# Kaon Physics

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# Kaon Physics in the New Millennium

Since about a decade a new generation of high-statistics kaon experiments are or were in operation

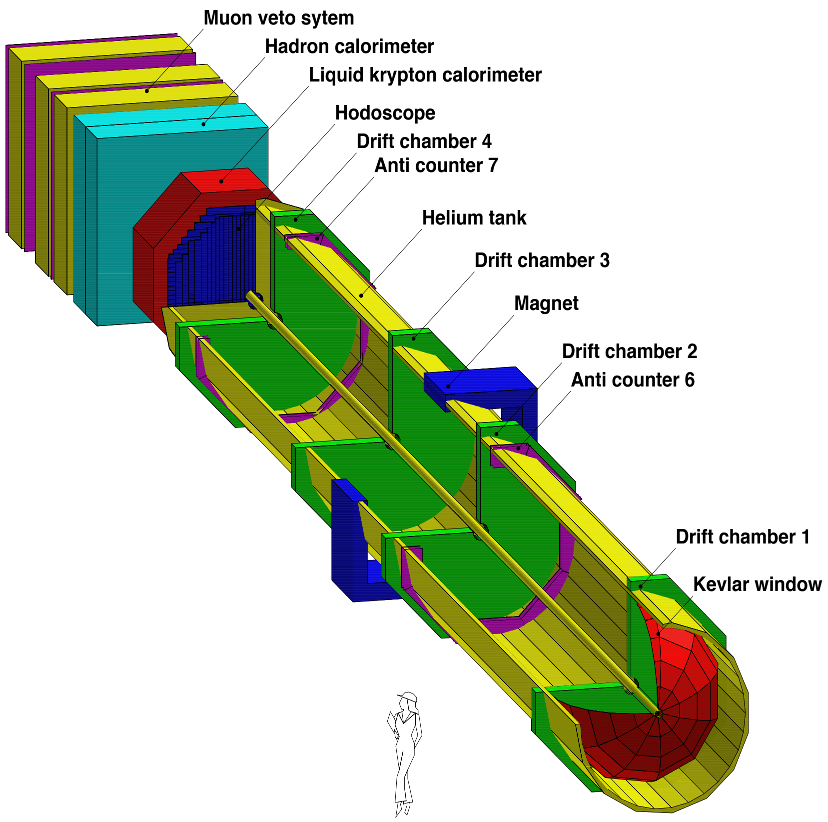
**KTeV, NA48, KLOE, ISTRA+, E787/949, NA62, E391a, ...**

Significant progress in many fields in the last couple of years:

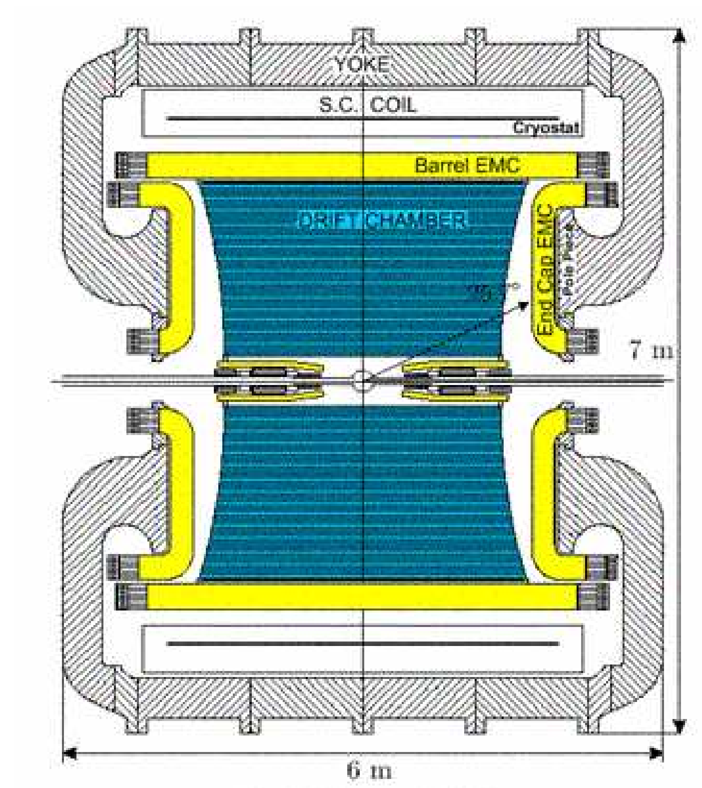
- Direct CP violation ($\varepsilon'/\varepsilon$)
- Precision determination of $|V_{us}|$
- **Precision tests of Chiral Perturbation Theory**
- **Search for Lepton Flavor Violation** **This Talk**
- **Search for New Physics in very rare decays**

# Some of the Experiments

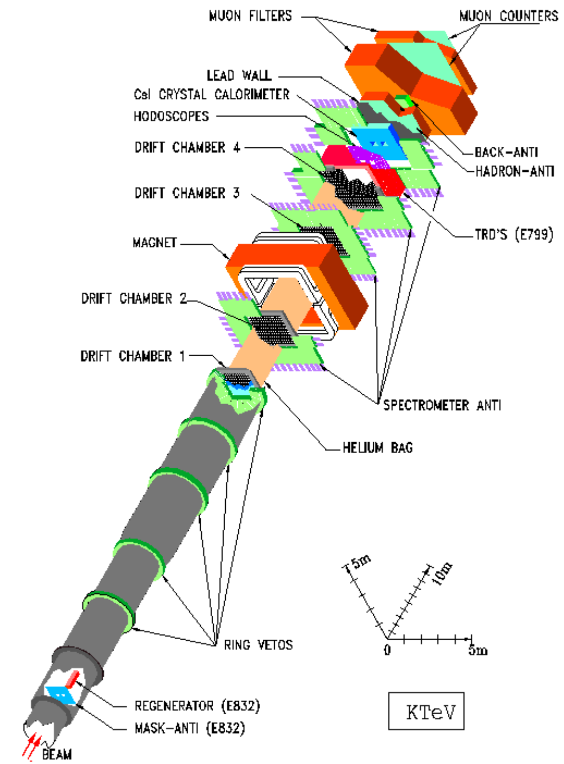
## NA48/NA62-$R_K$



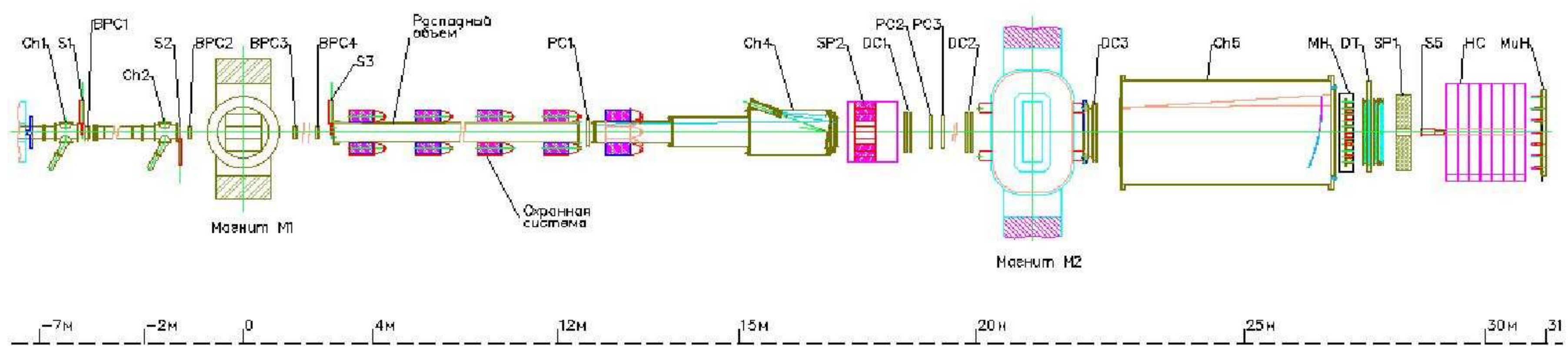

## KLOE




## KTeV




## ISTRA+

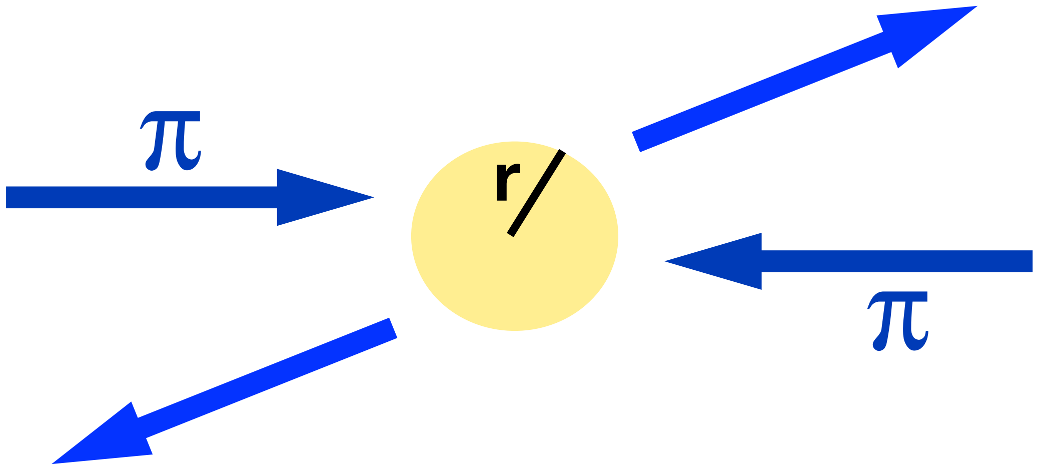


# Outline

- **Measurement of $\pi\pi$ scattering lengths**
  - **Wigner-cusp in $K^{\pm} \to \pi^{\pm} \pi^{0} \pi^{0}$**
  - **Decay kinematics of $K^{\pm} \to \pi^{+} \pi^{-} e^{\pm} \nu$ ($K_{e4}$) decays**
- **Search for Lepton Flavour Violation in $K^{\pm} \to e^{\pm} \nu$ / $K^{\pm} \to \mu^{\pm} \nu$**
- **The Golden Decays $K \to \pi \nu \bar{\nu}$**
- **Conclusions**

# Precision Measurement of $\pi\pi$ Scattering Lengths

# ππ Scattering Lengths




$$\mathbf{k} = \frac{\sqrt{\mathbf{2mE}}}{\hbar}$$

<u>**At low energy *k r << 1*:**</u> **S-wave** dominates scattering amplitude.
**Isospin *I = 0,2*** because of Bose statistics.

- Scattering matrix $\mathbf{S}|\pi\pi\rangle = \mathbf{e}^{\mathbf{2i}\delta}|\pi\pi\rangle$ parametrized by two phases:

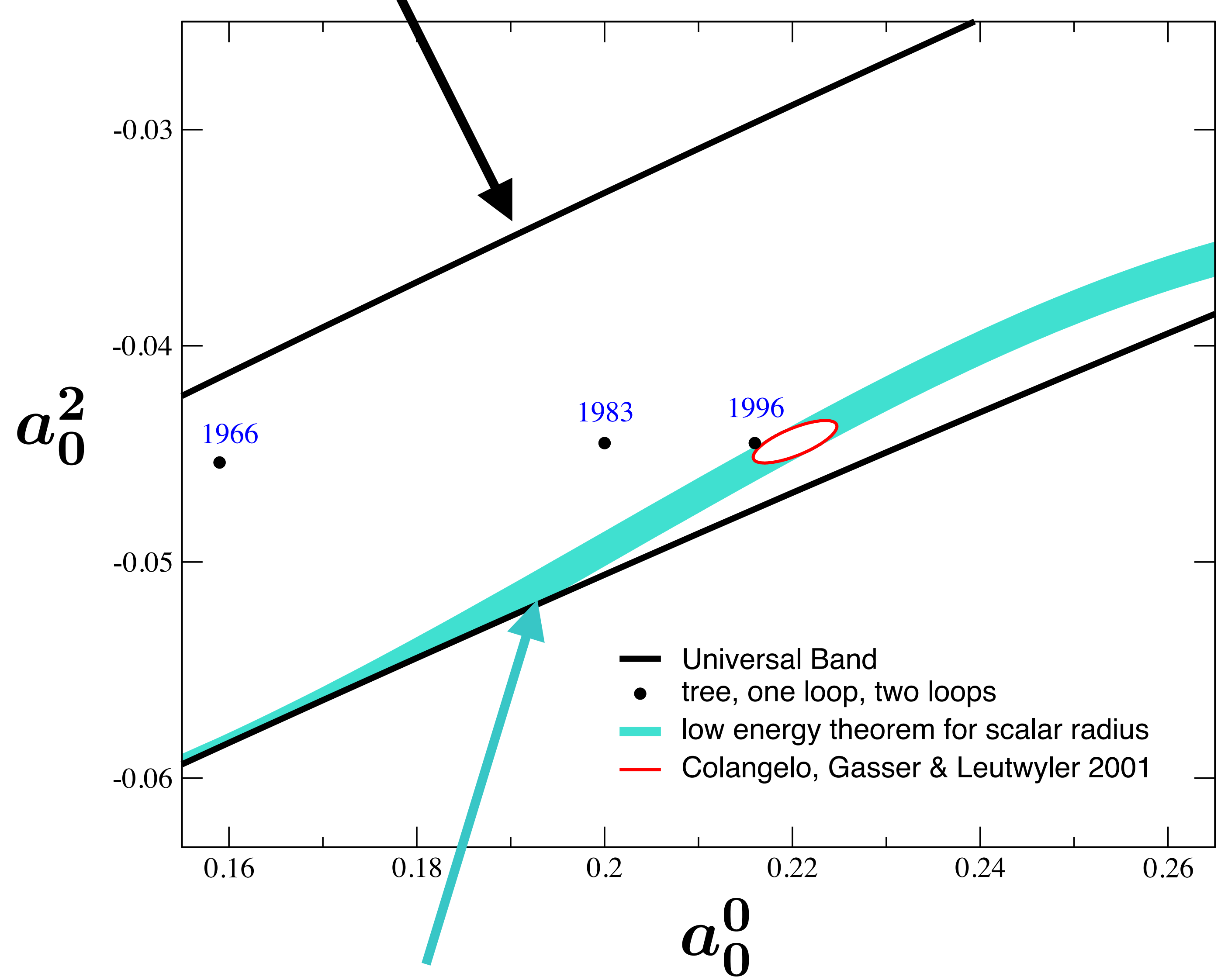
$$\delta_{\mathbf{0,2}} = -\,\mathbf{a_{0,2}} \cdot \mathbf{k} + \mathcal{O}(\mathbf{k^2})$$

- At low energy **S-wave scattering lengths $a_0$, $a_2$** are essential parameters of **Chiral Perturbation Theory (ChPT).**

*(In the following: $a_{0,2}$ quoted in units of $m_\pi$)*

# Theory predictions for $a_0$ and $a_2$

**Universal band** (from Roy equations)




- Scattering lengths $a_0$, $a_2$ are directly connected to $m_\pi$:

$$\boxed{\begin{aligned} a_0 &\sim \frac{7\,m_\pi^2}{32\pi\,F_\pi^2} = 0.16 \\ a_2 &\sim \frac{-\,m_\pi^2}{16\pi\,F_\pi^2} = -0.045 \end{aligned}}$$

(Weinberg, PRL 17 (1966) 216)

- Precise prediction within Chiral Perturbation Theory:

$$\boxed{\begin{aligned} a_0 &= 0.220 \pm 0.005 \\ a_2 &= -0.0444 \pm 0.0010 \end{aligned}}$$

(Colangelo, Gasser, Leutwyler, PRL 86 (2001) 5008)

**ChPT constraint:**

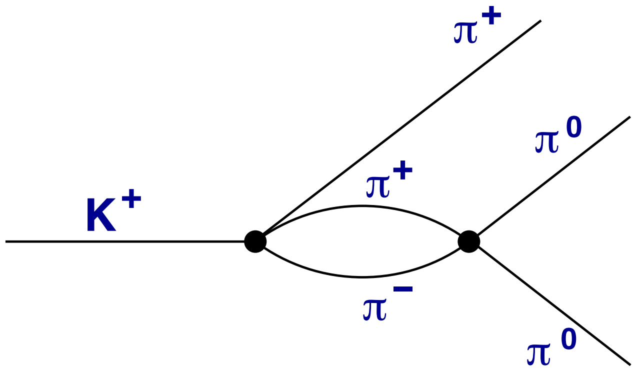
$$a_2 = -0.0444(8) + 0.236\,(a_0 - 0.22) - 0.61\,(a_0 - 0.22)^2 - 9.9\,(a_0 - 0.22)^3$$

# $\pi\pi$ Scattering Lengths in Kaon Decays

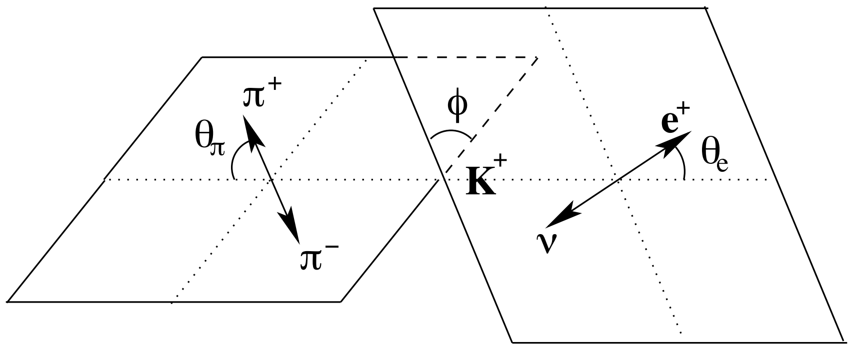
**How to measure pion scattering lengths in kaon decays:**

- Need two pions in the final state
  ➜ Can use $\mathbf{K \to 3\pi}$ or $\mathbf{K \to \pi\pi l\nu\ (K_{l4})}$

- <u>$\mathbf{K^\pm \to \pi^\pm \pi^0 \pi^0}$:</u>
  Rescattering from $K^\pm \to \pi^\pm\pi^+\pi^-$
  ➜ Wigner-cusp in $\pi^0\pi^0$ spectrum
  in $K^\pm \to \pi^\pm \pi^0 \pi^0$.

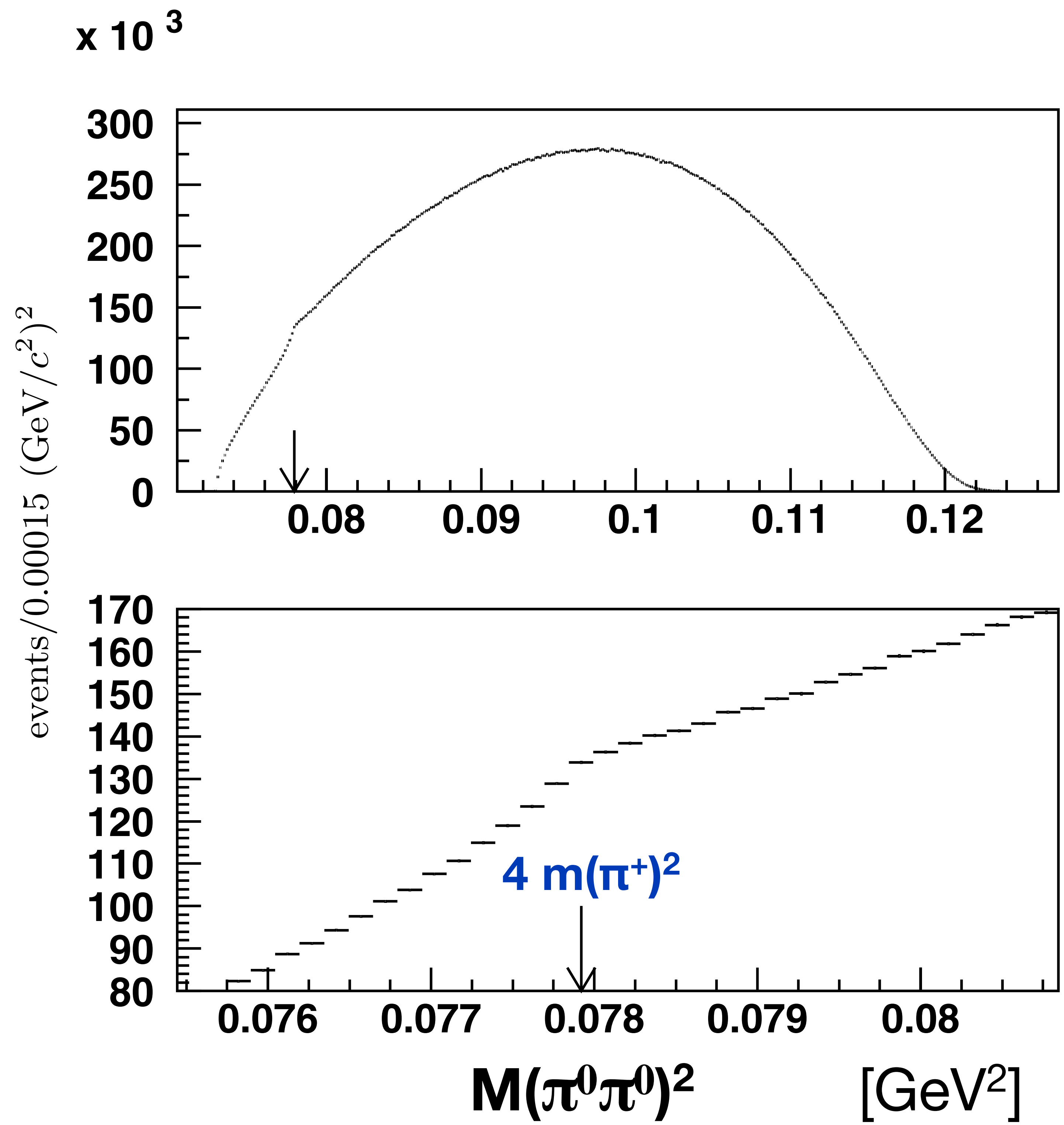



- <u>$\mathbf{K^\pm \to \pi^+ \pi^- e^\pm \nu}$:</u>
  Measurement of decay kinematics
  (historical method)




**NA48/2 has new precise results on both decays**

# Cusp in $K^{\pm} \to \pi^{\pm} \pi^{0} \pi^{0}$ Decays




**<u>All NA48/2 data:</u>**

- **60 million $K^{\pm} \to \pi^{\pm} \pi^{0} \pi^{0}$ events**
  (Br ~1.8%)
- Background completely negligible.

**<u>M($\pi^0\pi^0$) distribution:</u>**

Clear cusp at

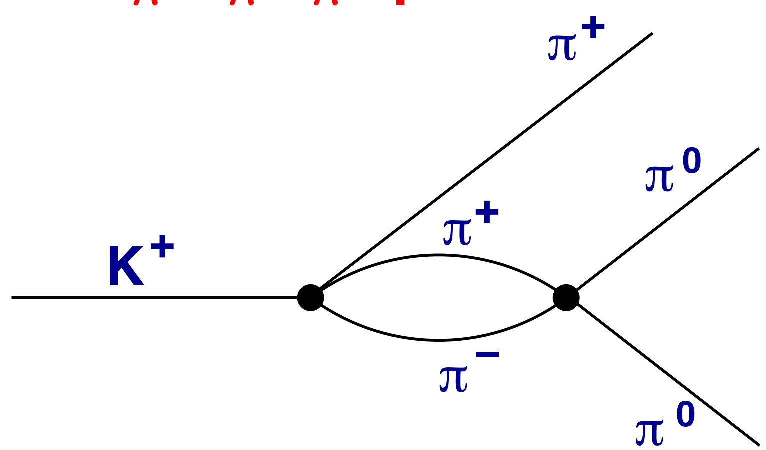
**$M(\pi^0\pi^0) = 2\ m(\pi^{\pm})$**

(were expecting peak from pionium formation $K \to \pi^{\pm} (\pi\pi)_{atom} \to \pi^{\pm} \pi^0 \pi^0$)

# Cusp in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ Decays

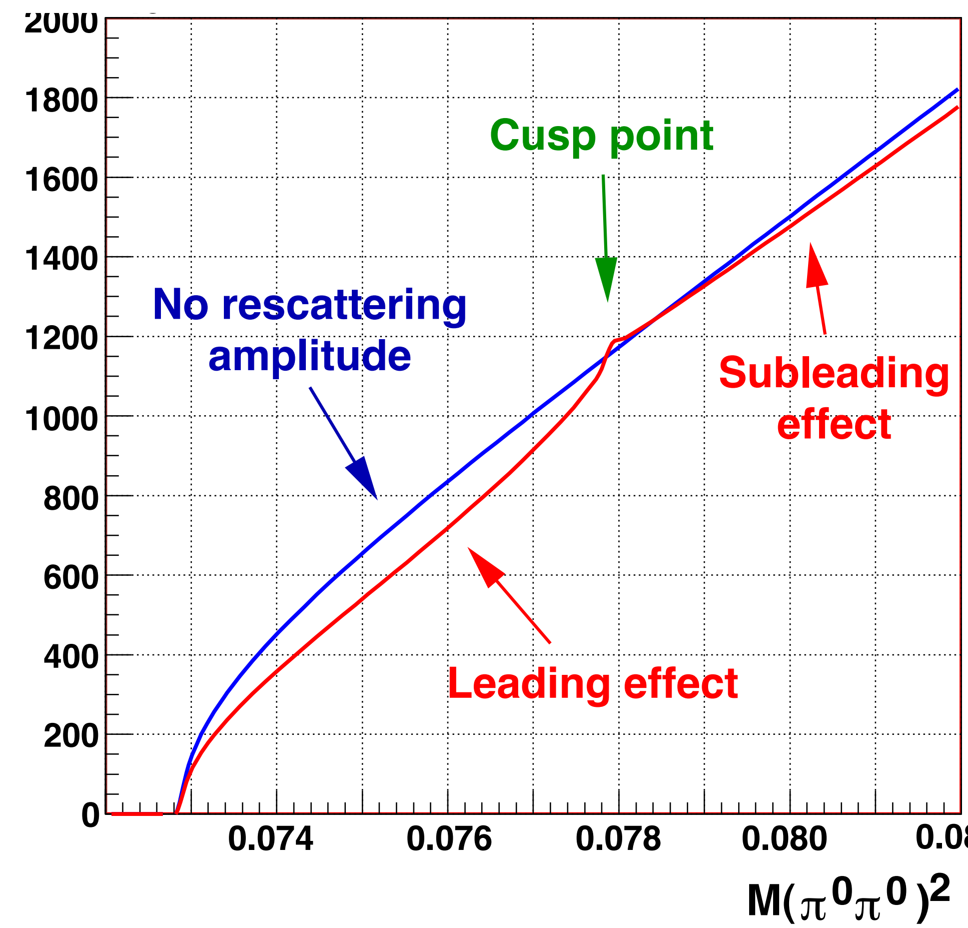
**Explanation:** (Cabibbo, PRL 93 (2004) 121801)

Rescattering of $\mathbf{K}^{+} \to \pi^{+}\pi^{+}\pi^{-}$
to $\mathbf{K}^{+} \to \pi^{+}\pi^{0}\pi^{0}$.



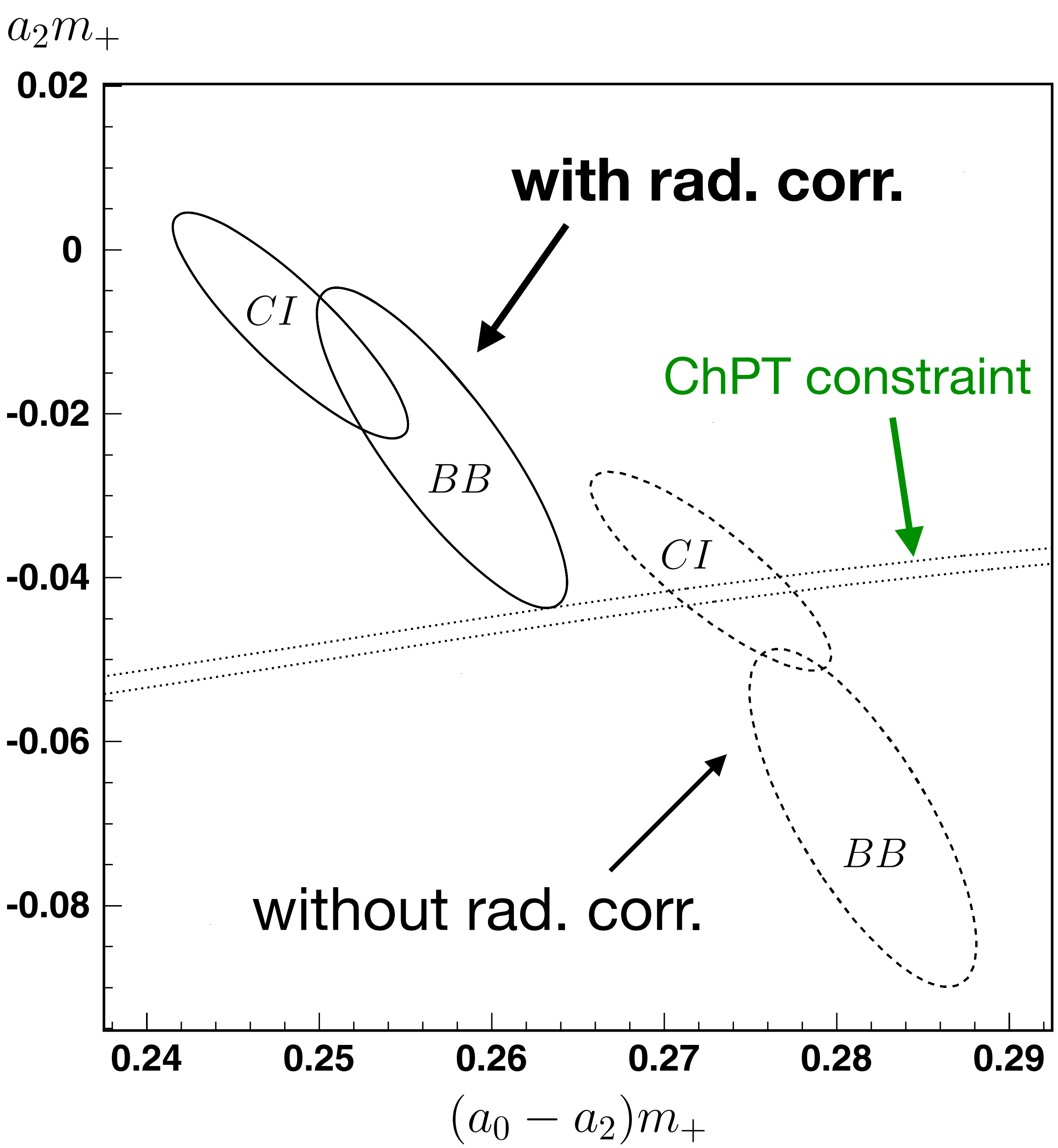

Measurement of $\pi\pi$ scattering length $a_0 - a_2$ possible!

- Second order computations by Cabibbo & Isidori **(CI)**
(JHEP03 (2005) 21)




- Full computation including all K→3π decays and radiative corrections by group from Bern & Bonn **(BB)**
(PLB 638 (2006) 187;
PLB 659 (2008) 576;
NPH B806 (2009) 178)

# Cusp Results on $a_0 - a_2$ and $a_2$




(only statistical uncertainties shown)

**Final result:** (EPJC 64 (2009) 589)

$$a_0 - a_2 = 0.257(5)_{stat}(3)_{sys}(1)_{ext}$$

$$a_2 = -0.024(13)_{stat}(9)_{sys}(2)_{ext}$$

(statistical correlation -0.839)

**With ChPT constraint:**

$$a_0 - a_2 = 0.2633(24)_{stat}(14)_{sys}(19)_{ext}$$

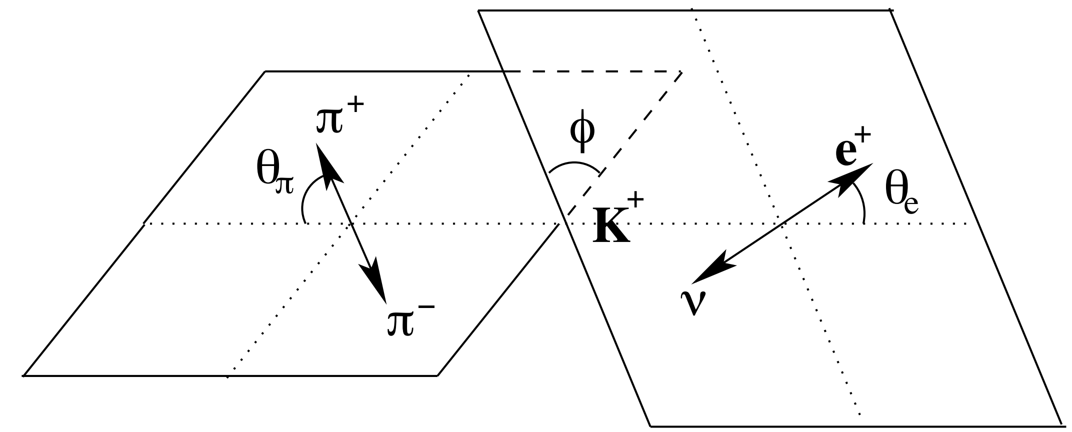
**ChPT prediction:**

$$a_0 - a_2 = 0.265(4)$$

# ππ Scattering Lengths from $K_{e4}$ Decays

**$K_{e4}$ decay:**

- $\mathbf{K_{e4} = K^{\pm} \rightarrow \pi^{+} \pi^{-} e^{\pm} \nu}$
- Very rare: **Br($K_{e4}$) ~ 4 x $10^{-5}$**
- Two pions in the final state allow **$a_0$, $a_2$ measurement**

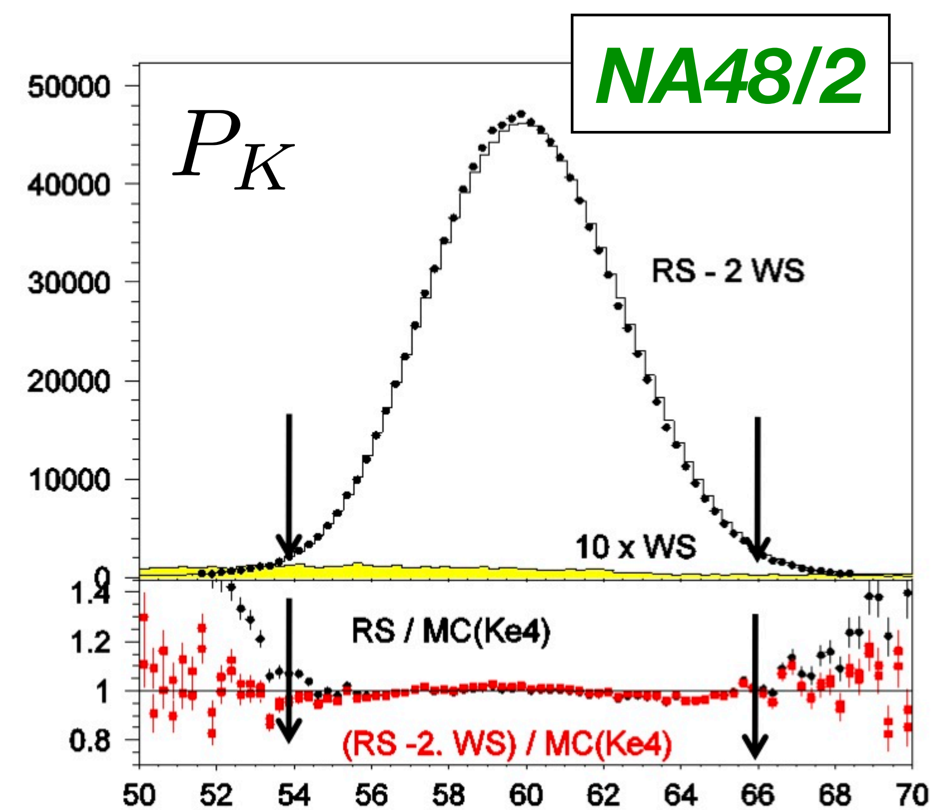



5 kinematic variables:
$M_{\pi\pi}$, $M_{e\nu}$, cos $\theta_\pi$, cos $\theta_e$, Φ

**NA48/2: $K_{e4}$ selection:**

- 3 charged tracks, 1 with e-ID, missing transverse momentum, $p_K \approx 60$ GeV/$c$

➜ **1.1 million $K_{e4}$ candidates**



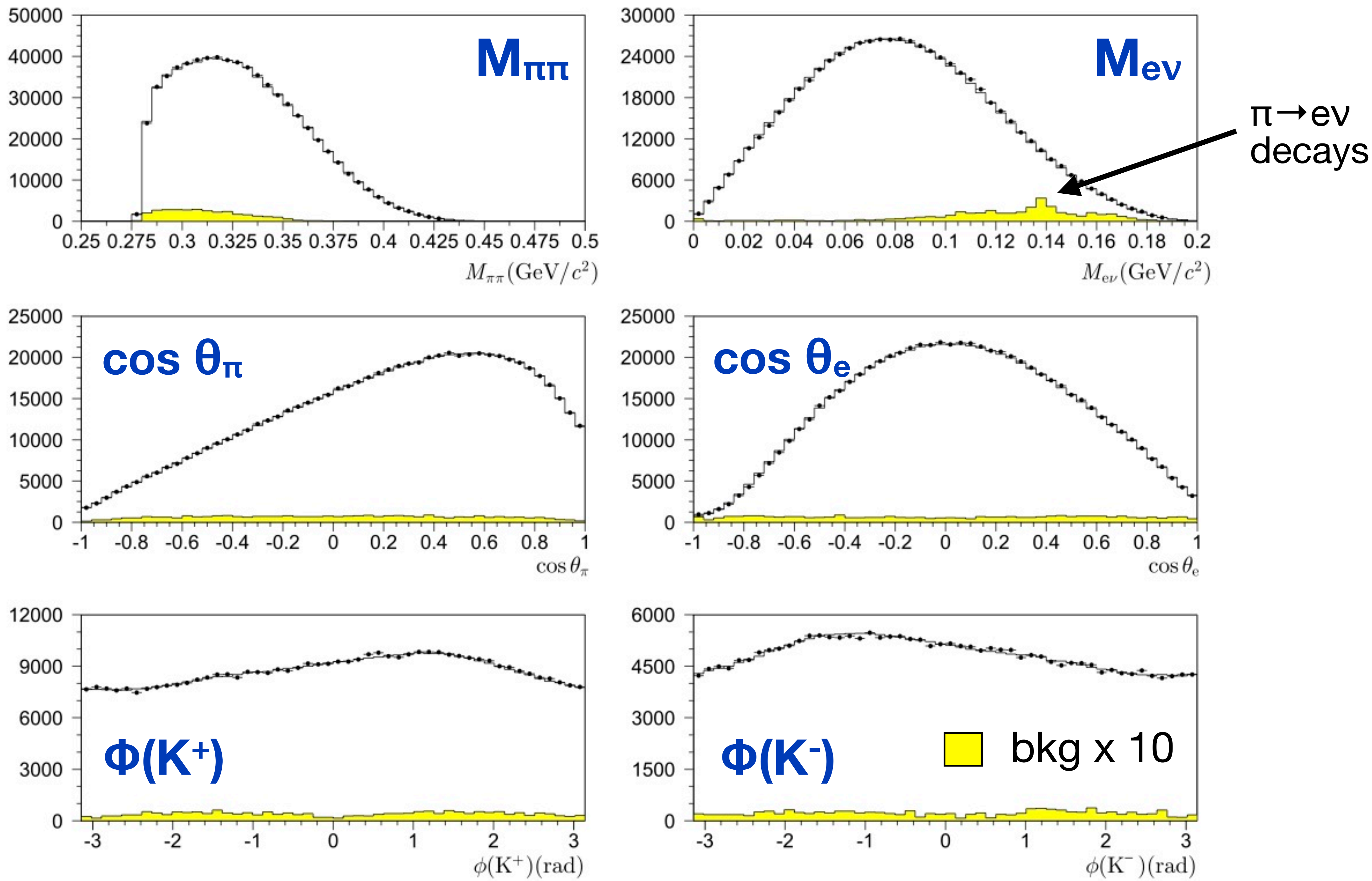

**Background:**

- $\mathbf{K^{\pm} \rightarrow \pi^{\pm} \pi^{+} \pi^{-}}$ with e.g. $\pi \rightarrow e\nu$
- $\mathbf{K^{\pm} \rightarrow \pi^{\pm} \pi^{0} (\pi^{0})}$ with $\pi^0 \rightarrow e^{+} e^{-} \nu$

➜ **Background ~ 0.6 %**

# NA48/2 $K_{e4}$ Fit Results

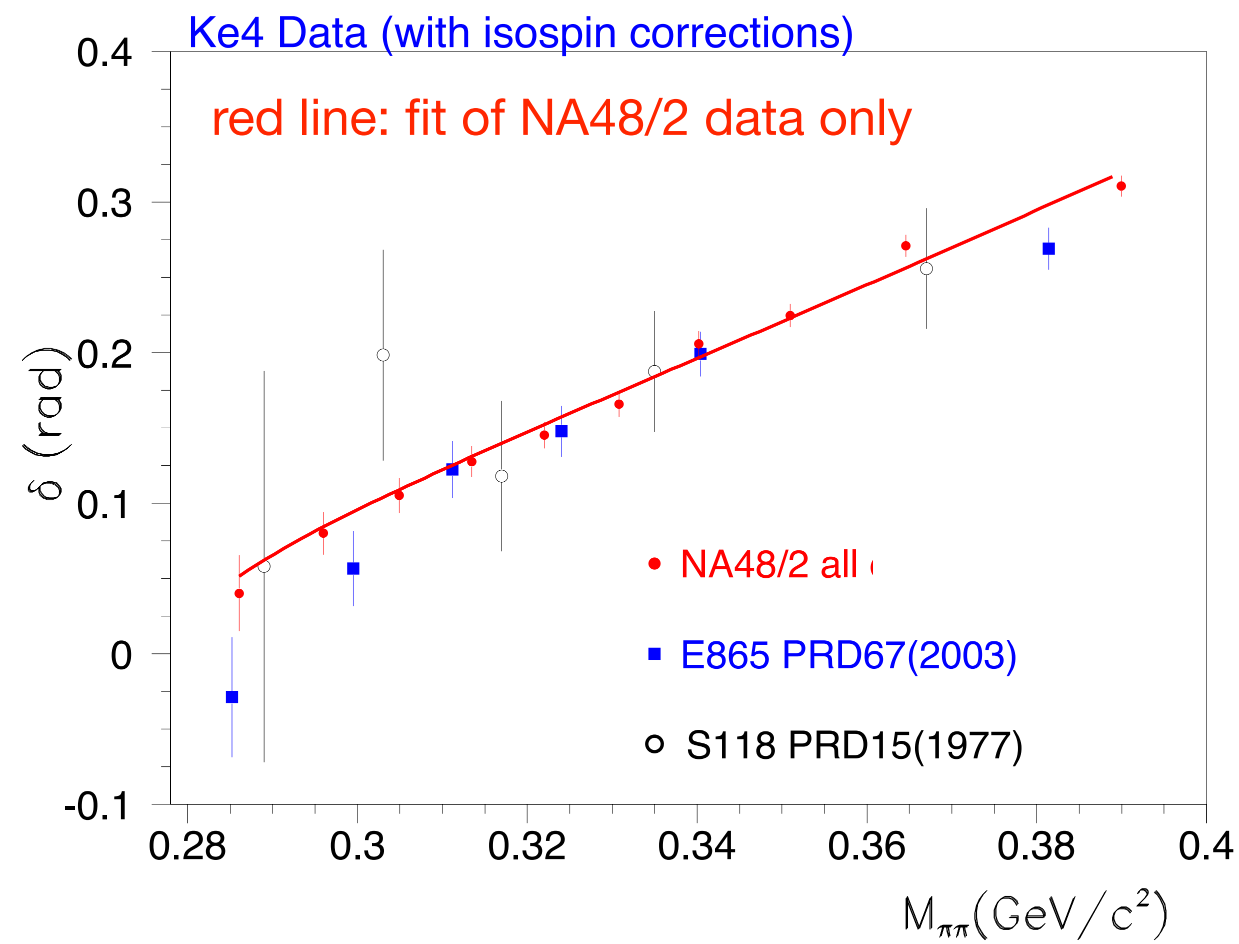
Fit in the 5-dimensional space of the kinematic variables:



# NA48/2 Fit of Phase Shift $\delta = \delta(a_0,a_2)$

Fit of phase shift difference
$\delta = \delta_{I=0} - \delta_{I=1}$ from $\Phi$ distributions.

- **Radiative effects:**
  Included in the simulation (Coulomb attraction, IB).
- **Mass effects:**
  **Isospin corrections** have to be applied to $\delta$. Developed in close contact with NA48/2.
  (Colangelo, Gasser, Rusetsky, EPJC 59 (2009) 777)




**Two-parameter fit:**

$$a_0 = 0.2220 \pm 0.0128_{\mathrm{stat}} \pm 0.0050_{\mathrm{syst}} \pm 0.0037_{\mathrm{theo}}$$
$$a_2 = -0.0432 \pm 0.0086_{\mathrm{stat}} \pm 0.0034_{\mathrm{syst}} \pm 0.0028_{\mathrm{theo}}$$

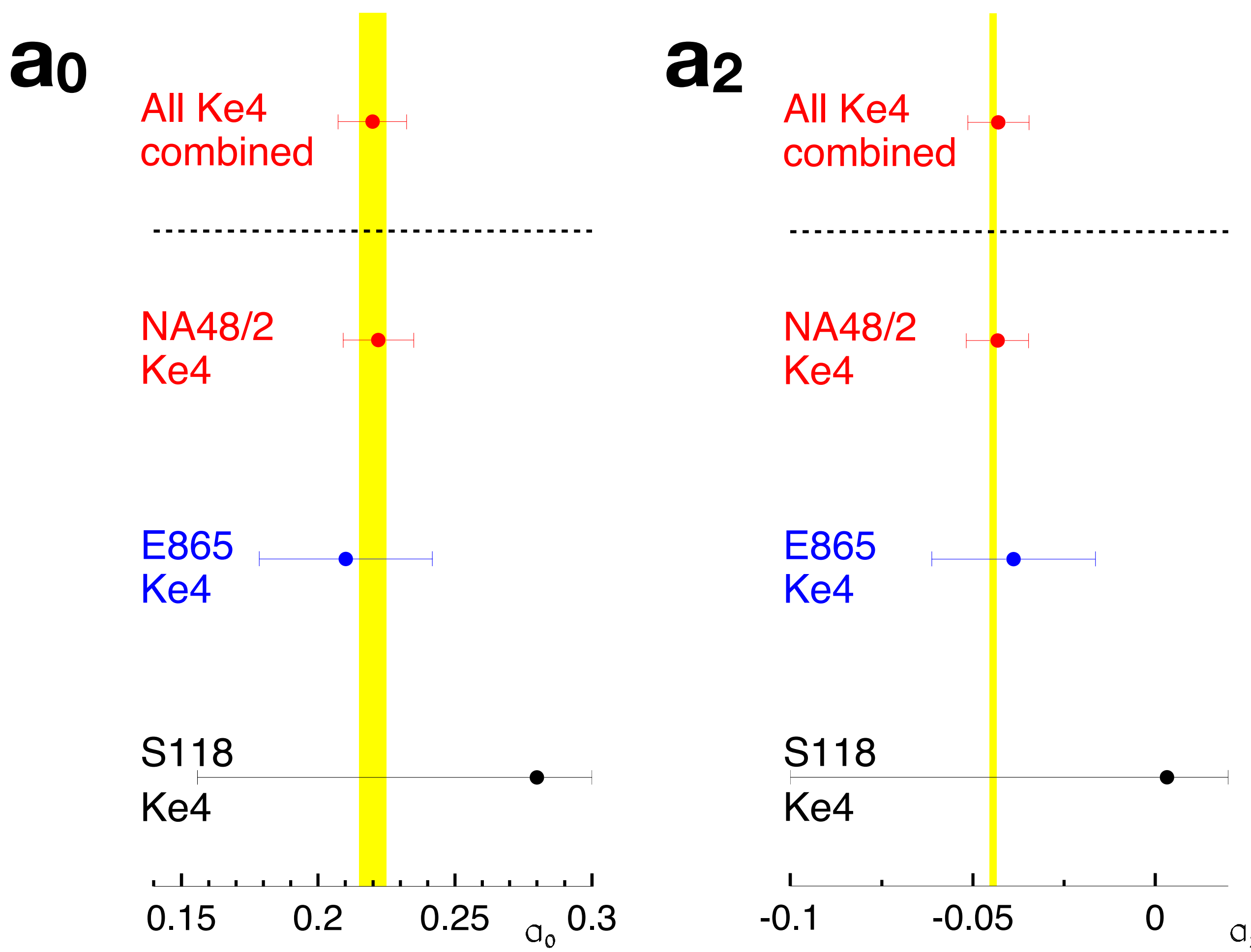
**One-parameter fit:**
(with ChPT constraint)

$$a_0 = 0.2206 \pm 0.0049_{\mathrm{stat}} \pm 0.0018_{\mathrm{syst}} \pm 0.0064_{\mathrm{theo}}$$

(EPJC 70 (2010) 635)

# Comparison with other $K_{e4}$ Results

Comparison of **$K_{e4}$ measurements**
(without ChPT constraint, old experiments isospin corrected):




- NA48/2 dominates $K_{e4}$ measurements
- **Perfect agreement with ChPT prediction!**

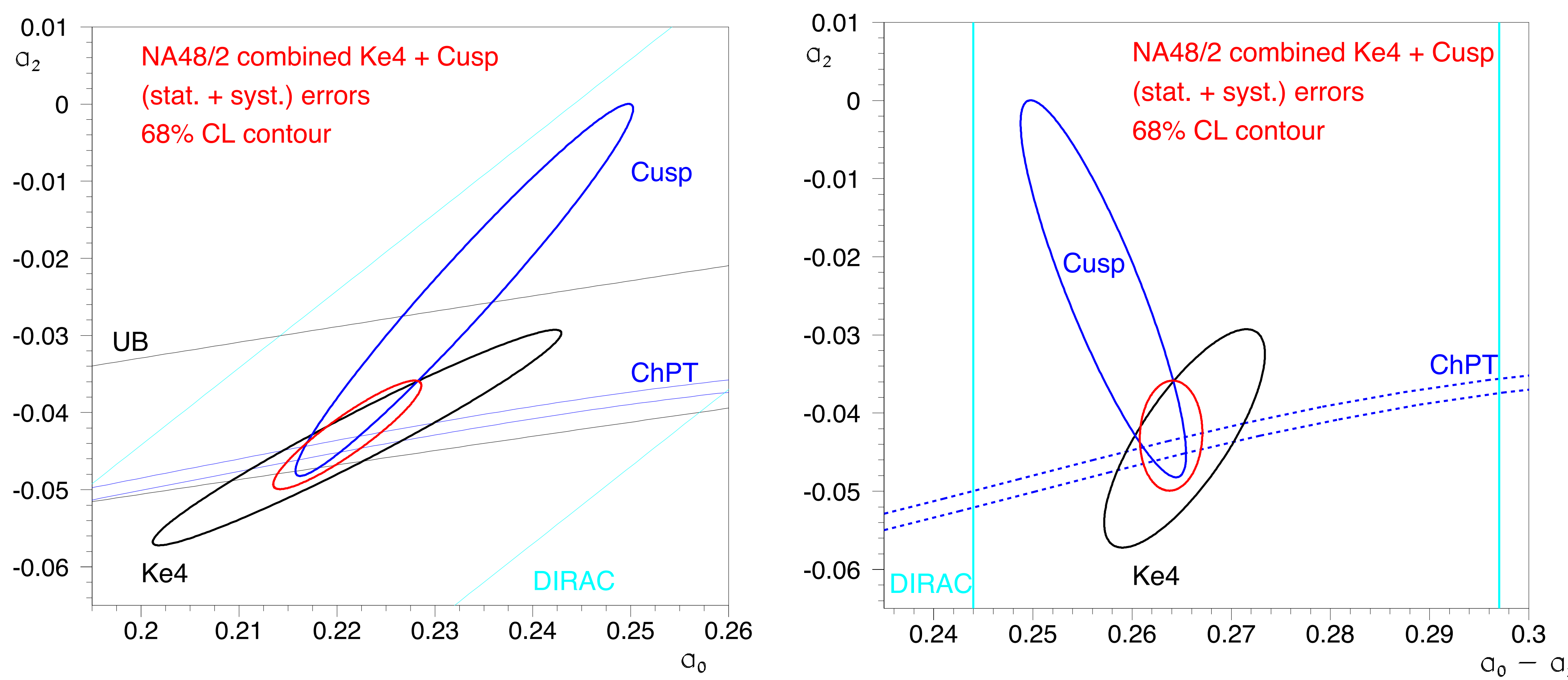
**Yellow lines:** Theory prediction

(*not* combination of measurements)

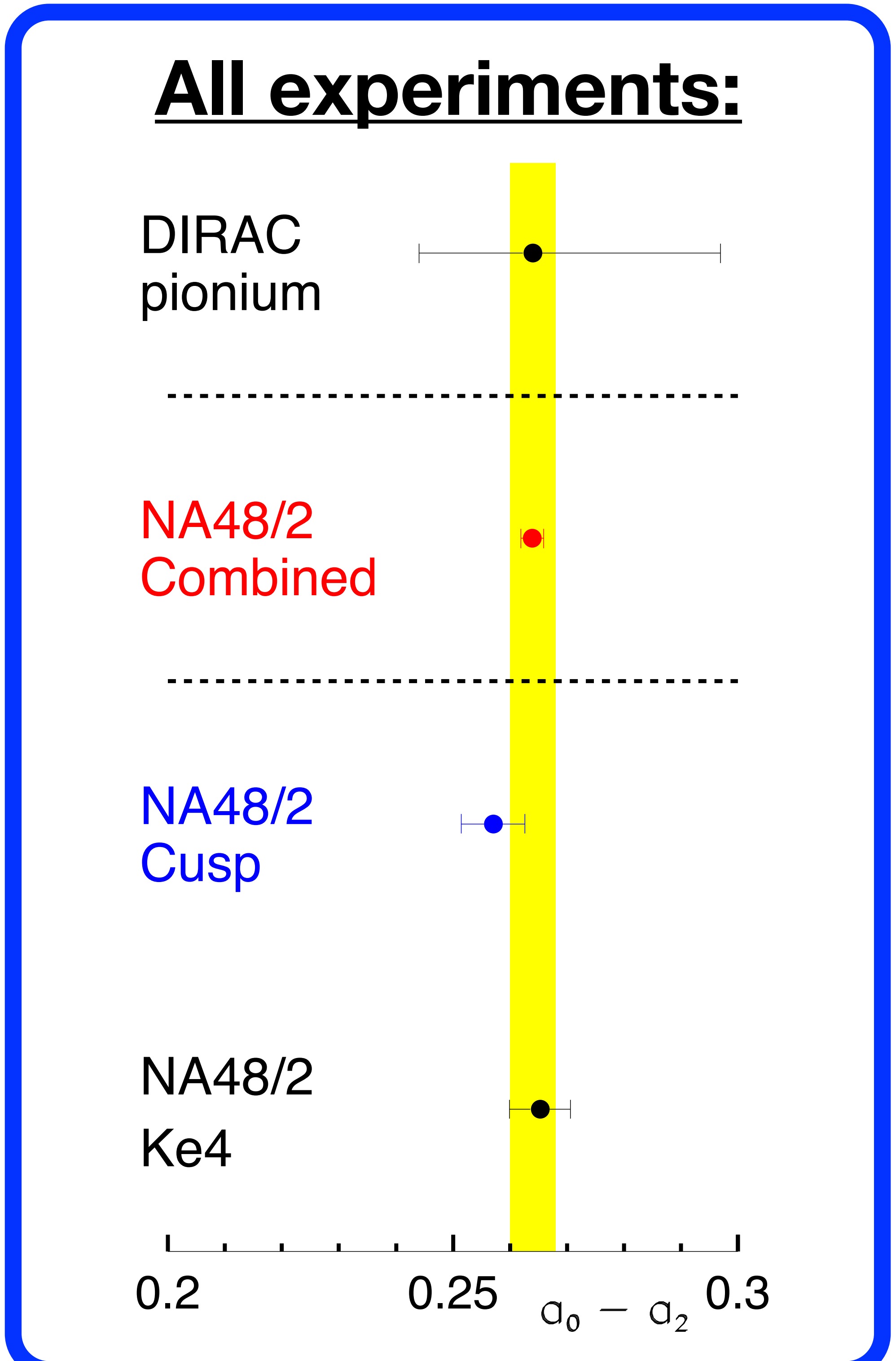
# Combination of $K_{3\pi}$ and $K_{e4}$

**Two independent measurements** with different samples, different systematics and different theory:

$$\begin{aligned} a_0 &= \phantom{-}0.2210 \pm 0.0047_{\rm stat} \pm 0.0040_{\rm syst} \\ a_2 &= -0.0429 \pm 0.0044_{\rm stat} \pm 0.0028_{\rm syst} \\ a_0 - a_2 &= \phantom{-}0.2639 \pm 0.0020_{\rm stat} \pm 0.0015_{\rm syst} \end{aligned}$$



# Combination with other Measurements




**Experimental data has reached theoretical precision**

**Perfect agreement with ChPT prediction**

**Yellow line:** Theory prediction

(*not* combination of measurements)

(no uncertainty from theory on cusp result)

# Search for Lepton Flavour Violation in $K_{e2}/K_{\mu 2}$

# $R_K = \Gamma(K\to e\nu)/\Gamma(K\to\mu\nu)$ in the SM

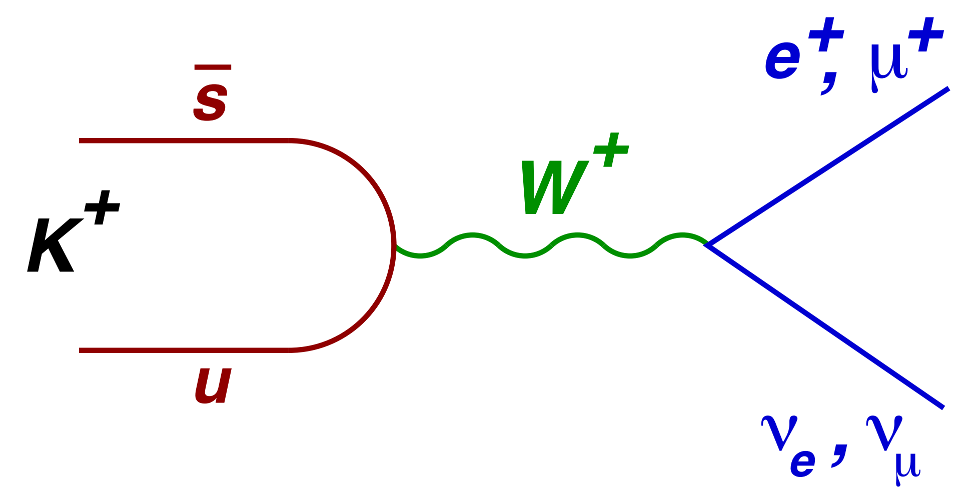
**SM Prediction on $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$:**

- Text book exercise for **helicity suppression**

  $\Longrightarrow$ $R_K$ very small.

- **Nearly exact**

  (hadronic uncertainties cancel, only radiative corrections to consider):




$$\mathbf{R_K} = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\mathrm{rad.corr.}})$$

$$= (2.477 \pm 0.001) \times 10^{-5}$$ (Cirigliano, Rosell, PRL 99 (2007) 231801)

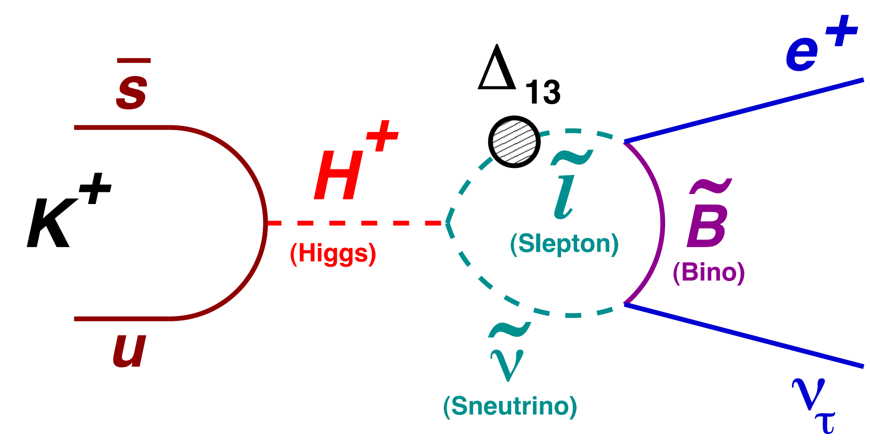
**➜ SM prediction has precision of 0.04%!**

# $R_K = \Gamma(K\to e\nu)/\Gamma(K\to\mu\nu)$ beyond the SM

**Possible MSSM scenario:**

(Masiero, Paradisi, Petronzio, PRD 74 (2006) 011701)

'Charged Higgs mediated SUSY LFV contributions can be strongly enhanced, in particular in kaon decays into an electron or a muon and a tau neutrino'




$$R_K^{\mathrm{LFV}} \approx R_K^{\mathrm{SM}} \left[1 + \frac{m_K^4}{M_{H^\pm}^4}\,\frac{m_\tau^2}{M_e^2}\,|\Delta_{13}|^2 \tan^6\beta\right]$$

**Example:** $\Delta_{13} = 5\times 10^{-4},\ M_H = 500\,GeV,\ \tan\beta = 40$:

$$\Longrightarrow\ \mathrm{R}_{\mathrm{K}}^{\mathrm{LFV}} \approx \mathrm{R}_{\mathrm{K}}^{\mathrm{SM}}(1+0.013)$$

$\Longrightarrow$ Effect of up to a few percent with a massive charged Higgs!

**Experimental siuation:**

- **PDG 2008:** three measurements of the 1970s (4.5% rel. error)
- **Now: new precise measurements of KLOE and NA62**

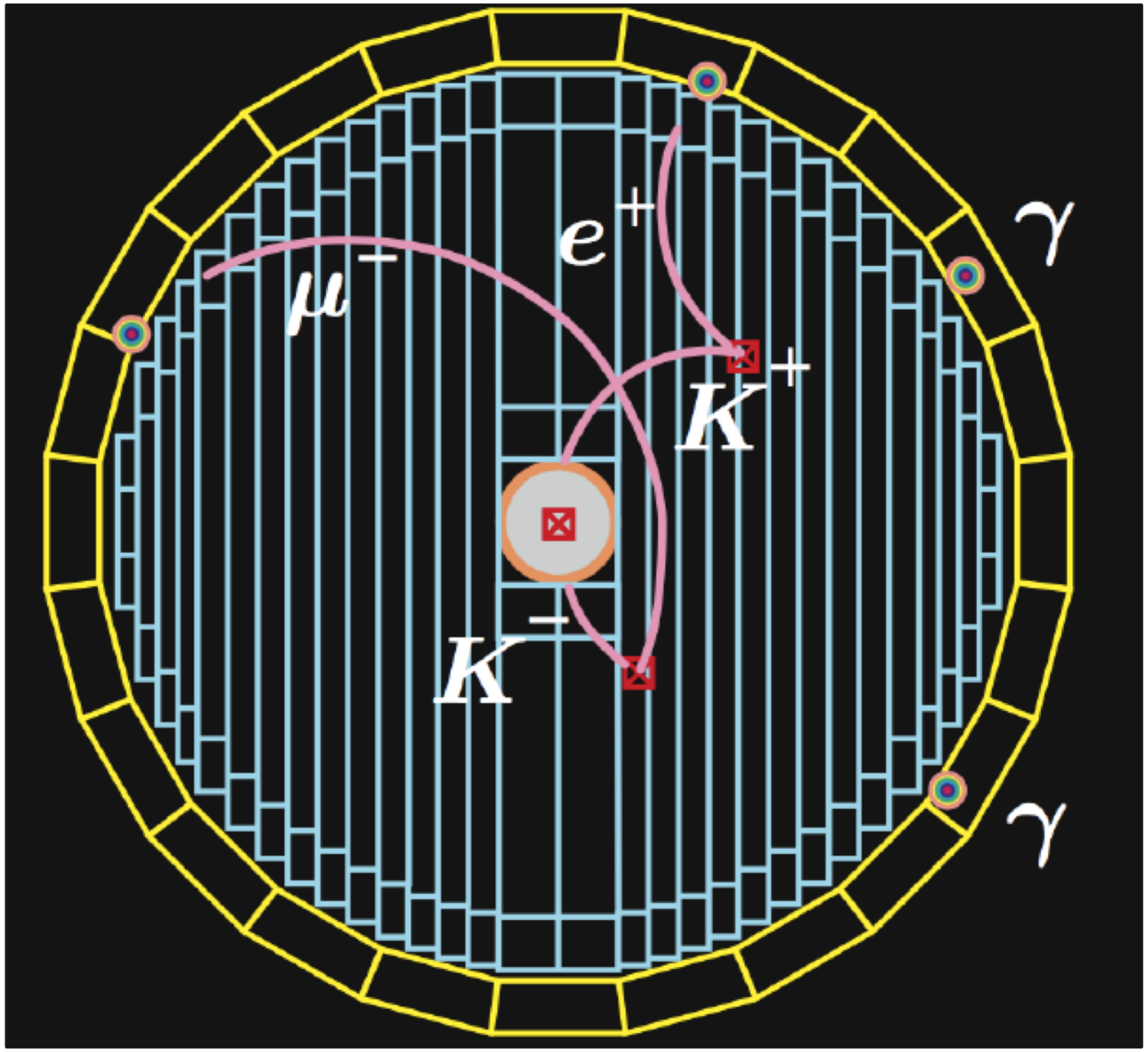
# $R_K$ from KLOE

## KLOE data:

- $2.2\ \text{fb}^{-1}$ in 2001–05
  $\Longrightarrow$ $\mathbf{3.3 \times 10^9}$ $\boldsymbol{K^+K^-}$ **pairs**

## KLOE kinematics:

- $\phi$ **decay at rest.**
  - $p_K \approx 100$ MeV
  - Constraint from 2-body decay
- **Particle ID** from kinematics, calorimeter (EMC) and ToF



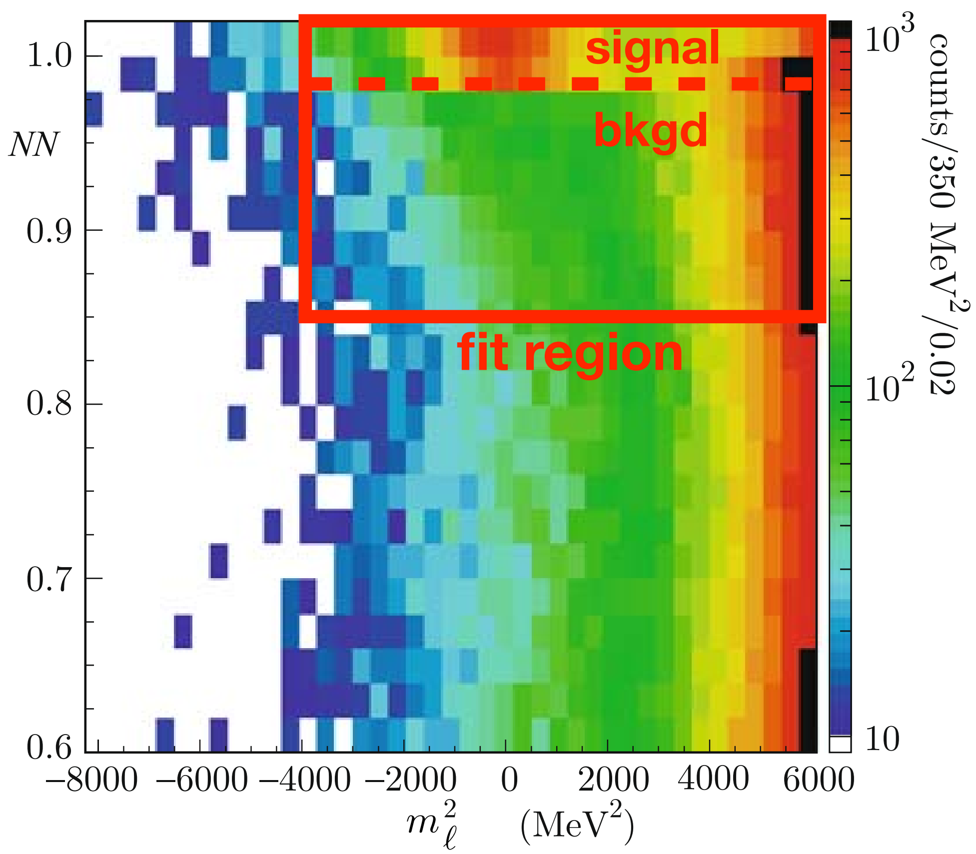
# $R_K$ from KLOE

**Full KLOE data set** (2001-2005):

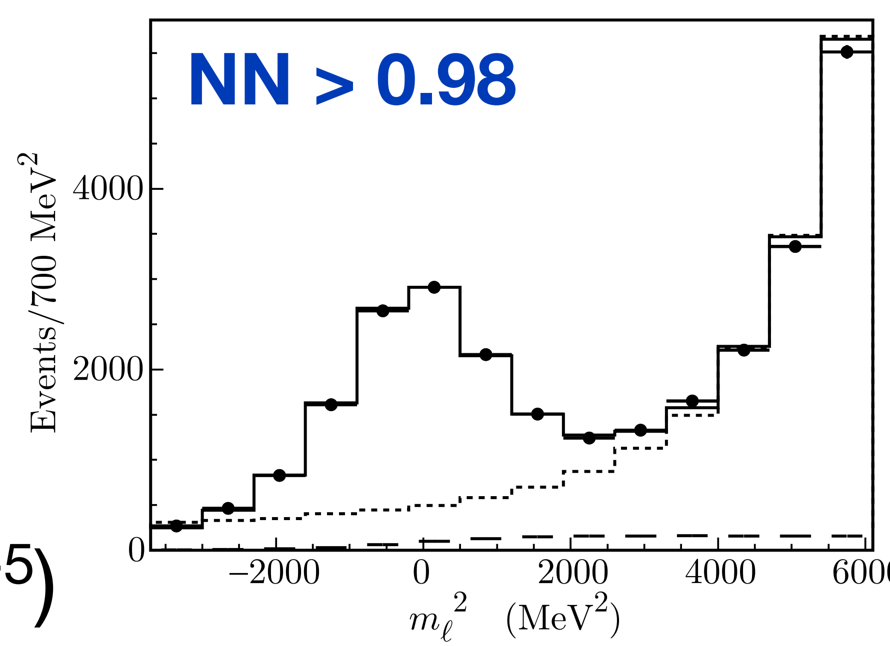
**13 814 $K^\pm \to e^\pm \nu$ candidates**

**$R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$**

(EPJ C64 (2009) 627)




Very good agreement with the SM prediction and a factor of 5 better than previous world average.




**KLOE-2** (starting soon):

Aiming for 0.4% precision ($\pm 0.01 \times 10^{-5}$)

# $R_K$ from NA62

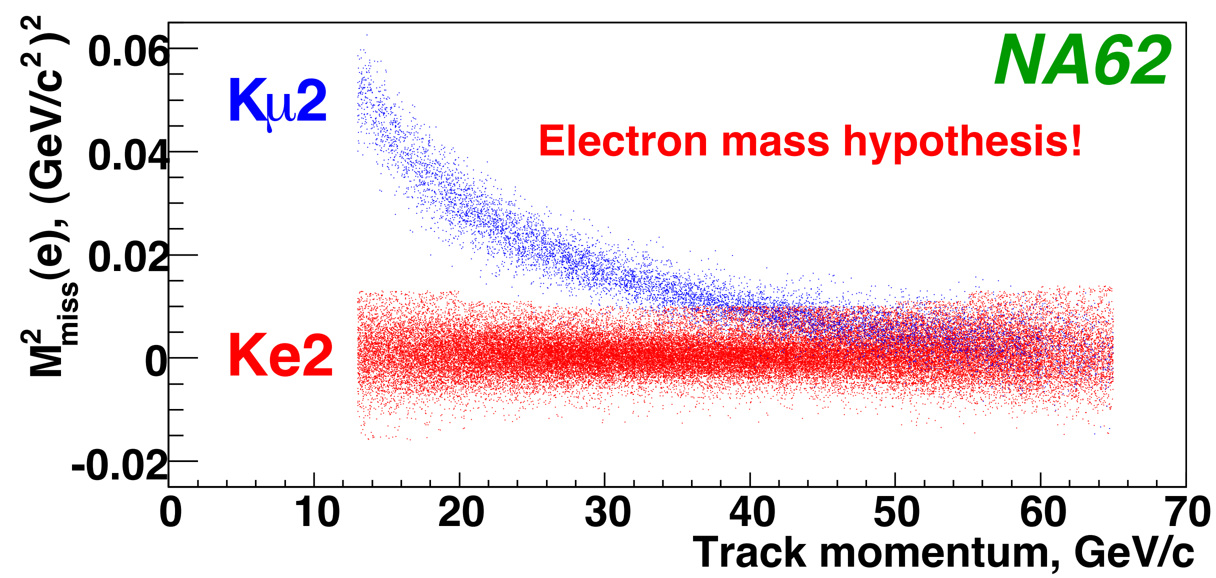
**NA62 in 2007/2008:**

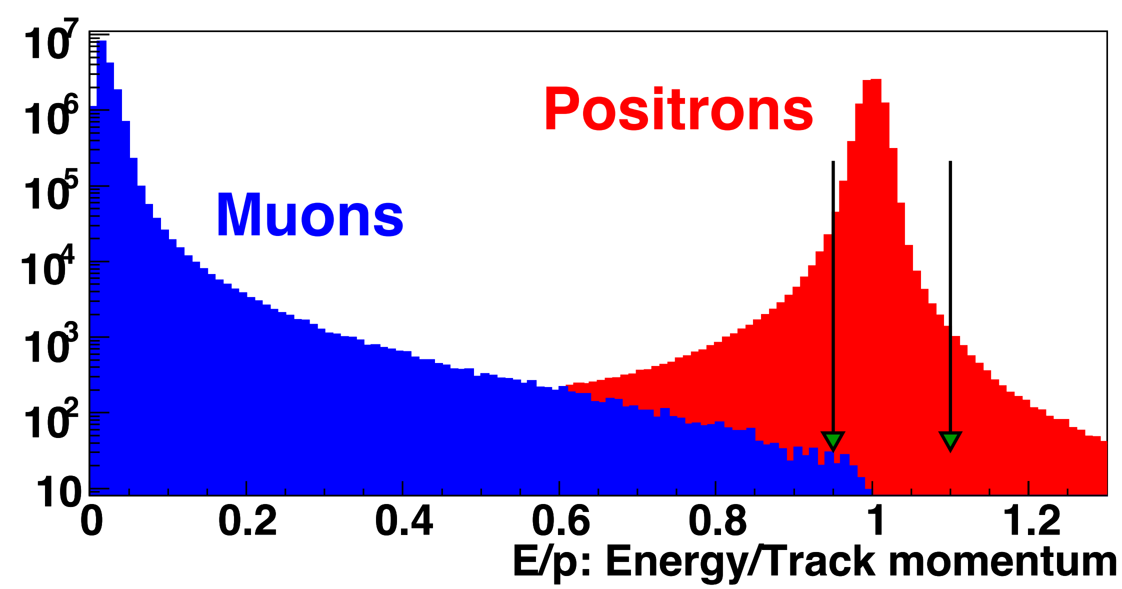
- Special running period for $K_{e2}/K_{\mu2}$ (still old NA48 detector)
- Minimum bias trigger: 1 track + E/p > 0.5 (otherwise just kinematics)

**Backgrounds/Corrections:**

- $K_{\mu2}$ with E/p > 0.95 (catastrophic bremsstrahlung, $\mu \to e$ decays)
- $K^\pm \to e^\pm \nu\gamma$ (SD)
- $K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$
- Muon beam halo
- He purity in decay region

**e/μ separation by kinematics and E/p**



# Main $K_{e2}$ Background: $K_{\mu2}$

**Problem:**

- **Catastrophic energy loss** of Muons in LKr ($\sim$some $10^{-6}$)

**Solution:**

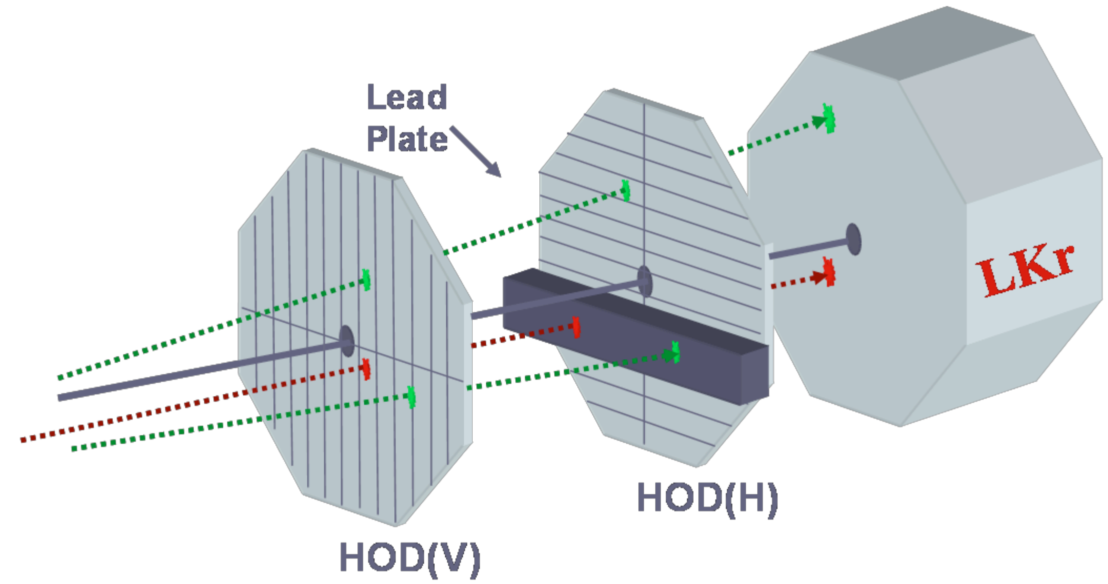
- Special **muon runs**
- During data taking: **lead bar** ($9X_0$) before LKr

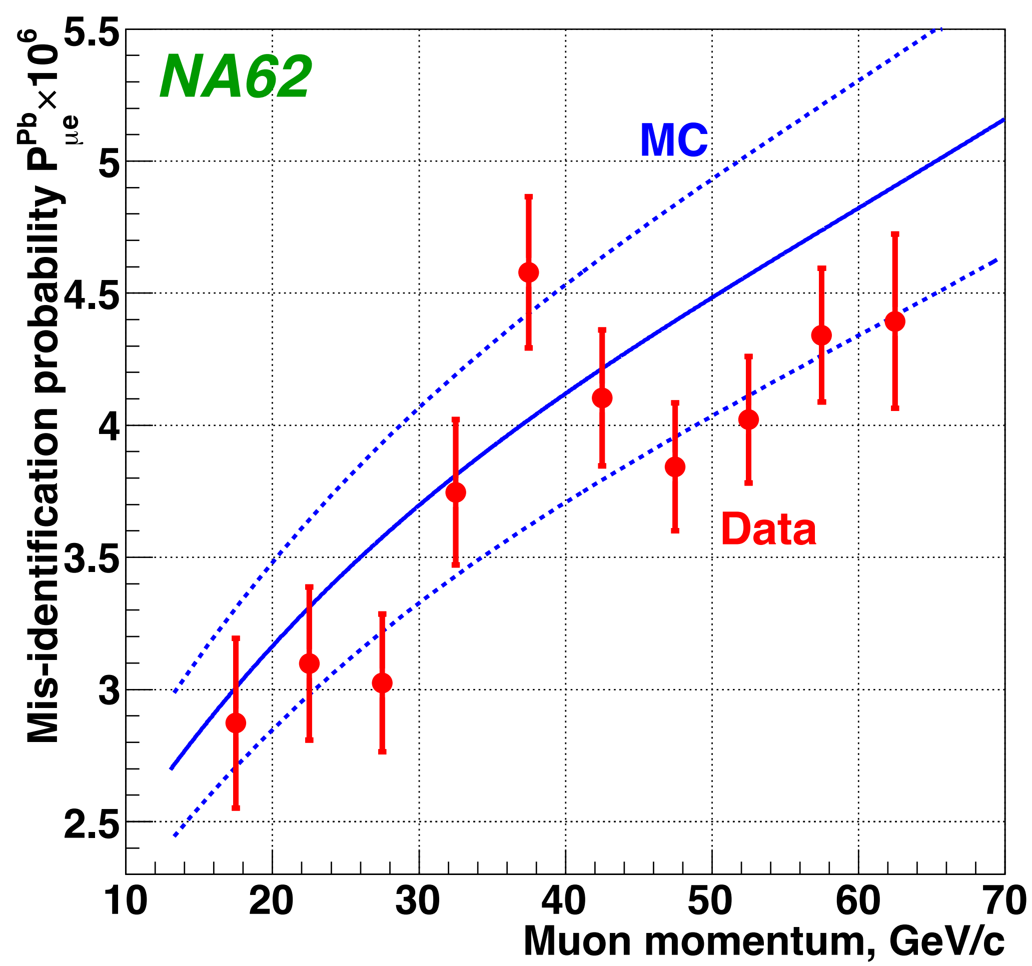
$\Longrightarrow$ Only muons pass

MC correction (GEANT4) for muon energy loss in lead

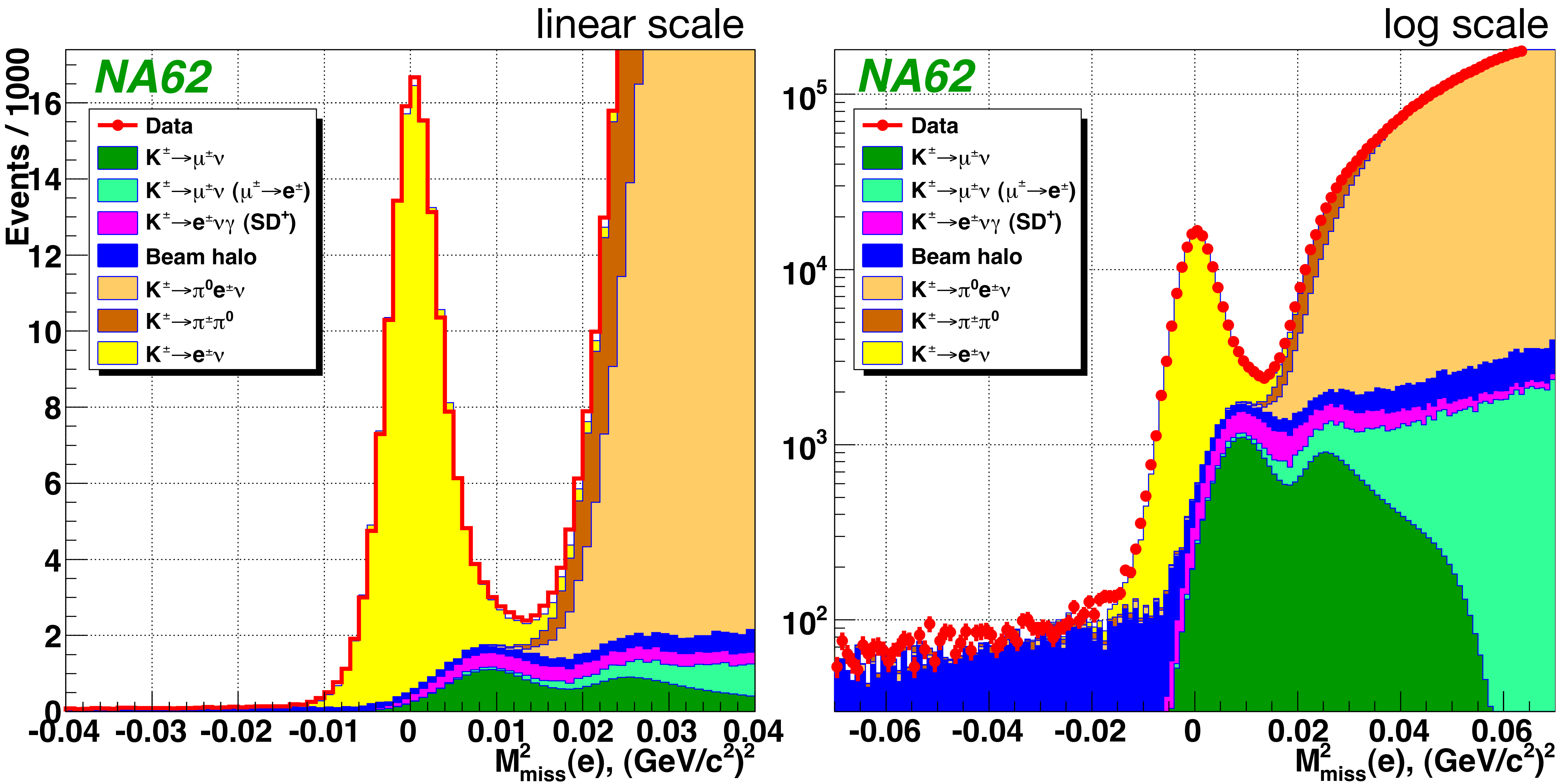
$$\boxed{B/(B+S) = (5.64 \pm 0.20)\%}$$

from $K_{\mu2}$ decays



# Full NA62 Data Set



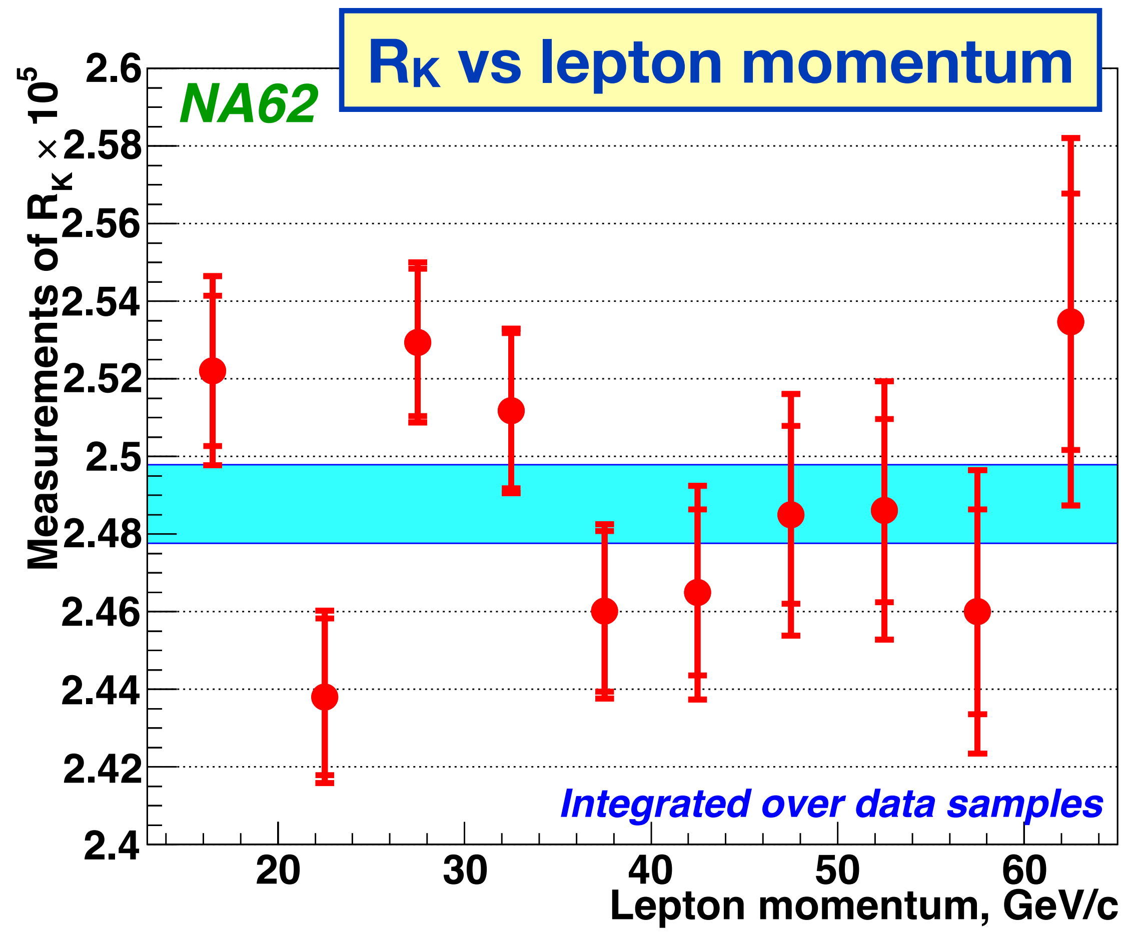

**145 958 $K^{\pm} \to e^{\pm}\nu$ candidates**

- Background: **(10.95 ± 0.27)%**
- e-ID efficiency: **(99.28 ± 0.05)%**

# NA62 Result on $R_K$

**Final NA62 result: (July 2011)**

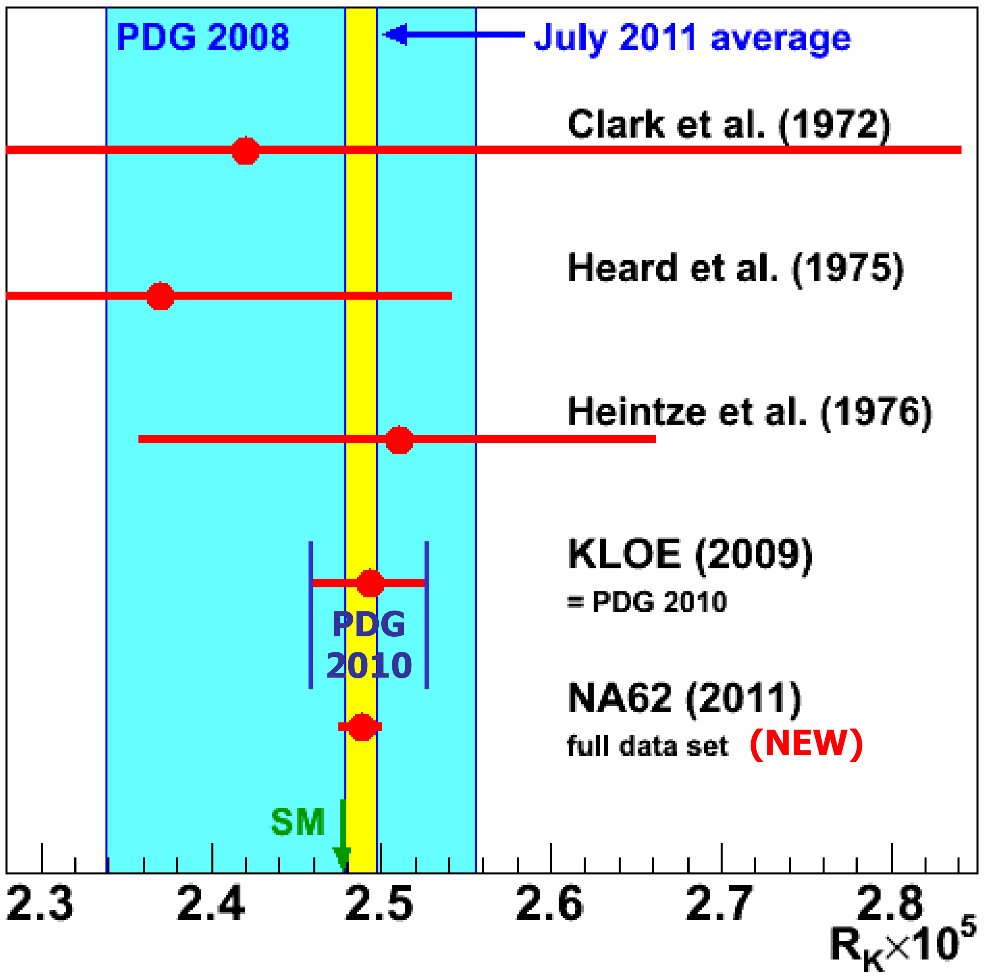
- Combined fit to 40 data samples (10 momentum bins, 2 kaon charges, with/without Pb)
- $\chi^2/n_{dof} = 47/39$
- Main systematics: Backgrounds & helium purity in decay volume

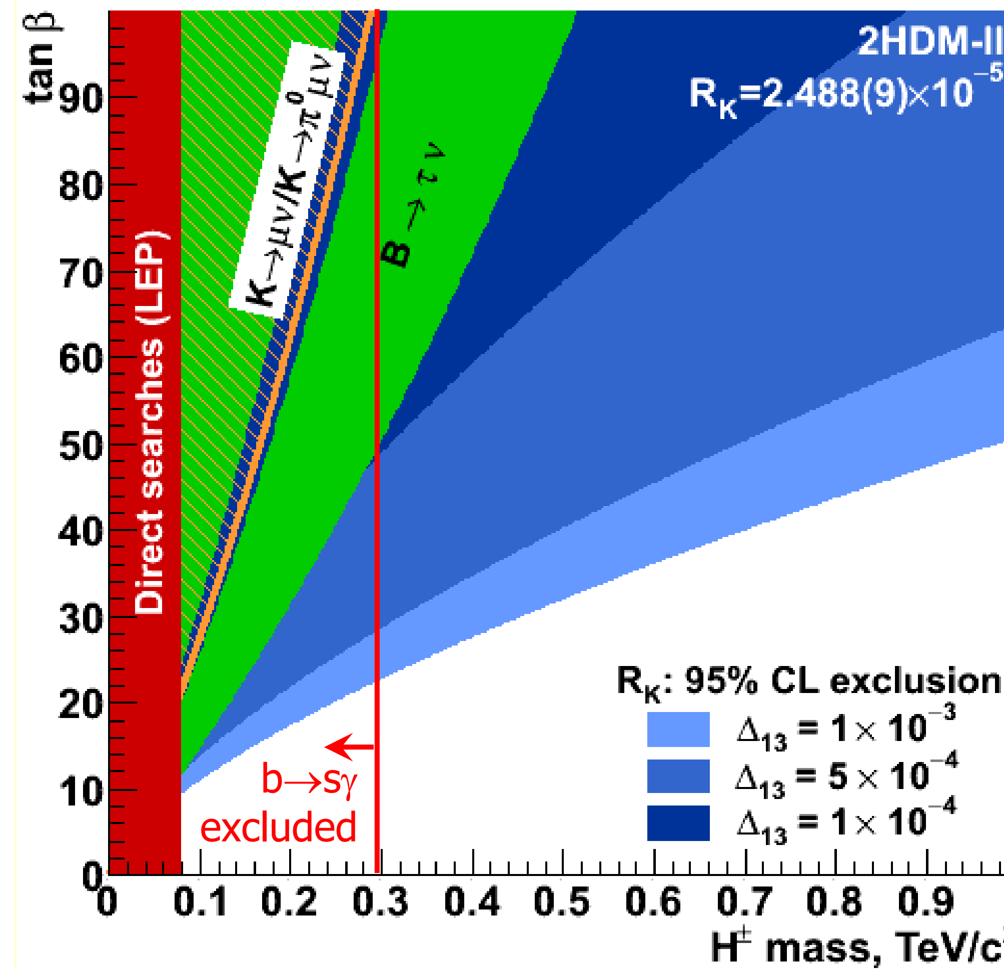



$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$$

- **Precision of 0.4%**, 3× better than PDG 2010 (i.e. KLOE measurement)

# 2011 World Average on $R_K$



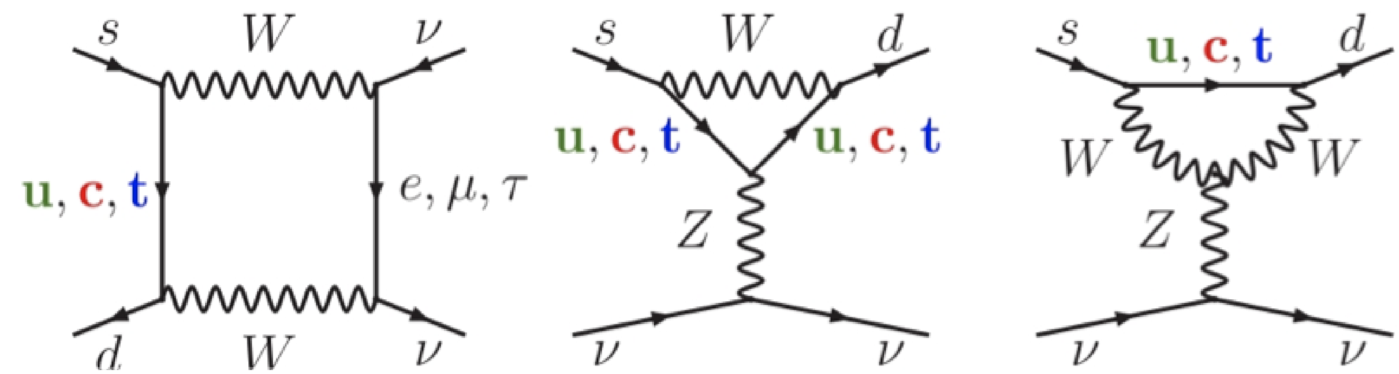

| World average | $R_K$ x $10^5$ | Precision |
|---|---|---|
| PDG 2008 | 2.447 ± 0.109 | 4.5 % |
| PDG 2010 | 2.493 ± 0.031 | 1.3 % |
| **July 2011** | **2.488 ± 0.009** | **0.4 %** |

**In agreement with SM expectation, but ~1σ above.**

# The Holy Grail: $K \rightarrow \pi \nu \bar{\nu}$

# $K \to \pi \nu \bar{\nu}$ in the SM

- **FCNC**, in the SM strongly suppressed by **box** and **penguin diagrams.**




- **Well predicted within the SM:**

$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \; \mathrm{Im}(V_{ts}^\star V_{td})^2 \; X(m_t, m_W)/|V_{us}^5|$$

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \; (V_{ts}^\star V_{td})^2 \; X(m_t, m_W)/|V_{us}^5| + \text{charm contr.}$$

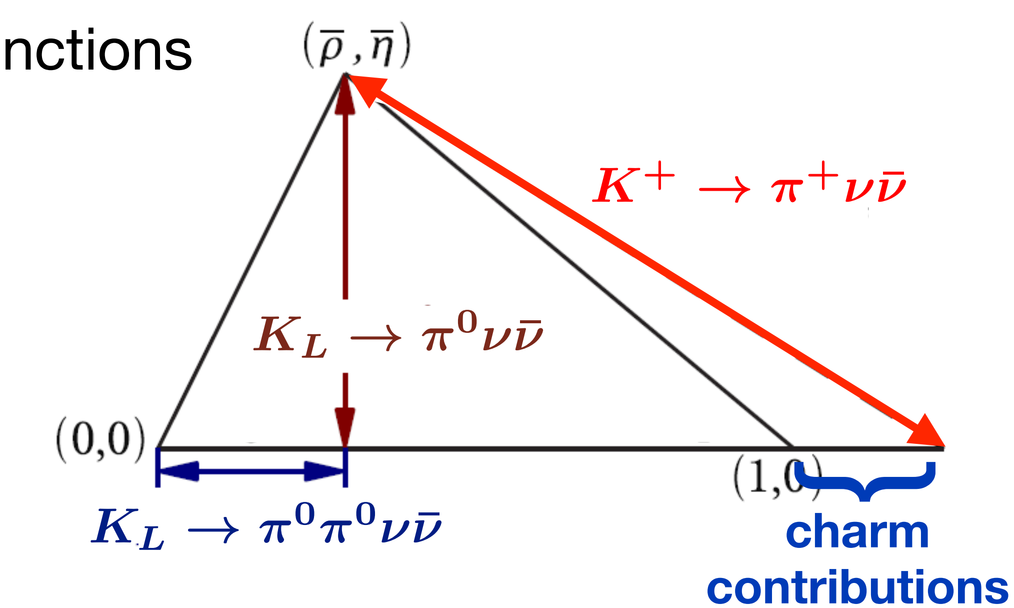
Hadronic uncertainties from $K \to \pi e \nu$

Known functions

- **SM prediction tiny:**

$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) = (2.4 \pm 0.4) \cdot 10^{-11}$$

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.0 \pm 1.1) \cdot 10^{-11}$$

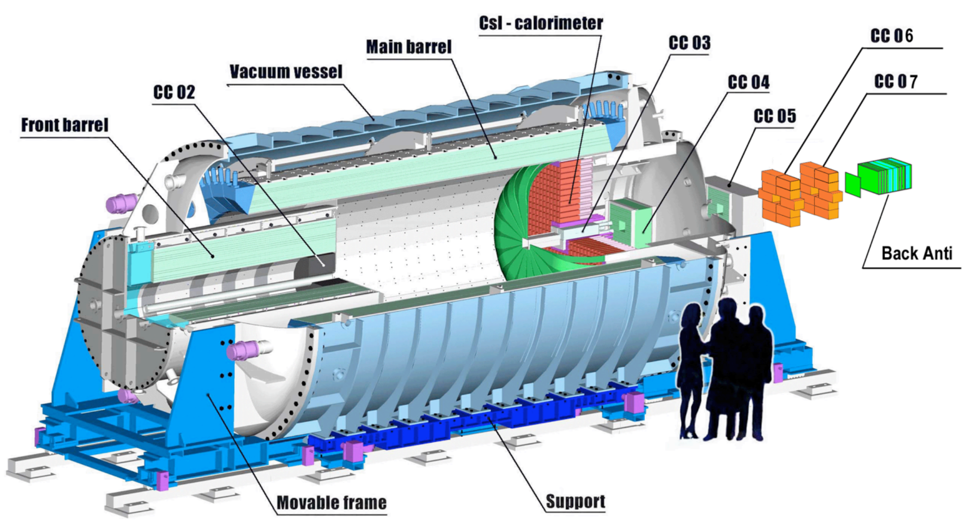


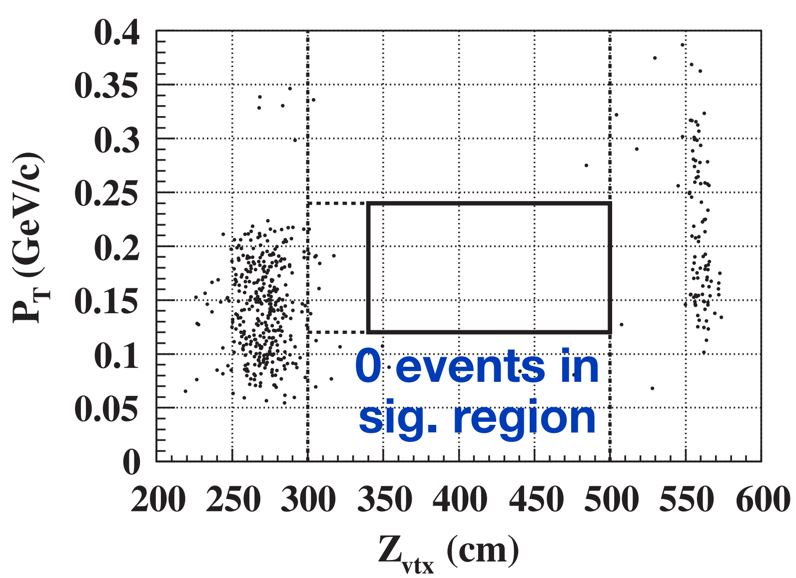

***Uncertainty almost only from knowledge on $|V_{ts}|$ !***

# $K \to \pi \nu \bar{\nu}$ Experimental Status

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

- E931a (KEK): (PRD 81 (2010) 072004)

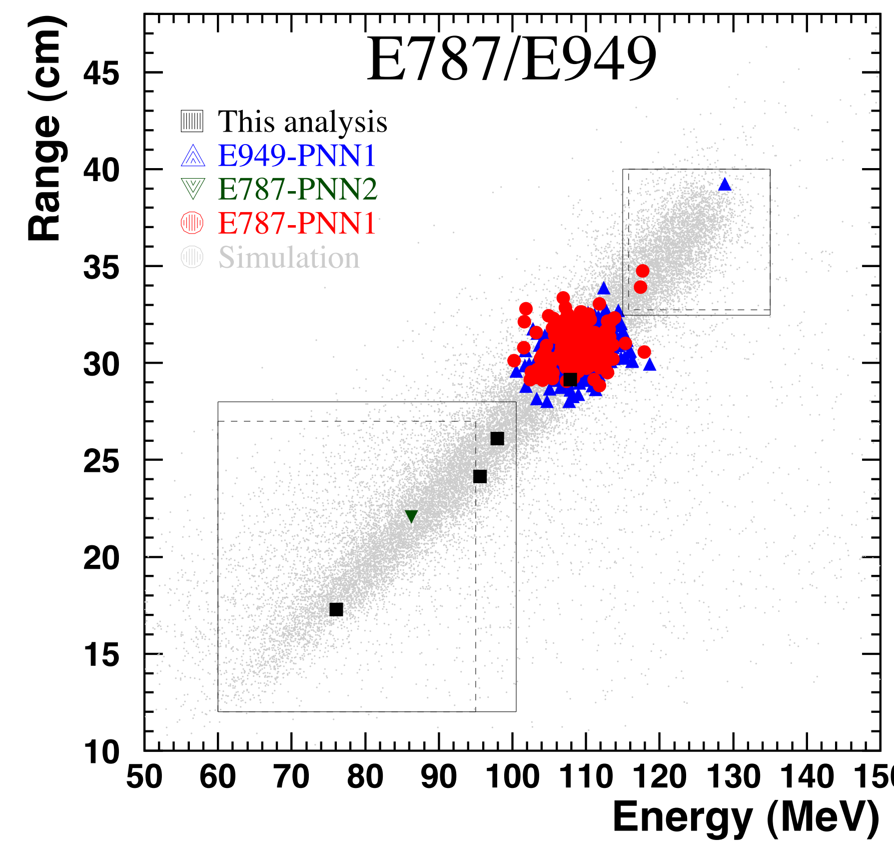



**BR < 2.6 x $10^{-8}$** (90% CL)

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

- E787/E949 (BNL):
(PRL 101 (2008) 191802)

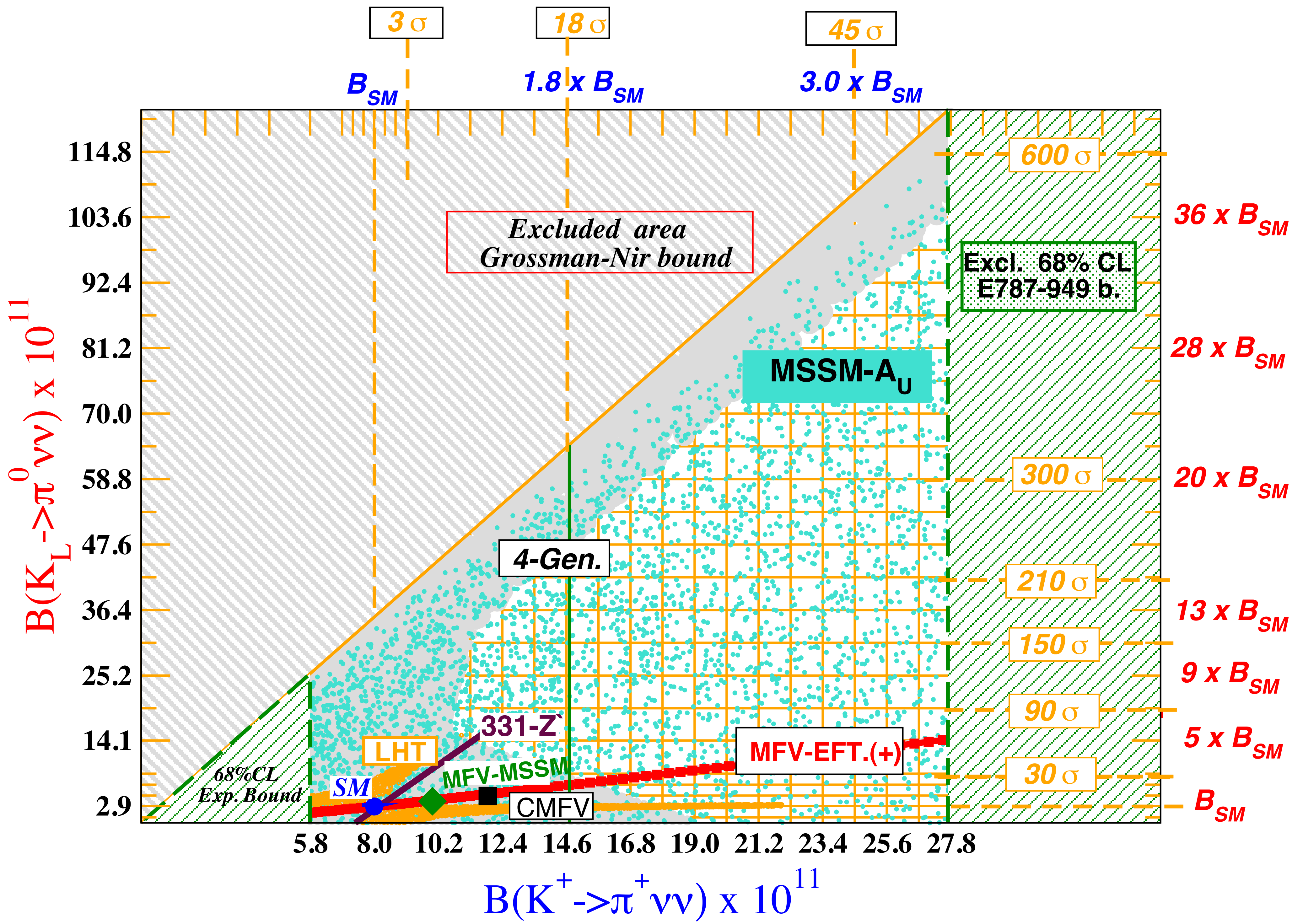



**7 candidate events**

**BR ≈ (17 ± 11) x $10^{-10}$**

# $K \rightarrow \pi \nu \bar{\nu}$ beyond the SM

FlaviAnet Kaon WG




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

# Future for $K_L \to \pi^0 \nu \bar{\nu}$

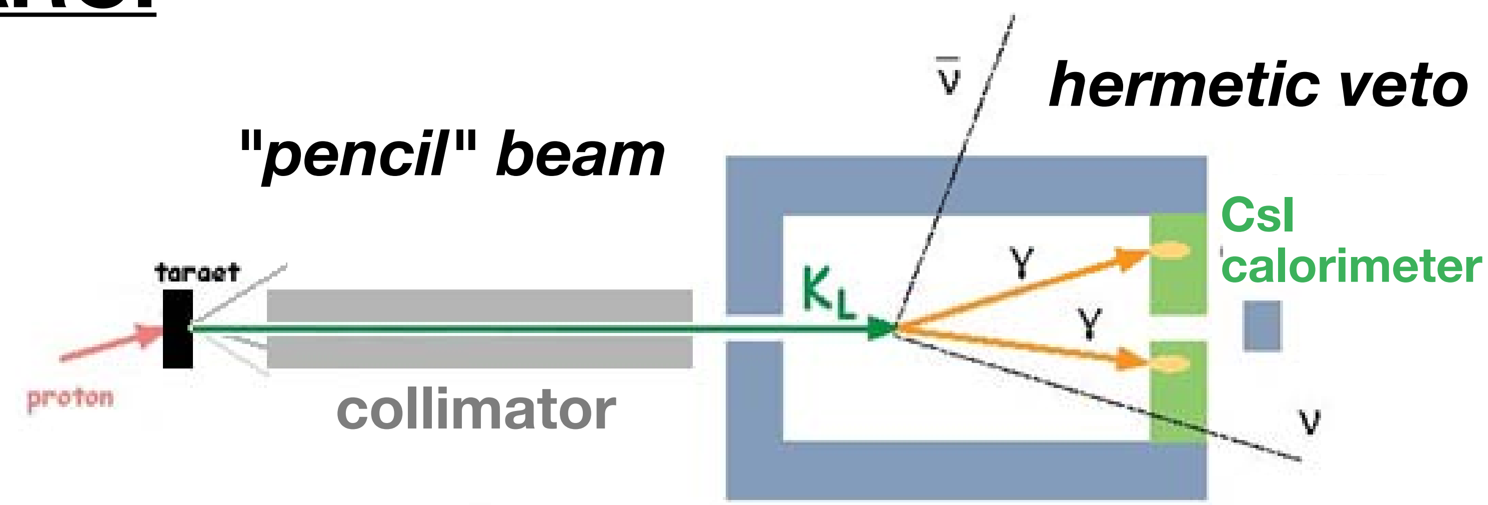
**KOTO experiment at J-PARC:**

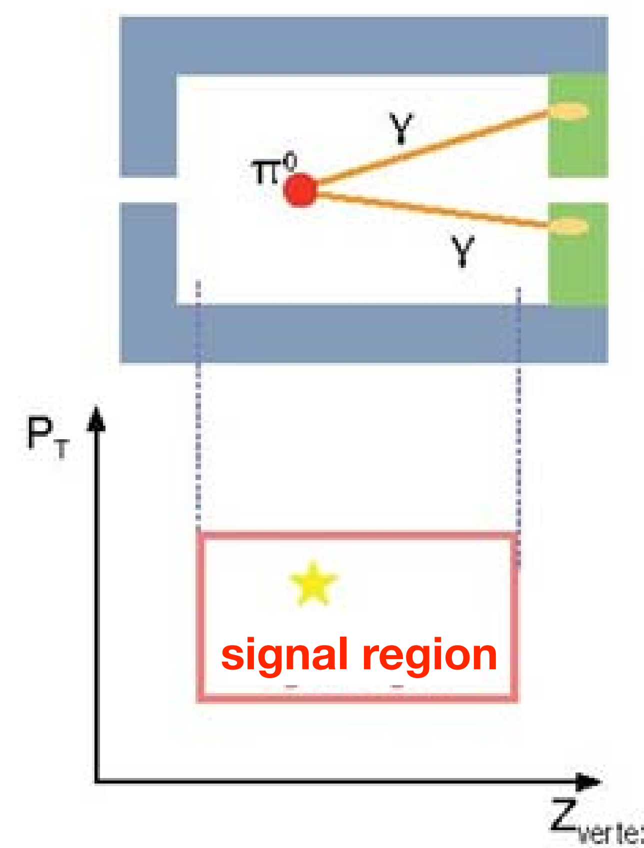
Successor of E931a,
same principle:

- Pencil beam
- $\pi^0$ reconstruction
- Hermetic veto

**Many improvements** w.r.t. E931a:

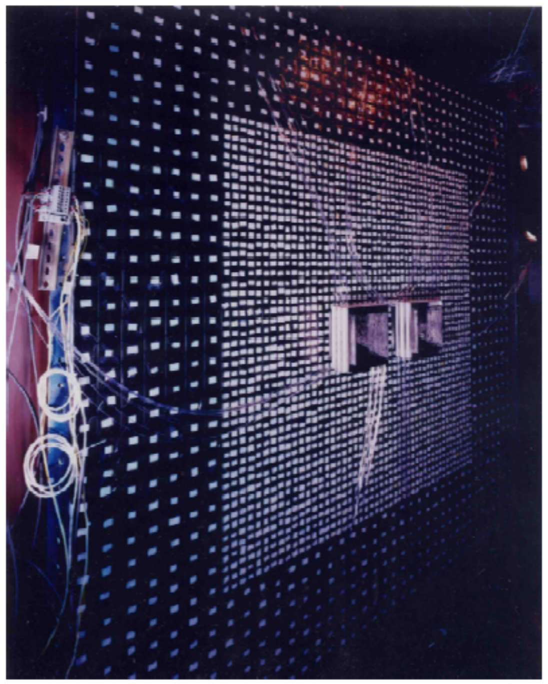
- **Beam line** (now J-PARC):
  higher p intensity (x100),
  lower neutron halo background
- New & better **Photon vetos.**
- **CsI calorimeter:**
  Replaced with KTeV CsI crystals,
  longer blocks and finer segmentation



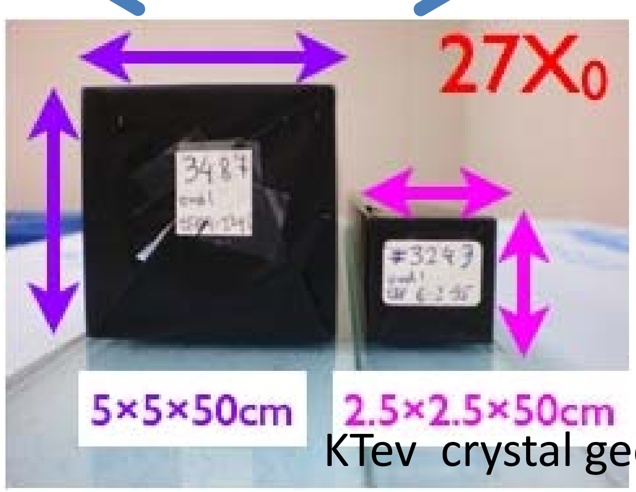



# KOTO CsI Calorimeter

**KTeV**
**CsI calorimeter**



E391 CsI crystal 7cmx7cmx30cm **16X$_0$**




KTev crystal geometry

Fermilab Today — Friday, Oct. 24, 2008

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**Calendar**

**Friday, Oct. 24**
**11:50 a.m. - 12:20 p.m.**
LHC Users meeting lecture - One West
Title: Perspectives from OSTP
Speaker: Jean Cottam, OSTP
**3:30 p.m.**
DIRECTOR'S COFFEE BREAK - 2nd Flr X-Over
**4 p.m.**
Joint Experimental-Theoretical Physics Seminar - One West
Speaker: Alan Boyle, *MSNBC*
Title: Magnetic Attraction: A Journalist's View of the LHC's Status in Popular Culture
**8 p.m.**
Fermilab International Film Society - Auditorium
Tickets: Adults $5
Title: A New Leaf

**Sunday, Oct. 26**

**Feature**

**KTeV crystals to shine again**

JPARC graduate students work to pack crystals from Fermilab's former KTEV experiment for shipment. JPARC will use the crystals in an experiment that will look for ultra-rare kaon decays.

From 1997 to 1999, scientists at Fermilab conducted an experiment using the most accurate energy-measuring device ever built for high-energy physics.

Then researchers carefully stored the experiment, KTeV.

Until now.

**From ISGTW**

**Catching quake**

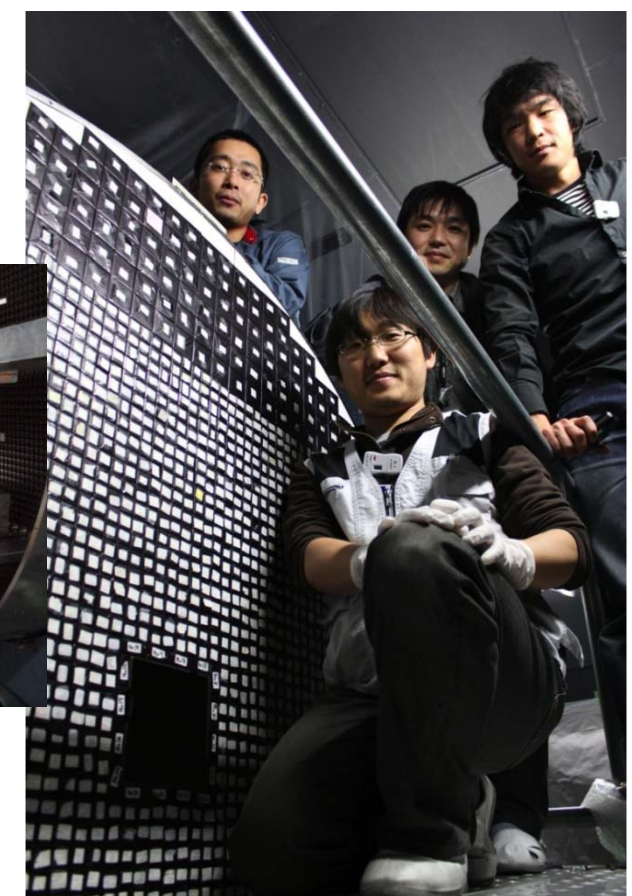
Inside your laptop is a sma protect the delicate moving sudden jolts.

It turns out that the same c earthquake sensor, too—e lots of them are compared, mundane sources of laptop

It's an approach that is sta project Quake Catcher Net about 1500 laptops connec detected several tremors, i quake in Los Angeles in Ju at the University of Califor Lawrence at Stanford Univ BOINC platform for volunte SETI@home rely on.

One of the benefits of this Research-grade earthquak between $10,000 and $10 much more sensitive, and

Ray Safarik, a technical specialist at Fermilab, shows the partially dismantled KTEV detector.



Feb,2011

(Slide from Jiasen Ma)

# KOTO Sensitivity and Timeline

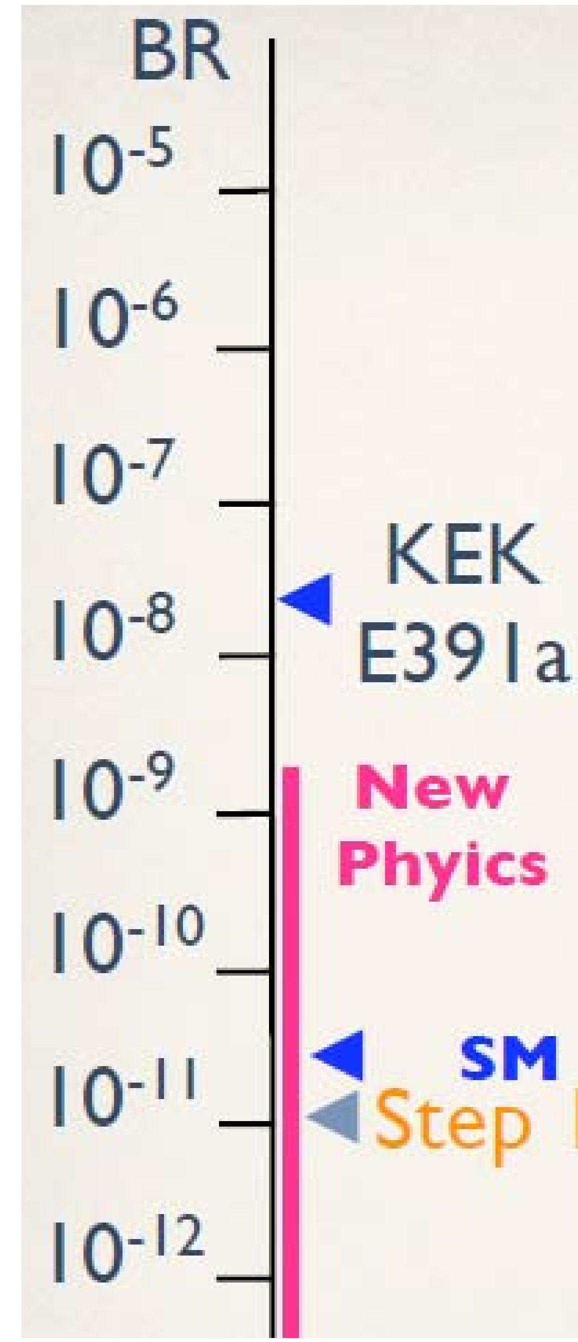
**Goal:**

- **3 SM events** / 3 years data-taking with S/N ~2

**Timeline:**

- **2009:** Beam survey → done
- **2010:** Calorimeter engineering → mostly done
- **2011:** Full engineering and first physics run planned ➜ Grossman-Nir limit (~13×SM) in 2012

**But:** Earthquake and scenario of accelerator power upgrade may cause delay (1 year?)



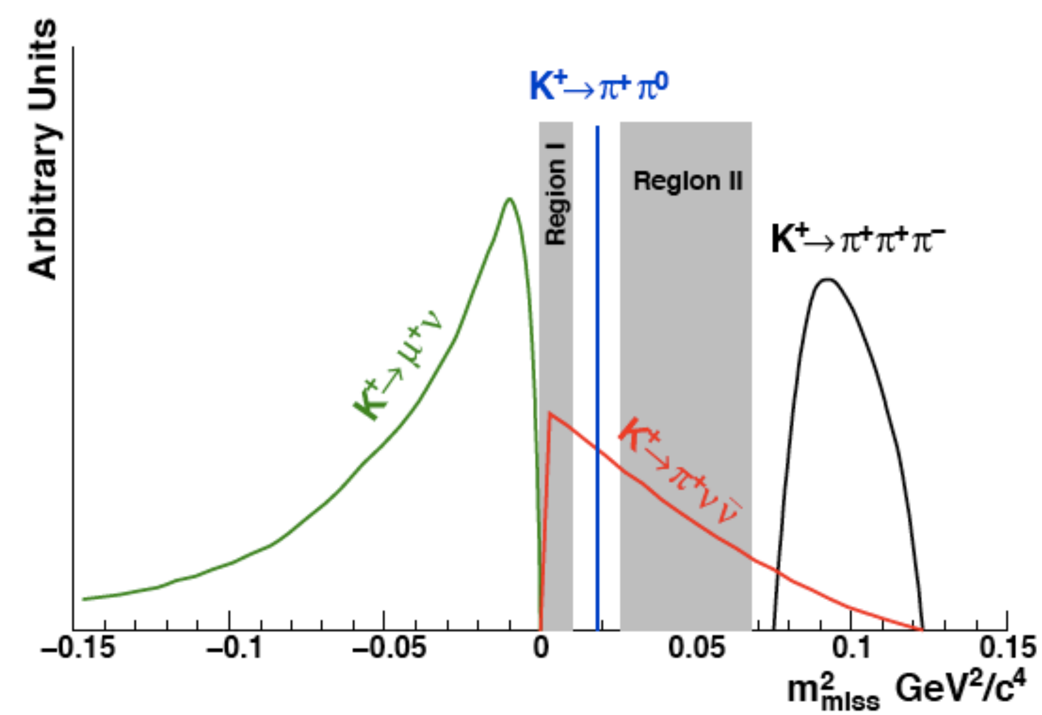
# Future for $K^+ \to \pi^+ \nu \bar{\nu}$

**NA62 experiment at CERN:**

- Successor of NA48/2, but new collaboration and detector ($K_{e2}/K_{\mu 2}$ measurement was still old NA48 detector)
- Aims to measure **100 SM events** in 2 years of data-taking with **S/N ~ 10.**

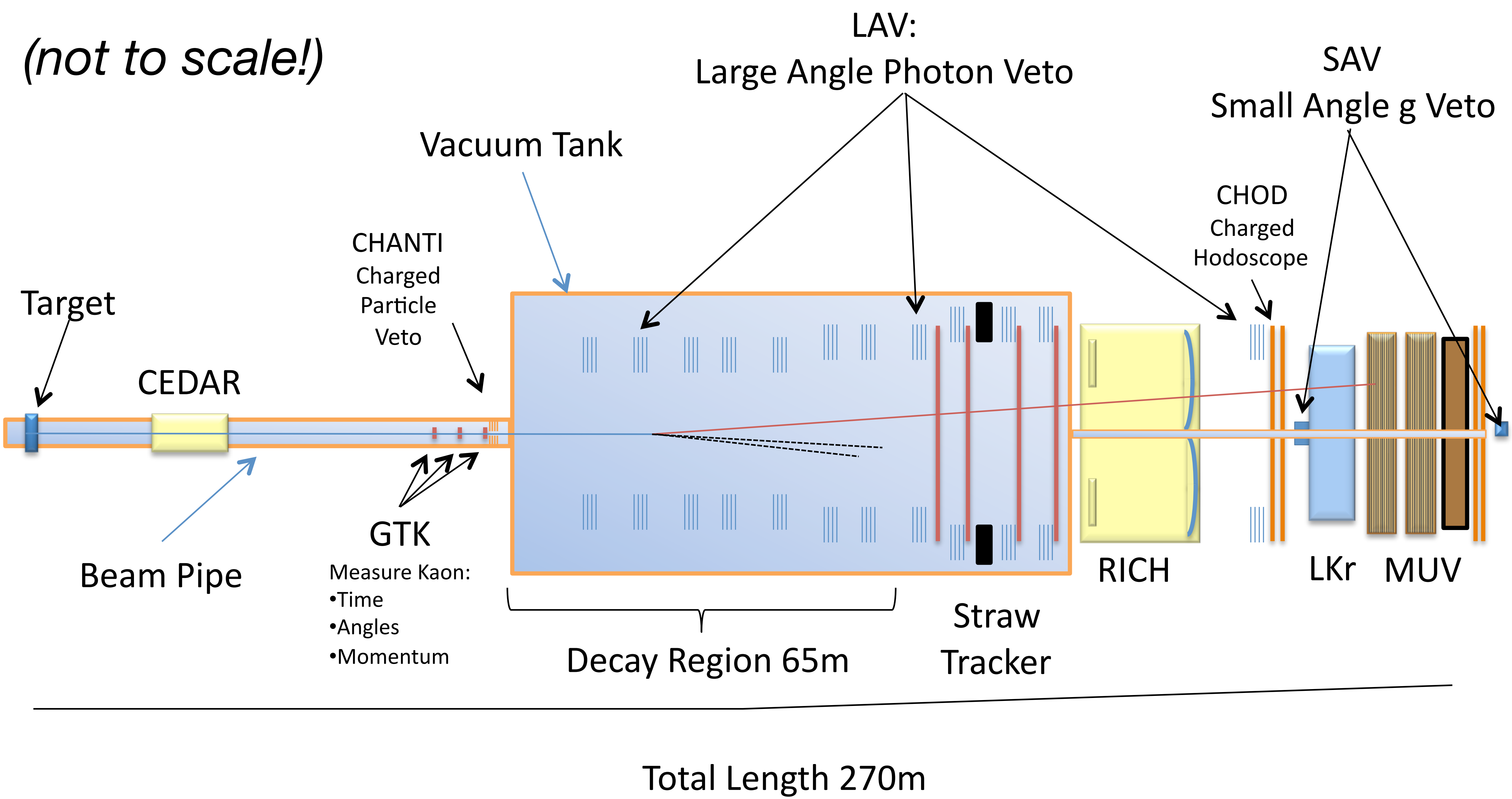
**Principle:**

- Precise kaon and pion ID and momentum measurements.
- Full angular coverage of photon detectors to veto $K^+ \to \pi^+ \pi^0$.
- Several detectors to veto $K^+ \to \mu^+ \nu$ (straws, RICH, muon vetos).



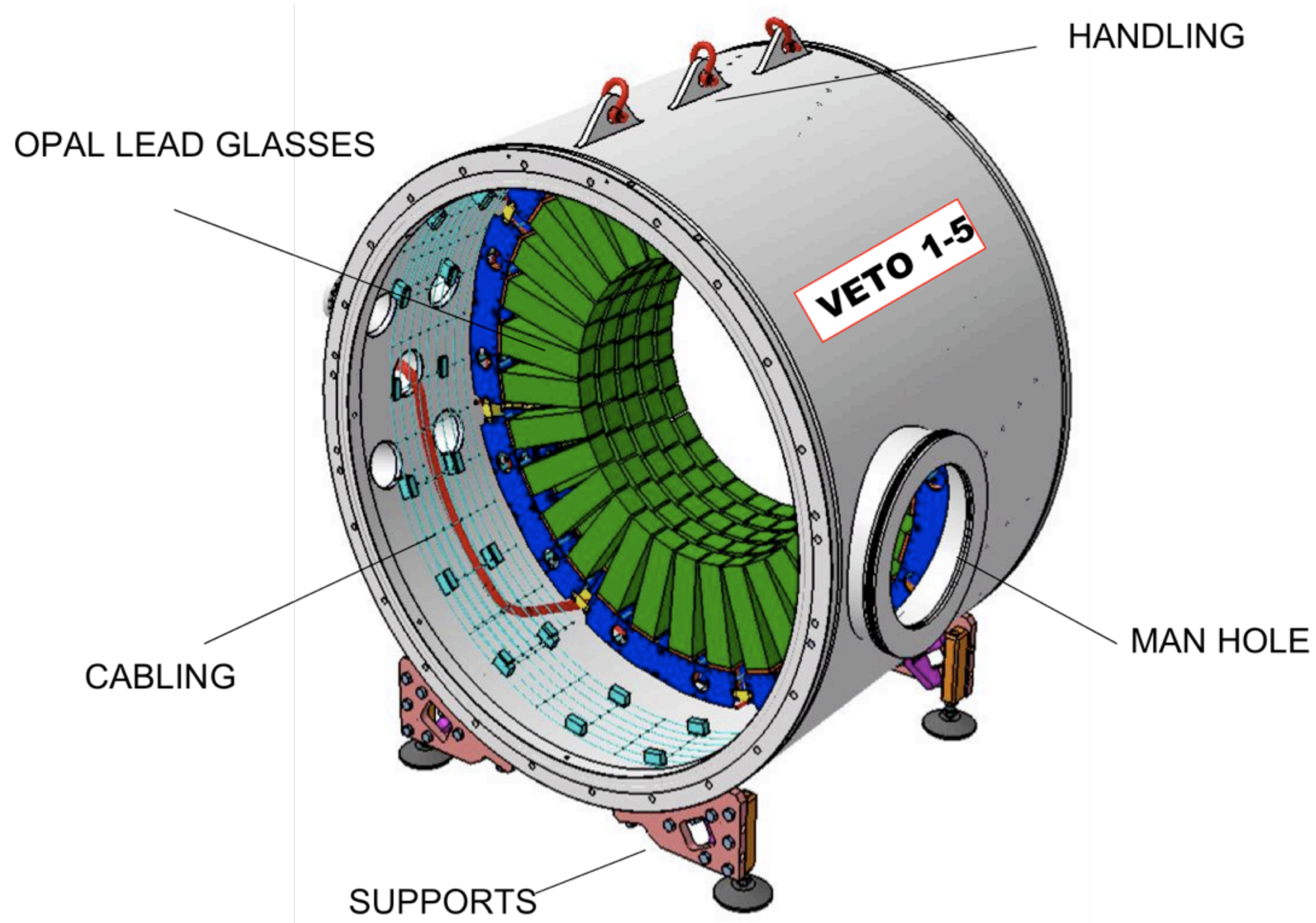

➜ **Two signal regions almost free of background**

# The NA62 Detector



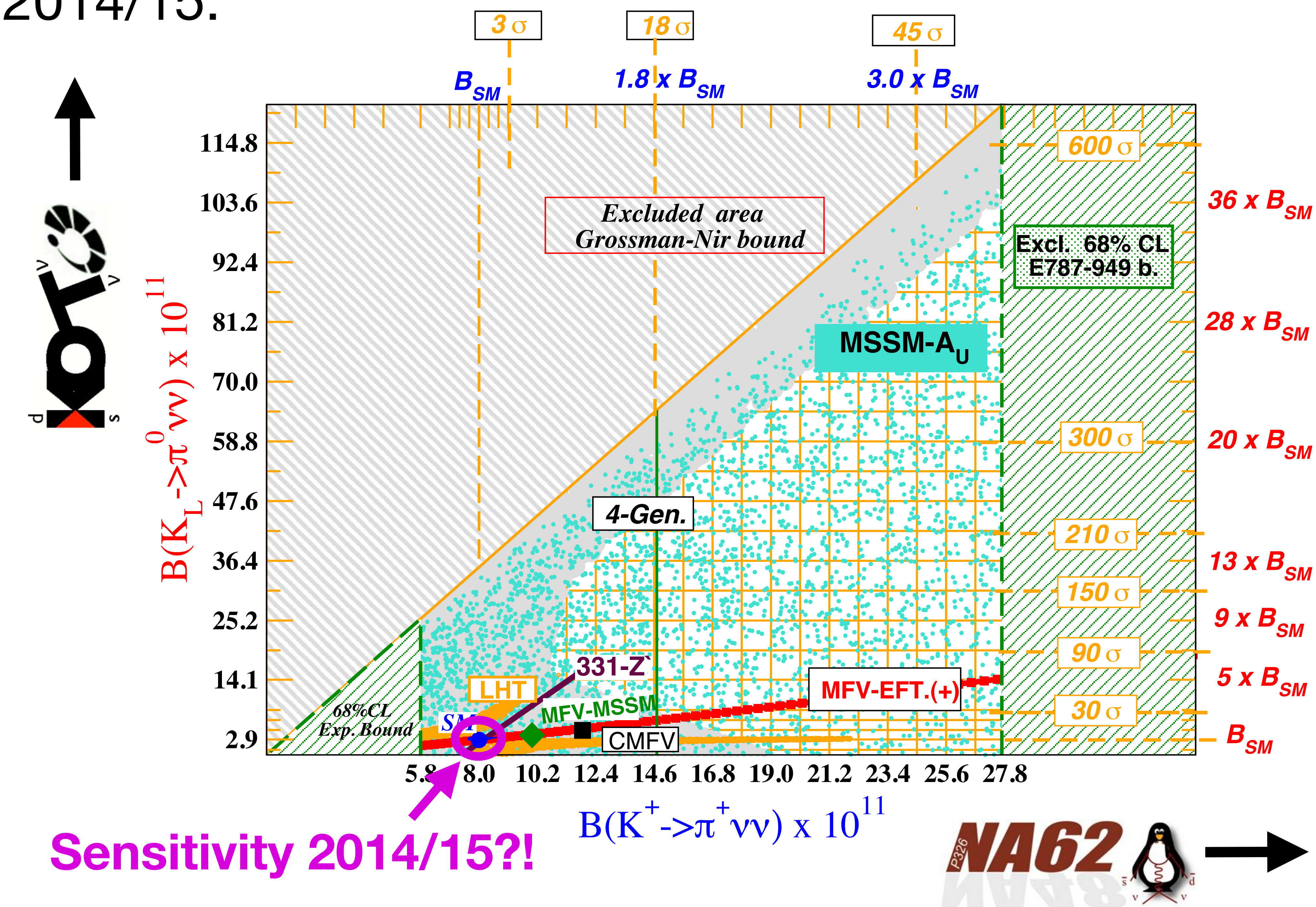
# First NA62 Detectors

First photon veto ring:




# Expectations for $K \to \pi \nu \bar{\nu}$

Assuming 3 SM events for $K_L \to \pi^0 \nu\bar{\nu}$ and 100 for $K^+ \to \pi^+ \nu\bar{\nu}$ by 2014/15:




Sensitivity 2014/15?!

# Conclusions

- With very high statistics, **NA48/2** has checked ChPT predictions on ππ scattering lengths with high accuracy using both $K^{\pm} \to \pi^{\pm} \pi^{0} \pi^{0}$ and $K_{e4}$ decays.

  ➜ **very strong test of ChPT theory**

- Very precise measurements by **KLOE** and **NA48/2** of the helicity-suppressed ratio $\Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$.

  ➜ **still good agreement with the SM**

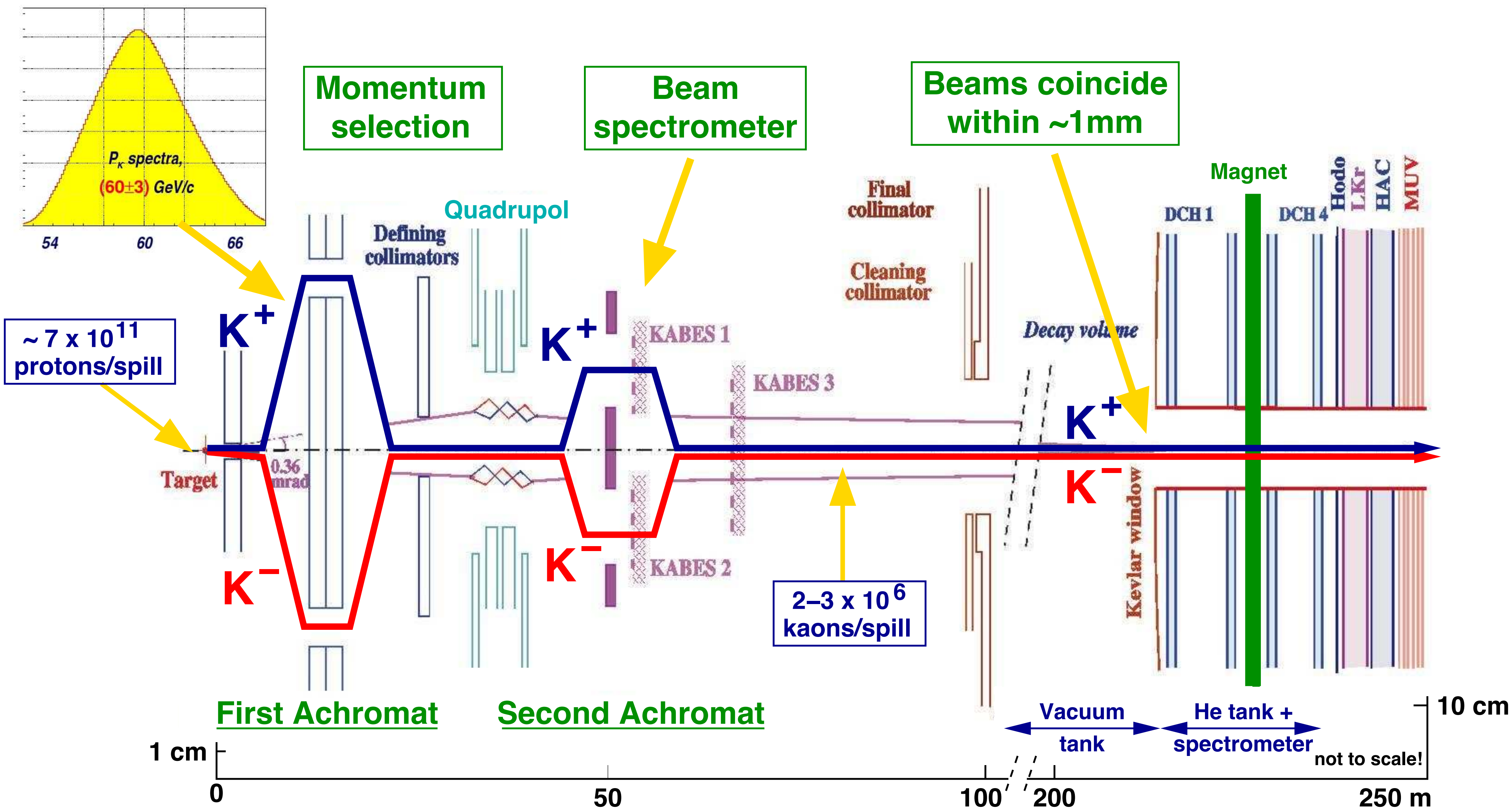
- **KOTO & NA62:** Searches for New Physics in $K^{0} \to \pi^{0} \nu \bar{\nu}$ and $K^{\pm} \to \pi^{\pm} \nu \bar{\nu}$ starting soon.

  ➜ **very high sensitivity for many New Physics models**

# Spares

# NA48/2 in 2003/2004

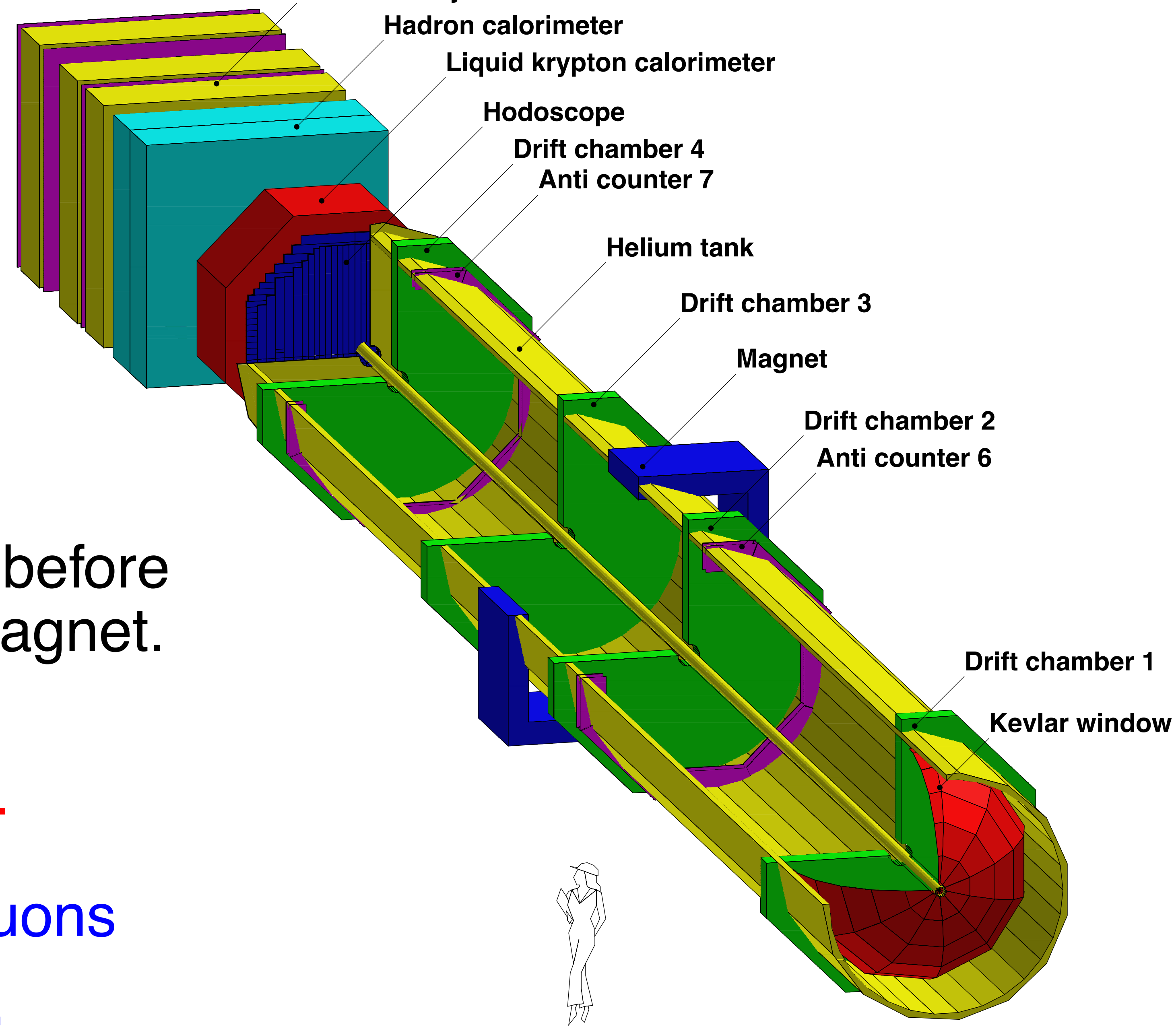
- **Simultaneous $K^+$ and $K^-$ beams** with $p_{K^\pm} = (60 \pm 3)$ GeV/$c$.




**Trigger:**
- **3 charged tracks** or
- **1 charged track + missing $p_T$**

→ **Efficiencies > 99 %**

# NA48/2 Detector



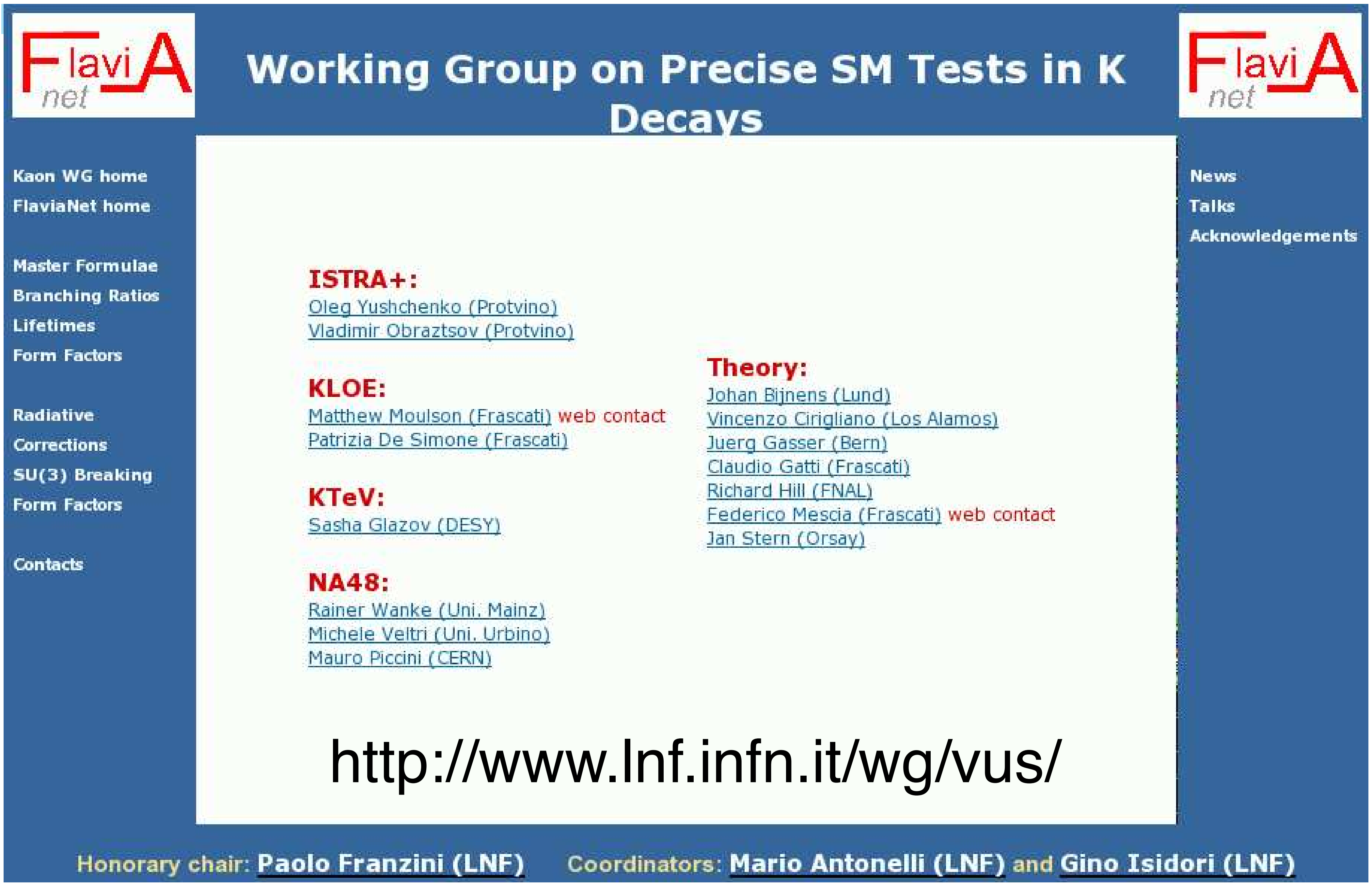

**Main detector components:**

- **Magnet spectrometer**
  - Two drift chambers each before and after spectrometer magnet.
  - Momentum resolution: $\leq 1\%$ for 20 GeV/$c$ tracks.
- Anti-counters for photons, muons
- **Liquid Krypton Calorimeter**

# Precision Determination of $|V_{us}|$

# Flavianet Kaon Working Group

Similar to HFAG: Combines all experimental and theoretical results in kaon physics (in particular for $|V_{us}|$ determination).



# $|V_{us}|$ Determination

**CKM Matrix:**

- Unitarity relation for first row of CKM matrix:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

- $|V_{ud}|$ = 0.97425(22) from super-allowed $0^+ \to 0^+$ transitions.
- $|V_{ub}|$ ~ 0.004 has 10% uncertainty, but is completely negligible.
- $|V_{us}|$ (Cabibbo angle) historically measured from semileptonic kaon decays:
  - Hadronic uncertainties small compared to other K decays (but still a major problem).
  - Easy production of large data samples.

**Historical situation:**

- $1 - |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 =$ , with the error dominated by $|V_{us}|$.

# $|V_{us}|$ from Semileptonic Kaon Decays

**Master formula for $K \to \pi l \nu$ ($K_{l3}$) decays:** *($l$ = e, μ)*

$$\boxed{\Gamma(K_{13(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^l (1 + 2\delta^l_{SU(2)} + 2\delta^l_{EM})}$$

with: $C_K^2 = 1$ for $K^0$, $= \frac{1}{2}$ for $K^\pm$.

$S_{EW} = 1.0232$: short-distance EW correction.

**To be measured by experiment:**

- $\Gamma(K_{13(\gamma)})$: Decay rates including radiative $\gamma$'s $\Longrightarrow$ BR's, $\tau$'s.
- $I_K^l$: Integral of form factors over phase space $\Longrightarrow$ slopes $\lambda_+$, $\lambda_0$.

**To be determined by theory:**

- $f_+(0)$: Hadronic matrix element at $q^2 = 0$ (different for $K^\pm$, $K^0$).
- $\delta^l_{SU(2)}$, $\delta^l_{EM}$: Form factor corrections for $SU(2)$ breaking and long-distance EM interactions.

# $K_{l3}$ Branching Fractions

FlaviAnet Kaon WG

## Global *Flavianet* fit to all kaon decay data

- Includes: All $K^{\pm}$, $K_L$, $K_S$ BR's, lifetimes, form factors

### $K_L$: 21 measurements

| Parameter | Value | Source |
|---|---|---|
| $\tau_{K_L}$ | 50.92(30) ns | KLOE |
| $\tau_{K_L}$ | 51.54(44) ns | Vosburgh |
| $BR(K_{e3})$ | 0.4049(21) | KLOE |
| $BR(K_{\mu3})$ | 0.2726(16) | KLOE |
| $BR(K_{\mu3})/BR(K_{e3})$ | 0.6640(26) | KTeV |
| $BR(3\pi^0)$ | 0.2018(24) | KLOE |
| $BR(3\pi^0)/BR(K_{e3})$ | 0.4782(55) | KTeV |
| $BR(\pi^+\pi^-\pi^0)$ | 0.1276(15) | KLOE |
| $BR(\pi^+\pi^-\pi^0)/BR(K_{e3})$ | 0.3078(18) | KTeV |
| $BR(\pi^+\pi^-)/BR(K_{e3})$ | 0.004856(29) | KTeV |
| $BR(\pi^+\pi^-)/BR(K_{e3})$ | 0.004826(27) | NA48 |
| $BR(\pi^+\pi^-)/BR(K_{\mu3})$ | 0.007275(68) | KLOE |
| $BR(K_{e3})/BR(2\text{ tracks})$ | 0.4978(35) | NA48 |
| $BR(\pi^0\pi^0)/BR(3\pi^0)$ | 0.004446(25) | KTeV |
| $BR(\pi^0\pi^0)/BR(\pi^+\pi^-)$ | 0.4391(13) | PDG ETAFIT |
| $BR(\gamma\gamma)/BR(3\pi^0)$ | 0.00279(3) | KLOE |
| $BR(\gamma\gamma)/BR(3\pi^0)$ | 0.00281(2) | NA48 |
| $BR(\pi^+\pi^-\gamma)/BR(\pi^+\pi^-)$ | 0.0208(3) | KTeV |
| $BR(\pi^+\pi^-\gamma_{DE})/BR(\pi^+\pi^-\gamma)$ | 0.689(21) | KTeV |
| $BR(\pi^+\pi^-\gamma_{DE})/BR(\pi^+\pi^-\gamma)$ | 0.683(11) | KTeV |
| $BR(\pi^+\pi^-\gamma_{DE})/BR(\pi^+\pi^-\gamma)$ | 0.685(41) | E731 |

### $K^{\pm}$: 17 measurements

| Parameter | Value | Source |
|---|---|---|
| $\tau_{K^{\pm}}$ | 12.422(40) ns | Koptev* |
| $\tau_{K^{\pm}}$ | 12.380(16) ns | Ott |
| $\tau_{K^{\pm}}$ | 12.443(38) ns | Fitch |
| $\tau_{K^{\pm}}$ | 12.347(30) ns | KLOE |
| $BR(K_{\mu2})$ | 0.6366(17) | KLOE |
| $BR(\pi\pi^0)$ | 0.2065(9) | KLOE |
| $BR(\pi\pi^0)/BR(K_{\mu2})$ | 0.3329(48) | PS183 |
| $BR(\pi\pi^0)/BR(K_{\mu2})$ | 0.3355(57) | Weissenberg |
| $BR(\pi\pi^0)/BR(K_{\mu2})$ | 0.3277(65) | Auerbach |
| $BR(K_{e3})$ | 0.04965(53) | KLOE |
| $BR(K_{e3})/BR(\pi\pi^0 + K_{\mu3} + \pi\pi^0\pi^0)$ | 0.1962(36) | E865 |
| $BR(K_{e3})/BR(\pi\pi^0)$ | 0.2470(10) | NA48/2 |
| $BR(K_{\mu3})$ | 0.03233(39) | KLOE |
| $BR(K_{\mu3})/BR(\pi\pi^0)$ | 0.1637(7) | NA48/2 |
| $BR(K_{\mu3})/BR(K_{e3})$ | 0.671(11) | KEK-E246 |
| $BR(\pi\pi^0\pi^0)$ | 0.01763(26) | KLOE |
| $BR(\pi\pi^0\pi^0)/BR(\pi\pi\pi)$ | 0.303(9) | Bisi |

**+ 5 $K_S$ measurements**

**+ form factor measurements**

# Corrections from Theory

FlaviA net Kaon WG

$$\Gamma(K_{l3(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^l (1 + 2\delta_{SU(2)}^l + 2\delta_{EM}^l)$$

isospin breaking / radiative corrections

- **Electromagnetic corrections:**
  Real and virtual photon emission, evaluated to second order ChPT. Errors estimated from higher order corrections.
  (Cirigliano, Giannotti, Neufeld, 2008)

| Mode | $\delta_{EM}^{K\ell}$ (%) |
|---|---|
| $K_{e3}^0$ | $0.495 \pm 0.110$ |
| $K_{e3}^\pm$ | $0.050 \pm 0.125$ |
| $K_{\mu3}^0$ | $0.700 \pm 0.110$ |
| $K_{\mu3}^\pm$ | $0.008 \pm 0.125$ |

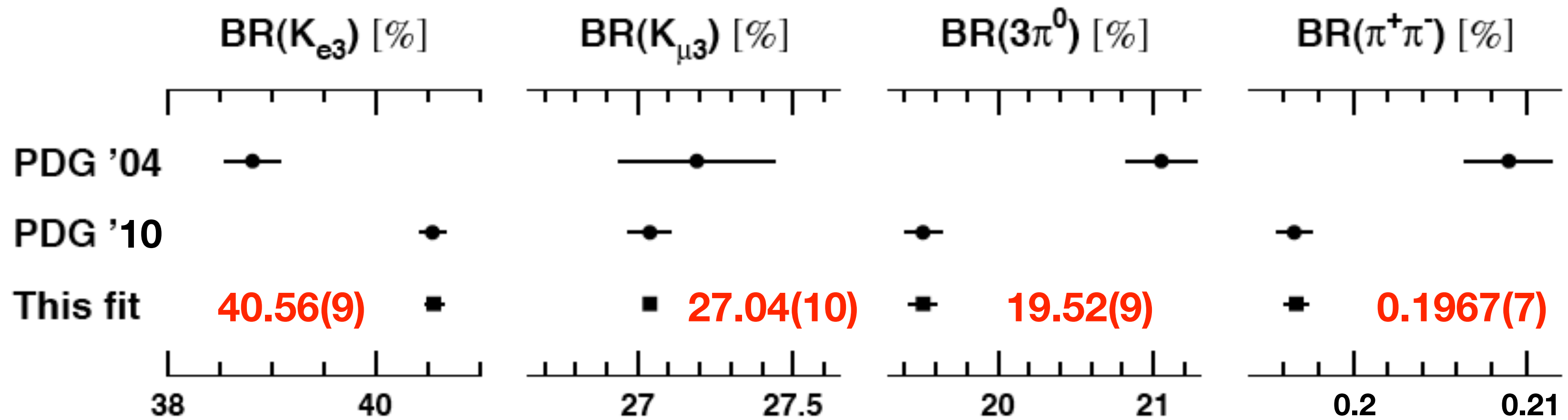
- **Isospin breaking corrections:**
  Isospin correction to be applied for $K^0 \to \pi^+ l\nu$, since $f_+(0) \equiv f_+^{K^+\pi^0}(0)$.
  Evaluated in NLO ChPT.
  (Kastner, Neufeld, 2008)

$$\delta_{SU(2)}^{K^+\pi^0} = 0.029 \pm 0.004$$

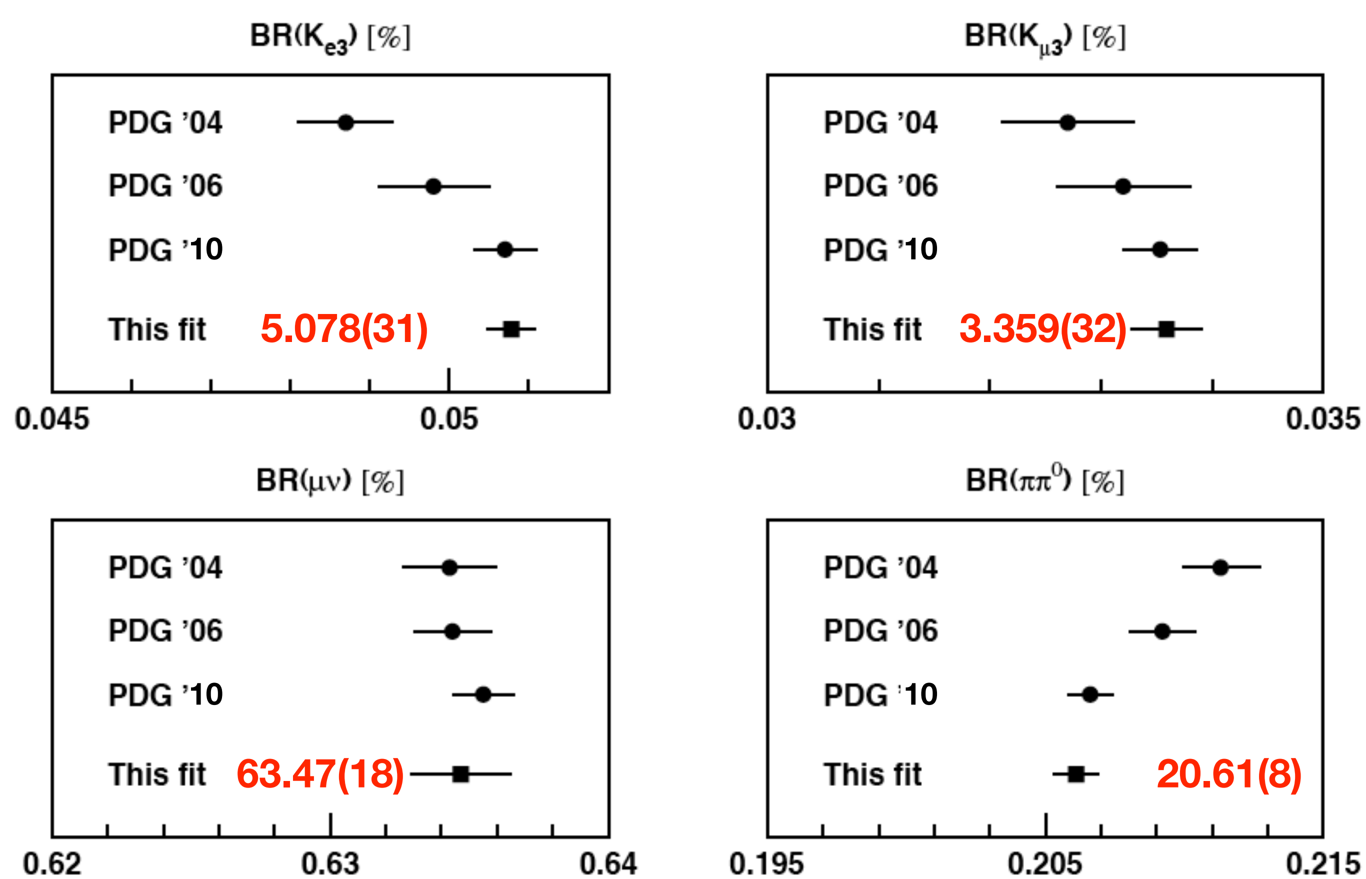
# Fit to Kaon Branching Fractions

FlaviA net Kaon WG

## $K^0$ decay rates:




## $K^\pm$ decay rates:

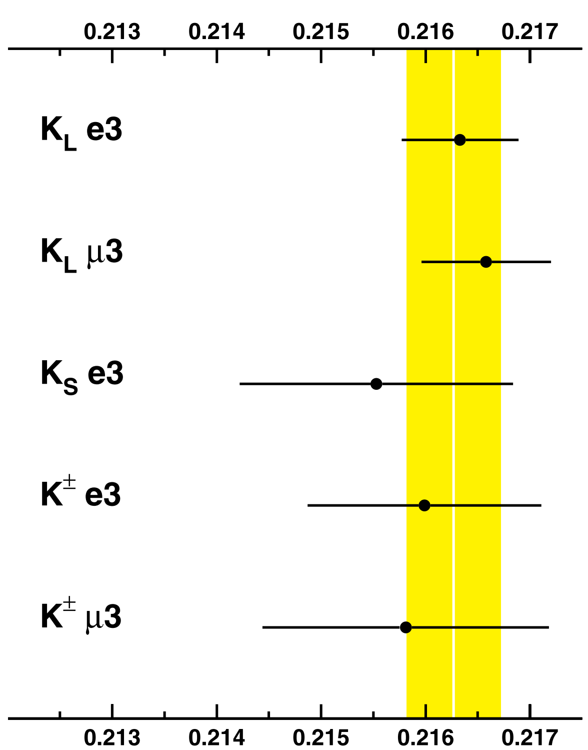



$\Longrightarrow$ **New KLOE $\pi^+\pi^0$ BR significantly shifts all $K^+$ results!**

# $|V_{us}|$ Determination

FlaviA net Kaon WG

| | | | | % error from | | |
|---|---|---|---|---|---|---|
| | **BR [%]** | $|\mathbf{V_{us}}| \times \mathbf{f_+(0)}$ | % err | BR | $\tau$ | $\Delta$ |
| $\mathbf{K_L e3}$ | **40.56(9)** | **0.2163(6)** | **0.26** | 0.09 | 0.20 | 0.11 |
| $\mathbf{K_L \mu 3}$ | **27.04(10)** | **0.2166(6)** | **0.29** | 0.15 | 0.18 | 0.11 |
| $\mathbf{K_S e3}$ | **0.0705(8)** | **0.2155(13)** | **0.61** | 0.60 | 0.03 | 0.11 |
| $\mathbf{K^\pm e3}$ | **5.078(31)** | **0.2160(11)** | **0.52** | 0.31 | 0.09 | 0.39 |
| $\mathbf{K^\pm \mu 3}$ | **3.359(32)** | **0.2158(14)** | **0.63** | 0.47 | 0.08 | 0.40 |
| **Average** | | **0.2163(5)** | | | | |




**Average:** $|V_{us}| \times f_+(0) = 0.2613(5)$

Use $f_+(0) = 0.965 \pm 0.005$ from Lattice QCD
(RBC/UKQCD, EPJ C69 (2010) 159)

$|V_{us}| = 0.2254(13)$

However: can still do better!

# $|V_{us}| / |V_{ud}|$ from $K_{\mu2} / \pi_{\mu2}$

FlaviA net Kaon WG

**Can also use $K_{\mu2}$ decays:**

- New BR from KLOE (~0.3% precision) + Flavianet fit:
  **$Br(K^+ \to \mu^+ \nu) = 0.6347 \pm 0.0018$**

- Take **$\tau(K^+)$** from Flavianet fit and build **$\Gamma(K_{\mu2})/\Gamma(\pi_{\mu2})$**

$(\Gamma(\pi \to \mu\nu) = 38.408(7)\ \mu s^{-1})$

$$\rightarrow \quad \frac{|V_{us}|}{|V_{ud}|} \frac{f_K}{f_\pi} = 0.2758 \pm 0.0005$$

- Use $f_K/f_\pi = 1.193(6)$ (from an average of lattice QCD estimates)

$$\rightarrow \quad \boxed{|V_{us}|/|V_{ud}| = 0.2312 \pm 0.0013}$$

# Putting It All Together

$|V_{ud}|$ from super-allowed nuclear β decays

$|V_{us}|$ from semileptonic K decays

$|V_{us}|/|V_{ud}|$ from $K_{\mu 2}$

**Global fit:**

$$\boxed{\begin{aligned} |V_{ud}| &= 0.97425(22) \\ |V_{us}| &= 0.2253(9) \end{aligned}}$$

**Unitarity check:**

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0001(6)$$