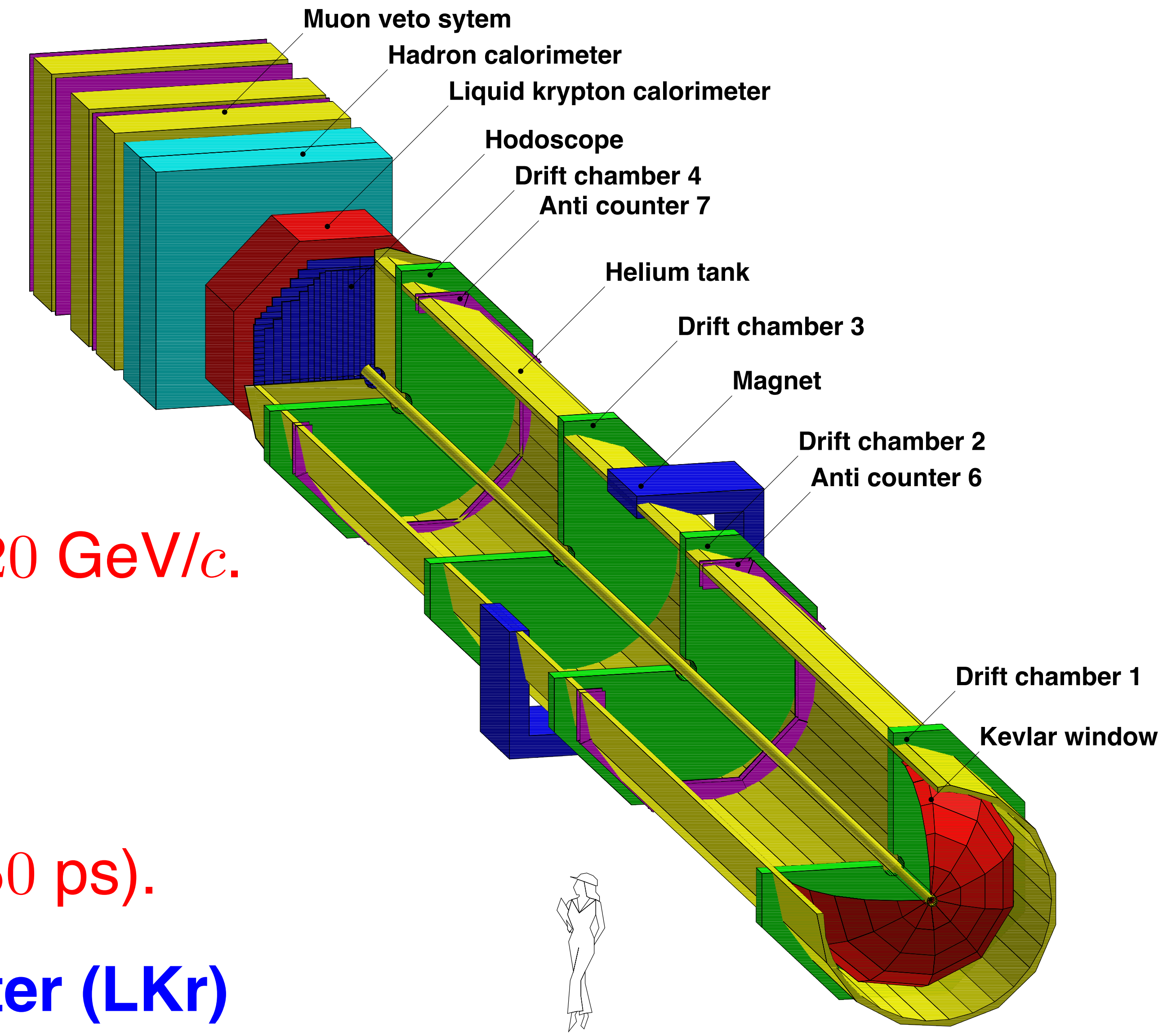
NA62 $K^+\to\pi^+\nu\bar{\nu}$	2012:	technical run	
	2014:	1st $K^+\to\pi^+\nu\bar{\nu}$ run	

NA48/2 Beam Line

- **Simultaneous K^+ and K^- beams** with $p_K = (60 \pm 1.8)$ GeV/c.



The NA48/2 Detector



- **Magnet spectrometer**

  4 sets of drift chambers.

  $\boldsymbol{\Delta p/p \approx 1.4\%}$ for $p = 20$ GeV/c.

- **Hodoscopes:**

  Fast trigger, precise time measurement ($\sigma_t = 150$ ps).

- **Liquid Krypton Calorimeter (LKr)**

  $\boldsymbol{\Delta E/E \approx 1.0\%}$ for $E_{e,\gamma} = 20$ GeV/c.

- **Hadron calorimeter, photon vetos, muon counters**

Outline

- **Several new and upcoming measurements to present:**
  - $K^\pm \to \pi^0 l^\pm \nu$, $K^\pm \to \pi^0\pi^0 e^\pm \nu$ form factors.
  - New measurements of $K^\pm \to \pi^\pm\gamma\gamma$.
  - First observation of $K^\pm \to \pi^\pm\pi^0 e^+ e^-$.
  - Future measurement of $K^+ \to \pi^+\nu\nu$.
  - Future prospects for rare and forbidden K^+ decays.

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  - Future prospects for rare and forbidden K^+ decays.

This talk

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

$K^\pm \to \pi^\pm\gamma\gamma$ — ChPT Description

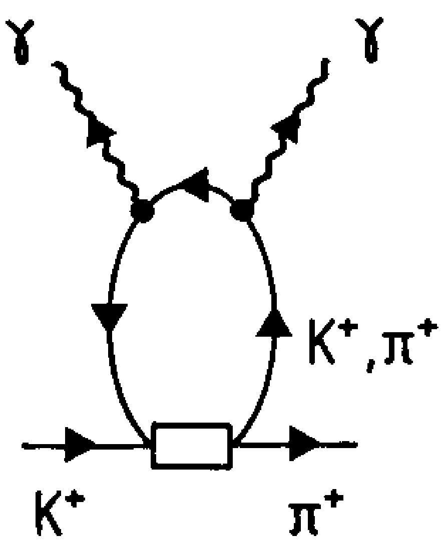
In ChPT the double differential rate in $K \to \pi\gamma\gamma$ decays is

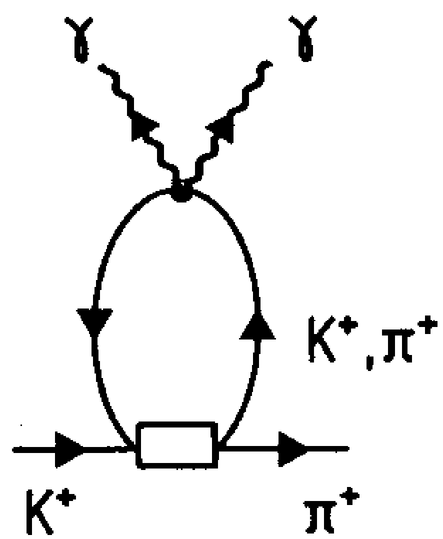
$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{M_K}{2^9\pi^3}\left\{z^2\left(|A+B|^2+|C|^2\right)+\left[y^2-\frac{1}{4}\lambda(1,r_\pi^2,z)\right]^2\left(|B|^2+|D|^2\right)\right\}$$

with no tree-level contributions from $\mathcal{O}(p^2)$.

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

$$r_\pi = \frac{m_\pi}{m_K}$$





Lorentz invariant variables:

$$z = \frac{(P_{\gamma_1}+P_{\gamma_2})^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2$$

$$y = \frac{P_K\,(P_{\gamma_1}-P_{\gamma_2})}{m_K^2}$$

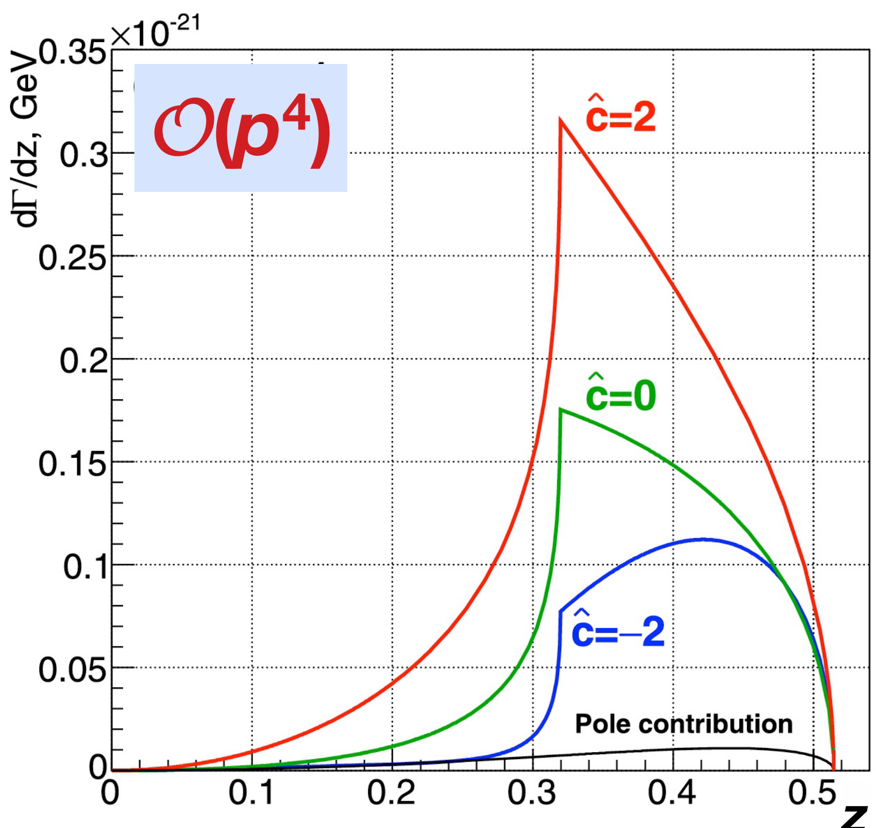
A, *B*, *C*, and *D* are functions of *z* and *y*.

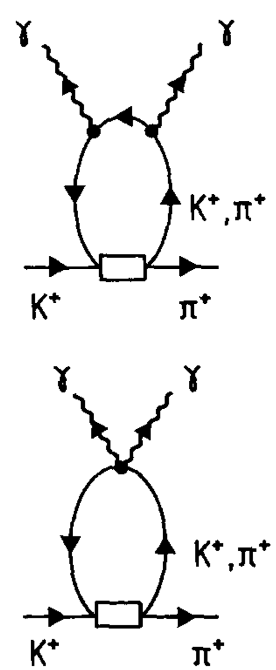
Rate and spectrum depend on a single unknown parameter $\hat{c}$ of $\mathcal{O}(1)$.

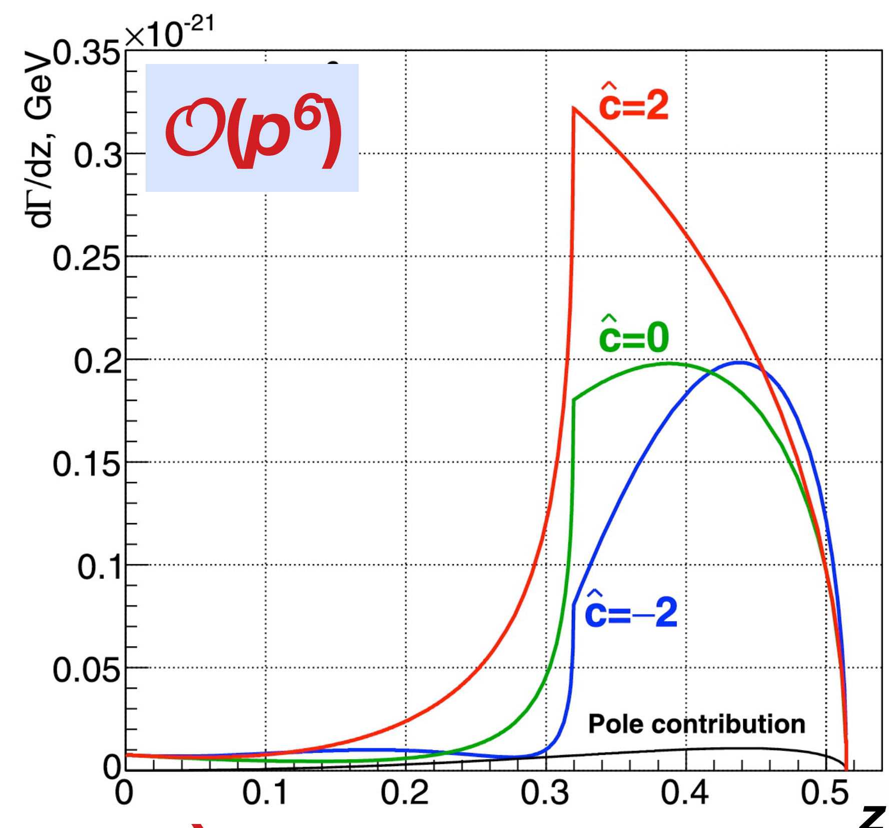
$K^{\pm} \to \pi^{\pm}\gamma\gamma$ — ChPT Description

- $\mathcal{O}(p^4)$:
  B and *D* amplitudes are still 0.
  [Ecker, Pich, de Rafael, NPB 303 (1988) 665]

- $\mathcal{O}(p^6)$:
  Unitary corrections result in a non-zero rate at $m_{\gamma\gamma} \to 0$.
  [D'Ambrosio, Portolés, PLB 386 (1996) 403, Gerard, Smith, Trine, NPB 730 (2005) 1]





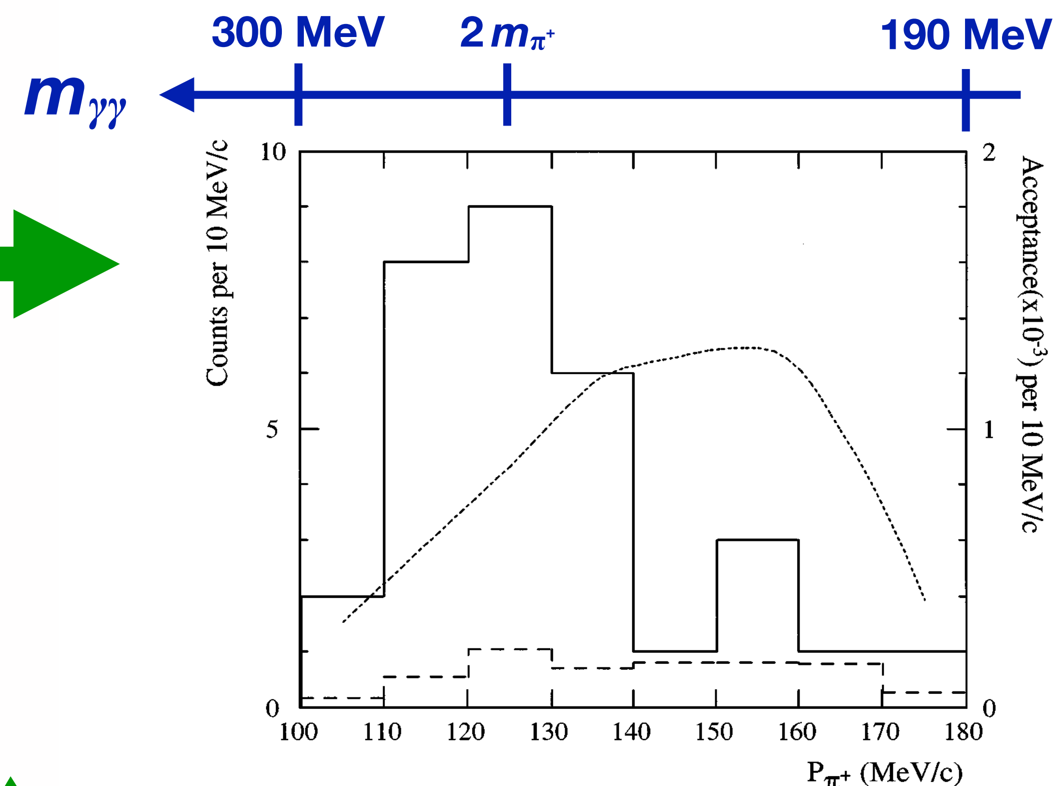


Cusp at $2\,m_{\pi^+}$

Unitarity corrections for $\mathcal{O}(p^6)$

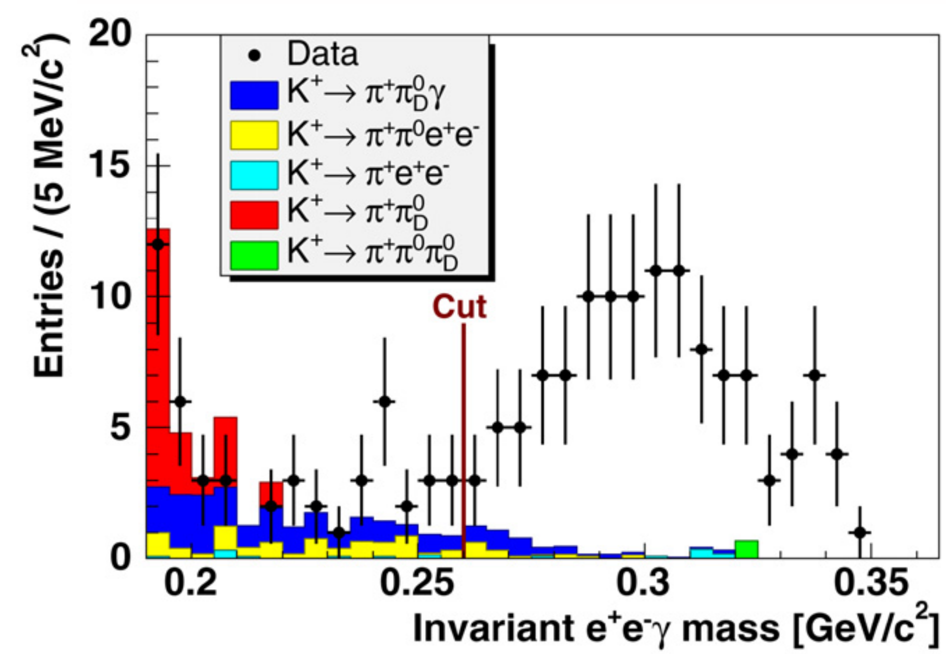
$K^\pm \to \pi^\pm\gamma\gamma$ — Experimental Status

- **E787 (BNL):**
  31 candidates with 5 bkg events:
  $\hat{c} = 1.8 \pm 0.6 \quad (\mathcal{O}(p^6))$
  [Kitching et al., PRL 79 (1997) 4079]



- **NA48/2** *$K^\pm \to \pi^\pm \gamma e^+ e^-$*:
  120 candidates with 5 bkg events:
  $\hat{c} = 0.90 \pm 0.45 \quad (\mathcal{O}(p^6))$
  [Batley et al., PLB 659 (2008) 493]

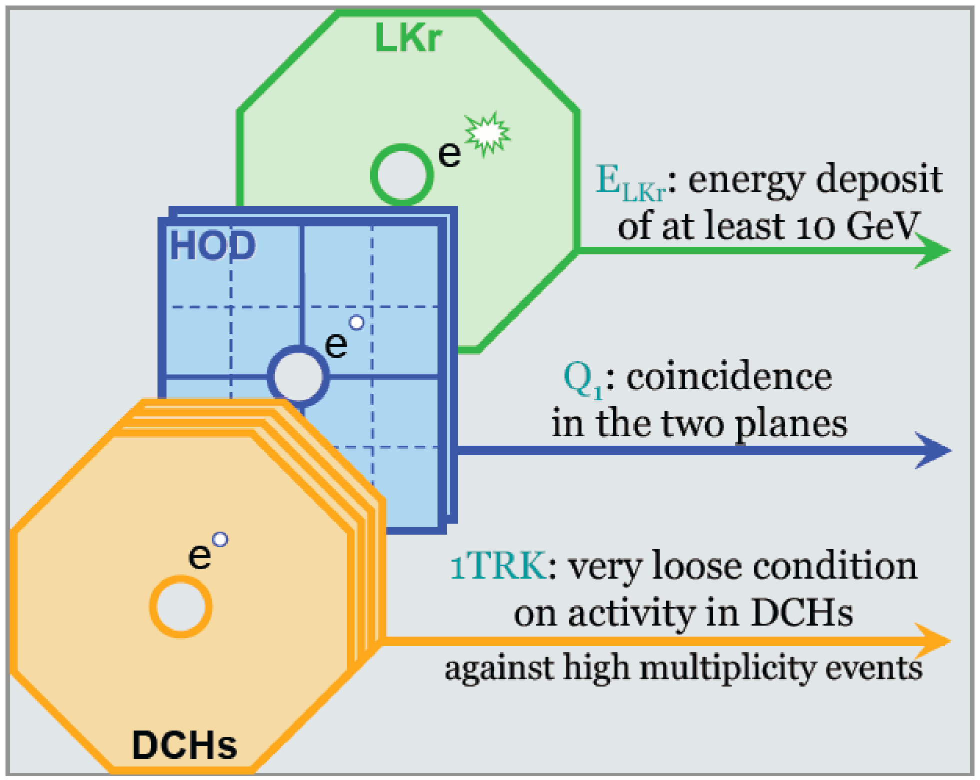
- **NA48/2** *preliminary*:
  > 1000 candidates from data taking with anti-$K_{2\pi}$ trigger
  ➜ very bad trigger efficiency
  ➜ no $\hat{c}$ measurement
  [Morales Morales (for NA48/2), Moriond QCD (2008)]



$K^\pm \to \pi^\pm\gamma\gamma$ — Data Samples

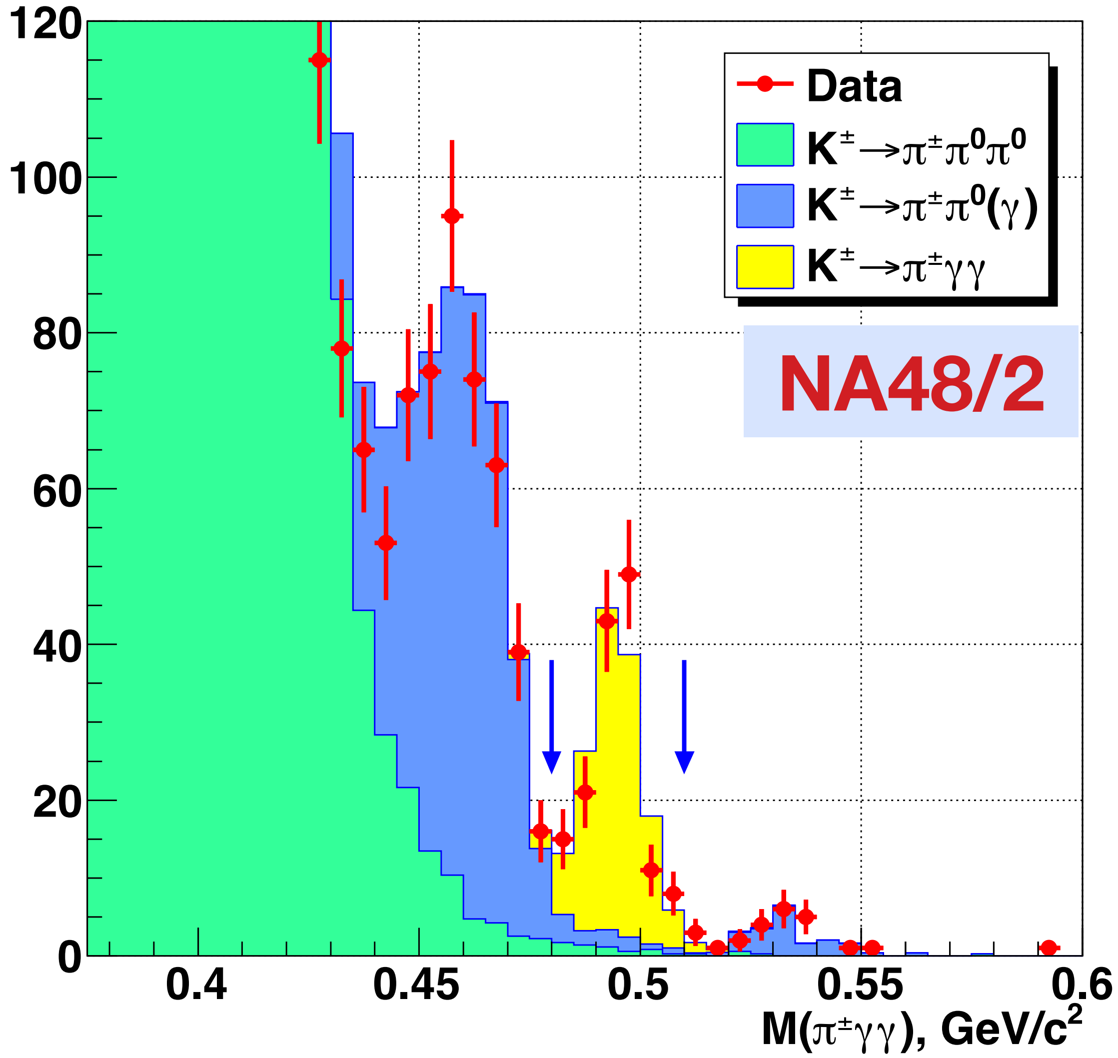
- **Problem:**
  $K^\pm \to \pi^\pm\gamma\gamma$ very similar to $K^\pm \to \pi^\pm\pi^0$.
  ➜ heavily trigger-suppressed!
  (was problem in preliminary measurement.)

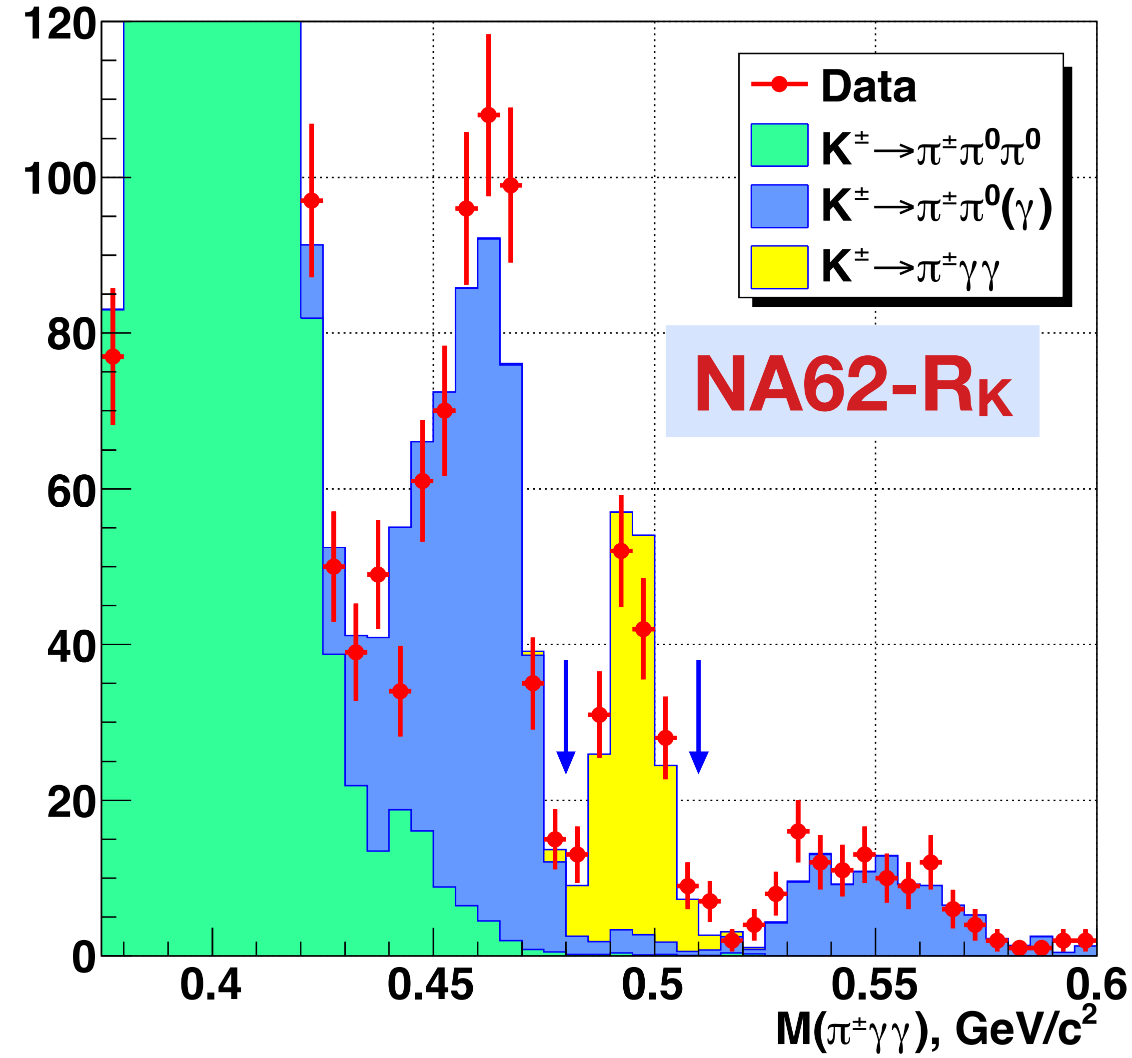
- **Special runs** with
  minimum bias trigger conditions:
  - **NA48/2:**
    12 hours (2003), 3 days (2004)
  - **NA62-R_K:**
    ~ 90 days with 5 downscaled control trigger chains (2007).



Example of some minimum bias condition

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





$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ candidates	**149**
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ background	11.4 ± 0.6
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ background	4.1 ± 0.4

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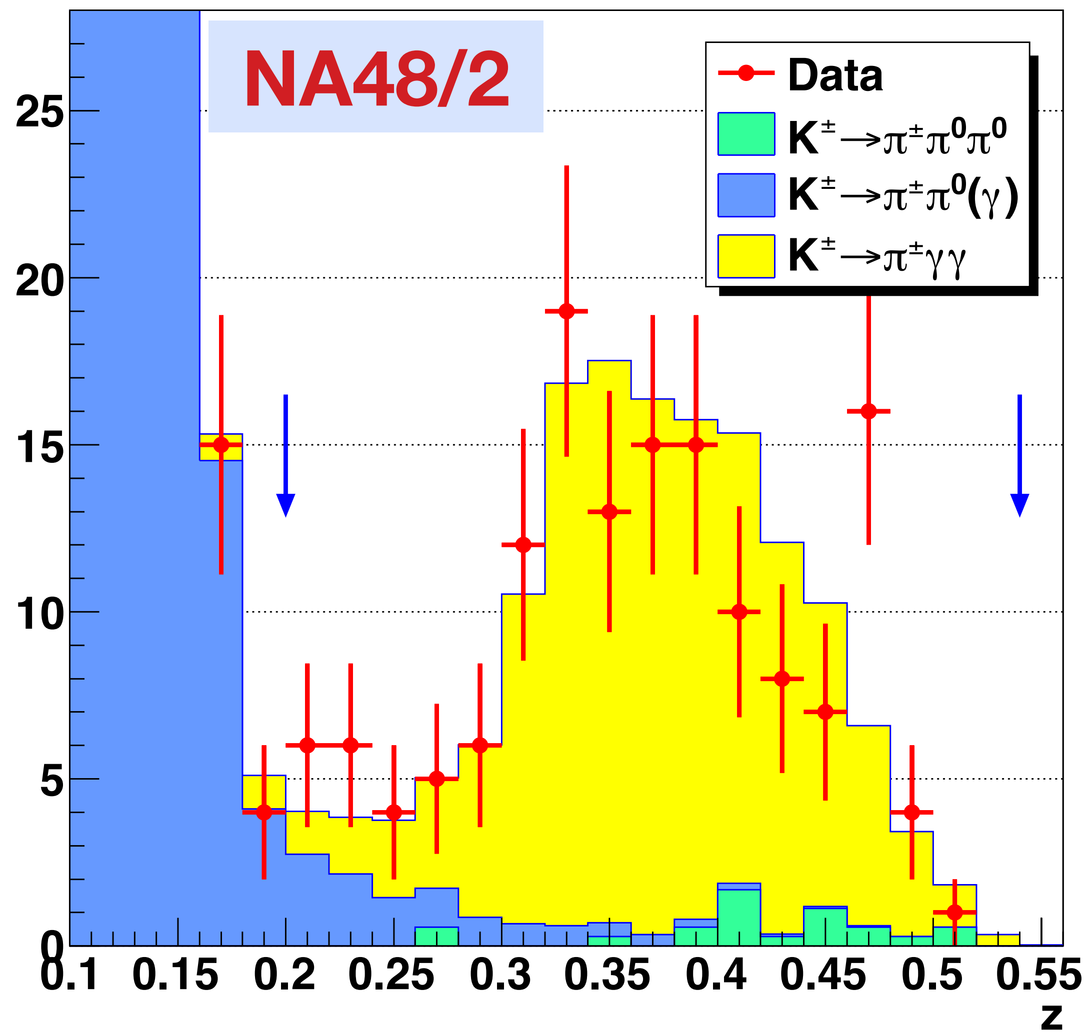
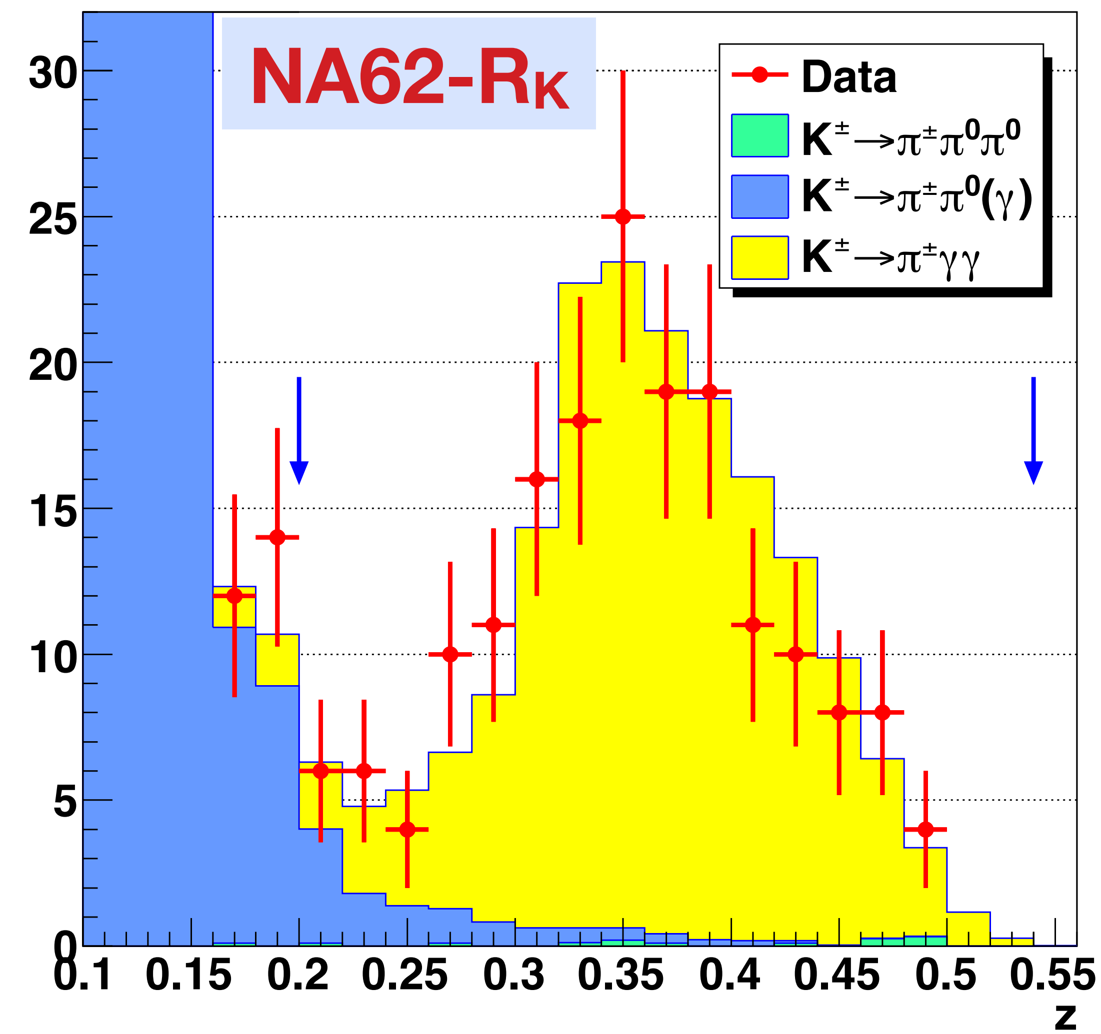
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ background	11.1 ± 1.0
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ background	1.3 ± 0.3

$K^\pm \to \pi^\pm\gamma\gamma$ — z Distribution





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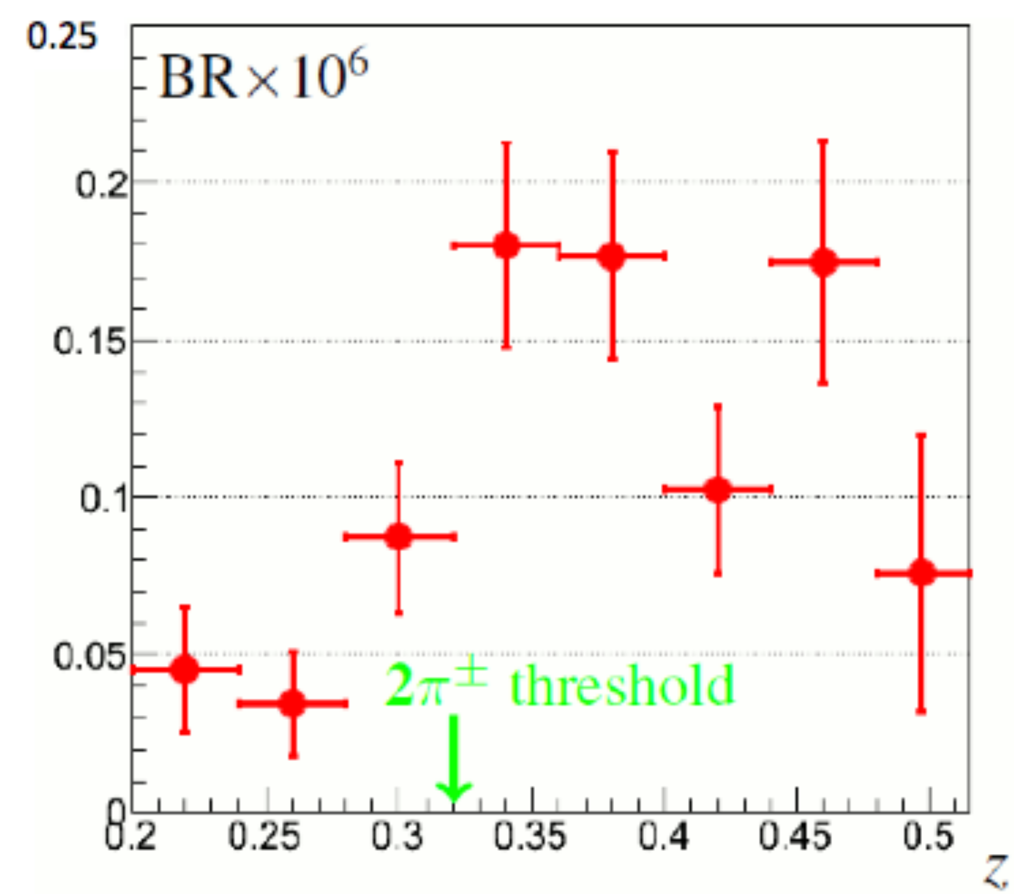
$K^\pm \to \pi^\pm\gamma\gamma$ — Model Independent Measurement

Model-independent branching fraction for $z > 0.2$:

Sum up all partial branching fractions of 8 bins with $z > 0.2$

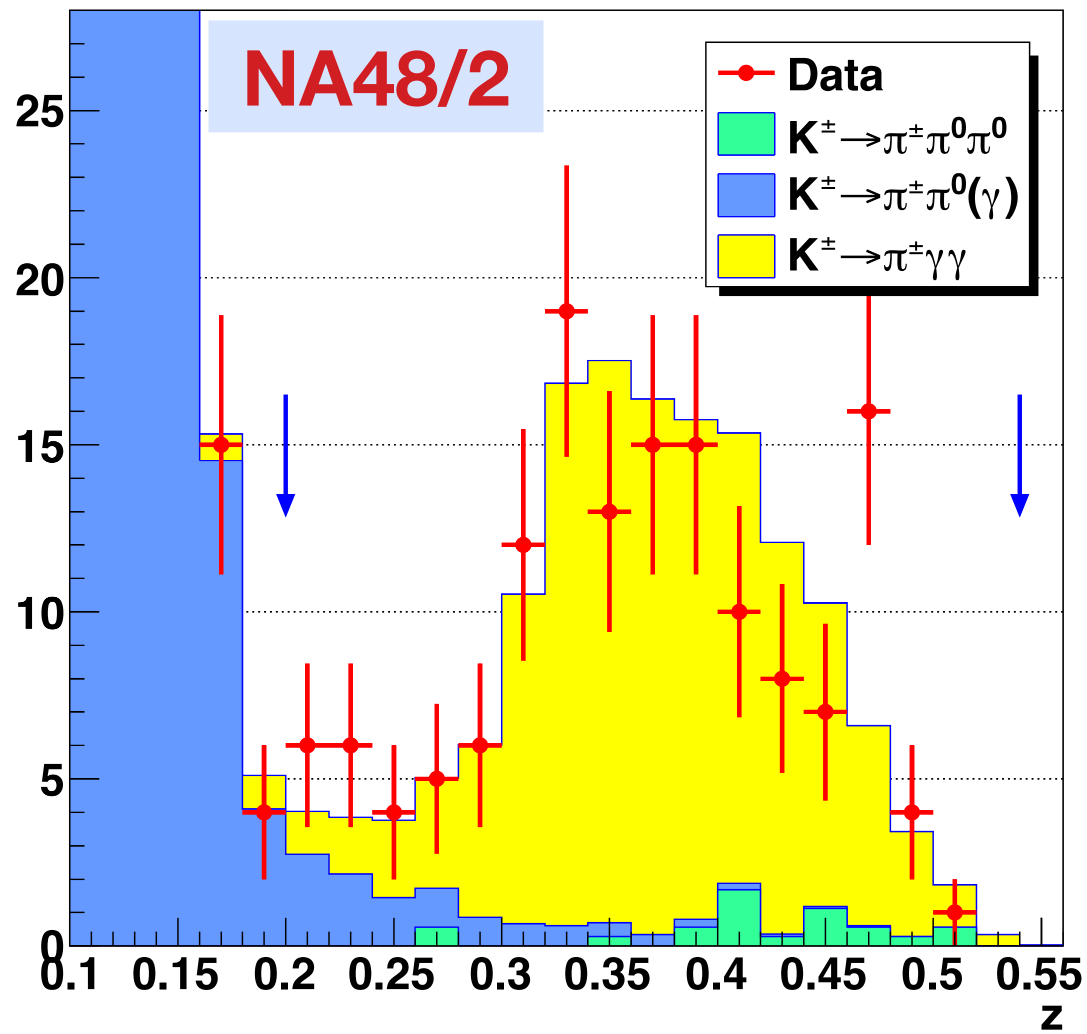
z range	N_j	N_j^B	A_j	$BR_j \times 10^6$
0.20-0.24	13	4.89	0.194	0.045 ± 0.020
0.24-0.28	9	2.73	0.198	0.034 ± 0.016
0.28-0.32	18	2.33	0.194	0.087 ± 0.024
0.32-0.36	33	1.30	0.190	0.180 ± 0.033
0.36-0.40	31	0.98	0.184	0.177 ± 0.033
0.40-0.44	18	1.61	0.173	0.103 ± 0.027
0.44-0.48	23	1.21	0.135	0.175 ± 0.038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

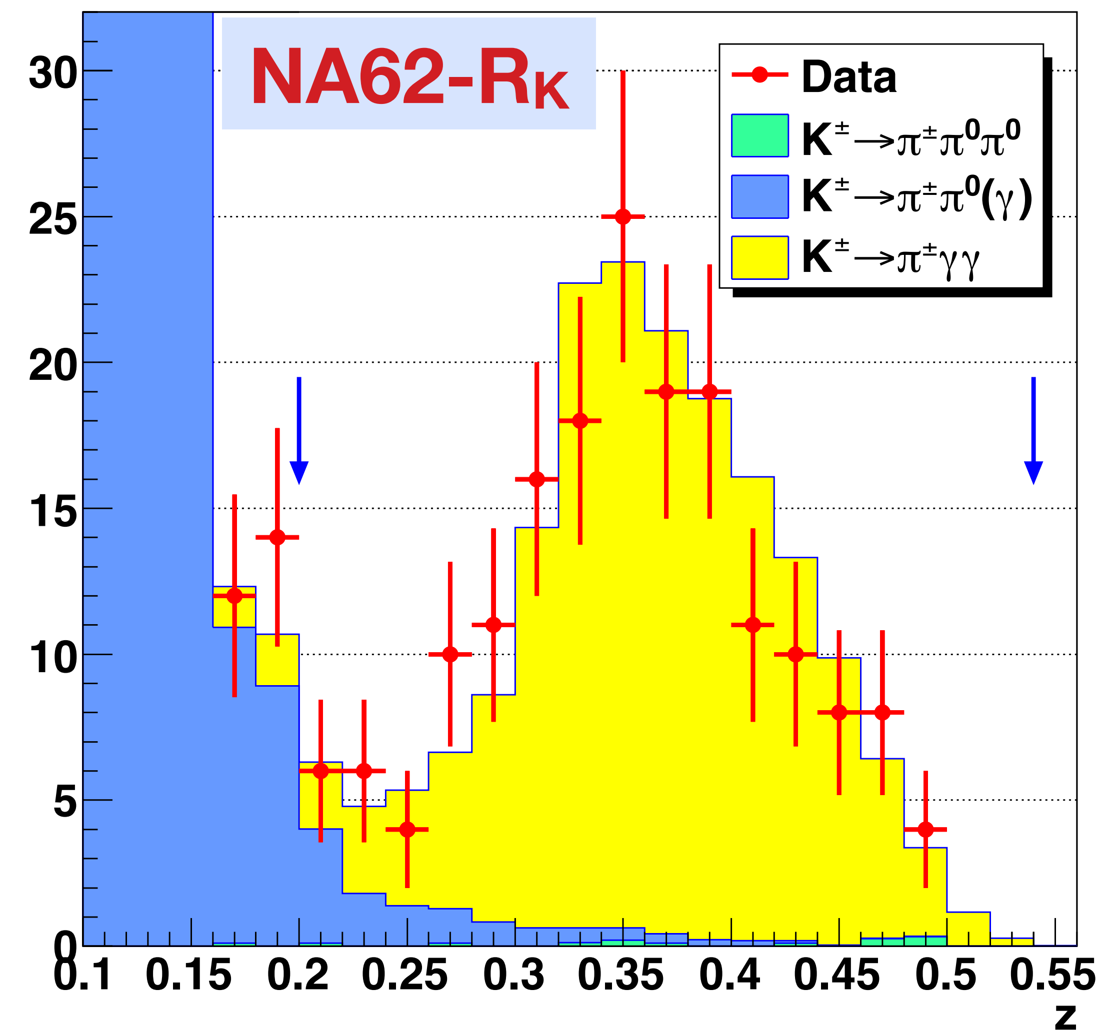


$$\mathcal{B}(K^\pm \to \pi^\pm\gamma\gamma, z > 0.2) = (0.877 \pm 0.087_{stat} \pm 0.017_{syst}) \times 10^{-6}$$

(final NA48/2 result [Batley et al. (2014)], NA62 to be published soon.)

$K^\pm \to \pi^\pm\gamma\gamma$ — Measurement of $\hat{c}$

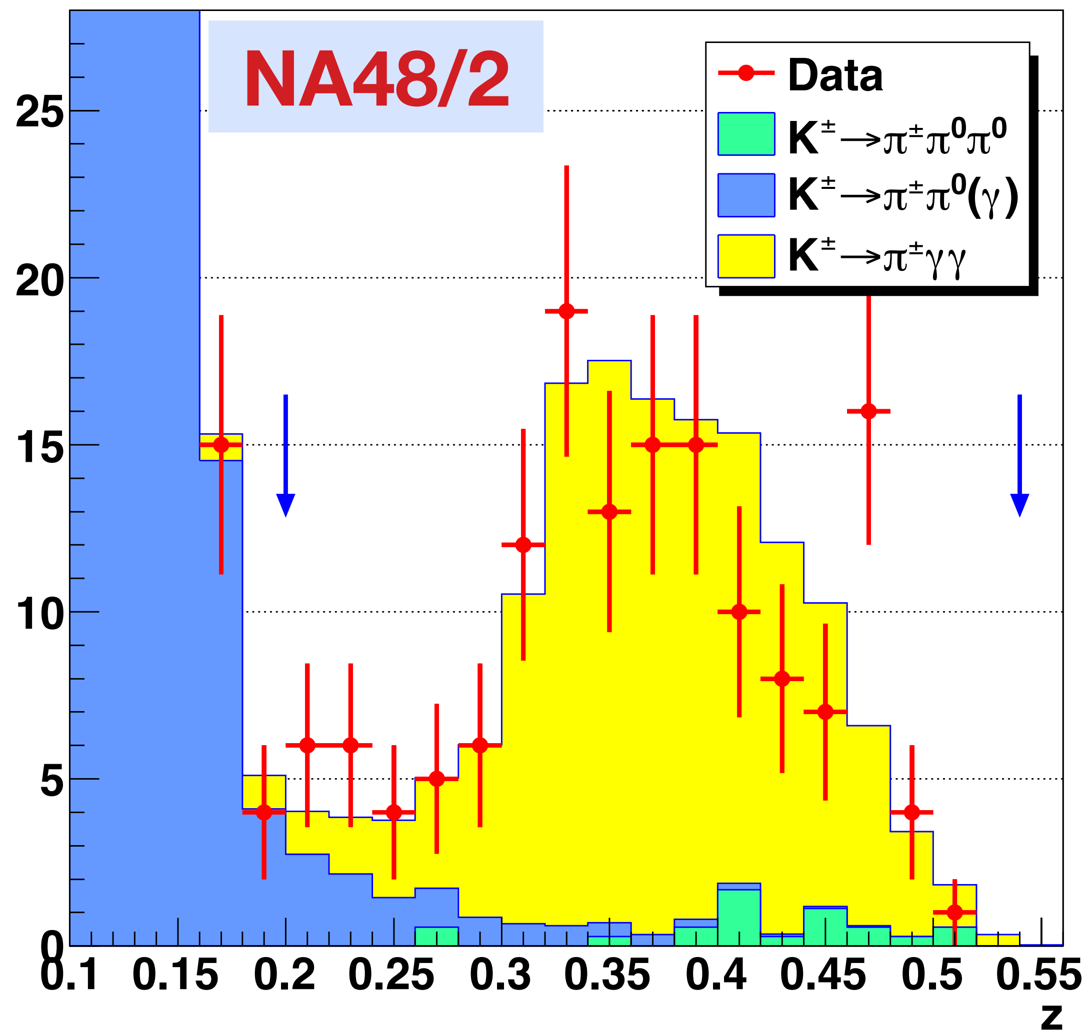


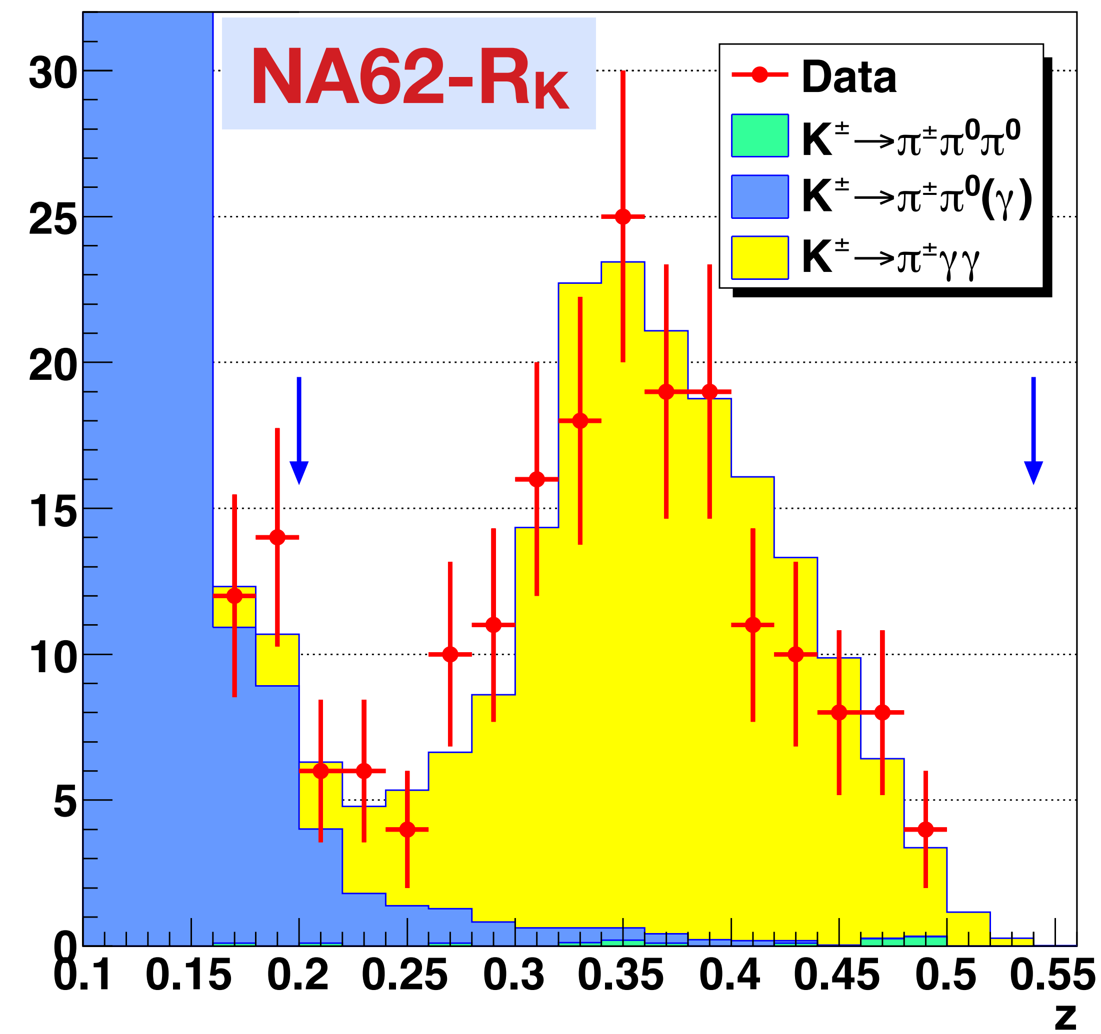


Data support the ChPT prediction of a cusp at the $\pi\pi$ threshold

➜ Fit to the z distributions to extract $\hat{c}$ in ChPT $\mathcal{O}(p^4)$ and ChPT $\mathcal{O}(p^6)$.

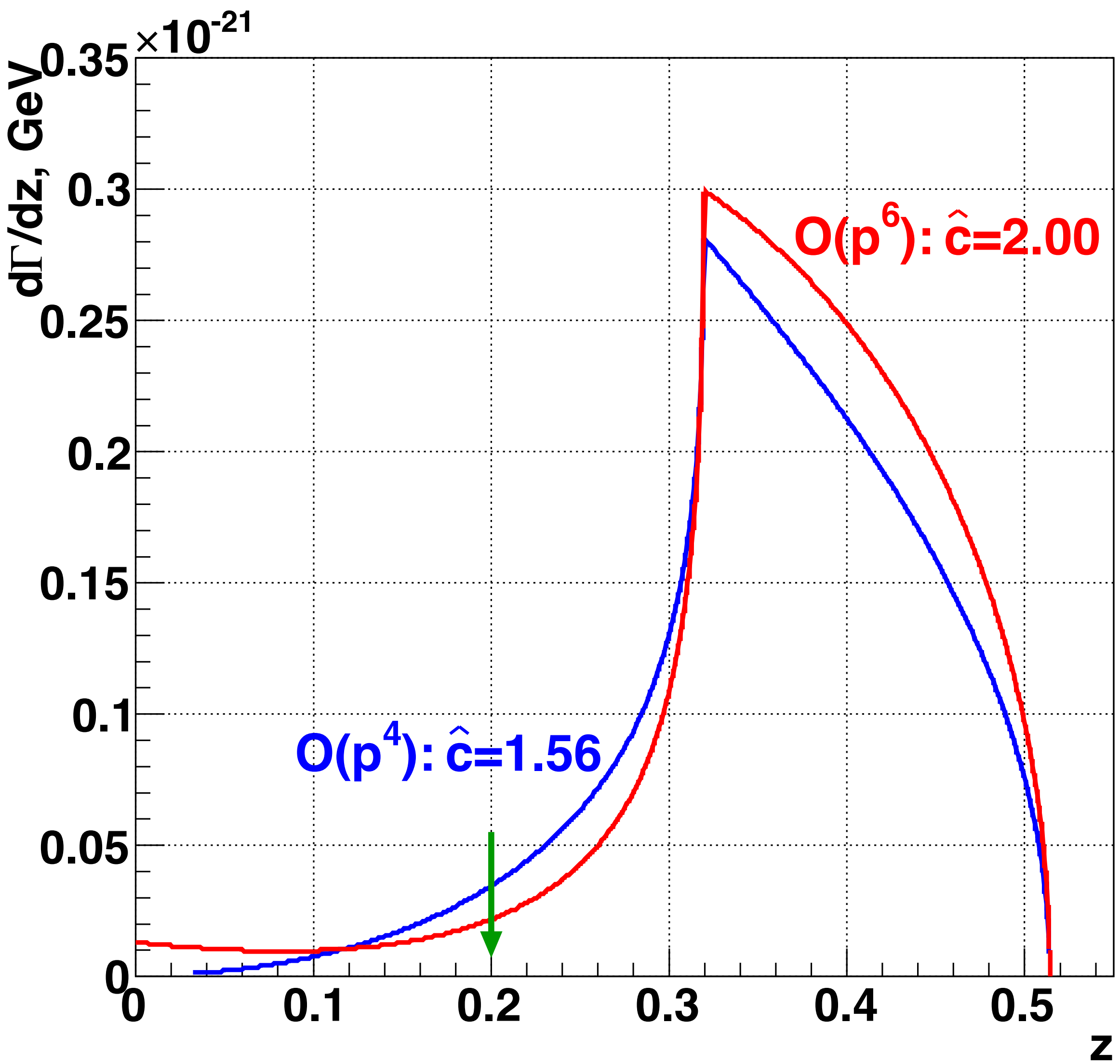
$K^{\pm} \to \pi^{\pm}\gamma\gamma$ — Measurement of $\hat{c}$

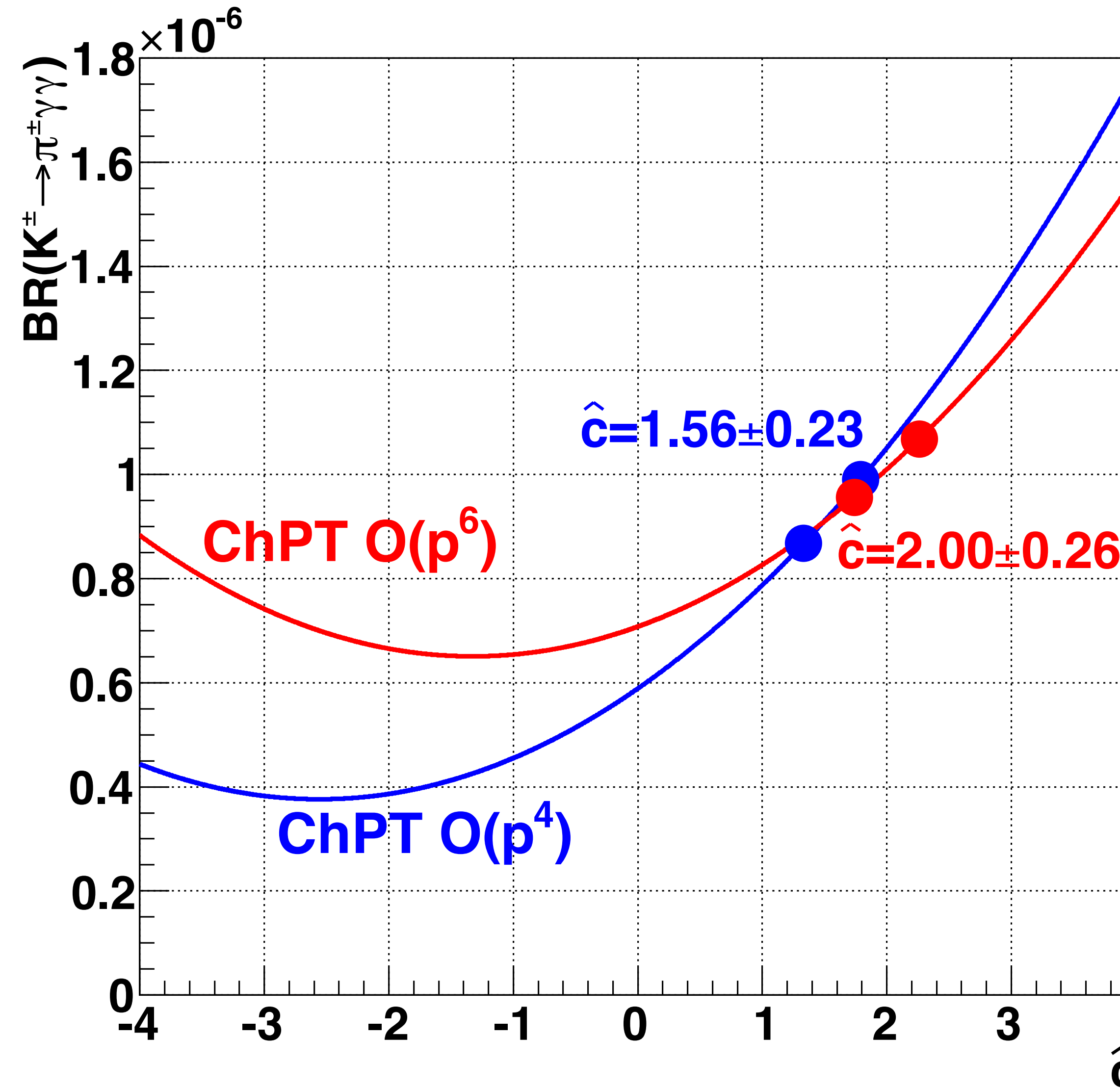




$\mathcal{O}(p^4)$: $\hat{c} = 1.36 \pm 0.33 \pm 0.07$	$\mathcal{O}(p^4)$: $\hat{c} = 1.71 \pm 0.29 \pm 0.06$
$\mathcal{O}(p^6)$: $\hat{c} = 1.67 \pm 0.39 \pm 0.09$	$\mathcal{O}(p^6)$: $\hat{c} = 2.21 \pm 0.31 \pm 0.08$

$K^\pm \to \pi^\pm\gamma\gamma$ — Measurement of $\hat{c}$





Combined
NA48/2 + NA62-R_K:

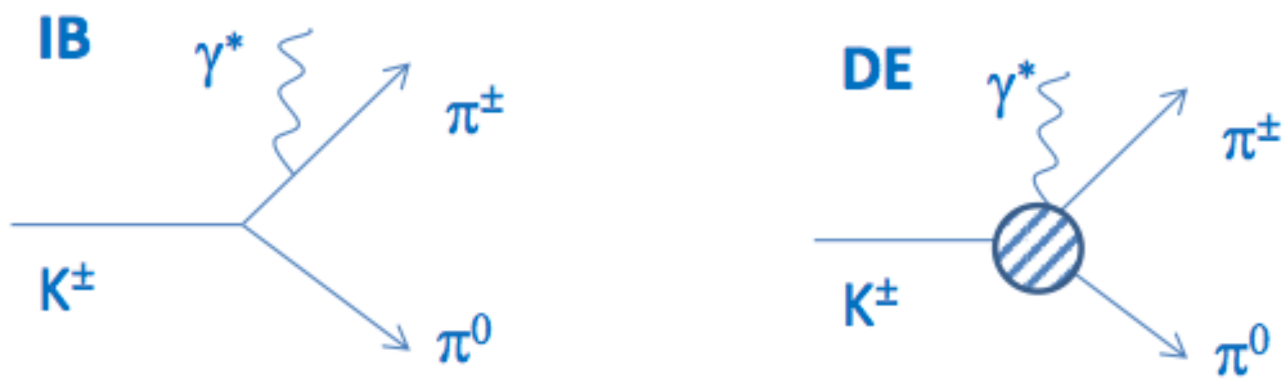
$\mathcal{O}(p^4)$: $\hat{c}$ = 1.56 ± 0.22 ± 0.07 = **1.56 ± 0.23**

$\mathcal{O}(p^6)$: $\hat{c}$ = 2.00 ± 0.24 ± 0.09 = **2.00 ± 0.26**

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$

$K^\pm \to \pi^\pm\pi^0\gamma$ and $K^\pm \to \pi^\pm\pi^0 e^+e^-$

- $K^\pm \to \pi^\pm\pi^0\gamma$ proceeds mainly via **inner bremsstrahlung (IB)**, but may also undergo **direct photon emission (DE)**.



- $K^\pm \to \pi^\pm\pi^0 e^+e^-$ similar with internal conversion $\gamma \to e^+e^-$.
- IB is a leading $\mathcal{O}(p^2)$ effect while DE is a sub-leading $\mathcal{O}(p^4)$ effect.
  [Pichl, EPJC 20 (2001) 371; Cappiello, Catà, D'Ambrosio, Gao, EPJC 72 (2012) 1872]

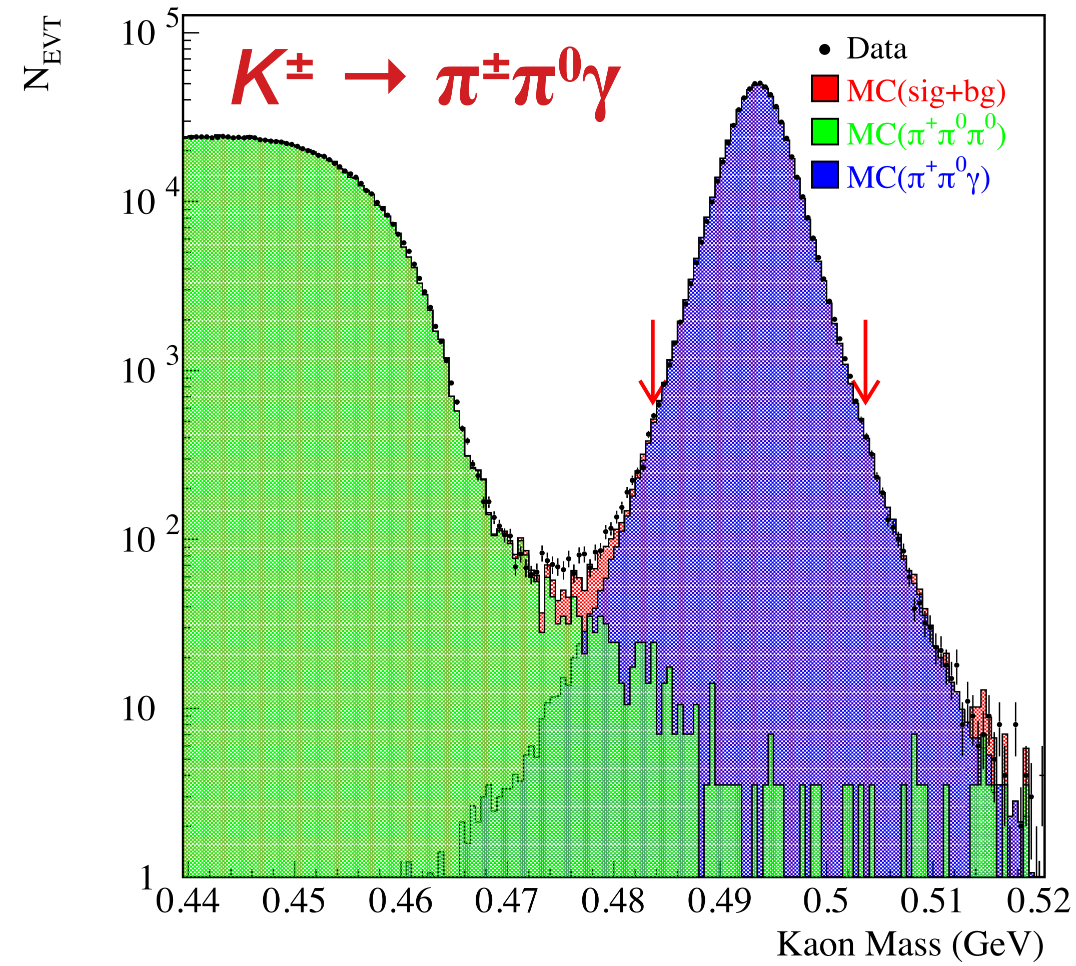
$$\frac{d^3\Gamma}{dE_\gamma^* \, dT_c^* \, dq^2} = \frac{d^3\Gamma_B}{dE_\gamma^* \, dT_c^* \, dq^2} + \frac{d^3\Gamma_E}{dE_\gamma^* \, dT_c^* \, dq^2} + \frac{d^3\Gamma_M}{dE_\gamma^* \, dT_c^* \, dq^2} + \frac{d^3\Gamma_{\text{int}}}{dE_\gamma^* \, dT_c^* \, dq^2}$$

IB **electric / magnetic DE amplitude** **interference term**

E_{γ^*} = $\gamma \to e^+e^-$ energy in $K^\pm$ rest frame
T_c^* = kinetic $\pi^\pm$ energy in $K^\pm$ rest frame
q^2 = e^+e^- invariant mass

$K^\pm \to \pi^\pm\pi^0\gamma$, $K^\pm \to \pi^\pm\pi^0 e^+e^-$ Exp. Status

- Measurement of $K^\pm \to \pi^\pm\pi^0\gamma$ by NA48/2 with **~ 1 million events**.
  [Batley et al., EPJC 68 (2010) 75]

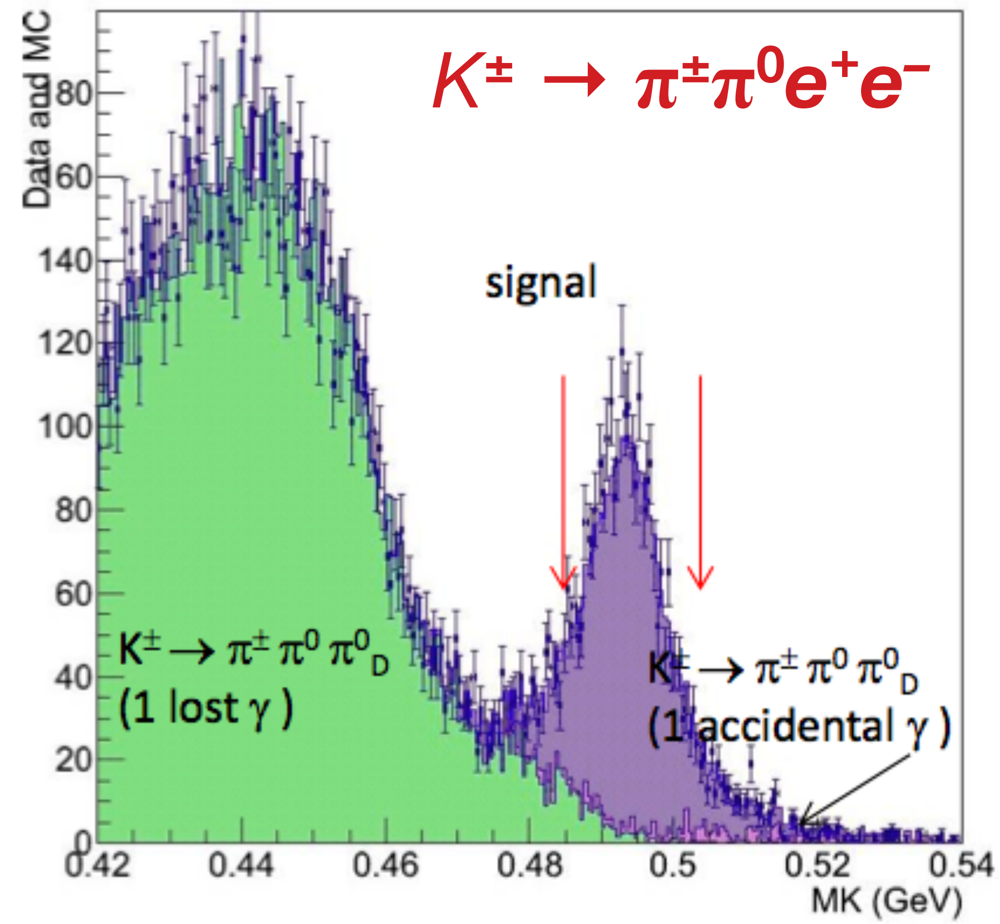


  - Precise measurement of Direct Emission and interference term.
  - No access to mass of photon or polarization (→CP violation).

- $K^\pm \to \pi^\pm\pi^0 e^+e^-$ never been observed so far.
  - Expectation: $\mathcal{B}(K^\pm \to \pi^\pm\pi^0 e^+e^-) \sim \alpha \times \mathcal{B}(K^\pm \to \pi^\pm\pi^0\gamma) \sim \mathbf{10^{-8}}$

$K^\pm \rightarrow \pi^\pm\pi^0 e^+e^-$

- First observation using the 2003 NA48/2 data sample (about 40% of all NA48/2 data).
- Main background contributions from:
  - $K^\pm \rightarrow \pi^\pm\pi^0\pi^0_D$ with $\pi^0_D \rightarrow e^+ e^- \gamma_{lost}$.
  - $K^\pm \rightarrow \pi^\pm\pi^0_D$ with $\pi^0_D \rightarrow e^+ e^- \gamma + \gamma_{acc}$.



About 2500 events in the signal region, with 280 estimated bkg events.

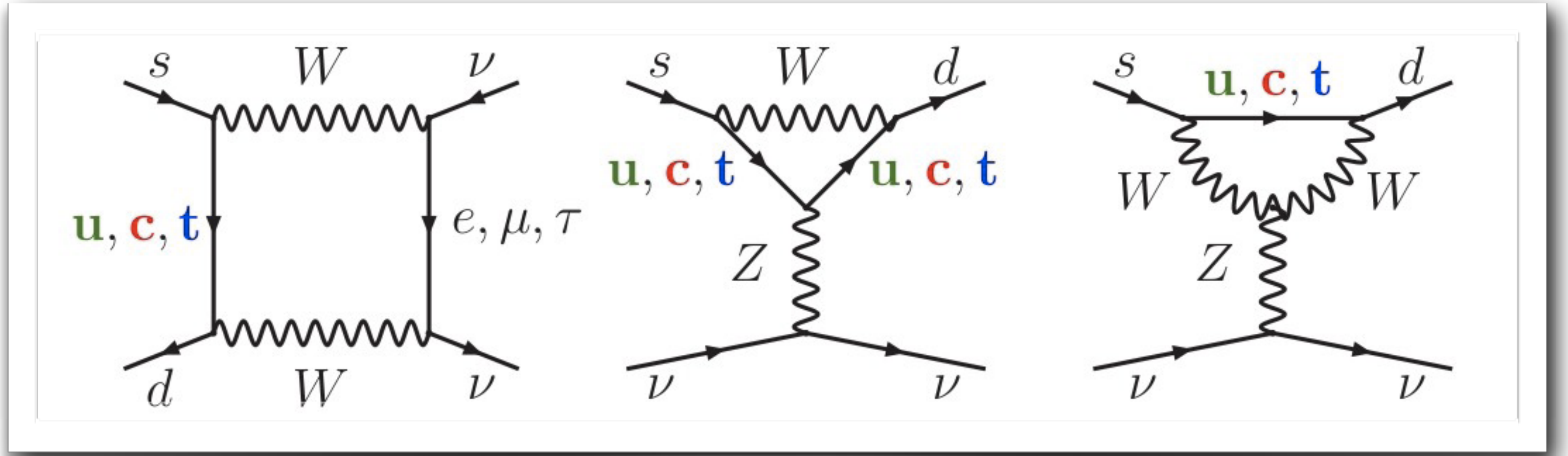
Future NA62 Experiment

Why $K^+ \to \pi^+ \nu\bar{\nu}$?

Kaon physics usually:

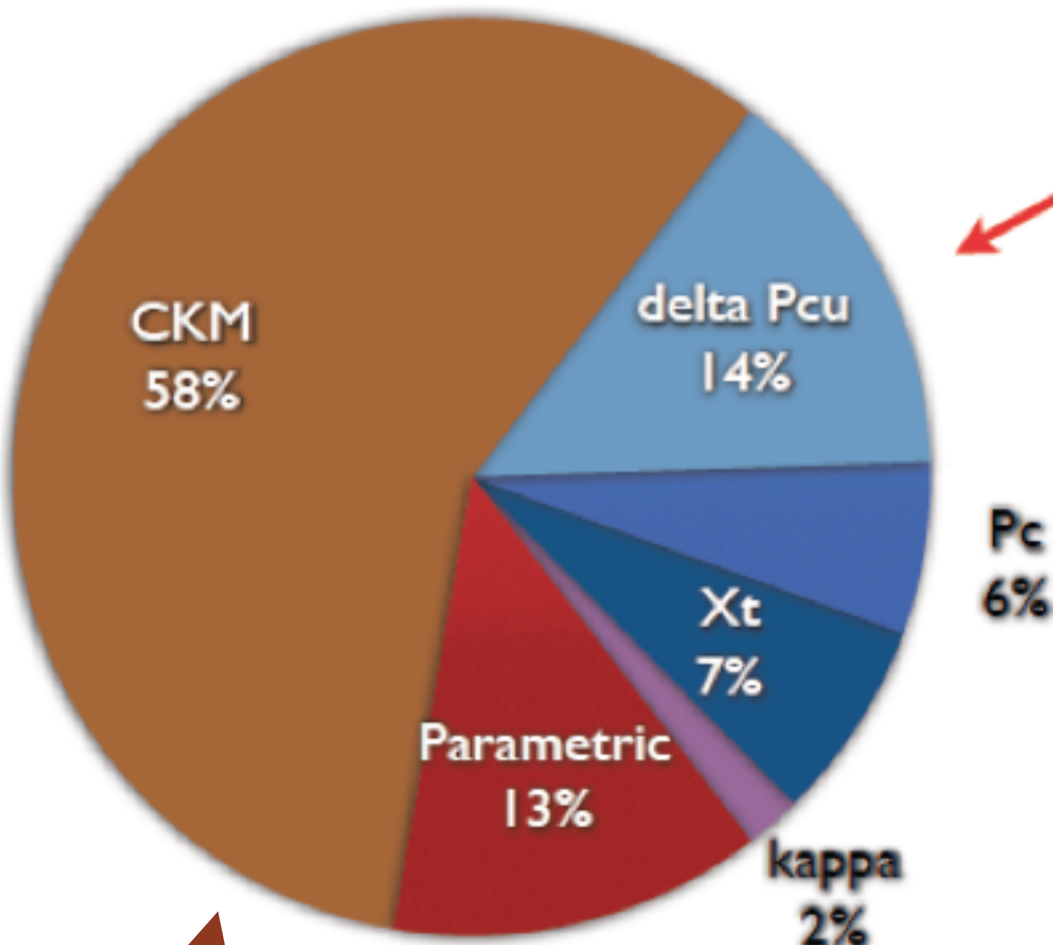
Exact predictions difficult because of hadronic contributions.

Exception: $\mathbf{K} \to \pi\nu\bar{\nu}$



- Decay $K \to \pi\nu\bar{\nu}$ proceeds only via box and penguin diagrams.
- Hadronic matrix element from $K \to \pi e \nu$ and isospin rotation.
- Uncertainties only from charm contributions ($K^+ \to \pi^+\nu\bar{\nu}$ only).

Errors on Theory Prediction



Improve by lattice QCD [Isidori et al. '05]

Experimental Result

[E787, E949 '08]

$$\mathrm{Br} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

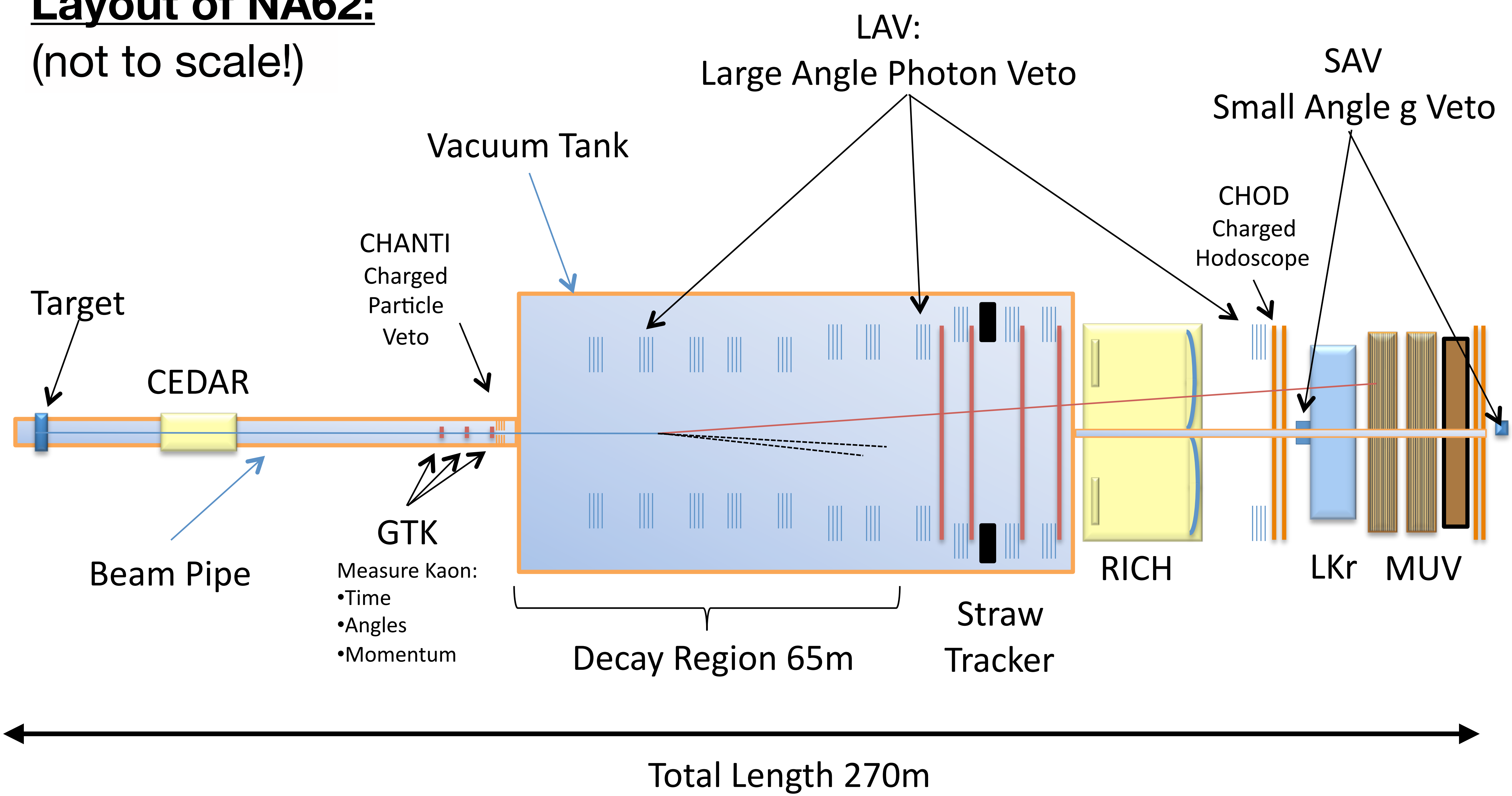
NA62 (CERN) aims at 10% measurement!

Error mostly current uncertainty on $V_{ts}V_{td}^*$

(Courtesy of Joachim Brod)

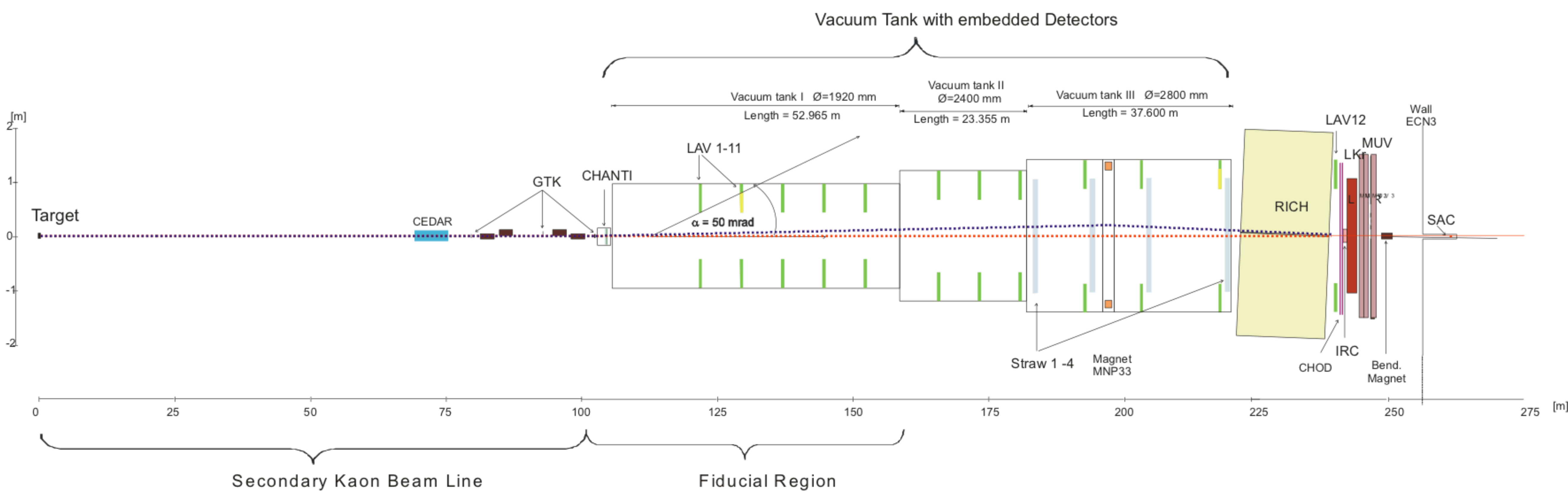
The NA62 Detector

Layout of NA62:
(not to scale!)



The NA62 Detector

Layout of NA62:
(still not to scale!)



NA62 Sensitivity

Estimated signal and background rates:

$K^+ \to \pi^+ \nu \bar{\nu}$ (signal)	45 events/year
$K^+ \to \pi^+ \pi^0$	5
$K^+ \to \mu^+ \nu$	1
$K^+ \to \pi^+ \pi^- e \nu$	<1
3 tracks	<1
$K^+ \to \pi^+ \pi^0 \gamma$	1.5
$K^+ \to \mu^+ \nu \gamma$	0.5
others	negligible
Expected bkg	**<10**

➡ ***~10% measurement in two years of data-taking.***

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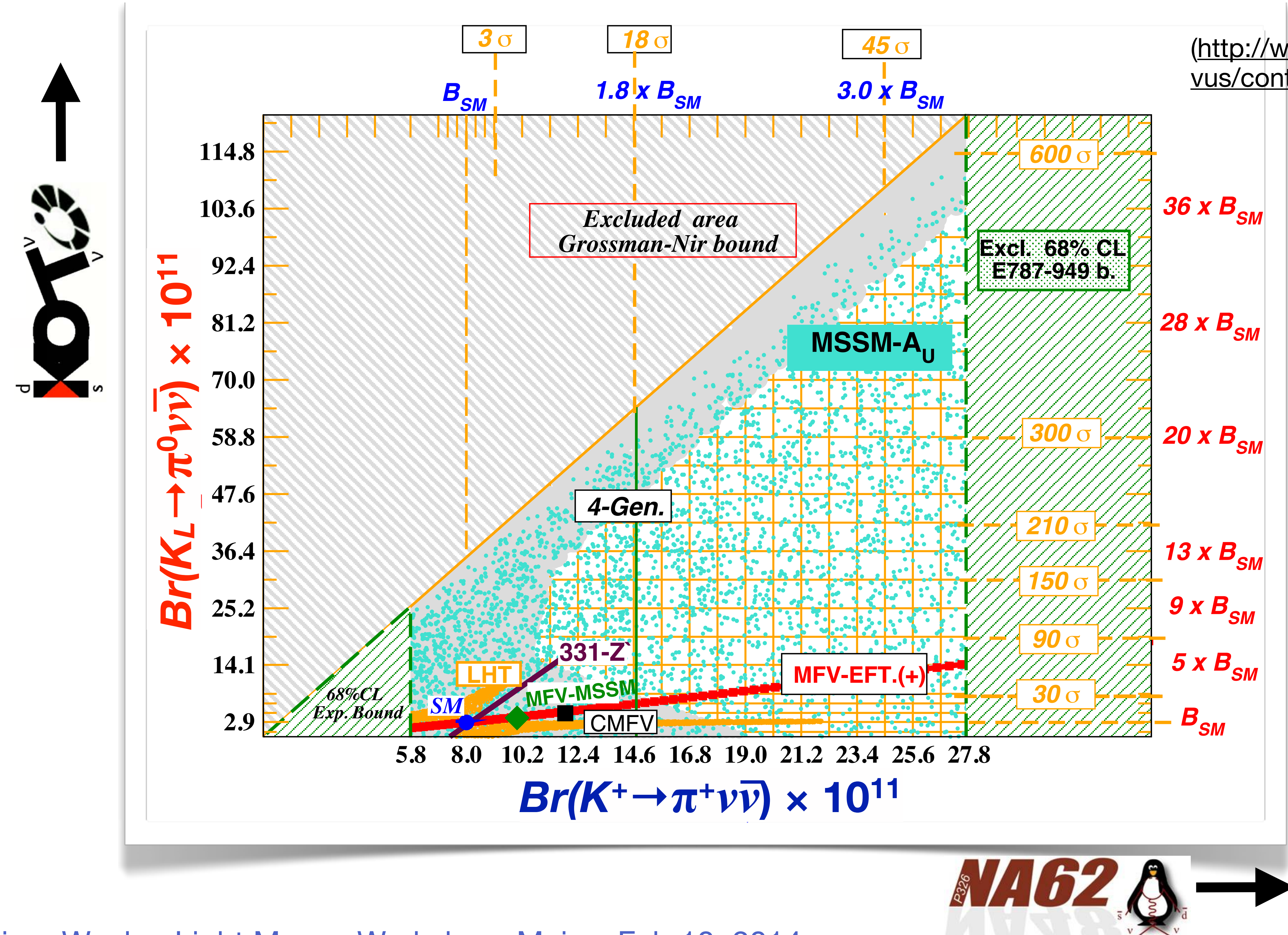
NA62 Plans & Timeline:

- **End of 2014:**
  Two months of data-taking
  ➜ Hope for SM sensitivity
- **2015/2016:**
  Two run periods for
  ~ **90 SM events**
- **≥ 2017:**
  Other rare K^+ decays,
  K_L decays (?)

NA62 Sensitivity

With 3 SM events for $K_L \to \pi^0 \nu\bar{\nu}$ and 100 for $K^+ \to \pi^+ \nu\bar{\nu}$ by 2015/16:



(http://www.lnf.infn.it/wg/vus/content/Krare.html)

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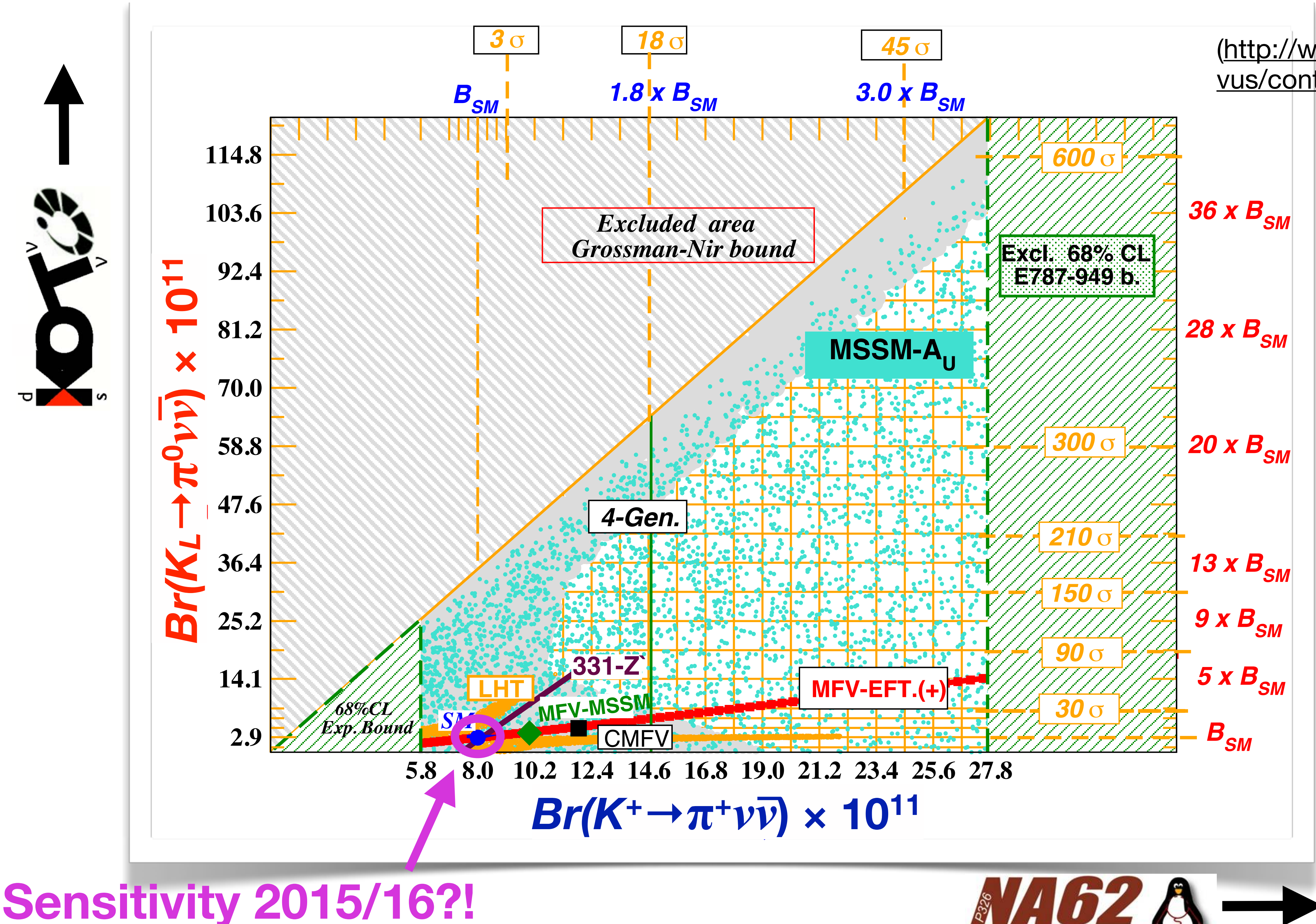


NA62 Reach for rare K^+ and π^0 Decays

NA62 will collect an unprecedented amount of K^+ decays giving the possibility to measure rare decays properties and look for forbidden and exotic decays.

- NA62 will collect **~10^{13} K^+ decays** and **~2.5×10^{12} π^0** decays in two years of data taking
- ➜ Single event sensitivity: ~10^{-12} for K^+, ~10^{-11} for π^0
- The clean environment allows to study tiny effects.
- The NA62 trigger system is flexible and fully reconfigurable (based on FPGAs).
    - Possibility to have special run periods for e.g. $K^+ \rightarrow \pi^+\gamma\gamma$.

Lepton-Flavour Violating Decays

Channel	Violation	90% CL Limit	Experiment	NA62 Reach
$K^+ \to \pi^+ \mu^+ e^-$	LFV	$< 1.3 \times 10^{-11}$	E865	$\sim 10^{-12}$
$K^+ \to \pi^+ \mu^- e^+$	LFV	$< 5.2 \times 10^{-10}$	E865	$\sim 10^{-12}$
$K^+ \to \pi^- \mu^+ e^+$	LFV, LNV	$< 5.0 \times 10^{-10}$	E865	$\sim 10^{-12}$
$K^+ \to \pi^- e^+ e^+$	LNV	$< 6.4 \times 10^{-10}$	E865	$\sim 2 \times 10^{-12}$
$K^+ \to \pi^- \mu^+ \mu^+$	LNV	$< 1.1 \times 10^{-9}$	NA48/2	$\lesssim 10^{-12}$
$K^+ \to \mu^- \nu e^+ e^+$	LNV	$< 2.0 \times 10^{-8}$	Geneva/Saclay	$\sim 5 \times 10^{-12}$
$\pi^0 \to \mu^- e^+$	LFV	$< 3.4 \times 10^{-9}$	KTeV	$\lesssim 10^{-10}$
$\pi^0 \to \mu^+ e^-$	LFV	$< 3.8 \times 10^{-10}$	KTeV	$\lesssim 10^{-10}$
$\pi^0 \to \mu^- \nu e^+ e^+$	LFV	$< 1.6 \times 10^{-6}$	JINR-Spec	$\lesssim 10^{-10}$

Non-LFV K^+ and π^0 Decays

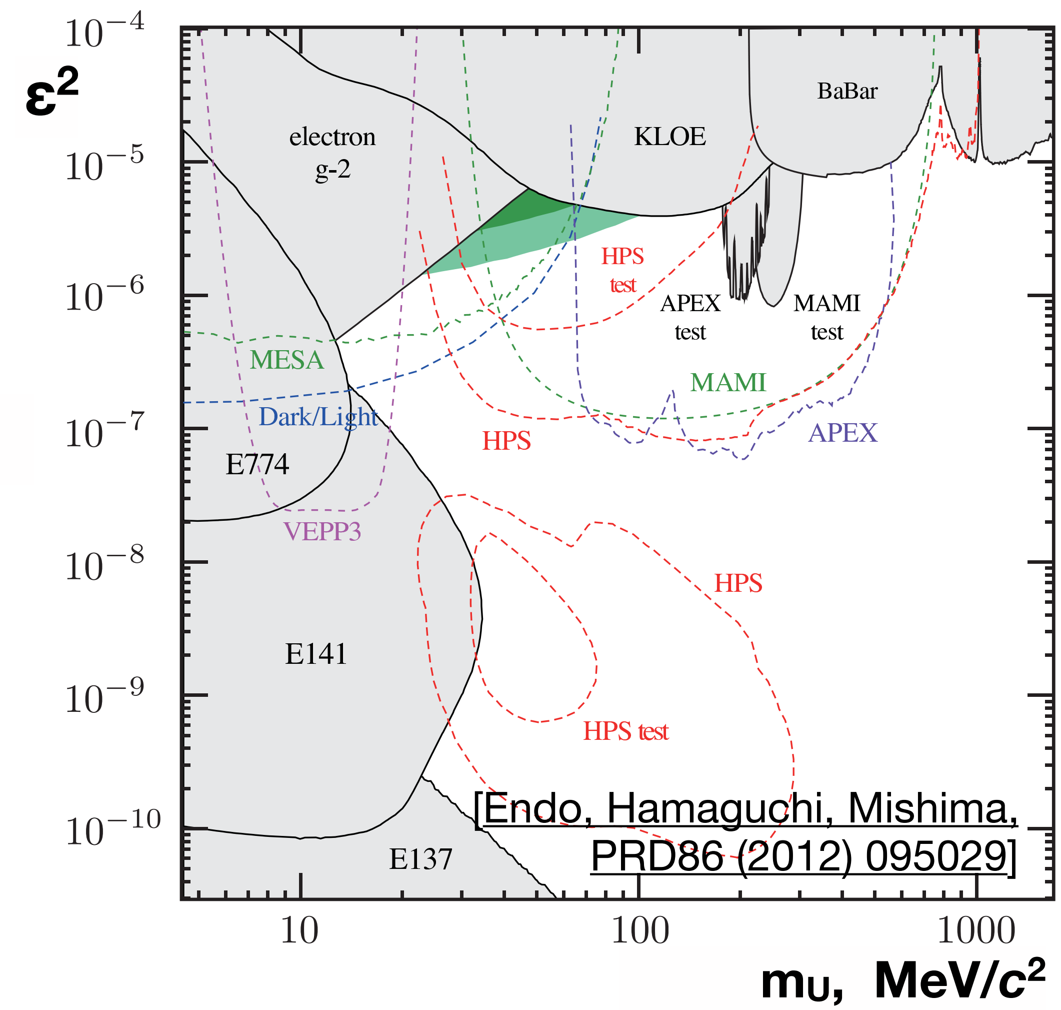
Channel	Motivation	90% CL Limit	Experiment
$K^+ \to \pi^+ X^0$	new particle	$< 5.9 \times 10^{-11}$ (m_X=0)	E787, E949
$K^+ \to \pi^+ \chi \chi$	new particles	——	E949
$K^+ \to \pi^+ \pi^+ e^- \nu$	$\Delta S \neq \Delta Q$	$< 1.2 \times 10^{-8}$	Geneva/Saclay
$K^+ \to \pi^+ \pi^+ \mu^- \nu$	$\Delta S \neq \Delta Q$	$< 3.0 \times 10^{-6}$	Geneva/Saclay
$\pi^0 \to e^+ e^- (\gamma)$	dark photon	——	——
$\pi^0 \to e^+ e^- e^+ e^-$	T violation	$C = -0.77 \pm 0.53$	Samios *et al.*
$\pi^0 \to \gamma \gamma \gamma$	C violation	$< 3.1 \times 10^{-8}$	Crystal Box
$\pi^0 \to \gamma \gamma \gamma \gamma$	light scalar	$< 2 \times 10^{-8}$	Crystal Box
$\pi^0 \to \nu \nu$	RH neutrino	$< 2.7 \times 10^{-7}$	E949

Search for Dark Photons

Search for the ***U* boson** ("dark photon") interesting as possible explanation of several SM anomalies:

- PAMELA e^+ excess
- Dama/Libra dark matter signals
- 3.6 σ anomalies in $(g\text{-}2)_\mu$

➜ Several dedicated experiments.

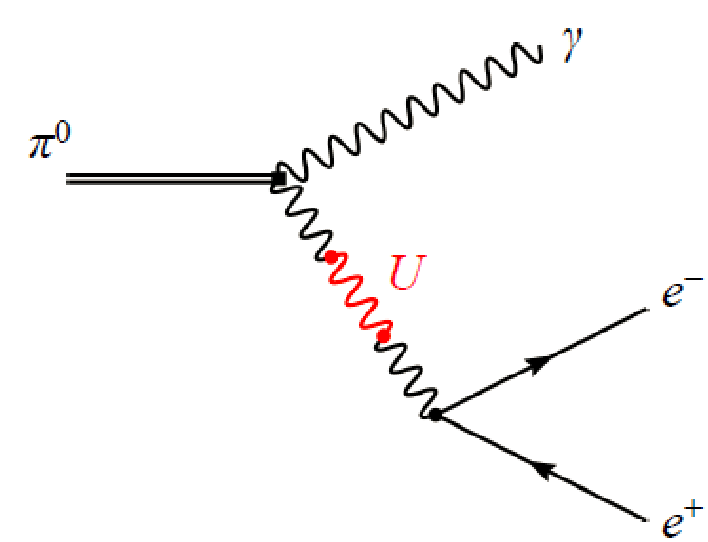


NA48/2 / NA62:

Search in $\pi^0 \to U\gamma$ decays (with $U \to e^+e^-$)

- NA48/2: already 2×10^7 $\pi^0 \to e^+e^-\gamma$ decays
- NA62: expect 10^8 $\pi^0 \to e^+e^-\gamma$ decays
- m_{ee} resolution of 1 MeV

➜ **Sensitive to m_U < 100 MeV with $\varepsilon \sim 10^{-3}$**



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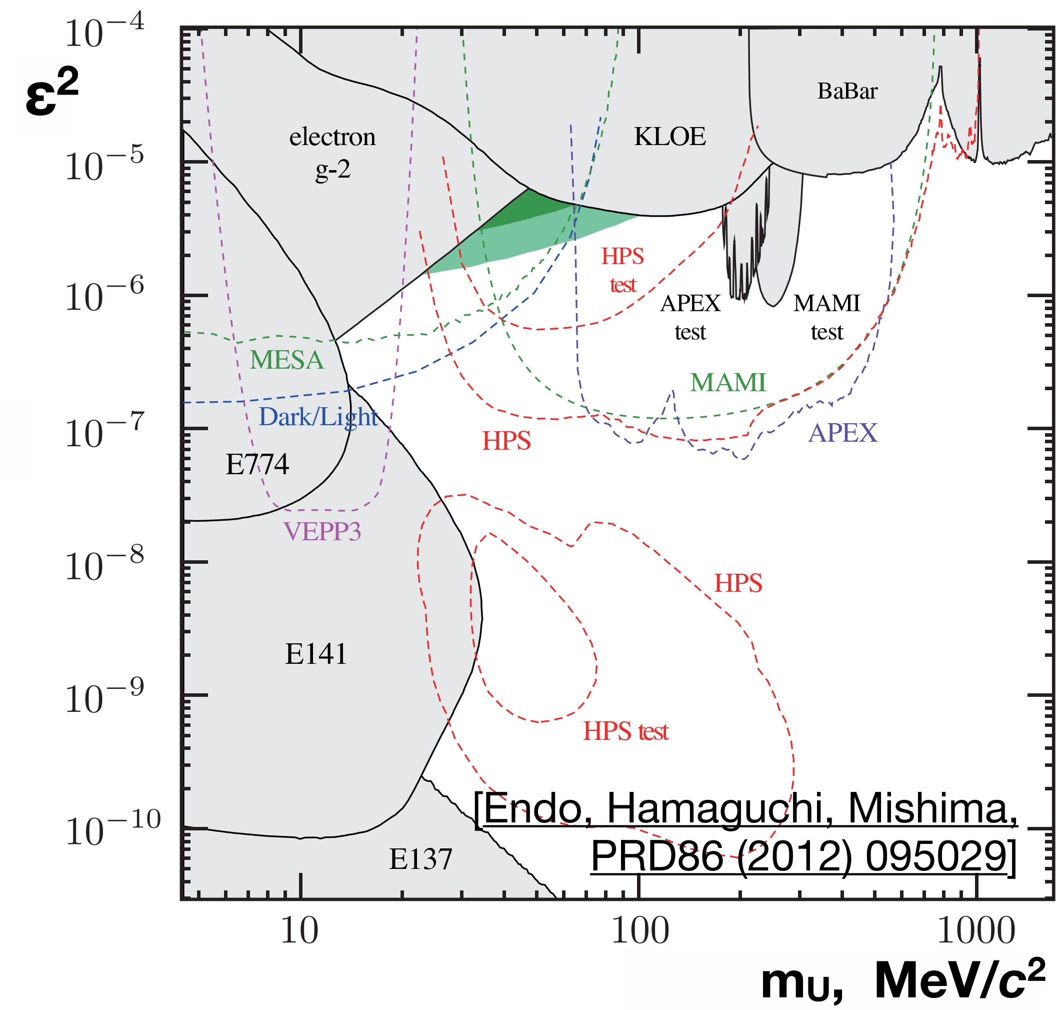

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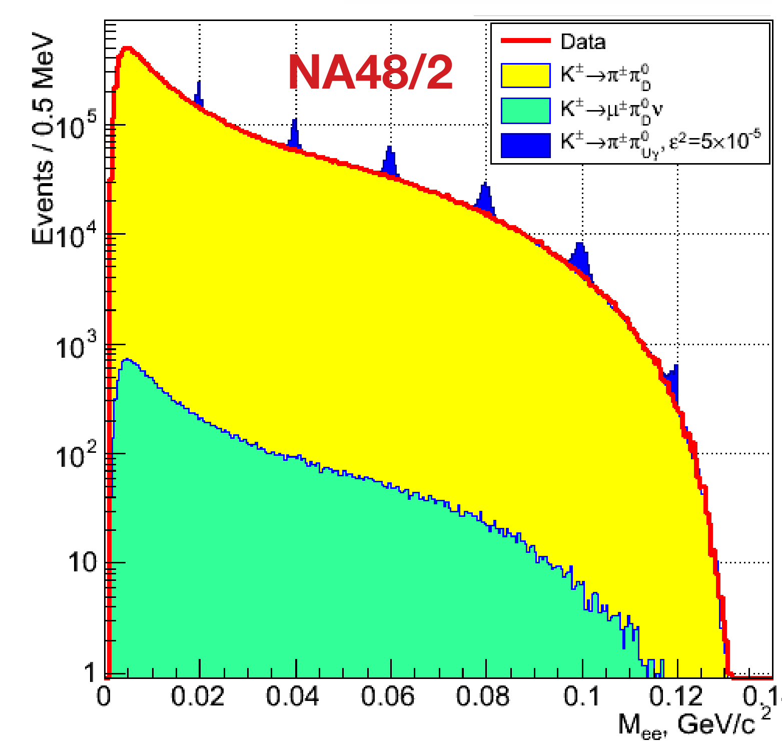

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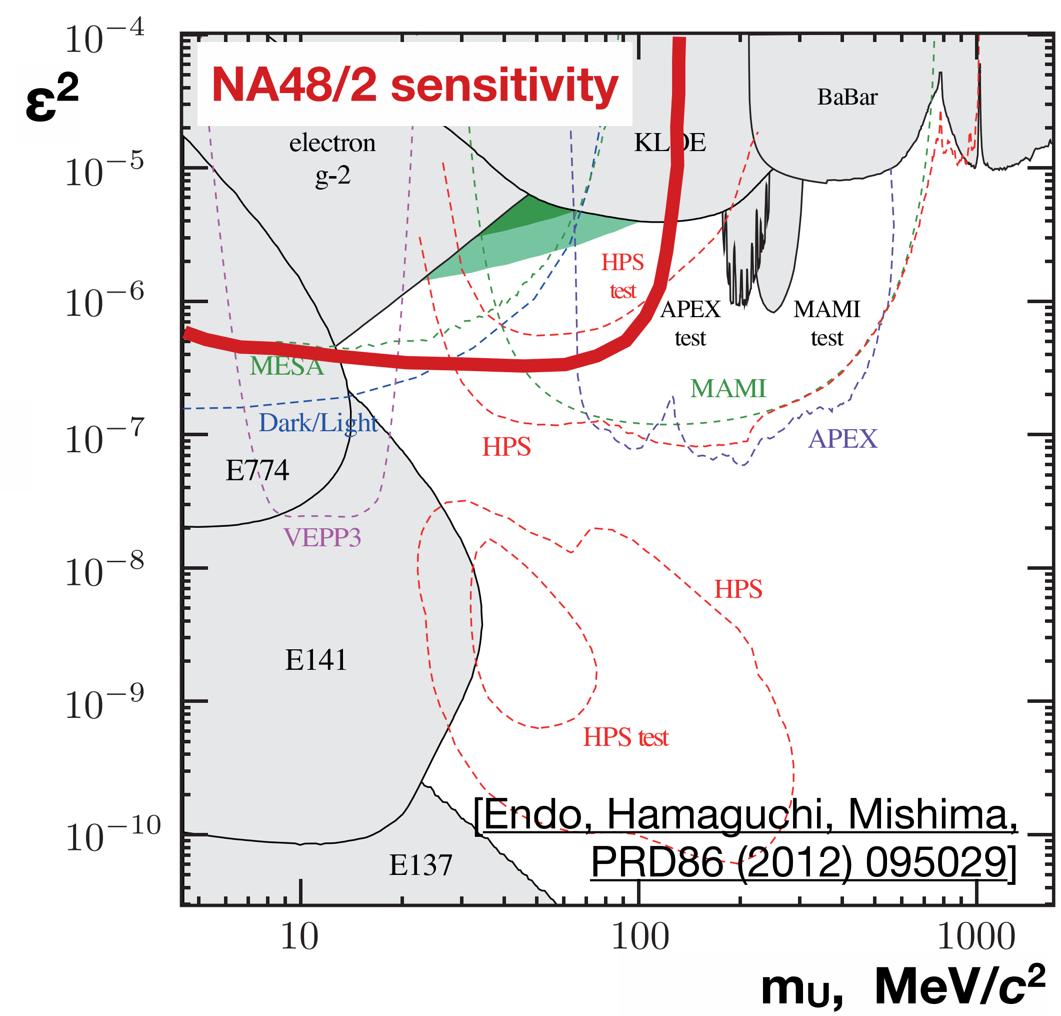

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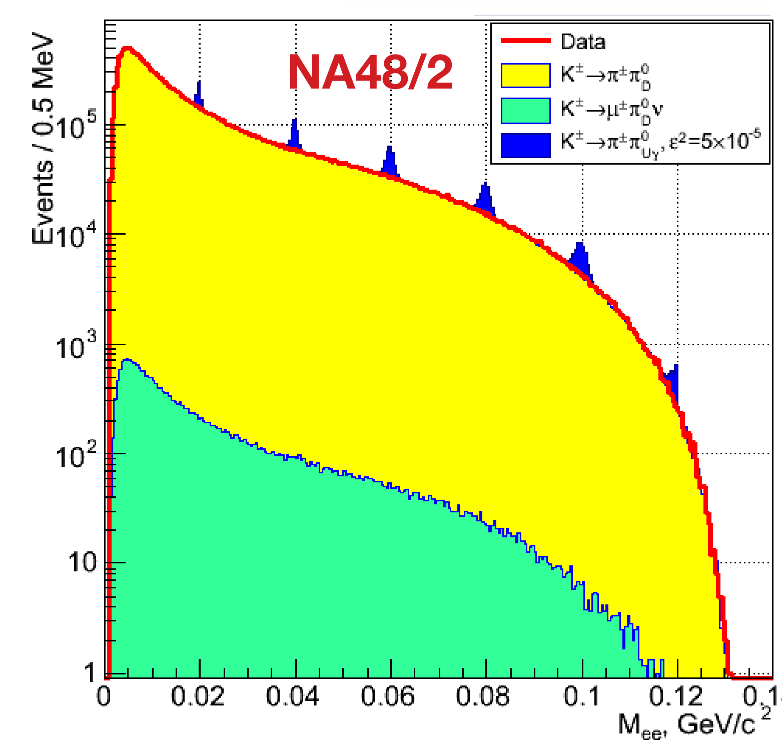

Conclusions

Kaon physics still a major player in particle physics.

➜ **very high sensitivity to many observables and new physics.**

$K^\pm \to \pi^\pm \gamma\gamma$: new measurement with **~200 events** and low background.

$K^\pm \to \pi^\pm e^+e^-\gamma$: first observation with **~2500 events**, expect result soon.

$K^+ \to \pi^+\nu\bar{\nu}$: one of the golden channels in flavour physics.

- Directly measures $V_{ts} V_{td}^*$ with small theoretical uncertainties.
- Very high **sensitivity to new physics** beyond the SM.

NA62 at CERN designed for measurement of **very rare kaon decays.**

- Under construction, first data-taking after LHC shutdown (end 2014)
- Goal: **~100 $K^+ \to \pi^+\nu\bar{\nu}$ events in 2 years** of data taking.
- In addition: Huge samples of practically all **K^+ decays**
  ➜ **Precise measurements on virtually all rare decays!**

Many thanks for the attention!