Recent results and prospects on kaon physics from CERN

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On behalf of the NA62 collaboration

XXVII Rencontres de Blois
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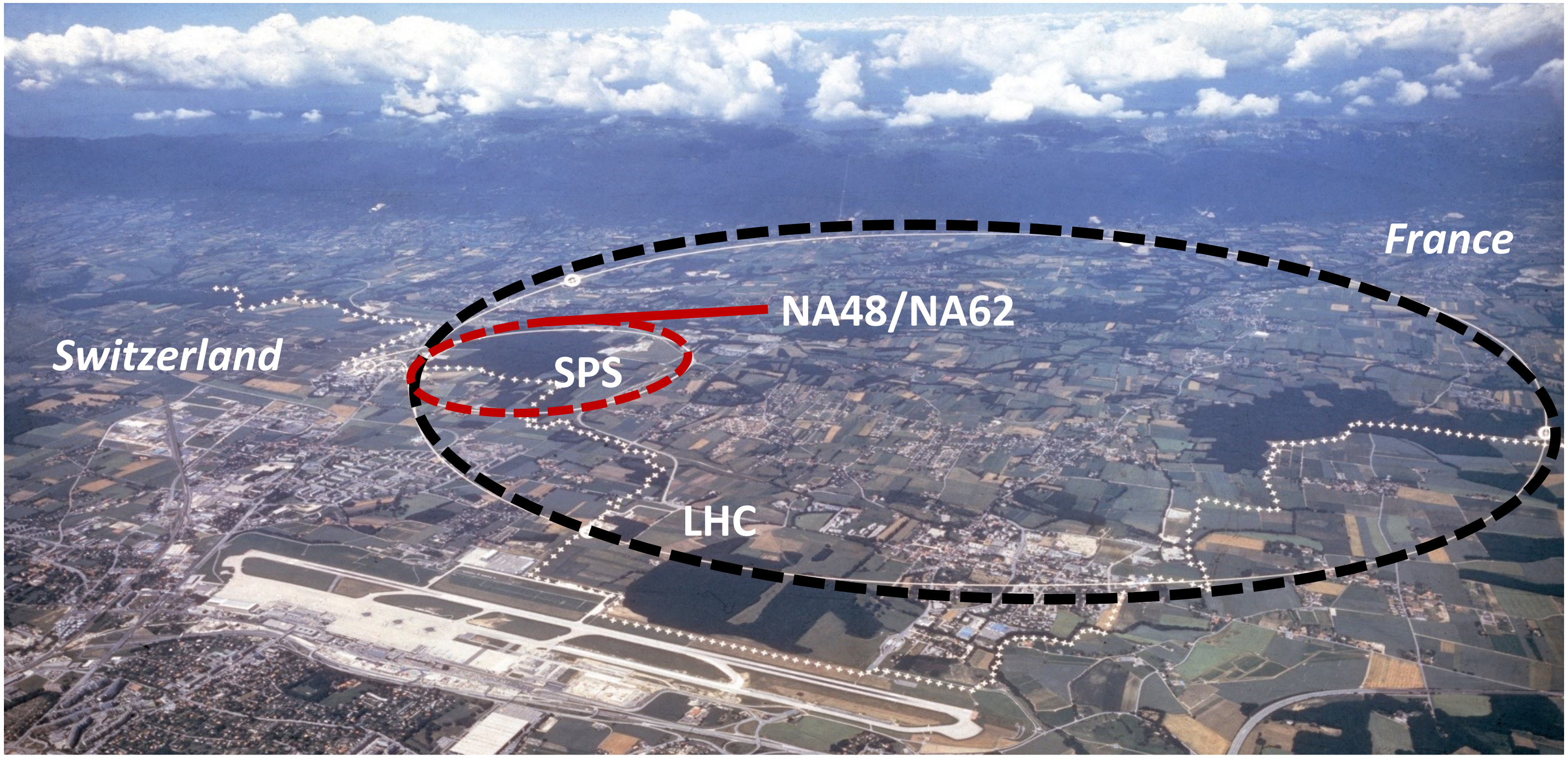
Outline

- Kaon experiments at the *CERN SPS*
- Search for the dark photon in π^0 decays at ***NA48/2***
- New measurement of $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ by ***NA48/2***
- Prospects for the ***NA62*** experiment
    - Precision test of the SM
    - Status after the 2014 run

NA48/NA62 experiments at CERN



North Area kaon experiments (after NA31)

NA48 (K_L/K_S)	1997 - 2001	Discovery of direct CPV, Re(ε'/ε)
NA48/1 (K_S/hyperons)	2002	Rare K_S/hyperon decays
NA48/2 (K^+/K^-)	2003 - 2004	Direct CPV, rare $K^\pm$ decays
NA62 R_K - phase (K^+/K^-)	2007 - 2008	$R_K = K^\pm{}_{e2}/K^\pm{}_{\mu 2}$
NA62 (K^+)	2014 - 2017	$BR(K^+ \to \pi^+ \nu\bar{\nu})$, rare K^+ and π^0

The NA48/2 detector

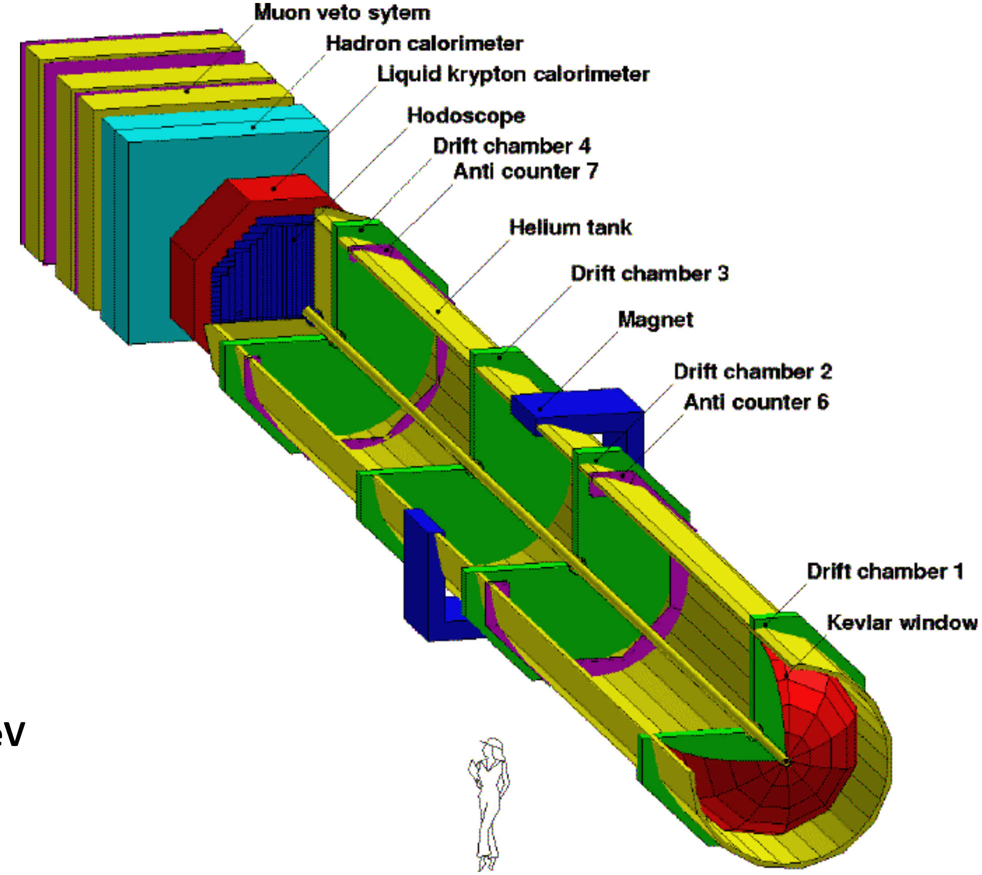
- **Narrow momentum band $K^{\pm}$ beams:**
  $p_K = 60$ GeV/c, $\delta p_K / p_K \sim 1\%$ *(rms)*
  Max $K^{\pm}$ decay rate $\sim$*100* kHz

- **Magnetic spectrometer:**
  4 drift chambers (DCH) and a dipole magnet
  $\sigma_p / p = (1.0 \oplus 0.044\ .p)\%$ *p* in GeV/*c*

- **Scintillator hodoscope (HOD):**
  Fast trigger, time measurement ($\sigma_t = 150$ ps)

- **LKr electromagnetic calorimeter:**
  High granularity , quasi-homogeneous (~$27X_0$)
  $\sigma_E / E = \left(3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42\right)\%$ *E* in GeV
  $\sigma_x = \sigma_y = \left(4.2/\sqrt{E} \oplus 0.6\right)$ mm

- **Iron-scintillator Hadron calorimeter**
  and **Muon counters**

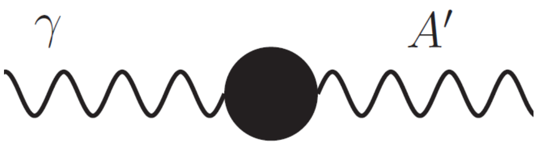


The dark photon @ NA48/2

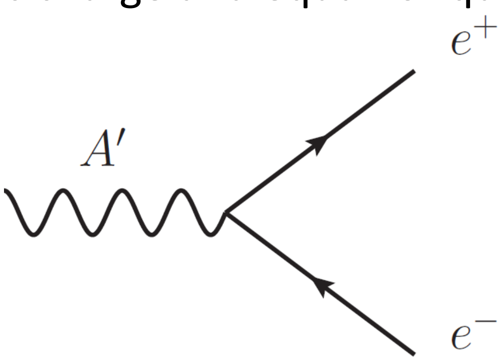
- If there is an additional U(1) symmetry in nature there can be mixing between the photon and the new gauge boson (**A'** or "**Dark Photon**")
  B. Holdom, Phys. Lett. **B166**, 196 (1986)

- The interaction of the hidden sector and the SM can be generated through **kinetic mixing** with the SM hyper-charge U(1)

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{dark}^{\mu\nu}$$



  - new coupling constant ε - proportional to electric charge and equal for quarks and leptons
  - Not all SM particles need to be charged under the new symmetry
  - QED-like interactions with SM fermions



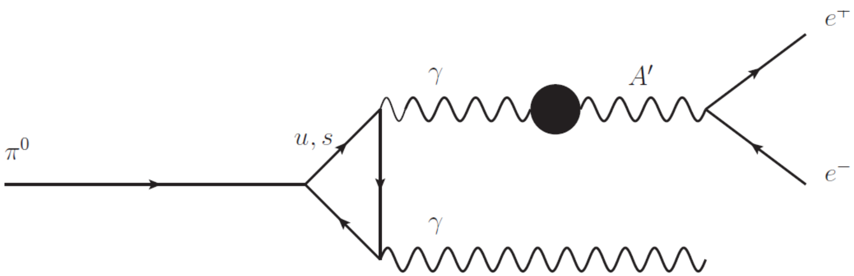
- **Could provide explanations** for the observed rise with energy of positron fraction in cosmic-rays (AMS-02, FERMI, PAMELA)
- and the muon gyromagnetic ratio g-2 problem

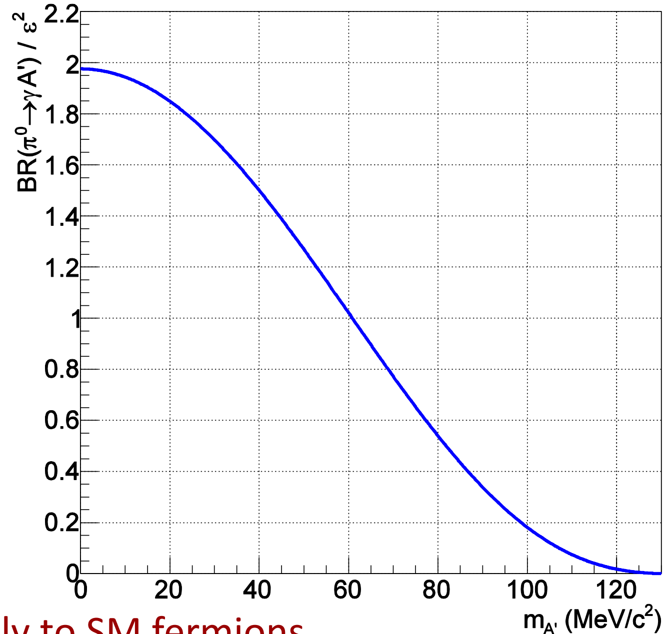
The dark photon @ NA48/2: DP production in π^0 decays

- **Kaon beams:** source of large tagged π^0 samples ($K^{\pm} \to \pi^{\pm}\pi^0$, $K^{\pm} \to \pi^0\mu^{\pm}\nu$)

- **A'** production in $\pi^0 \to \gamma A'$ due to **kinetic mixing**
  (Batell, Pospelov and Ritz, **PRD80** (2009) 095024)

$$\mathcal{B}(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathcal{B}(\pi^0 \to \gamma\gamma)$$





Kinematical suppression of $\pi^0 \to \gamma A'$ for $m_{A'}$ approaching m_{π^0}

Assume: no dark sector particles lighter than A' and A' decays only to SM fermions
$B(A' \to e^+e^-) \approx 1$ for A' in the range $2m_e < m_{A'} < m_{\pi^0}$

Total decay width: $\Gamma_{A'} \approx \Gamma(A' \to e^+e^-) = \frac{1}{3}\alpha\varepsilon^2 m_{A'}\sqrt{1 - \frac{4m_e^2}{m_{A'}^2}}\left(1 + \frac{2m_e^2}{m_{A'}^2}\right)$

Proper lifetime: $c\tau_{A'} = \hbar c/\Gamma_{A'} \approx 0.8\ \mu\text{m} \times \left(\frac{10^{-6}}{\varepsilon^2}\right) \times \left(\frac{100\ \text{MeV}/c^2}{m_{A'}}\right)$

Prompt decay at the production point ($\varepsilon > 10^{-7}$)

The dark photon @ NA48/2: Data sample

- Exclusive search for decay chains $K^{\pm} \to \pi^{\pm}\pi^{0}(\boldsymbol{K_{2\pi}})$ and $K^{\pm} \to \pi^{0}\mu^{\pm}\nu(\boldsymbol{K_{\mu 3}})$ followed by $\pi^{0} \to \gamma A'$, $A' \to e^{+}e^{-}$
  - Trigger based on HOD multiplicity (L1) and DCH track reconstruction (L2)
  - Selection: 3-track vertex topology; single isolated LKr energy deposit; fully reconstructed final state; presence of μ or π for a $K_{2\pi}$ or $K_{\mu 3}$ candidate;
  - $K^{\pm} \to \pi^{0}e^{\pm}\nu(\boldsymbol{K_{e3}})$ decay not considered for ambiguity due to $3e^{\pm}$ in final state
  - Search for a narrow peak in $e^{+}e^{-}$ invariant mass spectrum
  - Excellent $e^{+}e^{-}$ mass resolution: $\sigma_{m} = 0.011 \times m_{ee}$
- Signature identical to $K^{\pm} \to \pi^{\pm}\pi^{0}{}_{D}(\boldsymbol{K_{2\pi D}})$ and $K^{\pm} \to \pi^{0}{}_{D}\mu^{\pm}\nu(\boldsymbol{K_{\mu 3D}})$ with $\pi^{0}{}_{D} \to \gamma e^{+}e^{-}$
  - Sensitivity limited by irreducible $\pi^{0}{}_{D}$ background
- Acceptance for both $\boldsymbol{K_{2\pi}}$ and $\boldsymbol{K_{\mu 3}}$ depending on $\boldsymbol{M_{A'}}$, up to *4.5%*
- A scan for a DP signal in the m_{ee} spectrum in the range 9 MeV/c^2 < $M_{A'}$ < 120 MeV/c^2
  Mass resolution $\sigma_m(m_{ee})$ varies from 0.16 MeV/c^2 to 1.33 MeV/c^2 ;
  Mass step: $\sigma_m/2$; Window width: $\pm 1.5\sigma_m$; 404 $M_{A'}$ hypothesis tested;

The dark photon @ NA48/2: Study of the π^0_D background

- **Simulations** of $K_{2\pi}$, $K_{\mu3}$ and $K_{3\pi}$ followed by π^0_D
  - Final state radiation included for $K_{2\pi}$ and $K_{\mu3}$

- π^0_D decay is simulated using the lowest-order differential decay rate:

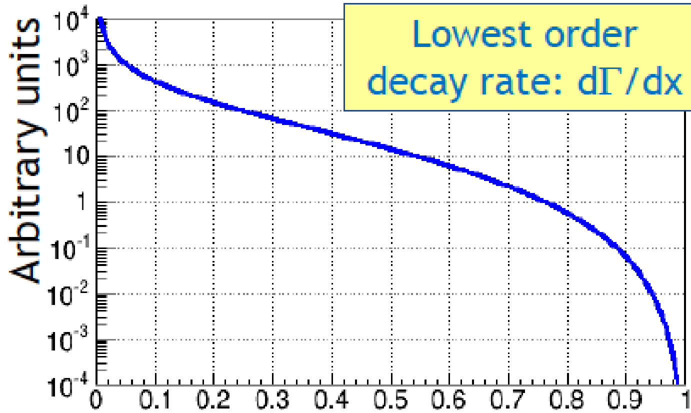
$$\frac{d^2\Gamma}{dxdy} = \Gamma_0 \frac{\alpha}{\pi} |F(x)|^2 \frac{(1-x)^3}{4x} \left(1 + y^2 + \frac{r^2}{x}\right)$$

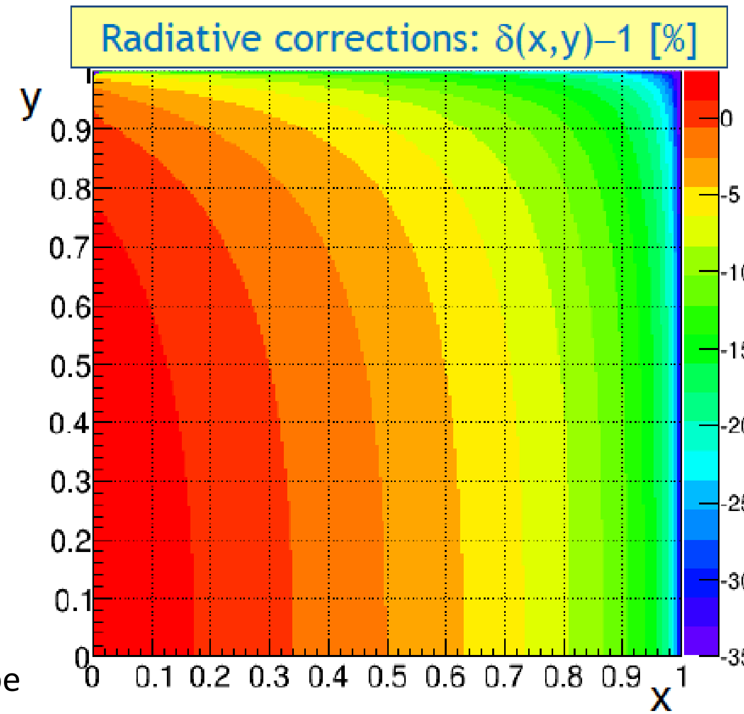
$$x = \frac{(Q_1+Q_2)^2}{m_{\pi^0}^2} = (m_{ee}/m_{\pi^0})^2, \qquad y = \frac{2P(Q_1-Q_2)}{m_{\pi^0}^2(1-x)}$$

- **Radiative corrections:** $\frac{d^2\Gamma^{rad}}{dxdy} = \delta(x,y)\frac{d^2\Gamma}{dxdy}$

Mikaelian and Smith, PRD5 (1972) 1763
Improved precision: T. Husek, K. Kampf and J. Novotny, arXiv:1504.06178

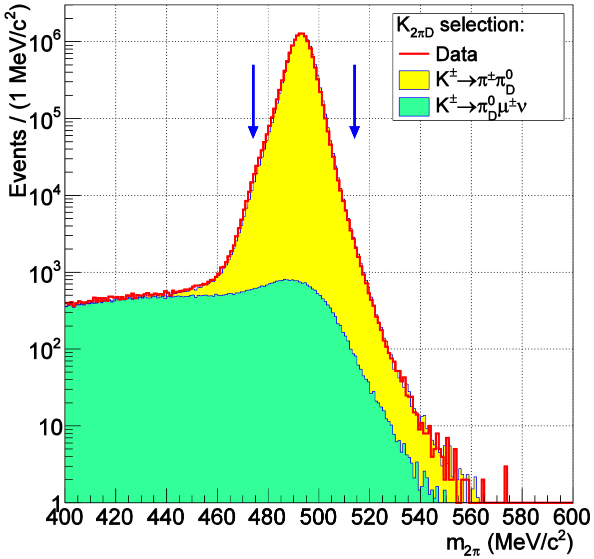
- **π^0 transition form factor: F(x) = 1 + ax**
  - TFF slope $a = 0.032 \pm 0.004$ (**PDG**, dom. by $e^+e^- \to e^+e^-\pi^0$ measurement)
  - Better description of the data with an effective TFF slope from a fit to the measured m_{ee} spectrum

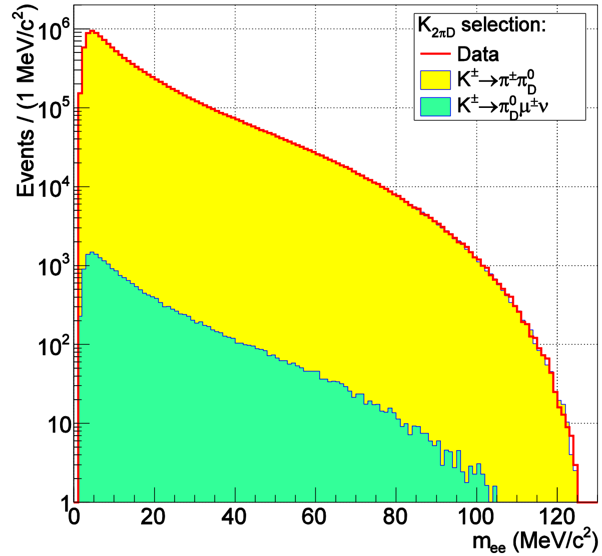


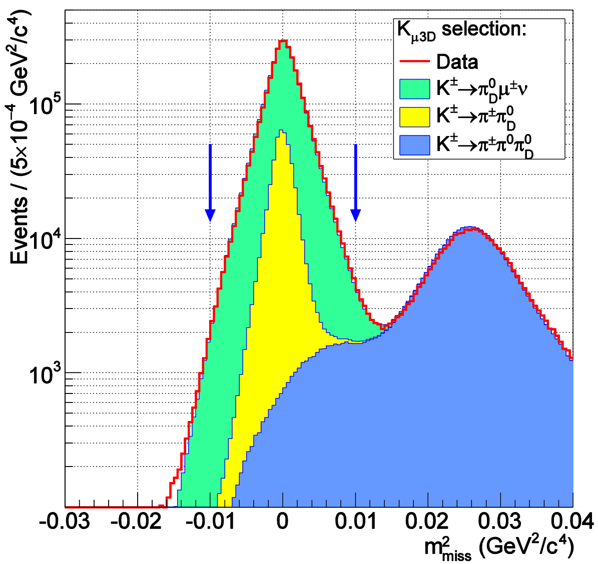


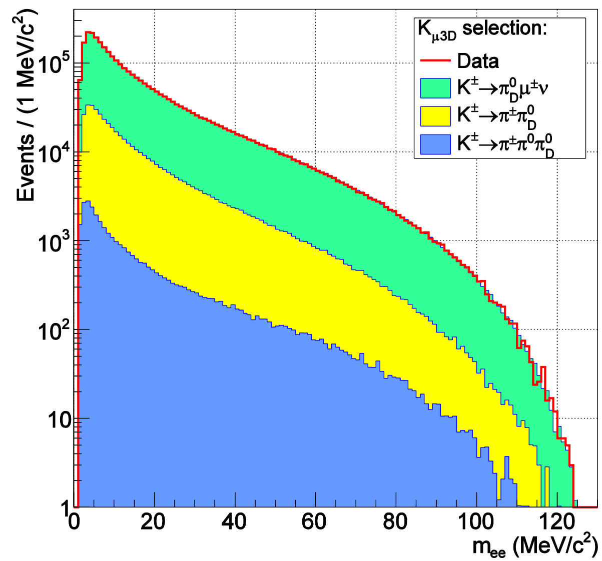
The dark photon @ NA48/2: Data sample

NA48/2 data (2003-2004): $(1.57 \pm 0.05) \times 10^{11} K^{\pm}$ decays in the fiducial volume





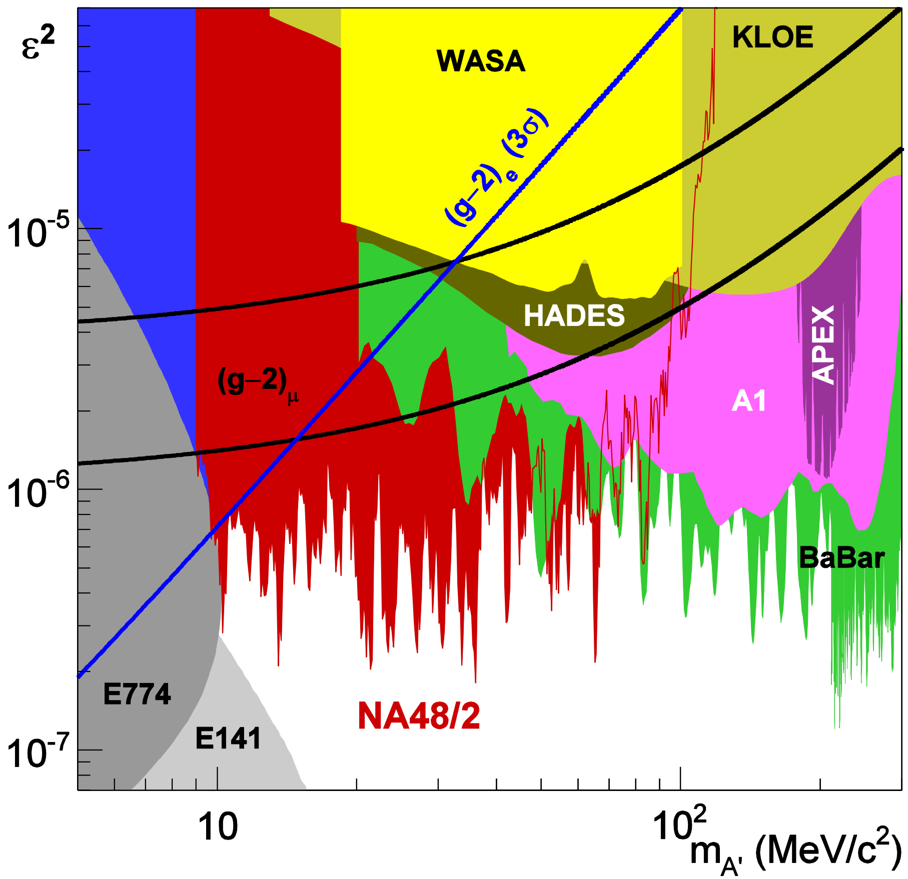




$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0} (K_{3\pi})$ only considered as background in $K_{\mu 3}$ sample

The dark photon @ NA48/2: Exclusion limit

DP exclusion summary



Phys.Lett. B746 (2015) 178

Upper limit at 90% C.L. on ε^2 for each DP mass hypothesis

- Statistical significance < 3σ: **No DP signal is observed.**
- Improvements of the existing limits on ε^2 in the range 9-70 MeV/c^2
- Most stringent limits on ε^2 at low DP mass where kinematic suppression of the $\pi^0 \to \gamma A'$ decay is weak
- If DP couples to SM fermions and photons and decays only to electrons, it is ruled out as explanation for the anomalous $(g-2)_\mu$
- Background-limited measurement: Modest improvement with this technique using larger samples (NA62 experiment)

ChPT studies @ NA48/2

- Kaon decays provide a great opportunity to test the weak part of ChPT lagrangian

$$L_{\Delta S=1} = L^2{}_{\Delta S=1} + L^4{}_{\Delta S=1} = \underbrace{G_8 F^4 \langle \lambda_6 D_\mu U^+ D^\mu U \rangle}_{K\to 2\pi/3\pi,\gamma\gamma} + \underbrace{G_8 F^2 \sum N_i W_i}_{K^+\to\pi^+\gamma\gamma,\ K\to\pi\pi\gamma}$$

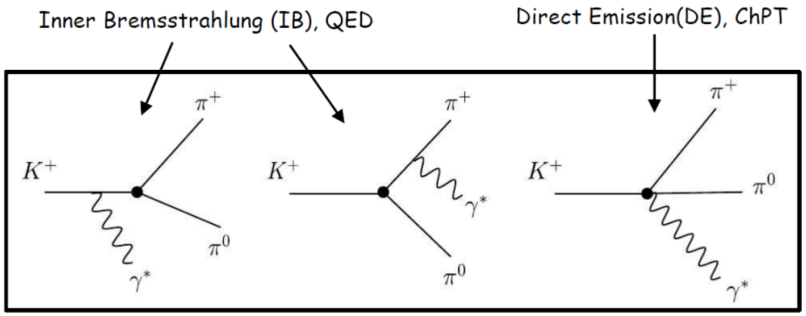
D'Ambrosio PoS (EFT09) 061

- 37 poorly known N_i coefficients and W_i operators
- Combinations of such couplings accessible by measuring kaon decays branching fractions and form factors

- ***NA48/2 can access all the charged kaon decays with high precision***

Decay	$\mathscr{L}^4_{\Delta S=1}$ counterterms	
$K^+ \to \pi^+ l^+ l^-$	$N^r_{14} - N^r_{15}$	***NA48/2*** PLB 677 (2009) 246-254, PLB 697 (2011) 107-115
$K_S \to \pi^0 l^+ l^-$	$2N^r_{14} + N^r_{15}$	***NA48/1*** Phys.Lett. B576 (2003) 43-54, PLB 599 (2004) 197-211
$K^\pm \to \pi^\pm \gamma\gamma$	$N_{14} - N_{15} - 2N_{18}$	***NA48/2*** NA48/2 Phys.Lett. B730 (2014) 141, ***NA62*** Phys. Lett. B732C (2014) 65
$K_S \to \pi^+\pi^-\gamma$	$N_{14} - N_{15} - N_{16} - N_{17}$	
$K^\pm \to \pi^\pm\pi^0\gamma$	$N_{14} - N_{15} - N_{16} - N_{17}$	***NA48/2*** EPJC 68 (2010) 75-87
$K_L \to \pi^+\pi^- e^+e^-$	$N^r_{14} + 2N^r_{15} - 3(N^r_{16} - N_{17})$	***NA48*** Eur.Phys.J. C30 (2003) 33-49
$K^+ \to \pi^+\pi^0 e^+e^-$	$N^r_{14} + 2N^r_{15} - 3(N^r_{16} - N_{17})$	**Still missing!** New measurement from ***NA48/2***
$K_S \to \pi^+\pi^- e^+e^-$	$N^r_{14} - N^r_{15} - 3(N^r_{16} + N_{17})$	***NA48*** Eur.Phys.J. C30 (2003) 33-49

$\mathrm{B}(\mathrm{K}^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-})$ @ *NA48/2*



$$\frac{d^3\Gamma}{dE^*_\gamma dT_c dq^2} = \frac{d^3\Gamma_{IB}}{dE^*_\gamma dT_c dq^2} + \frac{d^3\Gamma_{E}}{dE^*_\gamma dT_c dq^2} + \frac{d^3\Gamma_{M}}{dE^*_\gamma dT_c dq^2} + \frac{d^3\Gamma_{int}}{dE^*_\gamma dT_c dq^2}$$

L. Cappiello, O.Cata, G. D'Ambrosio, Dao Neng-Gao, **Eur. Phys. J. C 72:1872**

$\mathrm{K}^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ offers various opportunities for ChPT tests

- Electric interference ($\Gamma_{IB}\Gamma_{E}$) extraction can confirm the discrepancy in sign with the theoretical prediction observed by the NA48/2 in $\mathrm{K}^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ (EPJC 68 (2010) 75-87)
- Magnetic interference (genuine to $\mathrm{K}^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$) can be used to extract the sign of the magnetic term Γ_M (impossible to extract in $\mathrm{K}^{\pm} \to \pi^{\pm}\pi^{0}\gamma$)
- P violating observables in the dilepton pair coupling can be used to access short distance physics using K^{+}only (NA62)
- Charge asymmetry not contaminated by indirect CP violation (as in K^{0})

$B(K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-})$ @ *NA48/2*: data sample and selection

- **Data sample:** 2003 ***NA48/2*** run

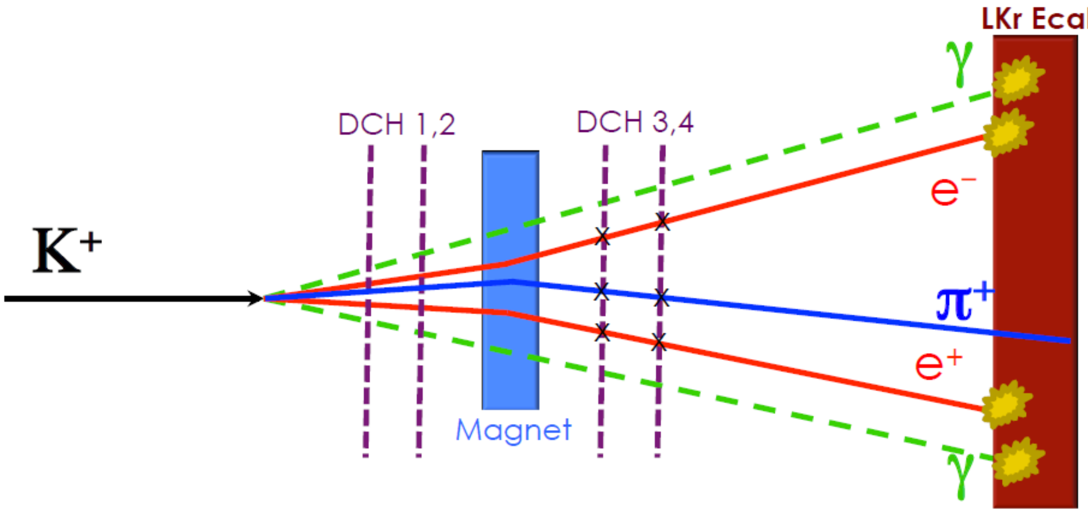
$\sim\mathbf{8 \times 10^{10}}$ $\boldsymbol{K}$ decays

- **Reconstruction strategy:**

3 good tracks and 2 photon clusters

$M_{\gamma\gamma}$ compatible with $M_{\pi 0}$

Identified 2 electrons and a pion by E/p



- **Main background sources:**

$\boldsymbol{K^{\pm} \to \pi^{\pm}\pi^{0}{}_{D} \to \pi^{\pm}e^{+}e^{-}\gamma}$ + **accidental or radiated** $\boldsymbol{\gamma}$**:** the $\boldsymbol{\gamma\gamma}$ system mimics a fake $\boldsymbol{\pi^{0}}$
$\boldsymbol{K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}{}_{D} \to \pi^{\pm}\pi^{0}e^{+}e^{-}\gamma}$ + **with the** $\boldsymbol{\gamma}$ **lost or merged with another LKr cluster**

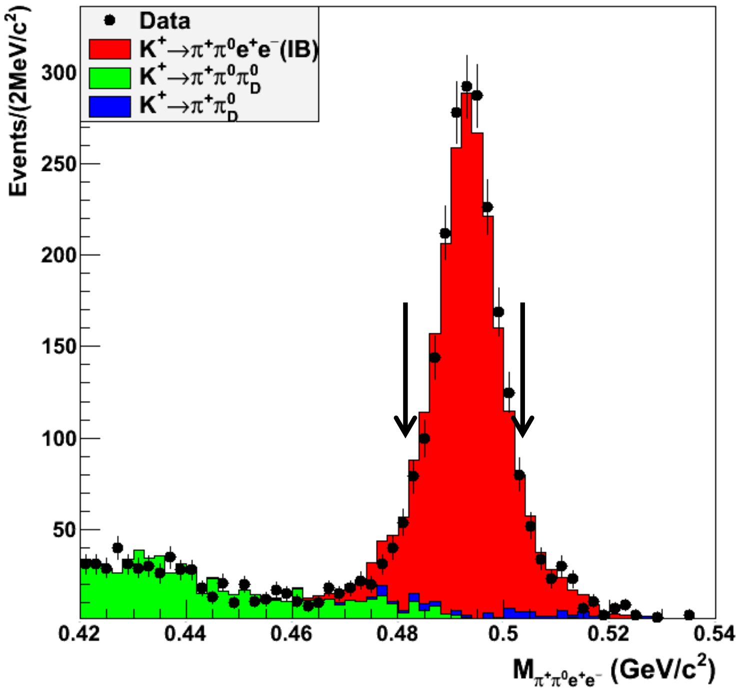
- **MC simulation**

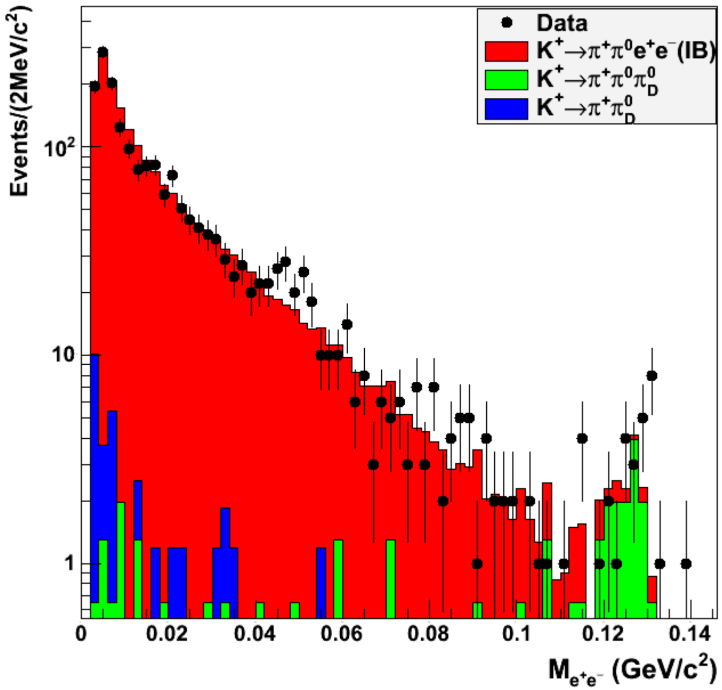
Tree-level description: Inner Bremsstrahlung, Direct Emission and Electric Interference generators (no magnetic interference) based **L. Cappiello, O. Cata, G. D'Ambrosio, Dao Neng-Gao, Eur. Phys. J. C 72:1872 (2012)**

Coulomb correction and real photon simulation (PHOTOS package) are additionally implemented in the MC simulation as far as there is no theoretical calculations for the exact radiative corrections.

$B(K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-)$ @ *NA48/2*: data sample

First observation!





- **Background suppression:**

  $K_{2\pi D}$ cut on $|M_{ee\gamma} - M_{\pi 0}| > 7\ \mathrm{MeV}/c^2$

  $K_{3\pi D}$ cut on $M^2{}_{\pi\pi} > 0.120\ \mathrm{GeV}^2/c^4$

- **Selecting mass in the region:**

  $|M_{\pi\pi ee} - M_K| < 10\ \mathrm{MeV}/c^2$

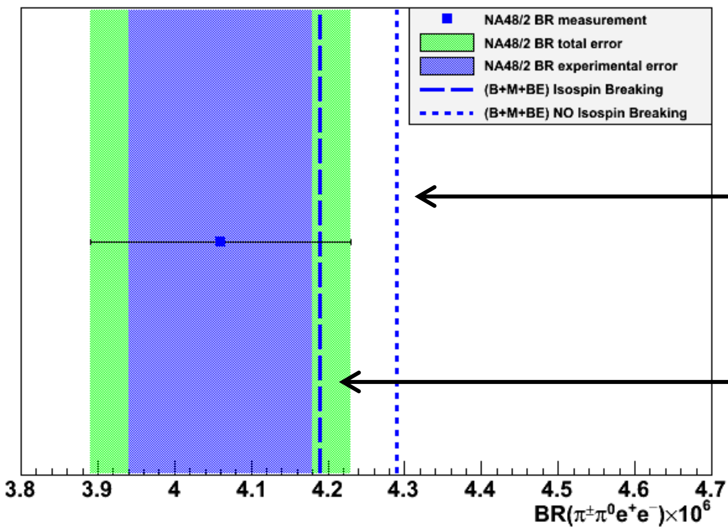
- **Total number of candidates: 1916**

  BG candidates from $K_{2\pi D} = 26 \pm 5.1$
  BG candidates from $K_{3\pi D} = 30 \pm 5.5$

$B(K^\pm \to \pi^\pm\pi^0 e^+ e^-)$ @ *NA48/2*: data sample

- $B(K^\pm \to \pi^\pm\pi^0 e^+ e^-)$ measured by normalising to $K^\pm \to \pi^\pm {\pi^0}_D(\gamma)$
- Systematic error dominated by model dependent acceptance
- External error from $B({\pi^0}_D \to \gamma e^+ e^-)$ dominates the total error
- With the present data sample NA48/2 is not sensitive to DE and INT contributions
- Model dependent BR computed using total acceptance in which the relative weight of the 3 components are obtained from (Eur. Phys. J. C (2012) 72:1872)

$$BR(K^\pm \to \pi^\pm\pi^0 e^+ e^-) = (4.06 \pm 0.10_{stat.} \pm 0.06_{syst.} \pm 0.13_{ext.}) \times 10^{-6}$$



Radiative correction included in the NA48/2 MC by using PHOTOS

Eur. Phys. J. C (2012) 72:1872
(no radiative correction included)

G. D'Ambrosio, O. Cata'
(unpublished private communication)

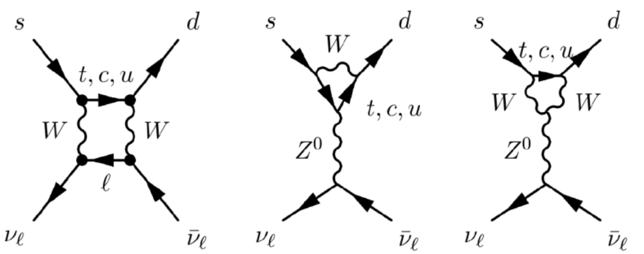
The NA62 experiment: main goal

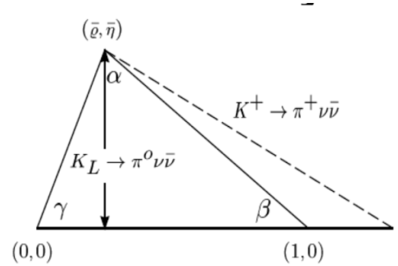
Major beam and detector upgrades for $B(K^+ \to \pi^+\nu\bar{\nu})$ measurement with 10% precision

- FCNC loop process, short distance dominated (GIM)
- Highly CKM suppressed ($B \sim |V_{ts}{}^* V_{td}|$)
- Extraction of V_{td}
- **High-sensitivity to New Physics**
- **High-precision theoretical prediction**

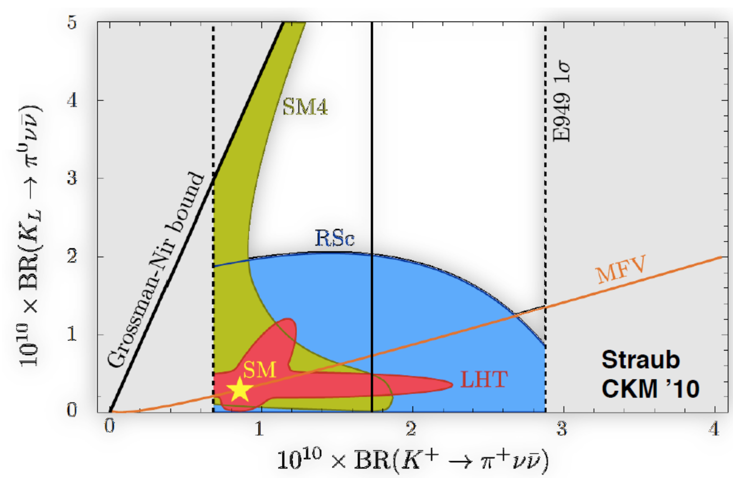
	SM prediction	Experiment
$B(K^+ \to \pi^+\nu\bar{\nu})$	$(9.11 \pm 0.72) \times 10^{-11}$ [1]	$(1.73 \pm 1.15) \times 10^{-10}$ [2]
$B(K_L \to \pi^0\nu\bar{\nu})$	$(3.00 \pm 0.30) \times 10^{-11}$ [1]	2.6×10^{-8} [3]

[1] Buras, Buttazo, Girbach-Noe, Knegjens, arXiv: 1503.02693
[2] BNL E787/E949: PRL101 (2008) 191802
[3] KEK E391a, PR D81 (2010) 072004





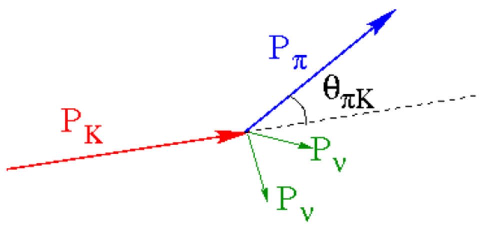
	NA48/2	NA62-R_K	NA62
Data taking	2003-4	2007-8	**2014-17**
Primary Intensity (ppp)	7×10^{11}	7×10^{11}	**3×10^{12}**
Solid angle (μsr)	~0.4	~0.4	**~12.7**
Beam momentum (GeV/c)	60	74	75
RMS momentum bite (GeV/c)	2.2	1.4	0.8
Spectrometer thickness (X_0)	2.8%	2.8%	1.8%
Spectrometer P_T kick (MeV/c)	120	265	270
$M(K^\pm \to \pi^\pm\pi^+\pi^-)$ resolution (MeV/c^2)	1.7	1.2	0.8
K decays in fiducial volume	2×10^{11}	2×10^{10}	**1.5×10^{13}**
Main trigger	Multi-track, $K^\pm \to \pi^\pm\pi^0\pi^0$	$1e^\pm$	$K^+ \to \pi^+\nu\nu$, ...



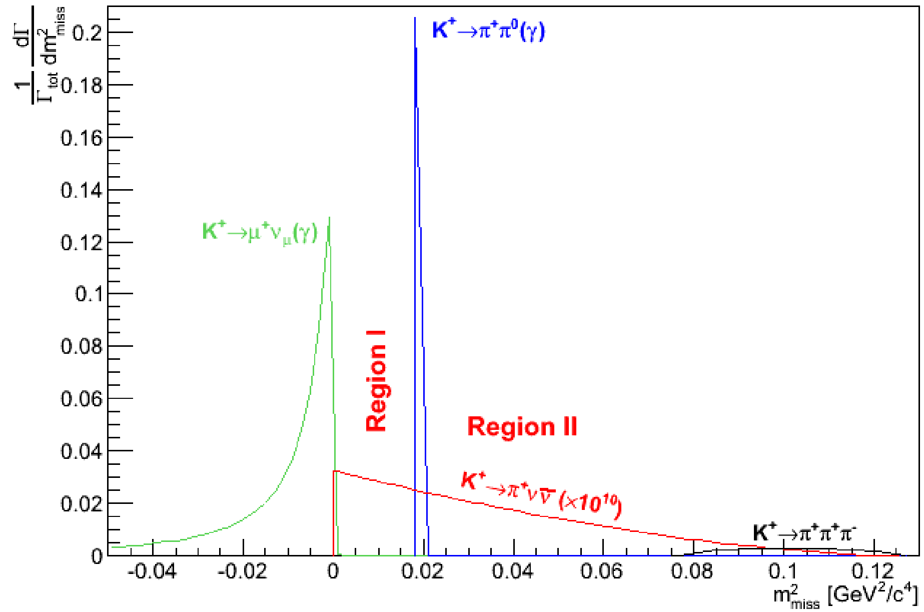
SM4: SM with 4th generation (Buras et al. 10) - largely ruled out by the Higgs discovery at 125 GeV
RSc: Randall-Sundrum (Blanke 09)
LHT: Littlest Higgs with T-parity (Blanke 10)
MFV: Minimal Flavour Violation (Hurth et al. 09)

The NA62 experiment: experimental strategy

- Signature: one track in the final state matched with a one beam kaon
- Kinematics defined by missing mass
  - two kinematic regions



$$m^2_{\mathrm{miss}} = (P_k - P_{\pi^+})^2$$



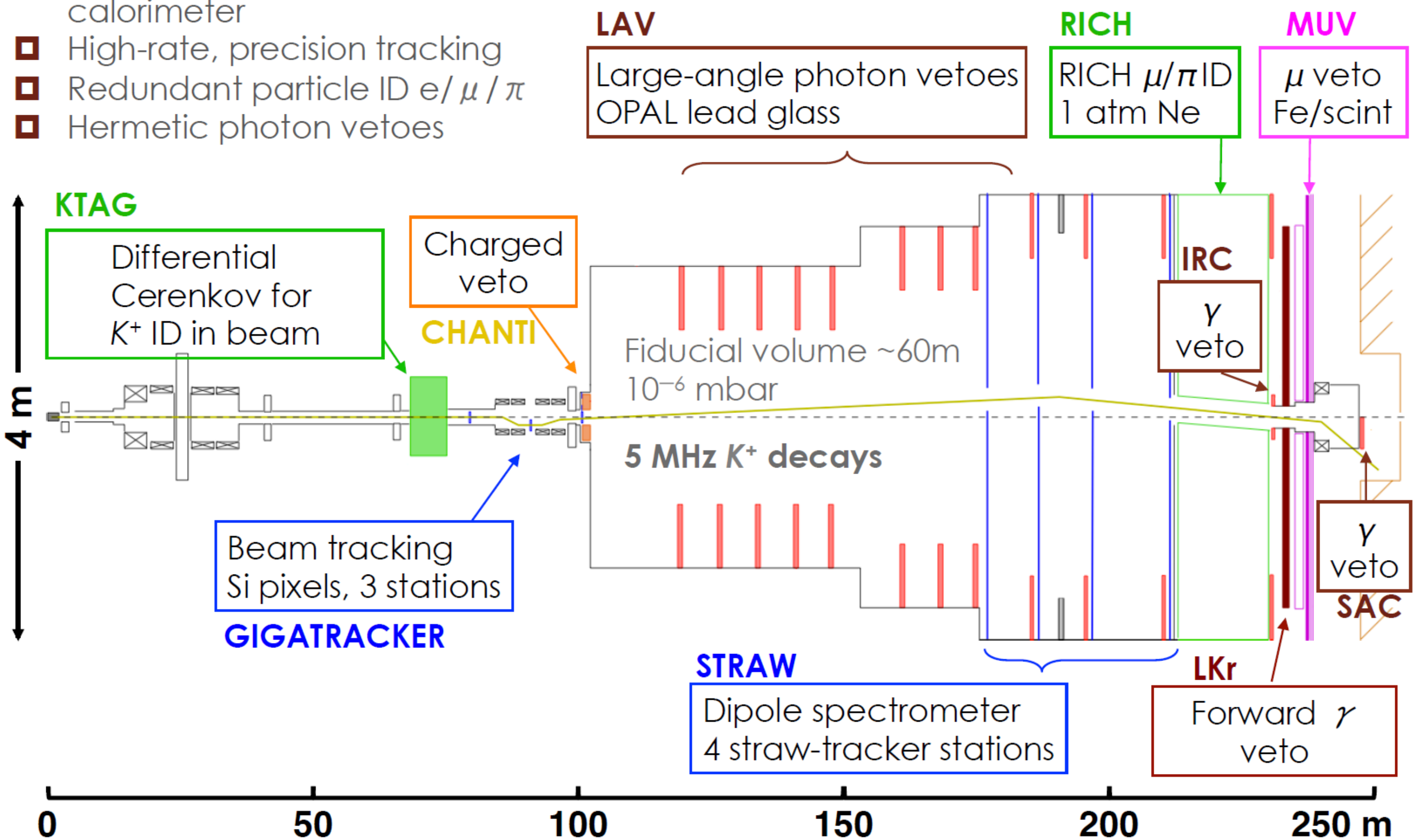
Decay	BR	Rejection
$K^+ \to \mu^+ \nu_\mu$	63%	μ-ID + kinematics
$K^+ \to \pi^+ \pi^0$	21%	γ-veto + kinematics
$K^+ \to \pi^+ \pi^+ \pi^-$	6%	π^--ID + multi-track + kinematics
$K^+ \to \pi^+ \pi^0 \pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3%	μ-ID + γ-veto
$K^+ \to \pi^0 e^+ \nu_e$	5%	e-ID + γ-veto

Required background suppression factors $O(10^{12})$

Kinematics	$O(10^4\text{-}10^5)$
Charged Particle ID	$O(10^7)$
γ detection	$O(10^8)$
Timing	$O(10^2)$

The NA62 experiment: new detector systems

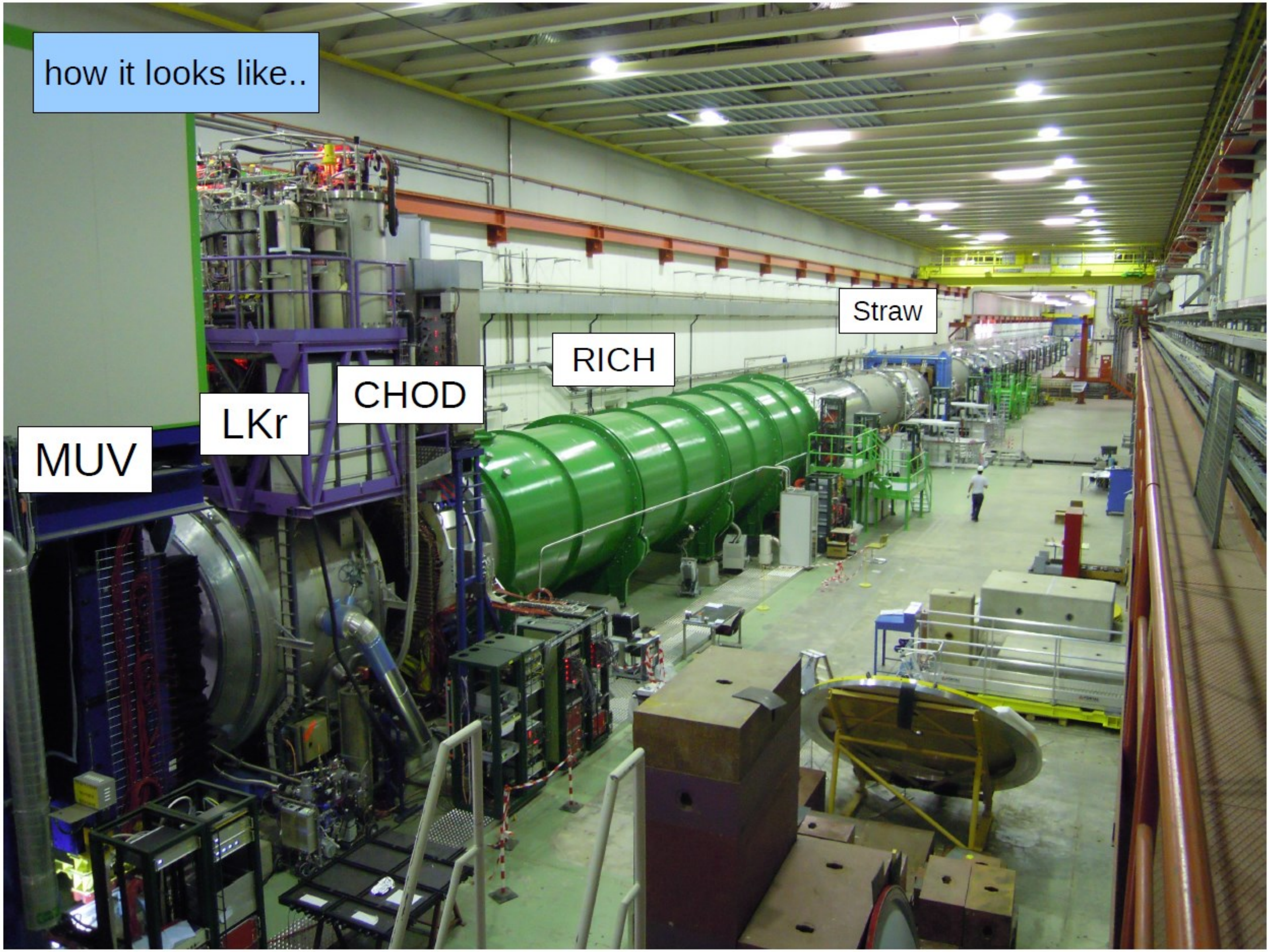
- High-performance EM calorimeter
- High-rate, precision tracking
- Redundant particle ID e/ μ / π
- Hermetic photon vetoes



- SPS 400 GeV/*c* proton beam interacts with a Beryllium target
- Sec. hadron beam: **positive 75 GeV/*c* particles (~6% K^+)**
- Nominal beam rate: **750 MHz (~45 MHz K^+)**

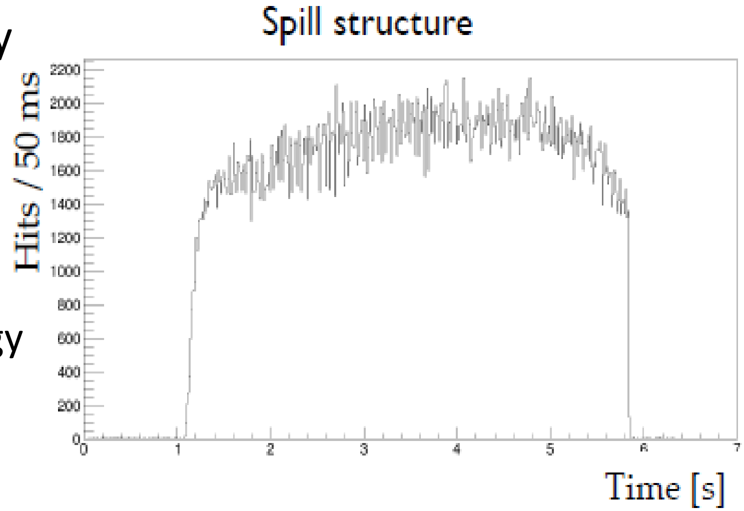
- **NA62 took first data in 2014!**
- **Pilot run with beam at up to 20% of the nominal intensity**
- **Almost all NA62 subsystems have been commissioned in 2014**
- Data analysis is in progress – the understanding of the detectors is improving every day.

The NA62 detector



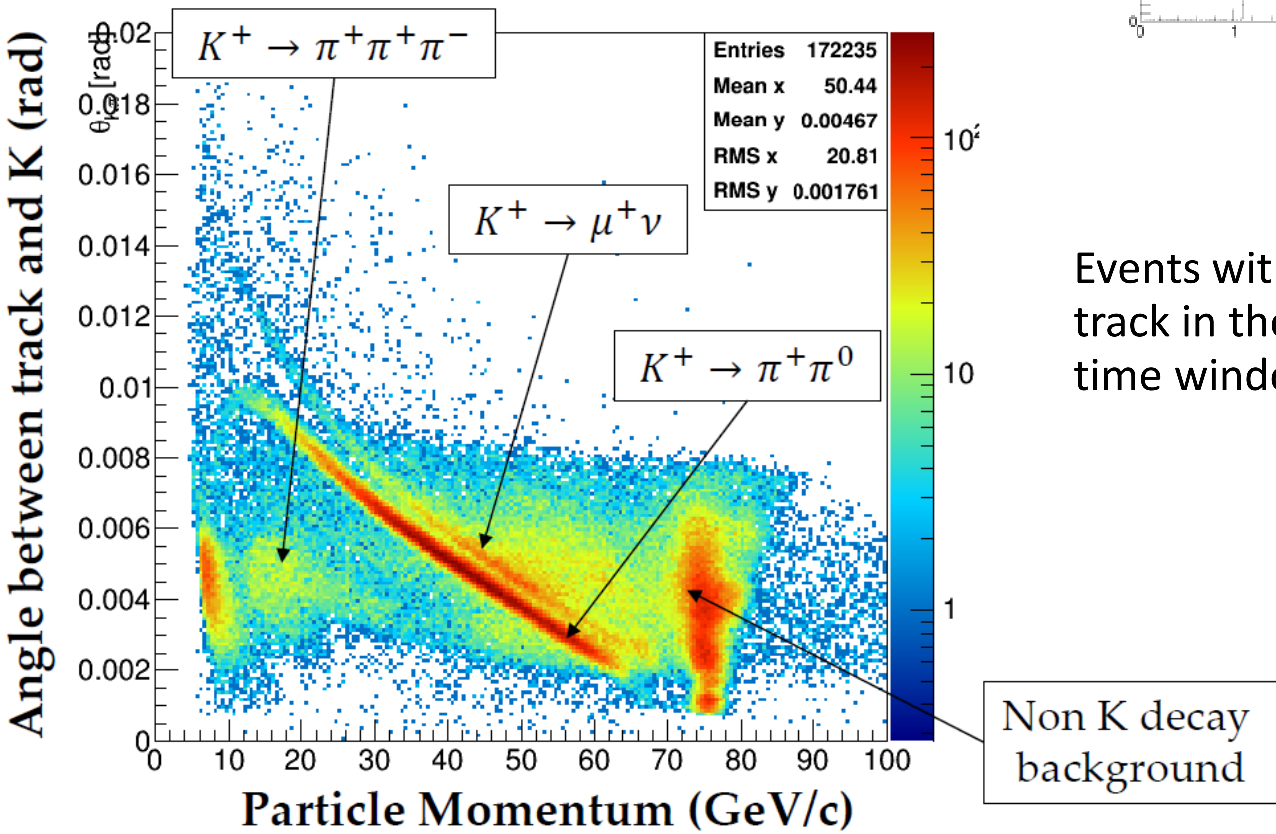
The NA62 experiment: first look at the 2014 data

~5% of nominal beam intensity



Preliminary studies:

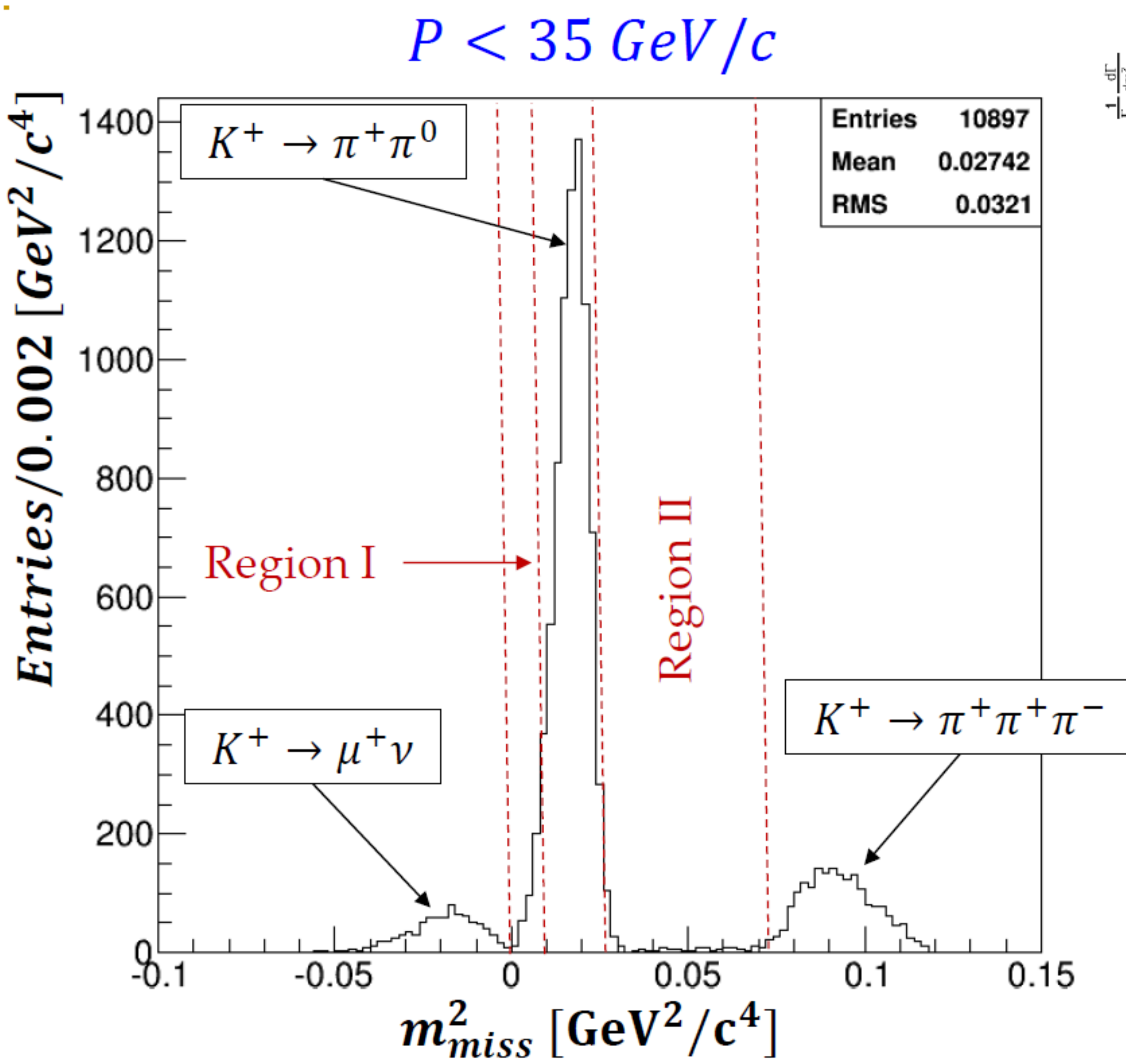
No GTK, Partial spectrometer (3 chambers used)
No offline RICH mirror alignment
No photon rejection exploited
Muon rejection applied online by triggering on hadronic energy
Preliminary LKr callibration

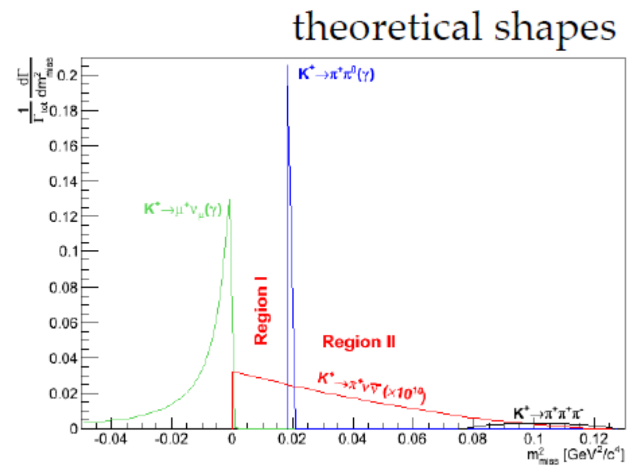


Events with only 1 reconstructed track in the spectrometer (40 ns time window)

The NA62 experiment: first look at the 2014 data

- Requiring K ID from KTAG in time with the track
- Requiring decay vertex in fiducial region





Summary

- **NA48/2: new results on the Dark Photon search**
  - Existing limits improved in the range $9\text{-}70\ \mathrm{MeV}/c^2$
  - Background limited measurement, will not improve beyond $\varepsilon^2 = 10^{-7}$
  - The whole region favoured by *(g-2)μ* has been excluded
  - **Paper with the final results accepted by PL B**
    CERN-PH-EP-2015-093 and arXiv:1504.00607

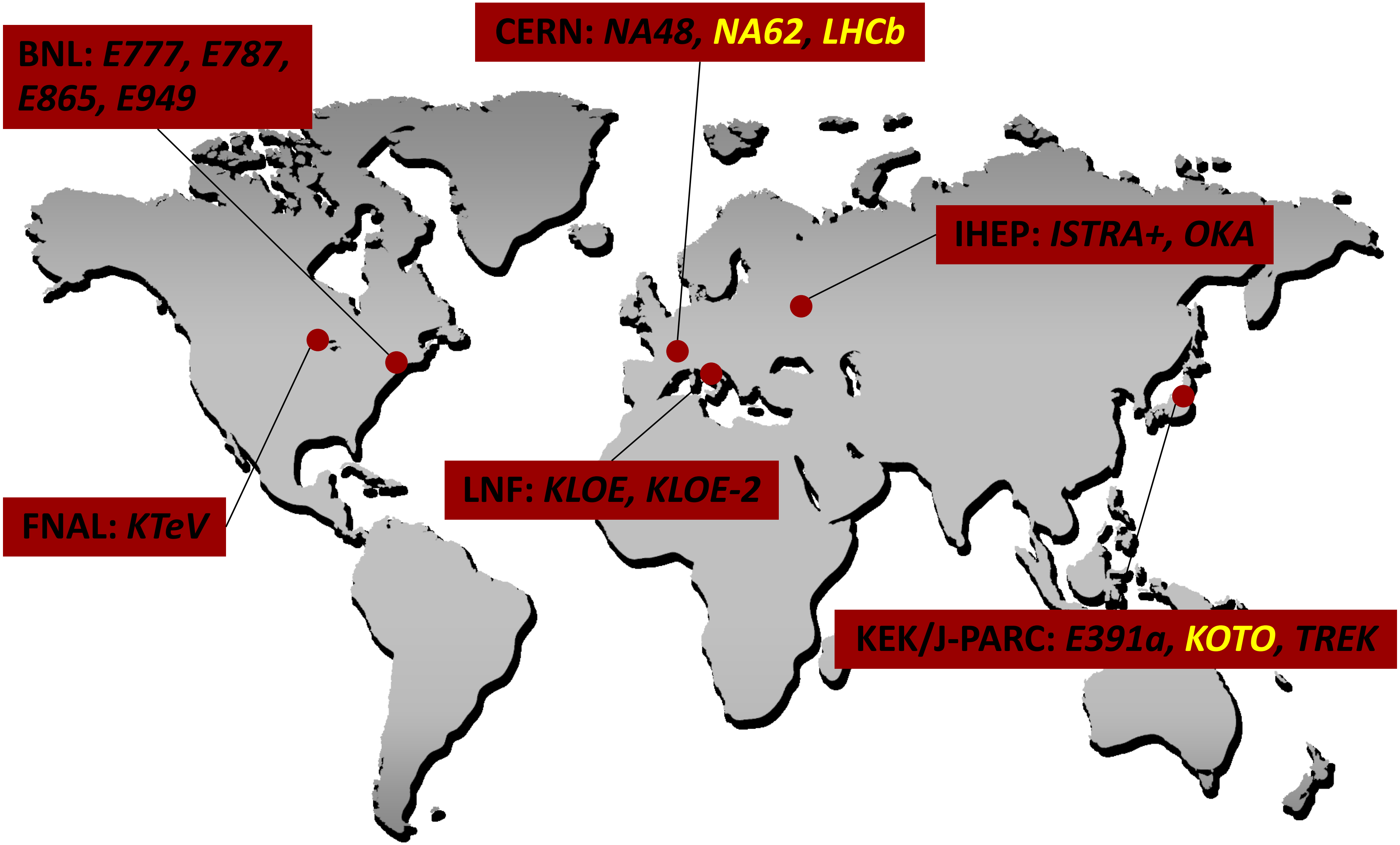
- **NA48/2: first observation of the decay $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$**
  - Observation of DE and INT components requires radiative correction in theoretical model.
  - Including 2004 data will bring 60% more events
  - Final result expected for the end of the year.

- **NA62:** a **substantial upgrade** of the previous CERN experiments
  - **NA62 took data for the first time in 2014 pilot run**
  - Almost all subsystems have been commissioned
  - All detectors have met their requirements
  - **Start 2015 data taking by end of June**
  - NA62 will collect the world largest sample of K^{+} decays

NA62 marks CERN's return to the exploration of the Standard Model using high-intensity kaon beams.

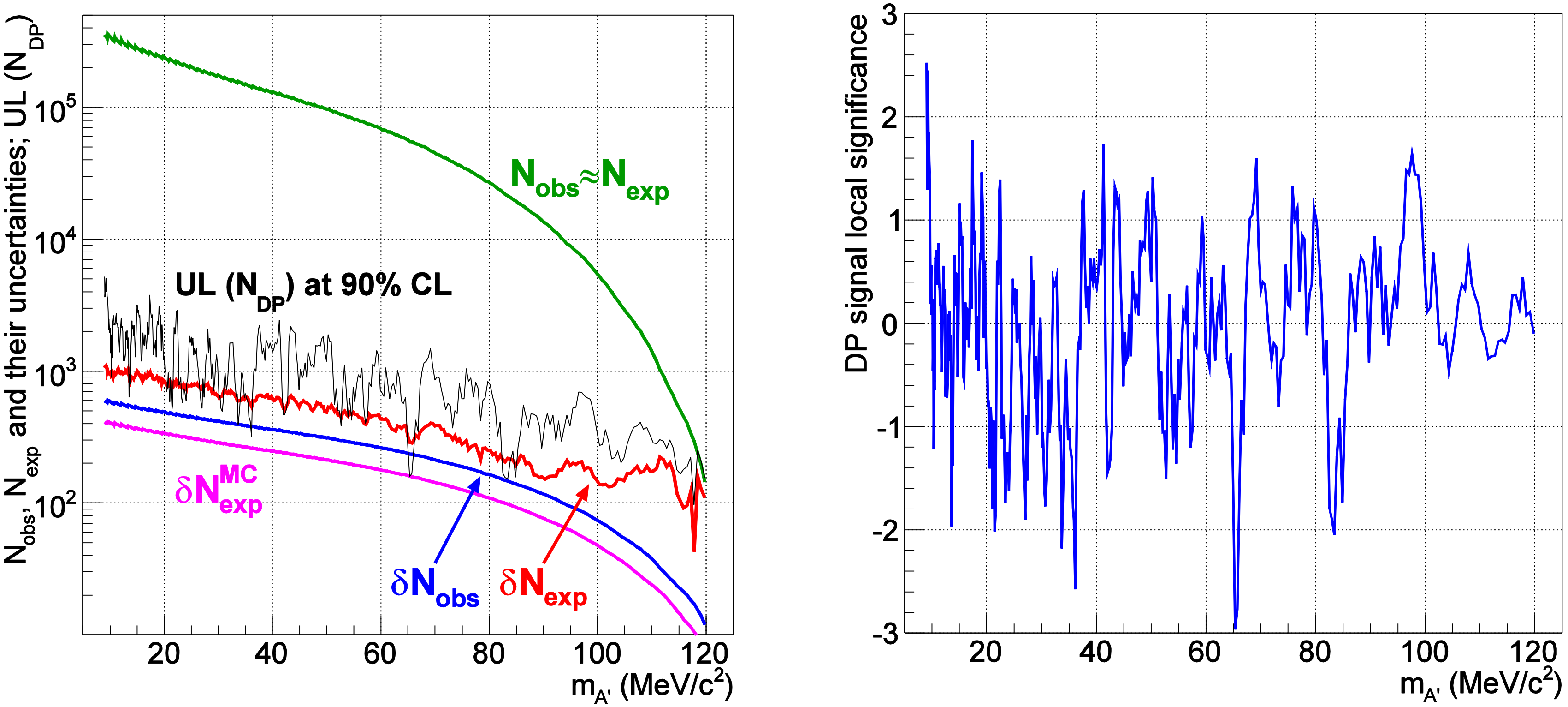
Back up

Kaon physcs facilities



- A variety of experimental techniques: *in-flight K decays* (**CERN**, **FNAL**), *stopped K* (**BNL**, **IHEP**, **J-PARC**) and a *φ factory* (**LNF**)

The dark photon @ NA48/2: Data sample



- A scan for a DP signal in the m_{ee} spectrum in the range 9 MeV/c^2 < $M_{A'}$ < 120 MeV/c^2

  Mass resolution $\sigma_m(m_{ee})$ varies from 0.16 MeV/c^2 to 1.33 MeV/c^2 ;
  Mass step: $\sigma_m/2$; Window width: $\pm 1.5\sigma_m$; 403 $M_{A'}$ hypothesis tested;

- Confidence intervals computed from N_{obs}, N_{exp} and δN_{exp} using Rolke-Lopez method

- Statistical significance < 3σ: **No DP signal is observed.**