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Review on kaon physics

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Outline

- Recent results on kaon physics (2012)
  - NA48/NA62 results:
    - Form factors of $K^{\pm}e3$ and $K^{\pm}\mu3$ decays
    - Update on $K^{+} \rightarrow e^{+}\nu\gamma$ (Ke2γ)
    - The $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ decay
  - LHCb result:
    - New limit on $K_s \rightarrow \mu^{+}\mu^{-}$
  - KLOE results:
    - The $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ decay
    - New limit on the BR of the $K^0_S \rightarrow \pi^0\pi^0\pi^0$ decay
- Future for kaon physics
  - KLOE-2
  - Measurement of BR $K^{+} \rightarrow \pi^{+}\nu\bar{\nu}$ at NA62
  - KOTO @ JPARK and ORKA @ FNAL

Thanks to E. De Lucia

Recent results (2012) from NA48 and NA62

NA48 and NA62

1997: $K_L + K_S$	
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 Discovery of direct CPV

2002: K_S/Hyperons

NA48/1

2003: $K^+ + K^-$
2004: $K^+ + K^-$

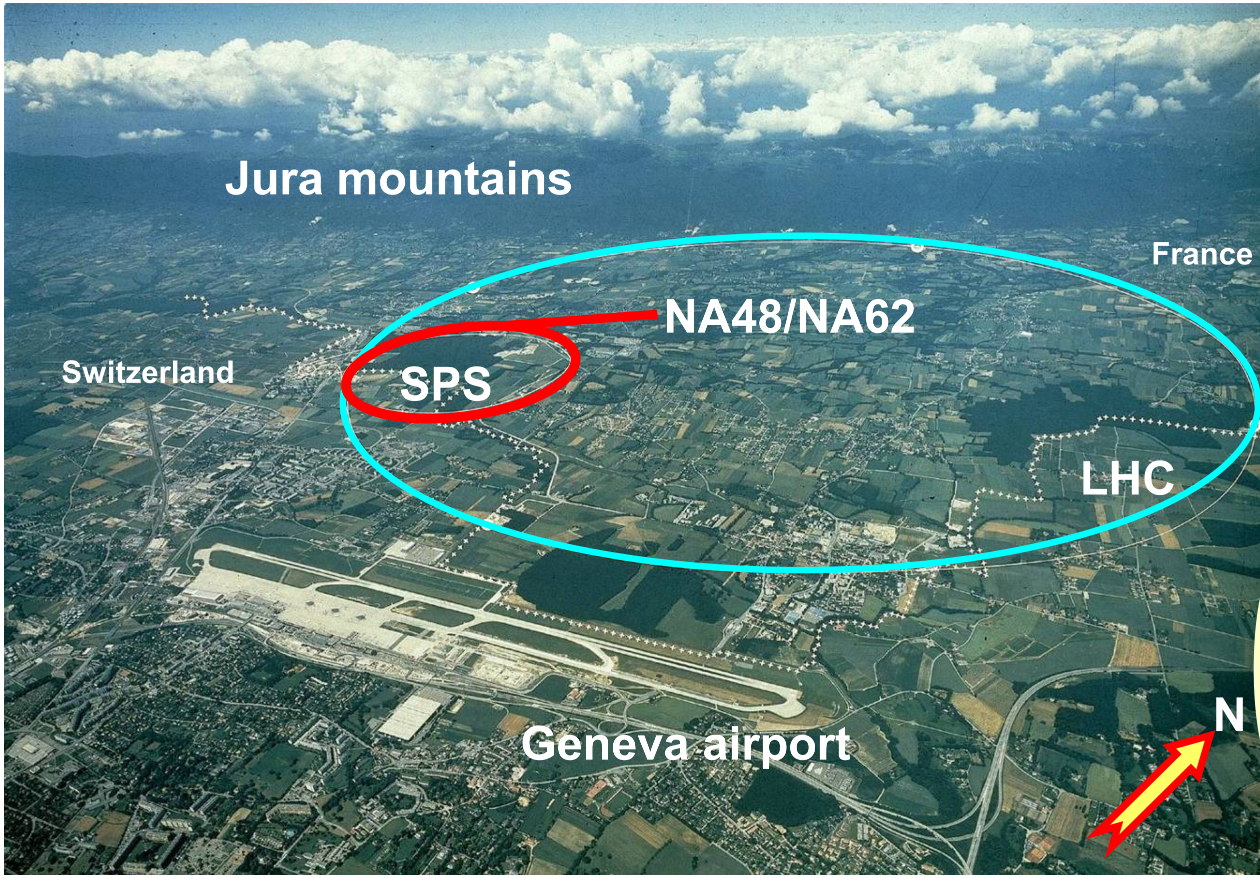
NA48/2

2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests

NA62 R_K phase

2007-2013:
Design & construction
2014-2016:
Data Taking

NA62 golden $K^+ \rightarrow \pi \nu \bar{\nu}$



NA62: Birmingham, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, IHEP Protvino, INR Moscow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin

The K^+ semileptonic decays

- $K \to \pi l \nu (K_{l3})$ decays provide the **most accurate** and **theoretically cleanest** way to access |Vus| :

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

Experimental Inputs:

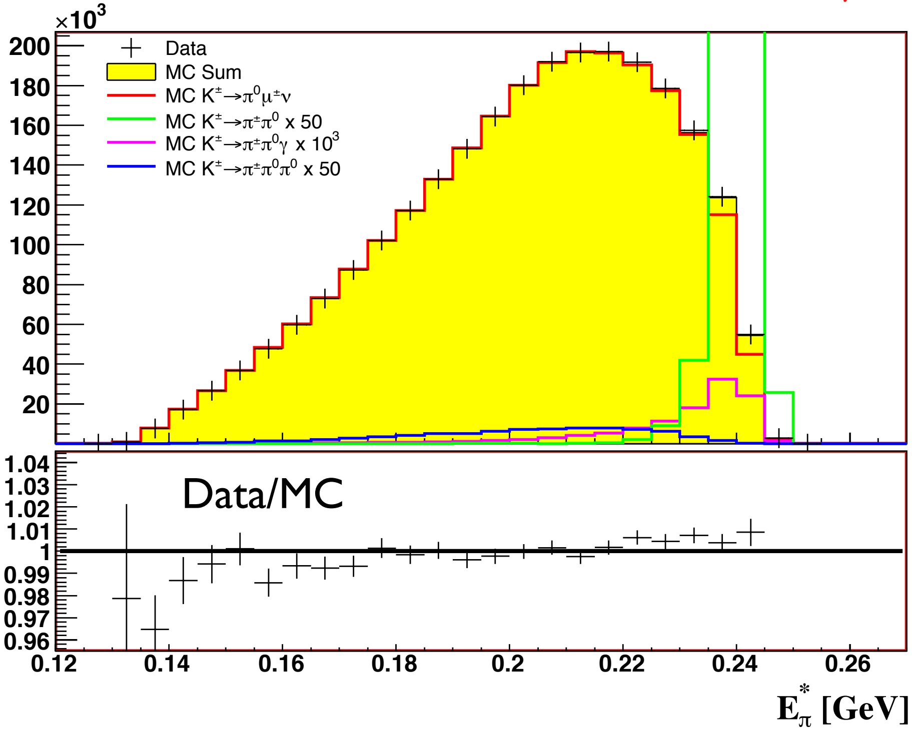
- $\Gamma(K_{l3(\gamma)})$ Branching ratios and kaon lifetimes
- $I^l_K(\lambda_{+0})$ Phase space integral depends on the form factors

Theory Inputs:

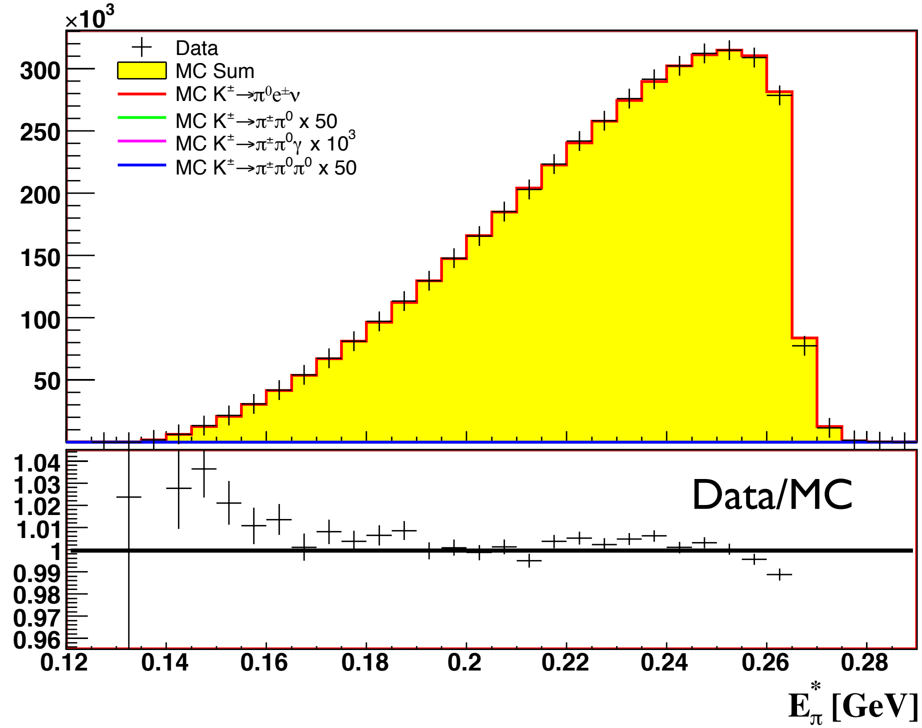
- S_{EW} Universal short distance EW corrections(1.0232±0.0003)
- $f_+(0)$ Form factor at zero momentum transfer
- $\delta^l_{SU(2)}$ Form factor correction for isospin breaking (ch. mode only)
- δ^l_{EM} Long distance EM effects

Data – MC comparison

- **Pion energy in the kaon rest frame: $K^{\pm}_{\mu 3}$**



- **Pion energy in the kaon rest frame: $K^{\pm}_{e3}$**

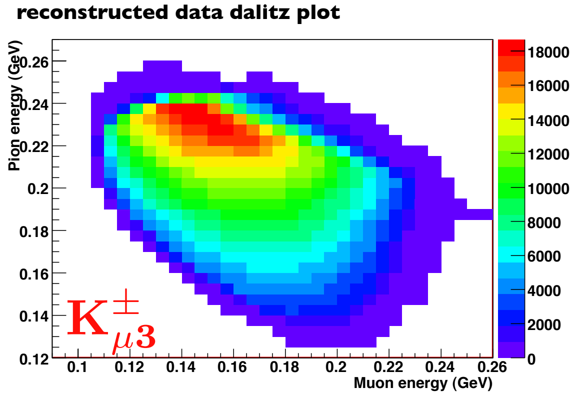


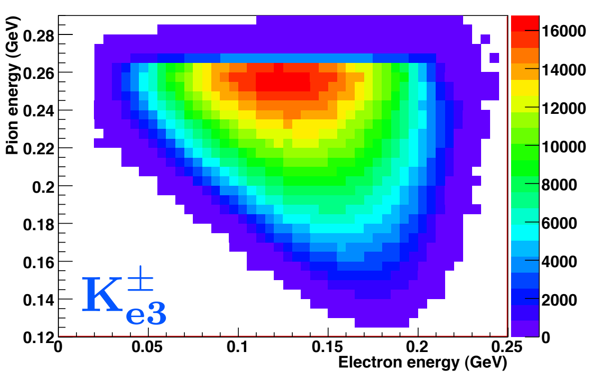
Form factors fitting procedure

To extract the form factors a fit to the Dalitz plot density is performed:

$$\rho(E_l^*, E_\pi^*) = \frac{d^2N(E_l^*, E_\pi^*)}{dE_\mu^* dE_\pi^*} \propto A f_+^2(t) + B f_+(t)(f_0 - f_+)\frac{m_K^2 - m_\pi^2}{t} + C\left[(f_0 - f_+)\frac{m_K^2 - m_\pi^2}{t})\right]^2$$

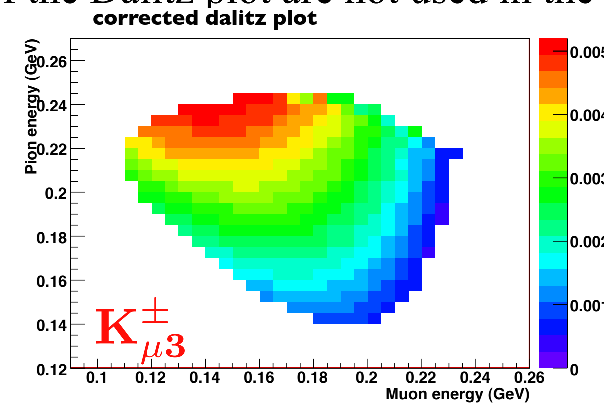
- E_l^* and E_π^* are the energy of the lepton and of the pion in the kaon rest frame
- A, B and C are kinamatical terms
- The fit is performed in cells of 5x5 MeV^2
- Cells which are outside or crossing the border of the physical region of the Dalitz plot are not used in the fit.

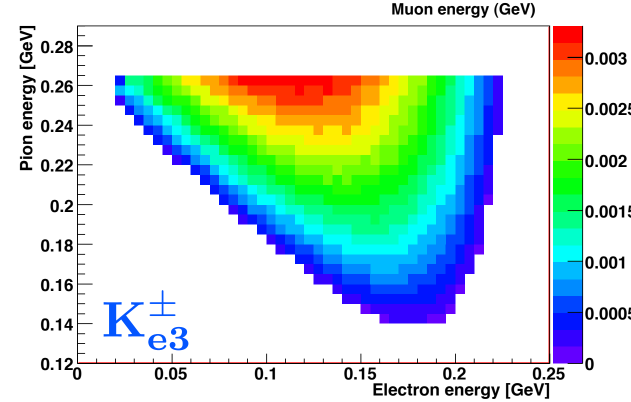




Applied corrections:

- Background subtraction
- Acceptance
- Radiative corrections

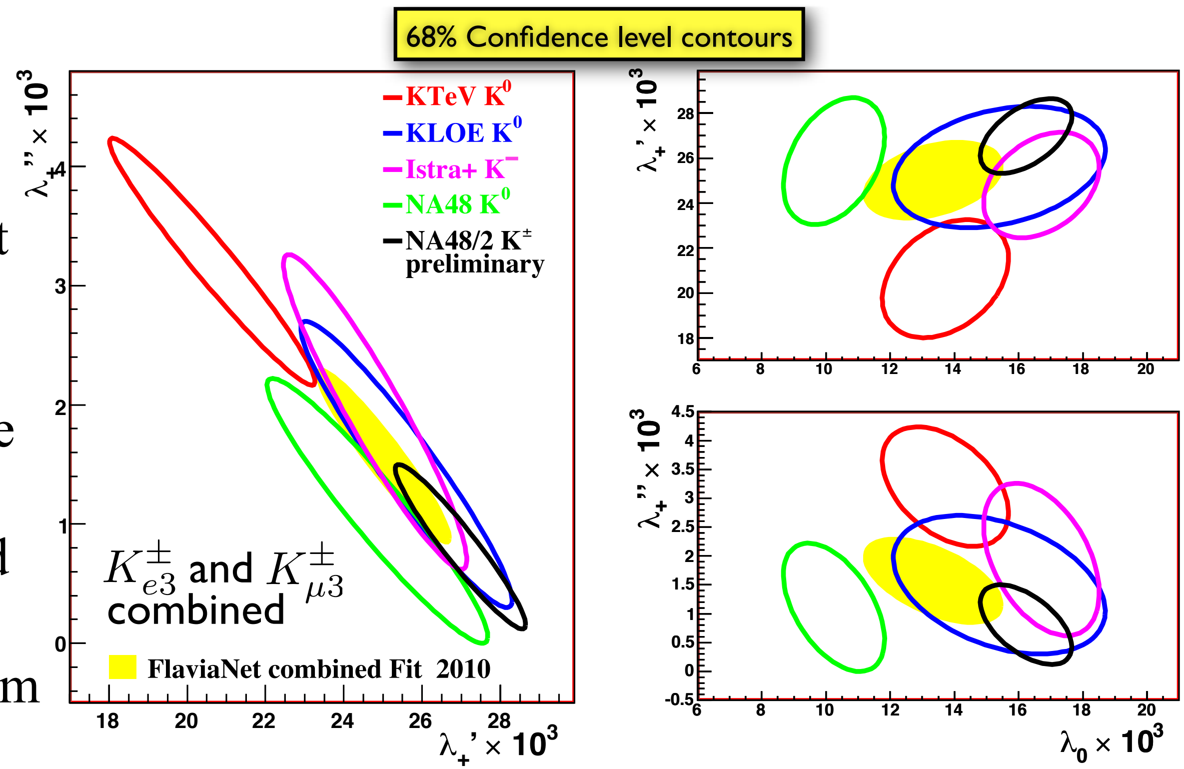




Preliminary results: combined

Quadratic $(\times 10^{-3})$	λ'_+	λ''_+	λ_0
$K^\pm_{\mu 3} K^\pm_{e3}$ combined	26.98 ± 1.11	0.81 ± 0.46	16.23 ± 0.95
Pole (MeV/c^2)	m_V		m_S
$K^\pm_{\mu 3} K^\pm_{e3}$ combined	877 ± 6		1176 ± 31

- Experimental situation: K^0_{l3} results from KLOE, KTeV and NA48, K^-_{l3} from ISTRA+
- NA48/2 is the first measurement with both $K^\pm_{e3}$ and $K^\pm_{\mu 3}$
- NA48/2 preliminary result with high precision - very competitive with the other results. Offers the smallest error with the combined result.
- The results for Ke3 and Kμ3 from NA48/2 are in good agreement



$K^+ \rightarrow e^+\nu\gamma$ (Ke2γ)

$$\frac{d^2\Gamma}{dxdy}(SD) = \frac{m_K^5 \alpha G_F^2 |V_{us}|^2}{64\pi^2} \times [(F_V + F_A)^2 f_{SD+}(x,y) + (F_V - F_A)^2 f_{SD-}(x,y)]$$

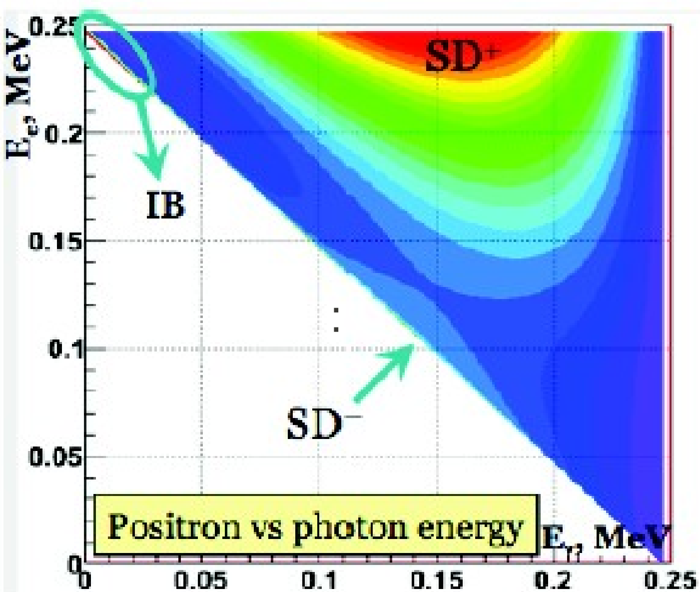
$$x = \frac{2E_\gamma^*}{m_K}, \quad y = \frac{2E_e^*}{m_K}$$

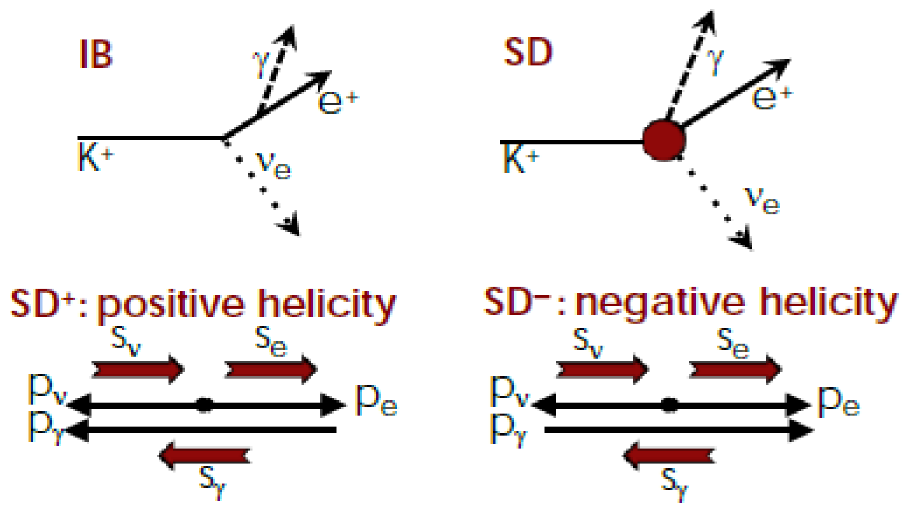
F_V and F_A: vector and axial Form Factors

ChPT O(p^4): F_V,F_A costants

ChPT O(p^6): F_V linear dependence from x [PR D77 (2008) 014004]

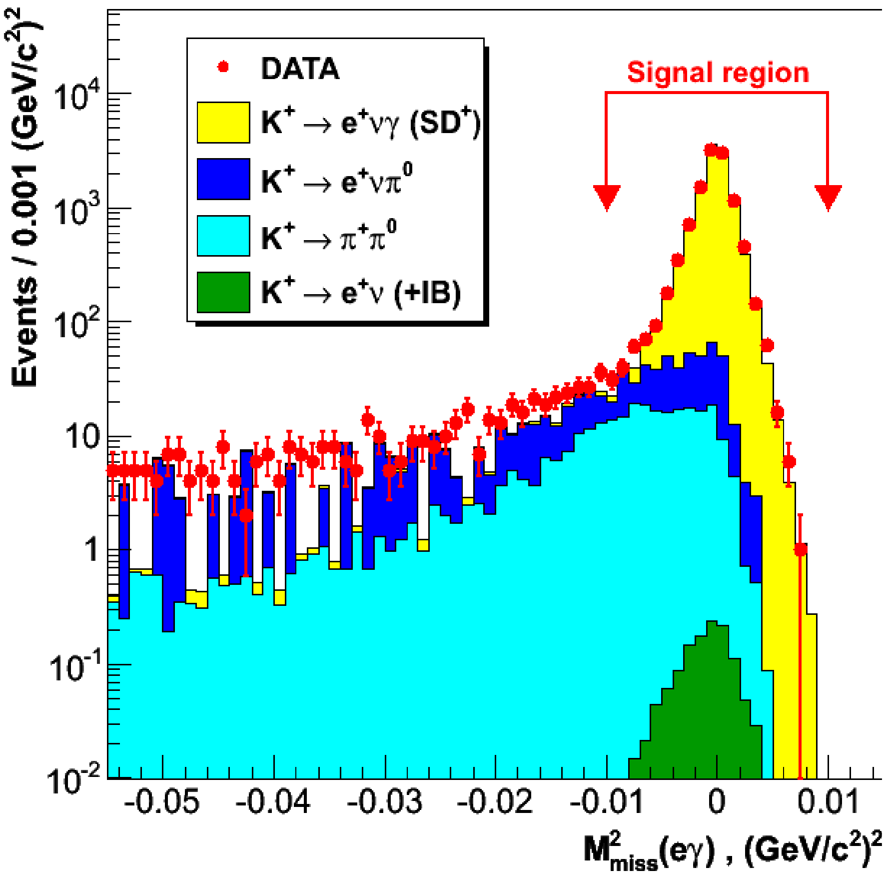
KLOE 2009: 1484 events with E^*_γ > 10 MeV and p^*_e > 200 MeV/c
~4% accuracy
Data suggest a slope for F_V, $\lambda = 0.38 \pm 0.20_{stat} \pm 0.02_{syst}$ (can't state $\lambda \neq 0$ @>2σ)

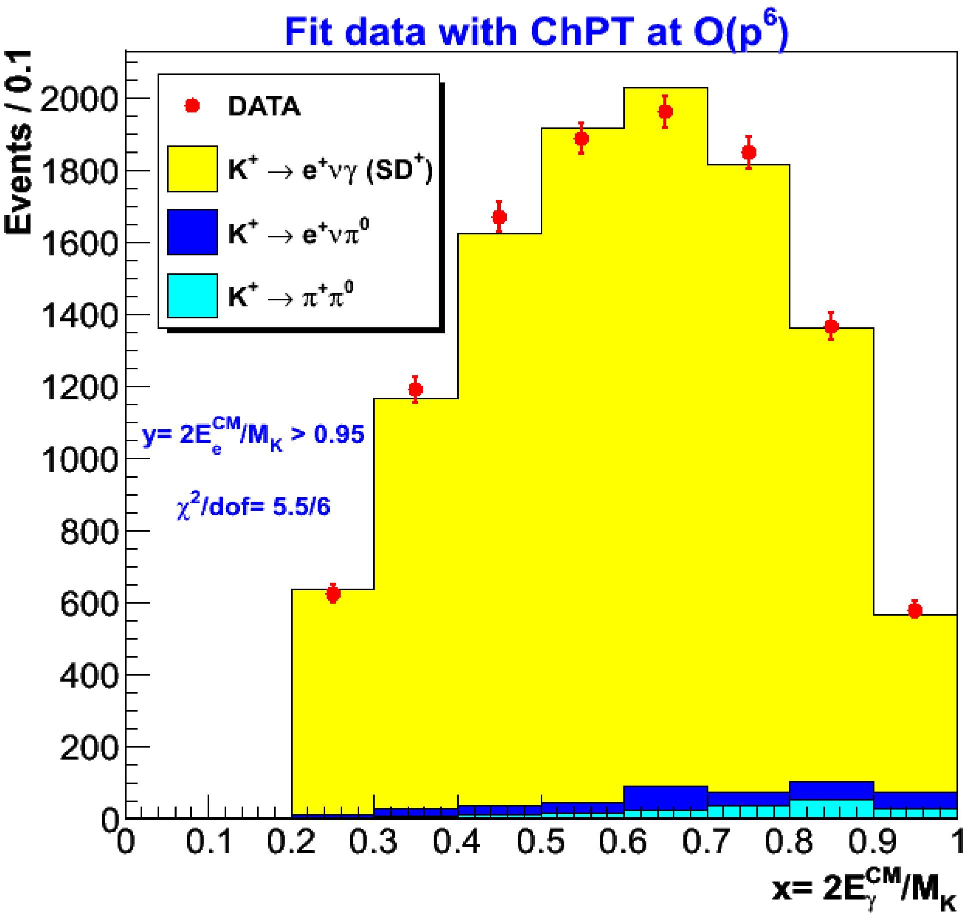




$K^+ \rightarrow e^+\nu\gamma$ (Ke2γ)

- ✔~10K events with $p^*_e > 234$ MeV/c and $E^*_\gamma > 50$ MeV
- ✔~7% of acceptance and ~5% of background ($K^+ \rightarrow e^+\pi^0\nu$, $K^+ \rightarrow \pi^+\pi^0$)





$K^{+-} \rightarrow \pi^{+-}\gamma\gamma$: introduction

ChPT description:

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

Leading contribution at $O(p^4)$ loop:

cusp at 2π threshold

[Ecker, Pich, de Rafael, NPB303 (1988) 665]

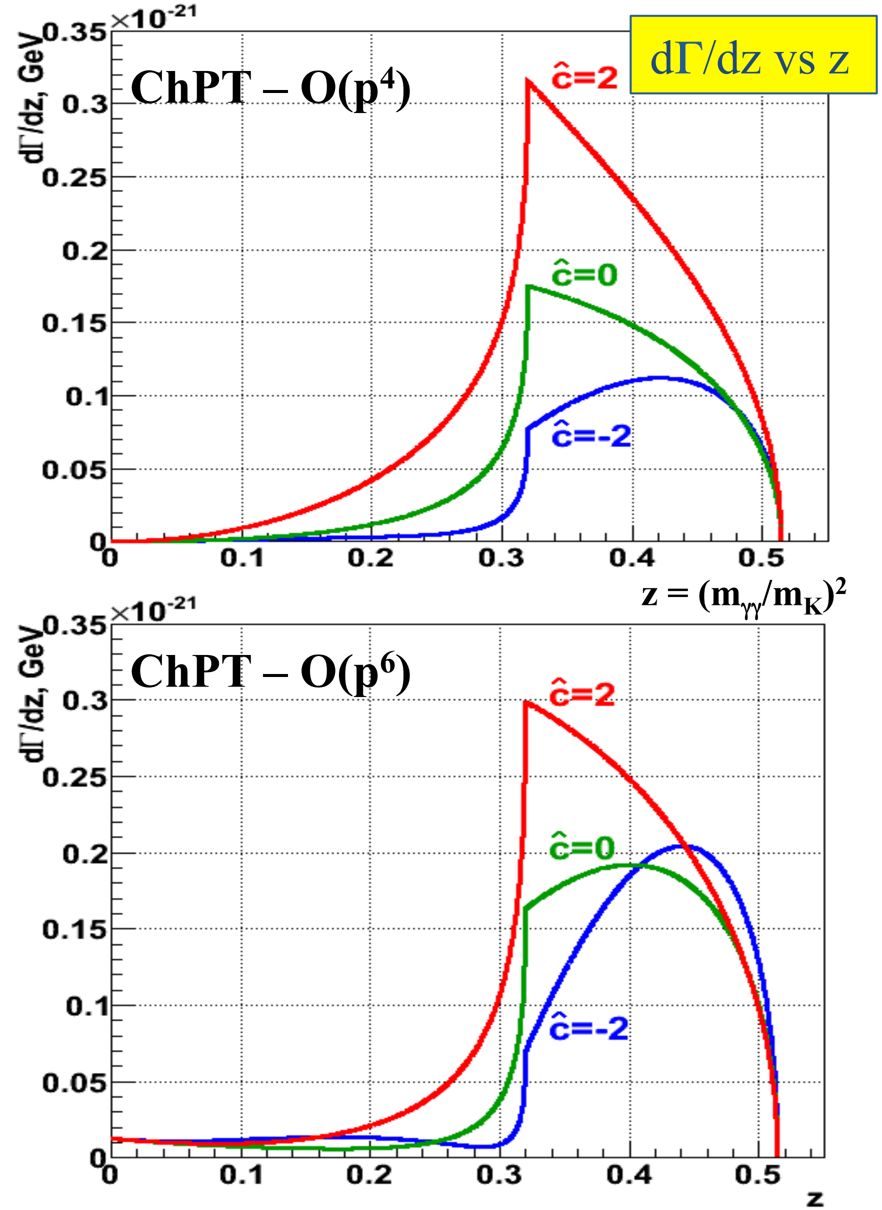
$O(p^6)$ "unitary corrections" increase BR at low $\hat{c}$ and result in a non-zero rate at $m_{\gamma\gamma}\rightarrow 0$.

[D'Ambrosio, Portolés, PLB386 (1996) 403]

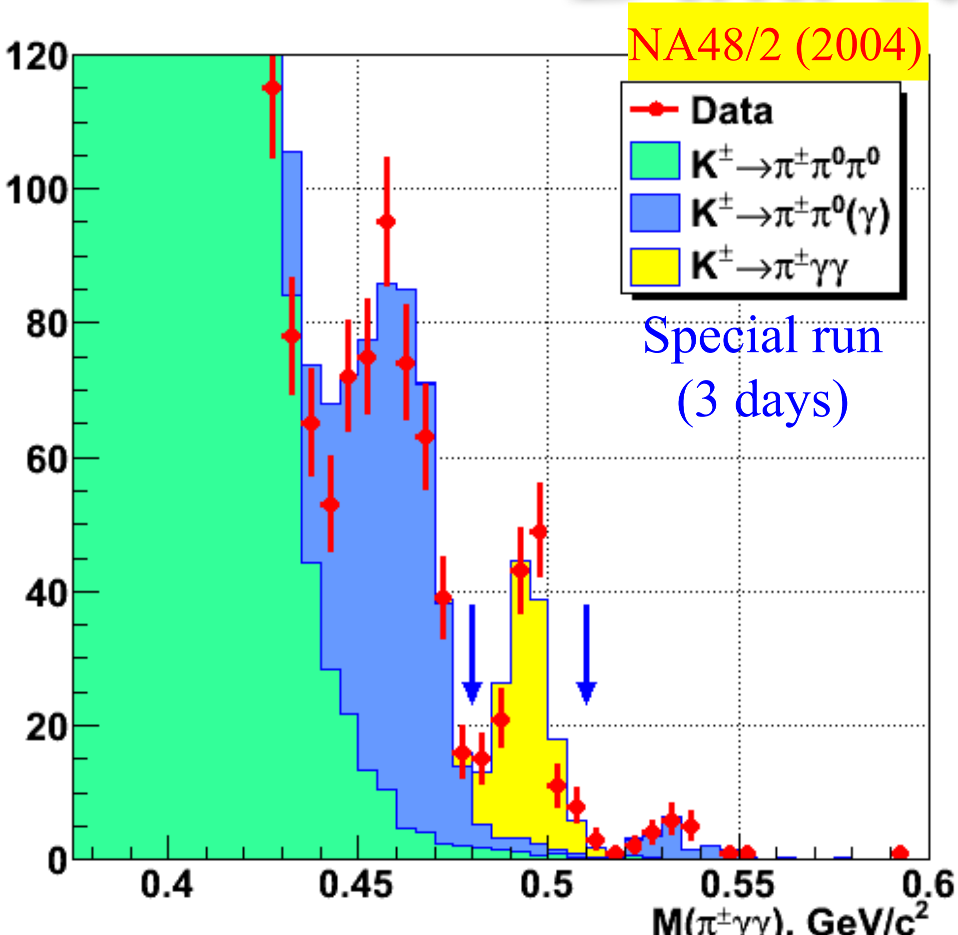
Experimental status:

- BNL E787: 31 candidates, $BR=(1.10\pm0.32)\times10^{-6}$. $O(p^6)$ full kinematic range [PRL79 (1997) 4079]
- NA48/2 (2003-2004): in the main data set measurement hindered by low trigger efficiency
- New strategy: minimum bias trigger samples from NA48/2 and NA62.

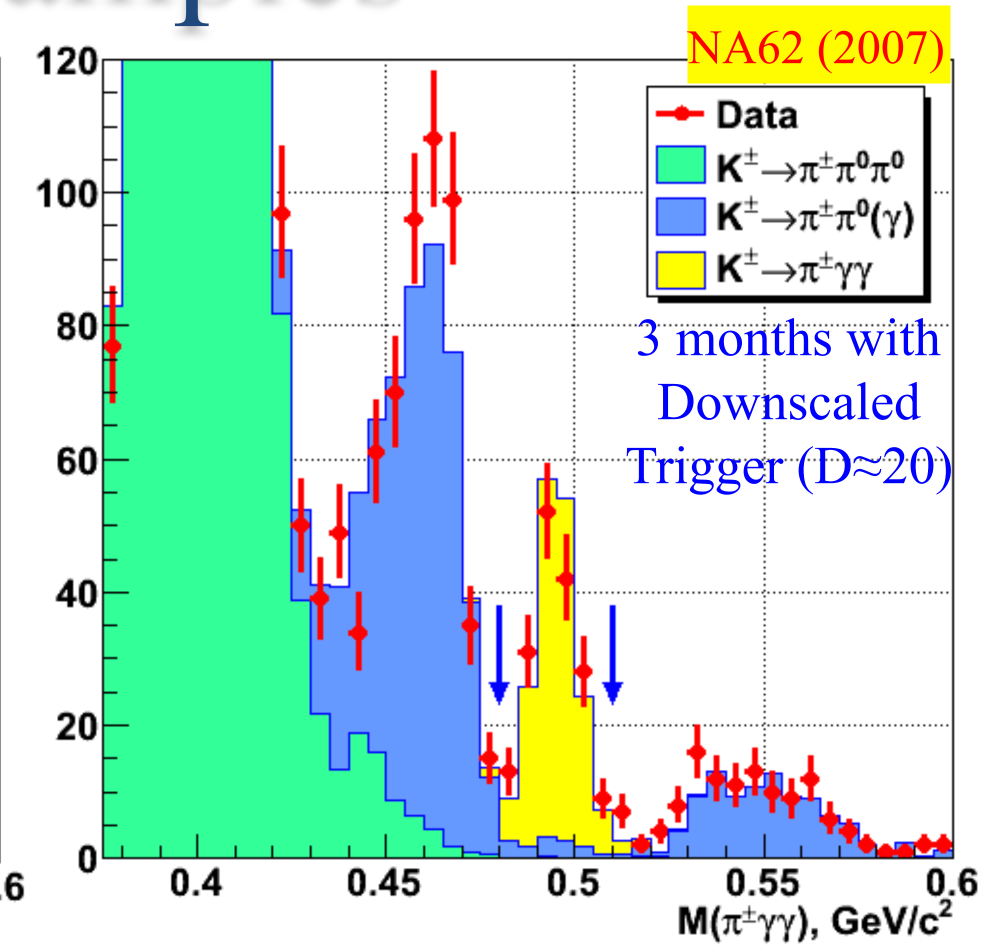
dΓ/dz vs z



Data samples

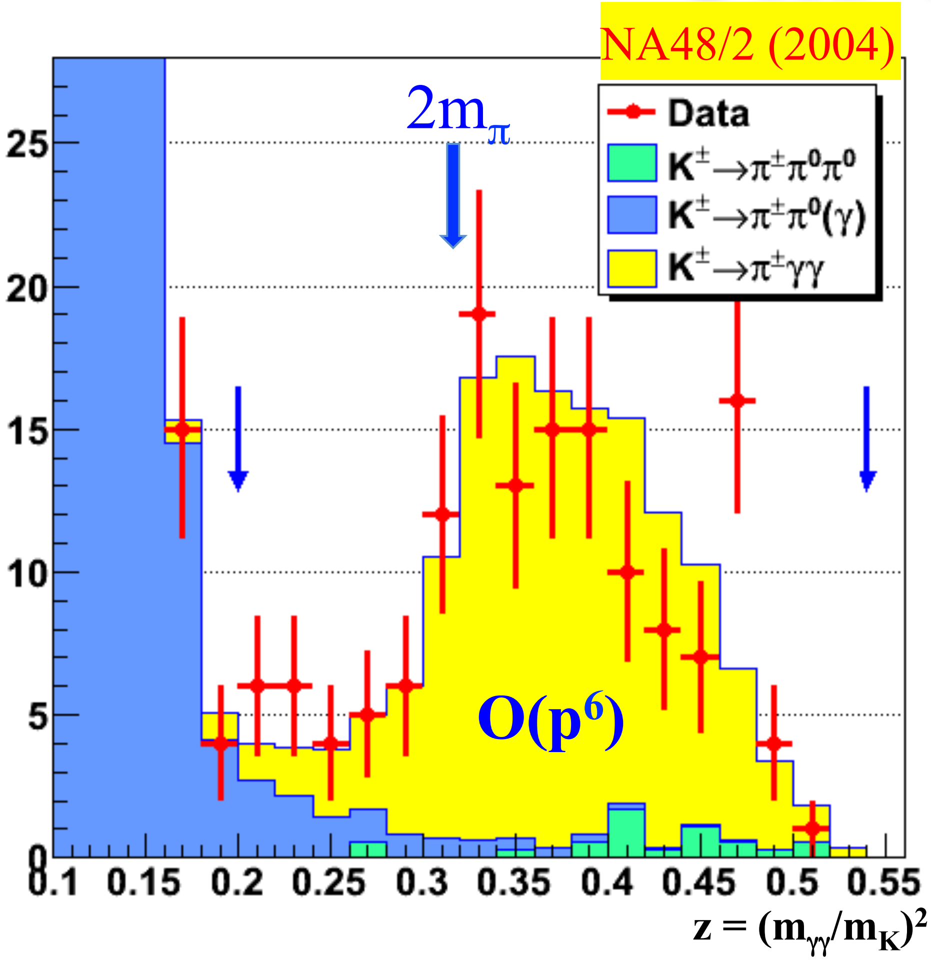


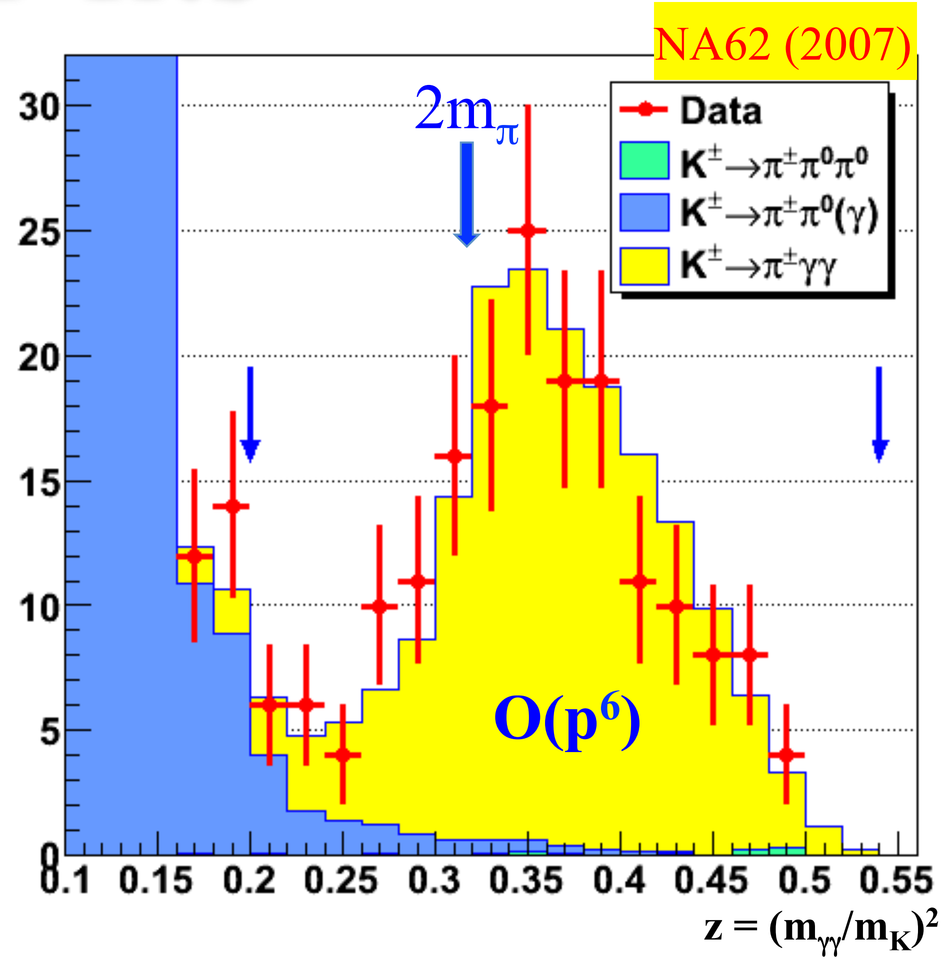
$K_{\pi\gamma\gamma}$ candidates	147
$K_{2\pi(\gamma)}$ background	11.0 ± 0.8
$K_{3\pi}$ background	5.9 ± 0.7
$K_{\pi\gamma\gamma}$ signal	130 ± 12



$K_{\pi\gamma\gamma}$ candidates	175
$K_{2\pi(\gamma)}$ background	11.1 ± 1.0
$K_{3\pi}$ background	1.3 ± 0.3
$K_{\pi\gamma\gamma}$ signal	163 ± 13

ChPT fits





→ Visible region is above the $K^\pm \to \pi^\pm \pi^0$ peak: $z > 0.2$, or $m_{\gamma\gamma} > 220$ MeV/c^2

→ Cusp-like behaviour at $z = (2m_\pi/m_K)^2$ is clearly observed.

Fit results (1)

PRELIMINARY **NA48/2 (2004)**

ChPT $O(p^4)$:

$\hat{c} = 1.36 \pm 0.33_{stat} \pm 0.07_{syst} = 1.36 \pm 0.34$

ChPT $O(p^6)$:

$\hat{c} = 1.67 \pm 0.39_{stat} \pm 0.09_{syst} = 1.67 \pm 0.40$

PRELIMINARY **NA62 (2007)**

ChPT $O(p^4)$:

$\hat{c} = 1.71 \pm 0.29_{stat} \pm 0.06_{syst} = 1.71 \pm 0.30$

ChPT $O(p^6)$:

$\hat{c} = 2.21 \pm 0.31_{stat} \pm 0.08_{syst} = 2.21 \pm 0.32$

[D'Ambrosio, Portolés, PLB386 (1996) 403]

COMBINED (correlated uncertainties)

ChPT $O(p^4)$:

$\hat{c} = 1.56 \pm 0.22_{stat} \pm 0.07_{syst} = 1.56 \pm 0.23$

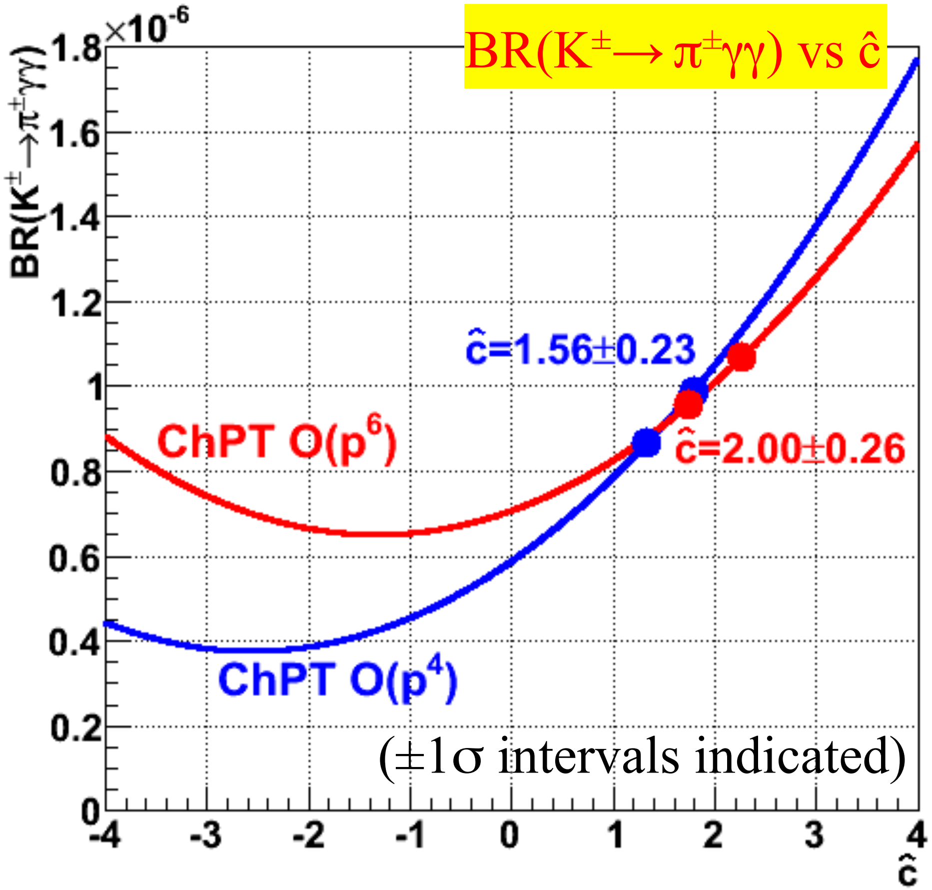
ChPT $O(p^6)$:

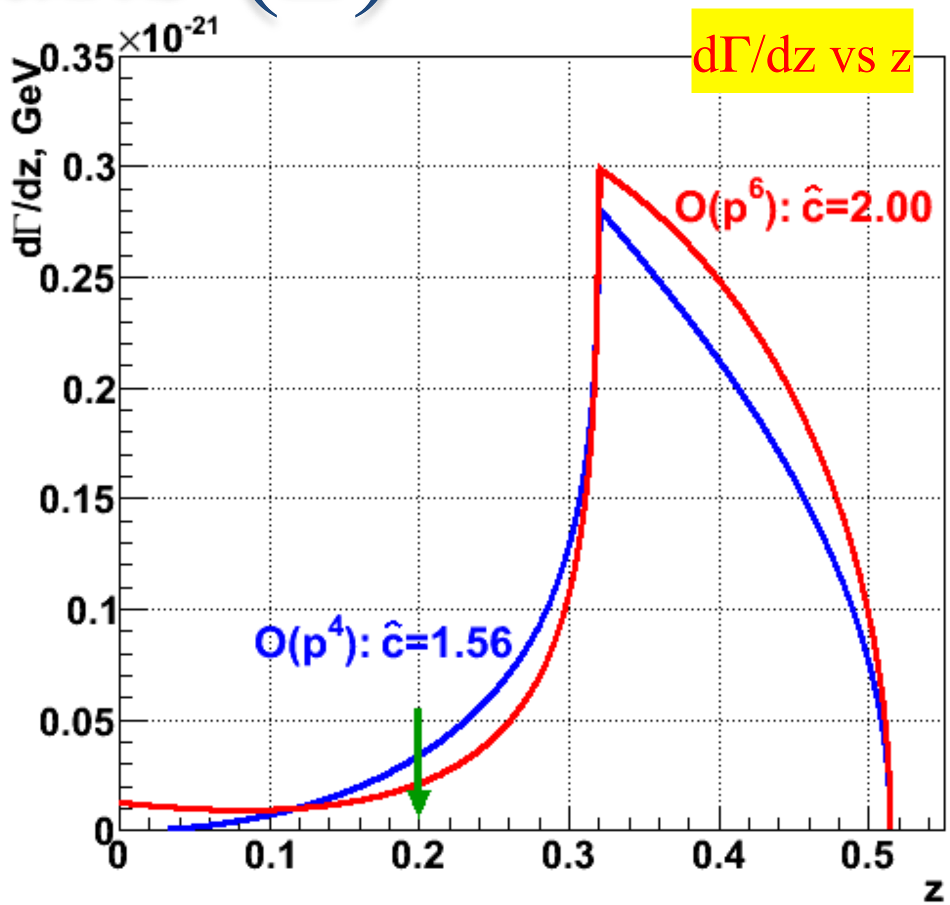
$\hat{c} = 2.00 \pm 0.24_{stat} \pm 0.09_{syst} = 2.00 \pm 0.26$

BR (model dependent): $(1.01 \pm 0.06)\times10^{-6}$

From PDG: BR = $(1.10 \pm 0.32)\times10^{-6}$ [PRL79 (1997) 4079]

Fit results (2)





- Total number of candidates (NA48/2 and NA62): 322
- Background contamination: (9±1)% due to $K^\pm\to\pi^\pm\pi^0(\gamma)$ and $K^\pm\to\pi^\pm\pi^0\pi^0$ with
- Very low systematic uncertainties, c
- ChPT $O(p^4)$ vs $O(p^6)$ models cannot be discriminated

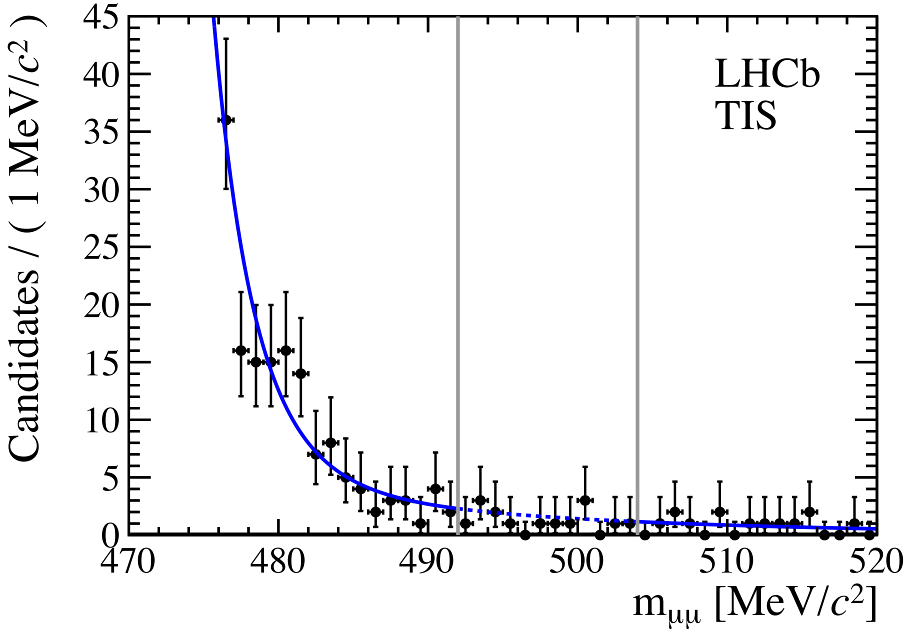
Measurement on K decay from LHCb

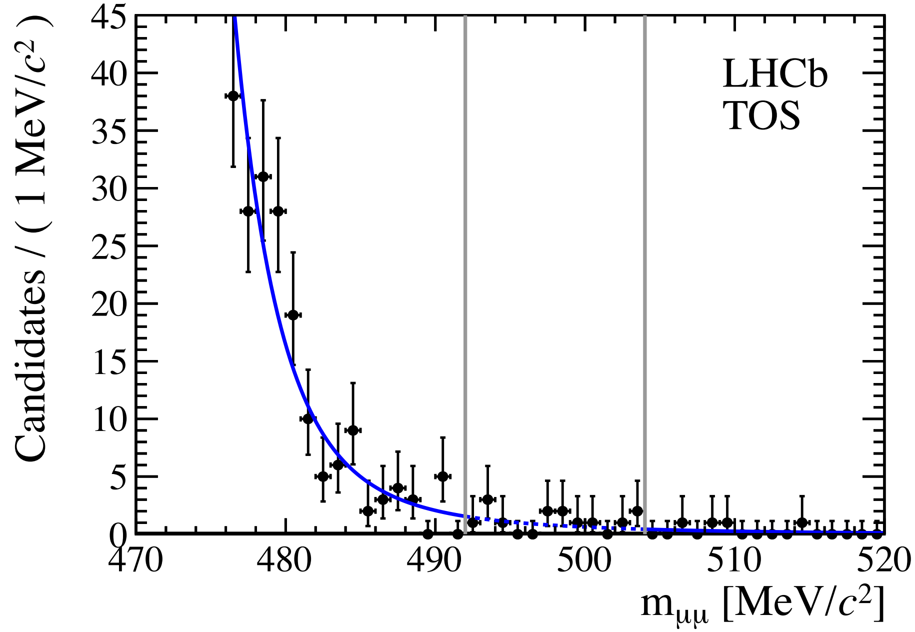
LHCb: New limit on $K^0_s \to \mu^+\mu^-$

Exploiting the $B^0 \to \mu^+\mu^-$ tools both at trigger and at analysis level

FCNC decay, in the Standard Model framework:

$$\Gamma(K^0_{\rm L,S} \to \mu^+\mu^-) = \frac{m_K}{8\pi}\sqrt{1-\left(\frac{2m_\mu}{m_K}\right)^2}\left[|A|^2 + \left(1-\left(\frac{2m_\mu}{m_K}\right)^2\right)|B|^2\right] \Rightarrow \mathcal{B}(K^0_{\rm S} \to \mu^+\mu^-) = (5.0 \pm 1.5)\times 10^{-12}$$





Published limit from 2011 data at 95 (90)% confidence level: $\mathcal{B}(K^0_{\rm S} \to \mu^+\mu^-) < 11(9)\times 10^{-9}$

30 times better than previous limit!

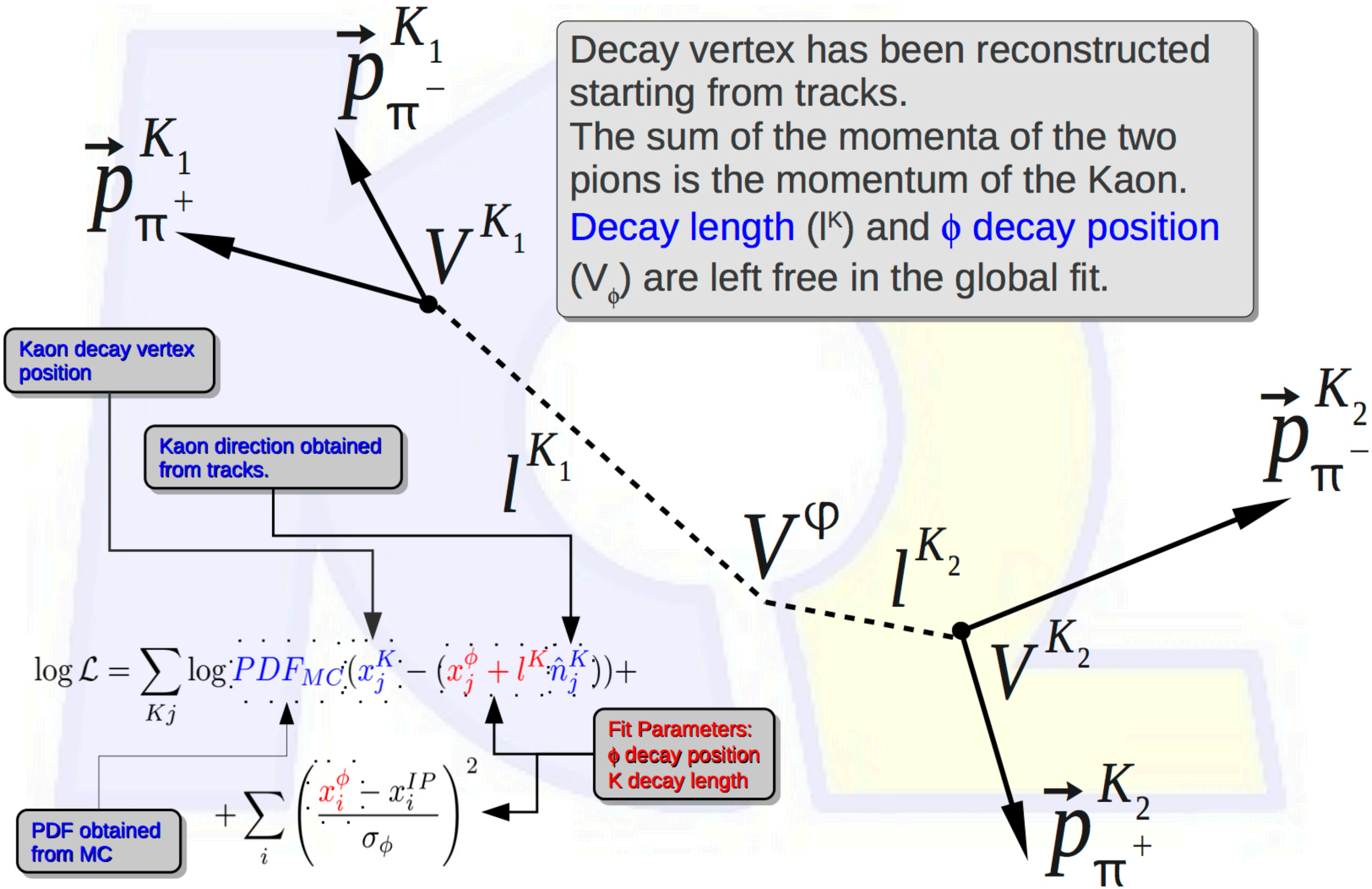
[JHEP 1301 (2013) 090, arXiv:1209.4029v3]

KLOE

Search for CPT violation

Looking for $\Phi \rightarrow K_S + K_L$, K_S and K_L then decaying in the same final state ($\pi^+\pi^-$)

Decay vertex has been reconstructed starting from tracks.
The sum of the momenta of the two pions is the momentum of the Kaon.
Decay length (l^K) and ϕ decay position (V_ϕ) are left free in the global fit.



$$\log \mathcal{L} = \sum_{Kj} \log PDF_{MC}\left(x_j^K - \left(x_j^\phi + l^K \hat{n}_j^K\right)\right) + \sum_i \left(\frac{x_i^\phi - x_i^{IP}}{\sigma_\phi}\right)^2$$

Search for CPT violation

$$I(f_1, f_2; \Delta t) = \frac{\Gamma_S^1 \Gamma_S^2}{2\Gamma} e^{-\Gamma|\Delta t|} \left[|\eta_1|^2 e^{\frac{\Delta\Gamma}{2}\Delta t} + |\eta_2|^2 e^{-\frac{\Delta\Gamma}{2}\Delta t} - 2\Re e\left(\eta_1 \eta_2 e^{-i\Delta m \Delta t}\right) \right]$$

$$\eta_1 = \eta_\pm = \varepsilon_K - \delta(\vec{p}_{K^1})$$

$$\eta_2 = \varepsilon_K - \delta(\vec{p}_{K^2})$$

δ_K is the CPT violation parameter in the Kaon system. According to the Standard Model Extension (Kostelecky) and anti-CPT theorem, CPT violation should appears together with Lorentz Invariance breaking → **Direction dependent modulation**

Preliminary results:

$\Delta a_0 = (-6.2 \pm 8.2_{stat} \pm 3.3_{sys})\ 10^{-18}$ GeV

$\Delta a_X = (3.3 \pm 1.6_{stat} \pm 1.5_{sys})\ 10^{-18}$ GeV

$\Delta a_Y = (-0.7 \pm 1.3_{stat} \pm 1.5_{sys})\ 10^{-18}$ GeV

$\Delta a_Z = (-0.7 \pm 1.0_{stat} \pm 0.3_{sys})\ 10^{-18}$ GeV

Really complex analysis:

For details see A. De Santis: "CPT&Lorentz invariance violation at KLOE", DISCRETE2012

The $K_S \to \pi^0\pi^0\pi^0$ decay

- For the $|K_S> \to 3\pi$ decay modes:

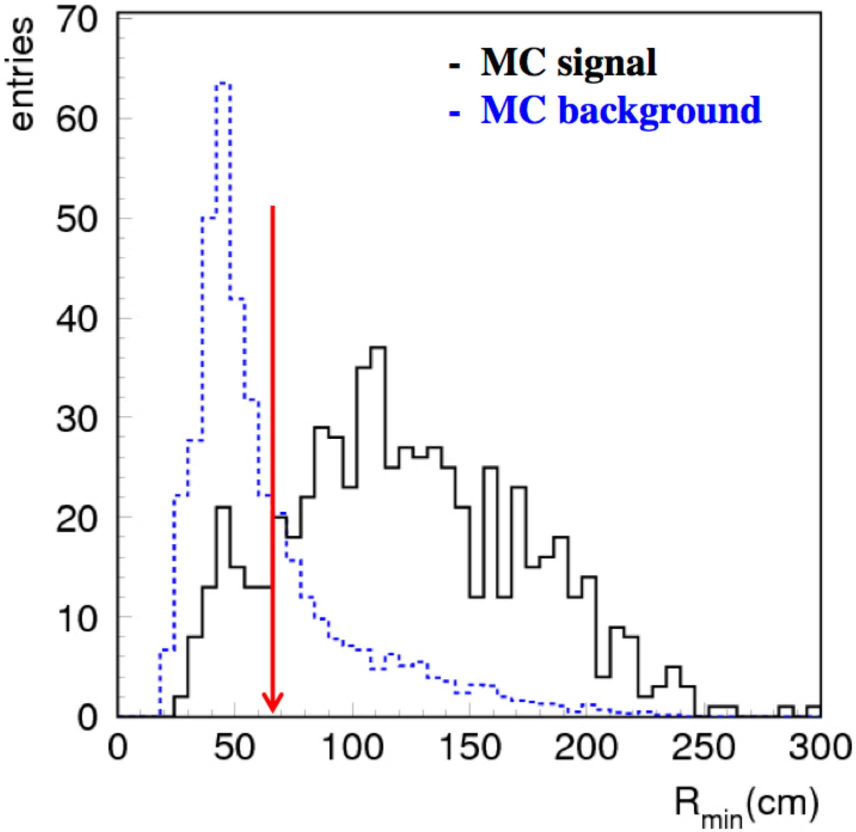
$$\eta_{000} = \frac{\langle \pi^0\pi^0\pi^0|H|K_S\rangle}{\langle \pi^0\pi^0\pi^0|H|K_L\rangle} = \varepsilon + \varepsilon'_{000}$$

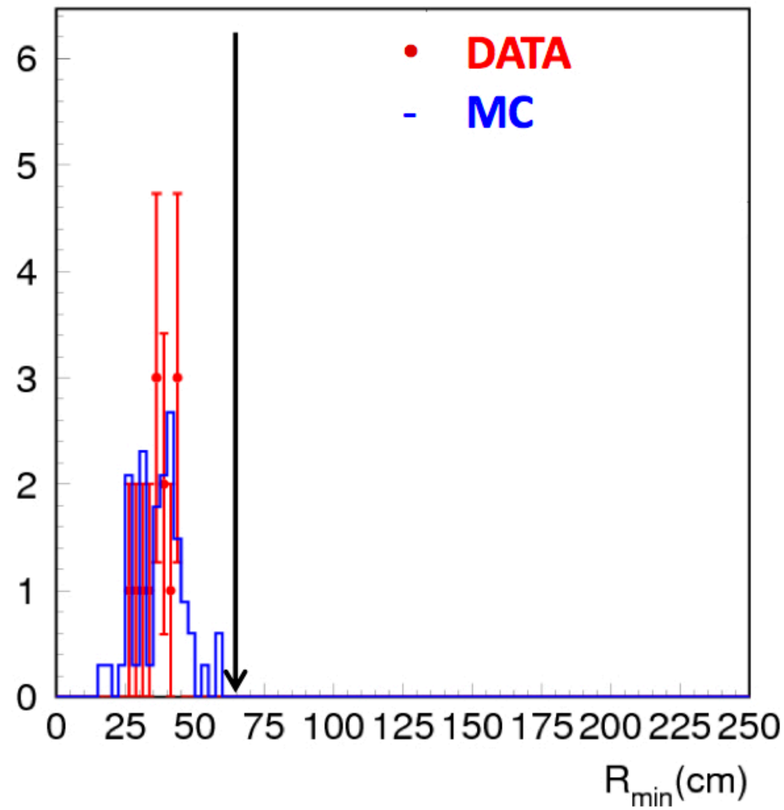
- Previous measurements of η_{000}:

SND (direct search) :	$BR(K_S \to 3\pi^0) < 1.4 \cdot 10^{-5}$
NA48 (interference measurement):	$BR(K_S \to 3\pi^0) < 7.4 \cdot 10^{-7}$
KLOE	$BR(K_S \to 3\pi^0) < 1.2 \cdot 10^{-7}$

Standard Model prediction: $BR(K_S \to 3\pi^0) = 1.9 \cdot 10^{-9}$

The $K_S \rightarrow \pi^0\pi^0\pi^0$ decay





0 event found in signal region, expected from signal + background: 0

90% Confidence Level:

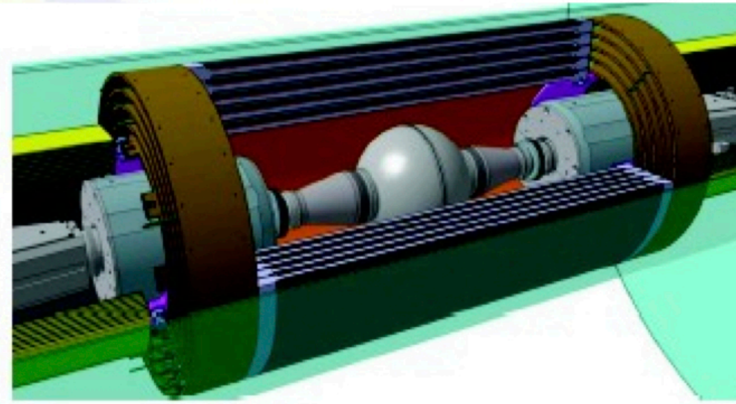
$$BR(K_S \rightarrow 3\pi^0) = \frac{N_{3\pi}/\varepsilon_{3\pi}}{N_{2\pi}/\varepsilon_{2\pi}} \times BR(K_S \rightarrow 2\pi^0) < 2.64 \times 10^{-8} \qquad |\eta_{000}| = \sqrt{\frac{\tau_L\, BR(K_S \rightarrow 3\pi^0)}{\tau_S\, BR(K_L \rightarrow 3\pi^0)}} < 0.0088$$

KLOE-2

Upgrade on detector

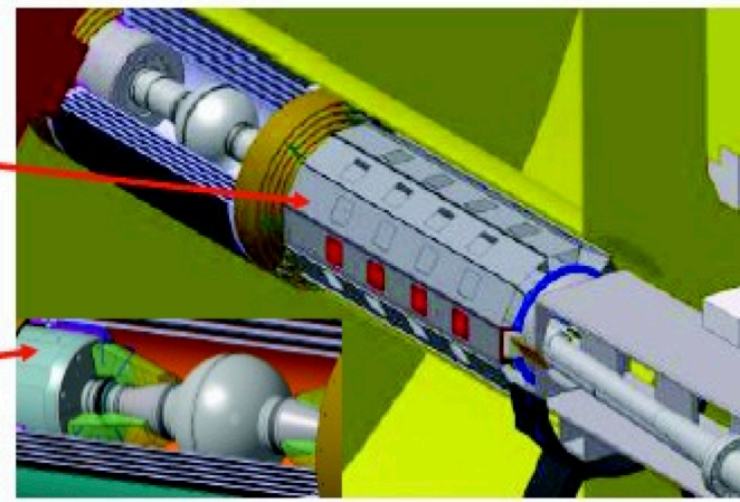
INNER TRACKER

- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks



QCALT

- W + scintillator tiles + SiPM/WLS
- Low-beta quadrupoles: coverage for K_L decays

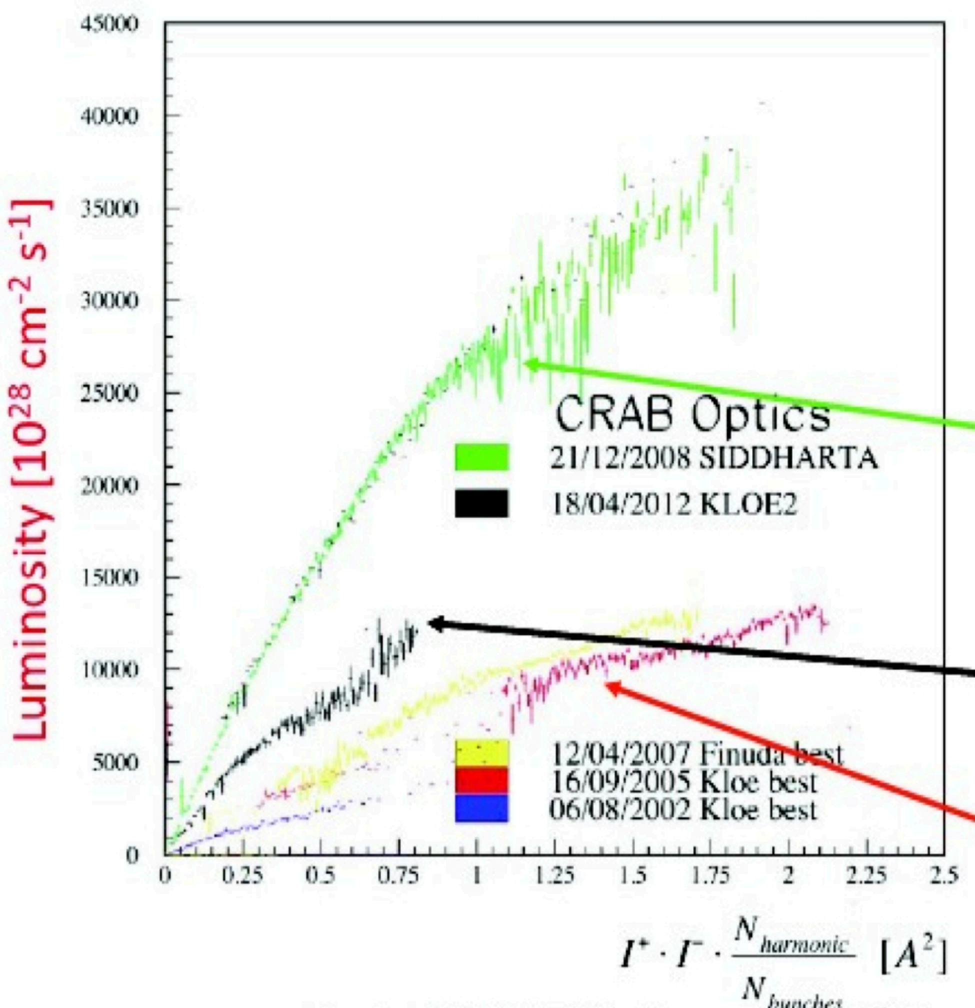


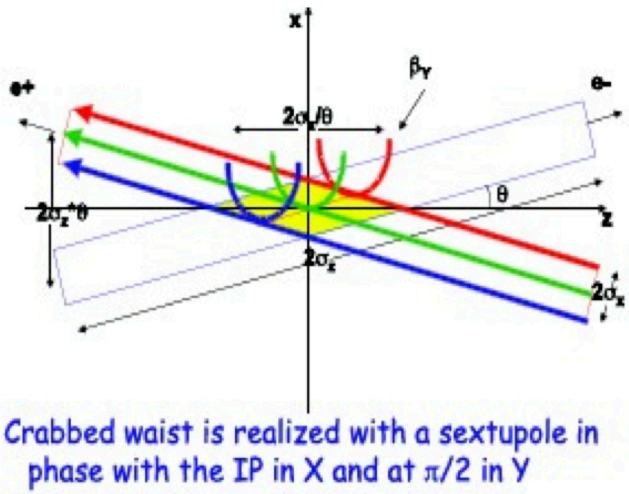
CCALT

- LYSO + APD
- Increase acceptance for γ's from IP (21°→10°)

Upgrade on collider

Crabbed waist scheme at DAΦNE





NEW COLLISION SCHEME:
Large Piwinski angle
Crab-Waist compensation SXTs

Present commissioning phase
New coll. scheme + KLOE det.

Old collision scheme

max. expected at KLOE-2 : L_{int} ~ 20 pb^{-1}/day x 200 dd/year = 4 fb^{-1} /year

Perspectives

For details see [Eur.Phys.J. C68 (2010) 619-681 (arXiv:1003.3868)]

Among all: VUS extraction

		NOW				KLOE-2		
		% err	BR	τ		% err	BR	τ
$K_L e3$	0.2163(6)	0.26	0.09	0.20		0.20	0.09	0.13
$K_L \mu 3$	0.2166(6)	0.29	0.15	0.18		0.21	0.10	0.13
$K_S e3$	0.2155(13)	0.61	0.60	0.03	…	0.32	0.30	0.03
$K^{\pm} e3$	0.2160(11)	0.52	0.31	0.09		0.47	0.25	0.05
$K^{\pm} \mu 3$	0.2158(14)	0.63	0.47	0.08		0.48	0.27	0.05

The golden channels:

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

$$K^0 \rightarrow \pi^0 \nu\bar{\nu}$$

Ultra rare kaon decays & CKM

The Unitarity Triangle describes in the (ρ,η) plane the CKM matrix

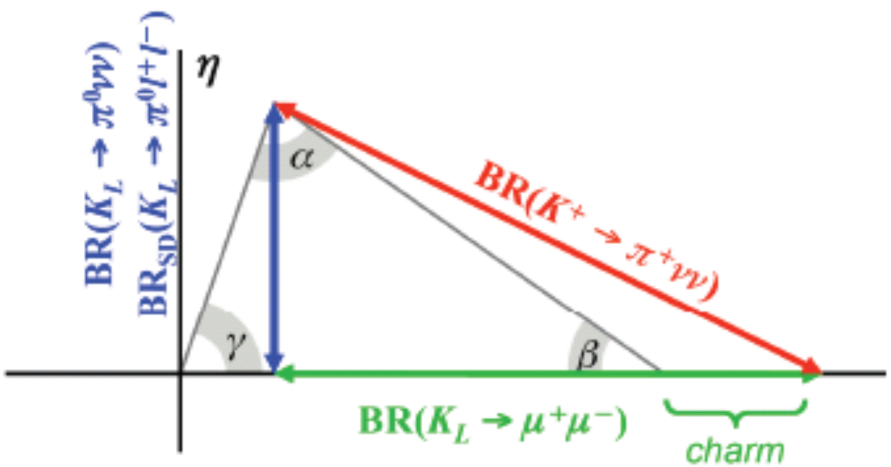
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The "Standard" Unitarity Triangle

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

The "Kaon" Unitarity Triangle

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0$$



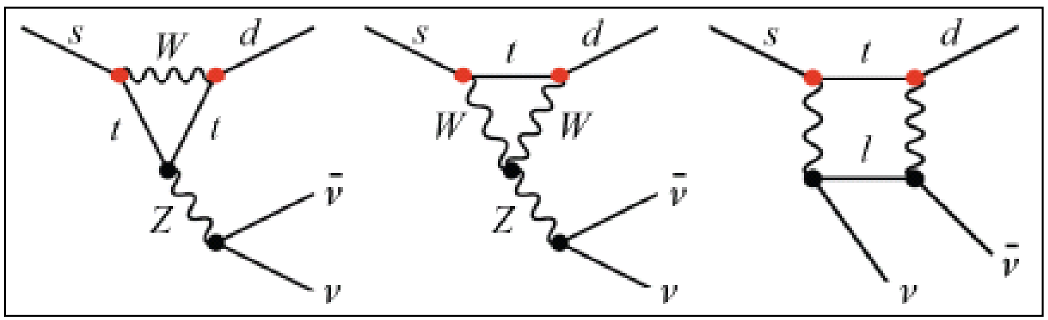
$K^+ \to \pi^+ \nu\bar\nu$	$\lvert V^*_{ts} V_{td} \rvert$
$K_L \to \pi^0 \nu\bar\nu$	$\mathrm{Im}\,(V^*_{ts} V_{td}) \propto \eta$

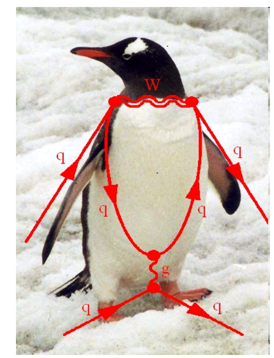
the holy grail

Alternative way to measure the Unitarity Triangle parameters with smaller theoretical uncertainty

In the Standard Model…

- FCNC process forbidden at tree level ⟹ room for NP up to 10xSM
- Short distance contribution dominated by Z penguin and W box diagrams
- "Super-clean" theoretically
  - hadronic matrix element can be extracted from measured quantities(Ke3)
- Very small BR due to the CKM top coupling
  - $A \sim (m_t/m_W)^2 |V_{ts}{}^* V_{td}| \approx \lambda^5$
- Measurement of $|V_{td}|$ complementary to those from B-B mixing and $B \to \rho\gamma$
- $\delta BR/BR = 10\%$ ⟹ $\delta|V_{td}|/|V_{td}| = 7\%$.





$BR \times 10^{10}$	SM Prediction	Experiments
$K^+ \to \pi^+ \nu \bar{\nu}$	$0.781 \pm 0.075 \pm 0.029$ [1]	$1.73^{+1.15}_{-1.05}$ [2]
$K^0 \to \pi^0 \nu \bar{\nu}$	$0.243 \pm 0.039 \pm 0.006$ [1]	< 260 (@90% CL) [3]*

[1] Brod, Gorbahn, Stamou: PRD83(2011) 034030, arXiv 1009.0947
[2] BNL E787/E949: PRL101 (2008) 191802, arXiv 0808.2459
[3] KEK E391a: PR D81 (2010) 072004, arXiv 0911.4789

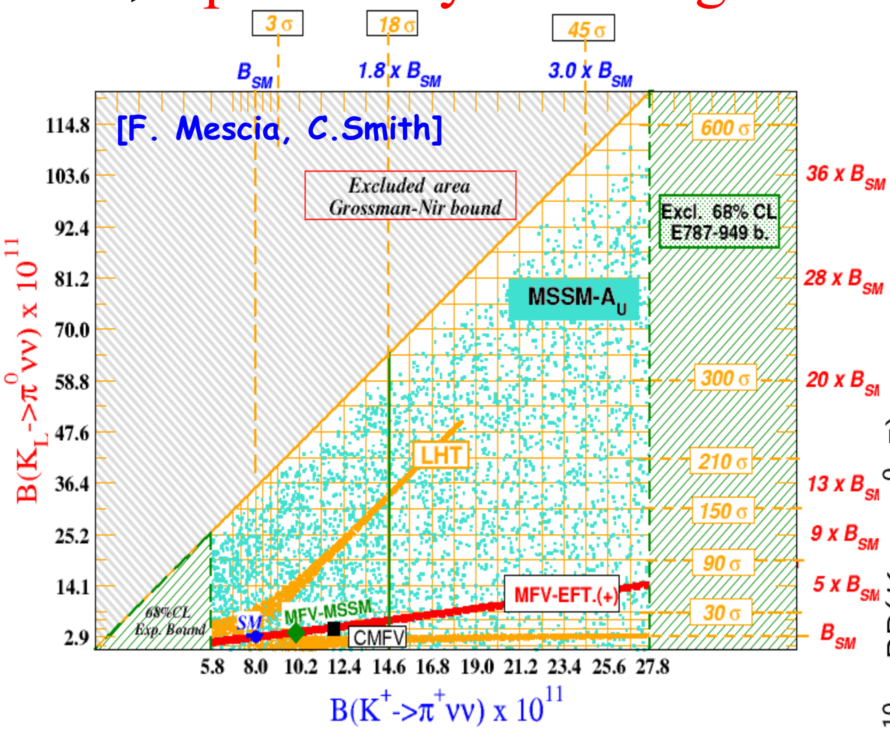
*Grossman-Nir limit smaller

7 events: twice as large as, but still consistent with SM expectation

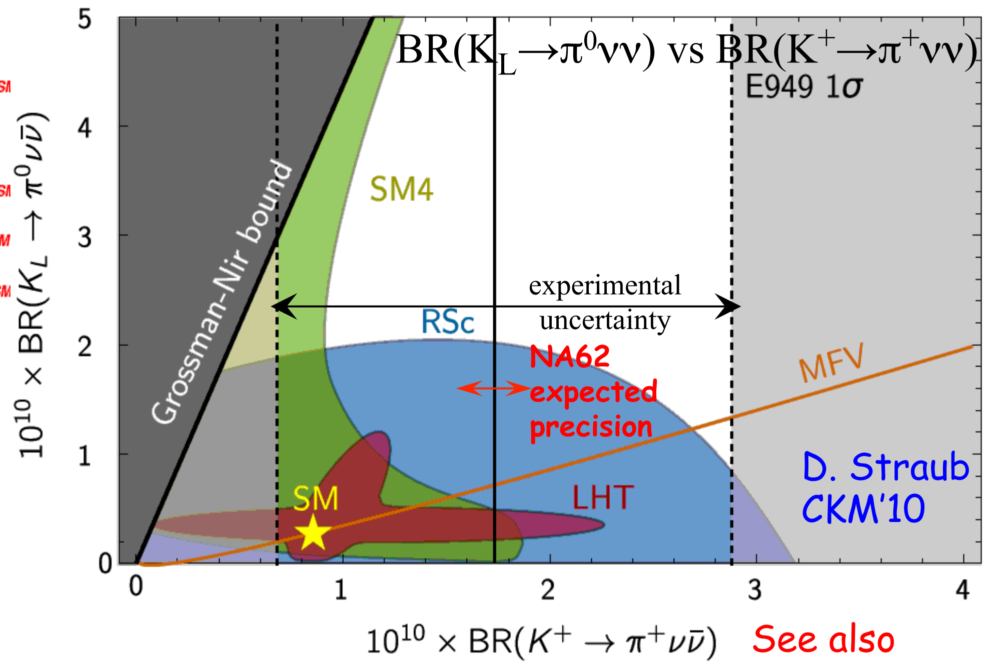
…and beyond Standard Model

Several SM extensions predict sizable deviations for the BR

→ possibility to distinguish among different models



Chargino / $H^\pm$ loops (MSSM at low/large tanβ), R-parity violation (non MFV), enhanced EW Penguins, Little Higgs, extra dimensions, 4th generation, …..



Concrete NP models predicting high deviations from MFV

Randall-Sudrum,

Littlest Higgs with T-parity,

SM 4th generation

(hep-ph/0906.5454, hep-ph/0812.3803, hep-ph/0604074, hep-ph/1302.4651)

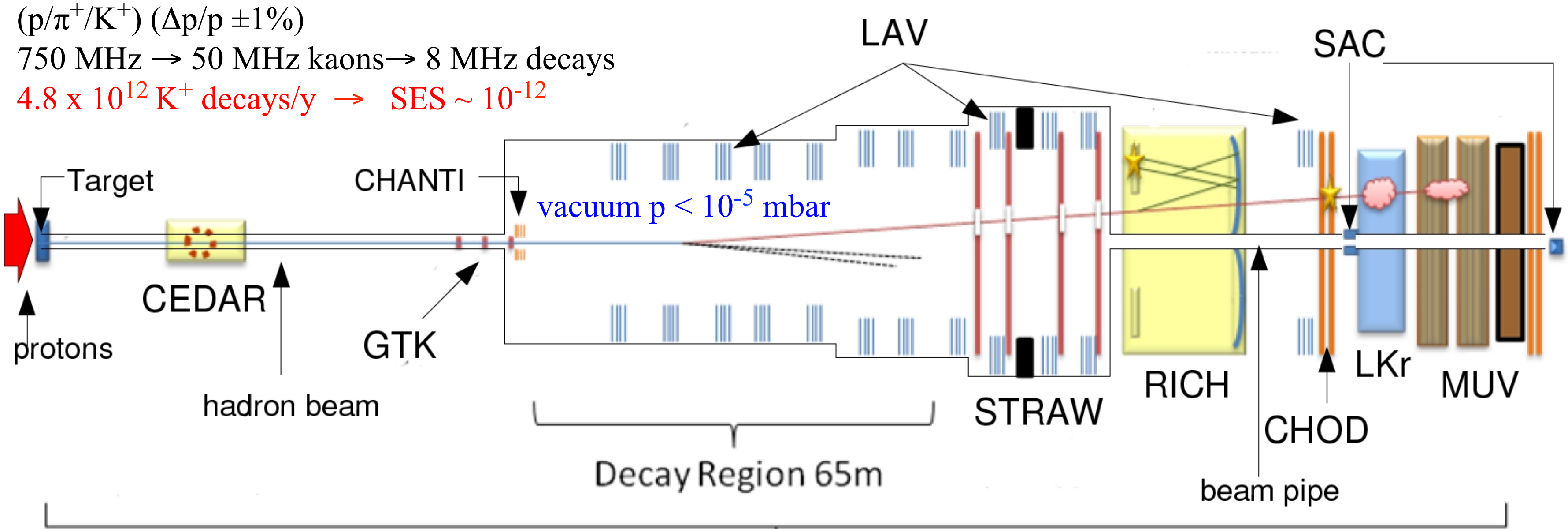
See also D. Straub Moriond QCD 2013

Next NA62 phase

Experiment layout & sensitivity

- 400 GeV/c SPS primary protons
- 75 GeV/c kaons unseparated hadron beam
- $(p/\pi^+/K^+)$ $(\Delta p/p \pm 1\%)$
- 750 MHz → 50 MHz kaons → 8 MHz decays
- 4.8×10^{12} K^+ decays/y → SES ~ 10^{-12}

Target: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

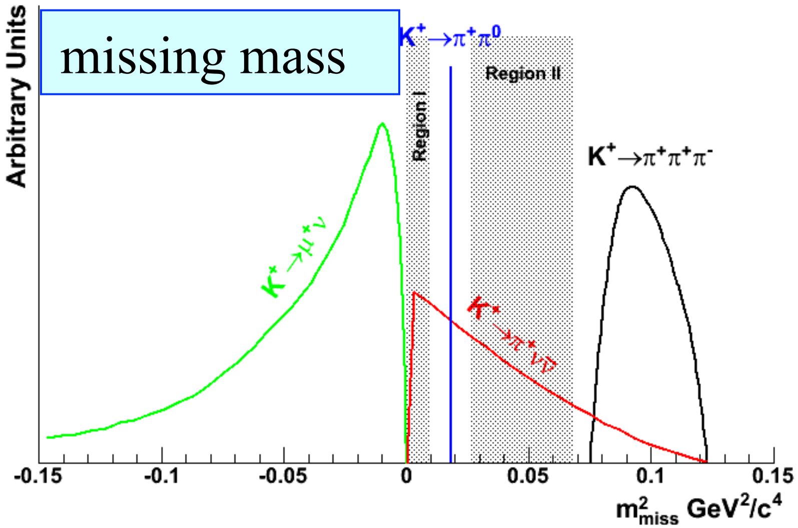


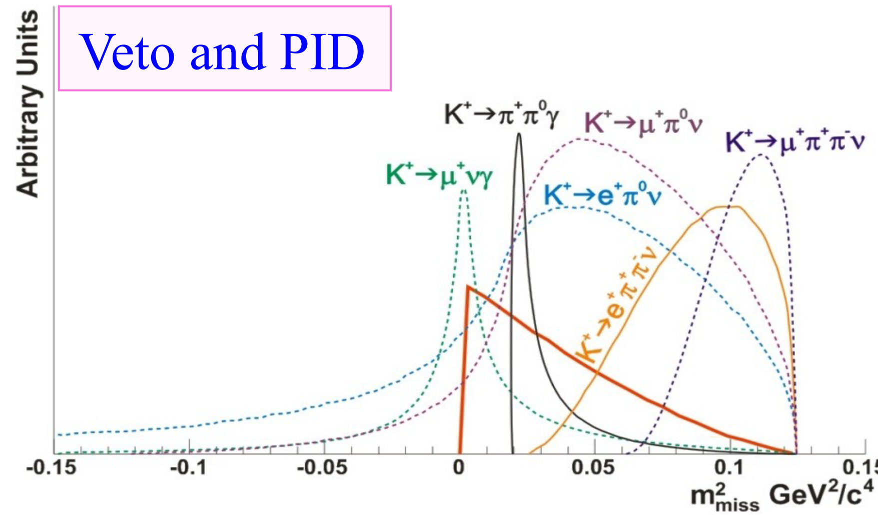
Signal	45 evt/y
$K^+ \rightarrow \pi^+\pi^0$	4.3%
$K^+ \rightarrow \mu^+\nu$	2.2%
$K^+ \rightarrow \pi^+\pi^+\pi^-$	< 4.5%
$K^+ \rightarrow \pi^+\pi^0\gamma$	~ 2%
$K^+ \rightarrow \mu^+\nu\gamma$	0.7%
total background	< 13.5%

Background and kinematics

92% Bkg separated from signal by kinematic cuts

8% not separated





$m^2_{miss} = (P_K - P_\pi)^2$ defines low bkg signal regions separated by $K^+ \rightarrow \pi^+\pi^0$

extend in the signal region
kinematics doesn't help

- ✓ high resolution m^2_{miss} reconstruction
- ✓ measure precisely kaon and pion momenta
- ✓ keep multiple scattering as low as possible

Gigatracker (Kaon)
Straw chambers (pion)

- ✓ Suppress $K^+ \rightarrow \pi^+\pi^0$ background
- ✓ Reject offline decays with γ
- ✓ K^+ identification in the had beam
- ✓ 10^{-3} π-μ separation

Photon veto system
Particle Identification

NA62: Experimental principles

- Goal → 10% precision Branching Ratio measurement
- O(100) $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events in two years of data taking

→ Statistics
- BR(SM) ~ 7.8×10^{-11}
- Acceptance: 10%
- K decays: 10^{13}

→ Systematics
- $\geq 10^{12}$ background rejection
- $\leq$10% precision on background measurement

Kaon intensity & signal efficiency

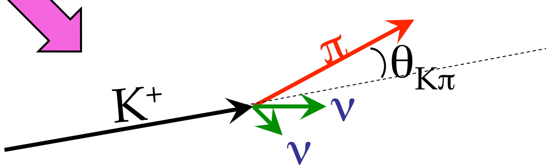
Signal purity & detector redudancy

High momentum K^+ beam

Decay in-flight technique

Very challenging experiment

Weak signature for signal decay

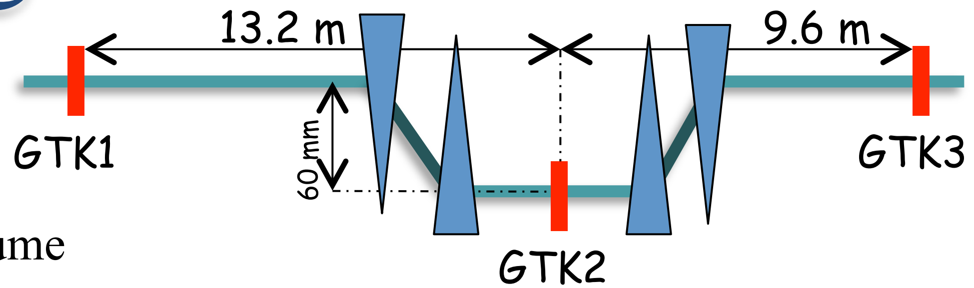


$m^2_{miss} = (P_K - P_\pi)^2$

Huge background →

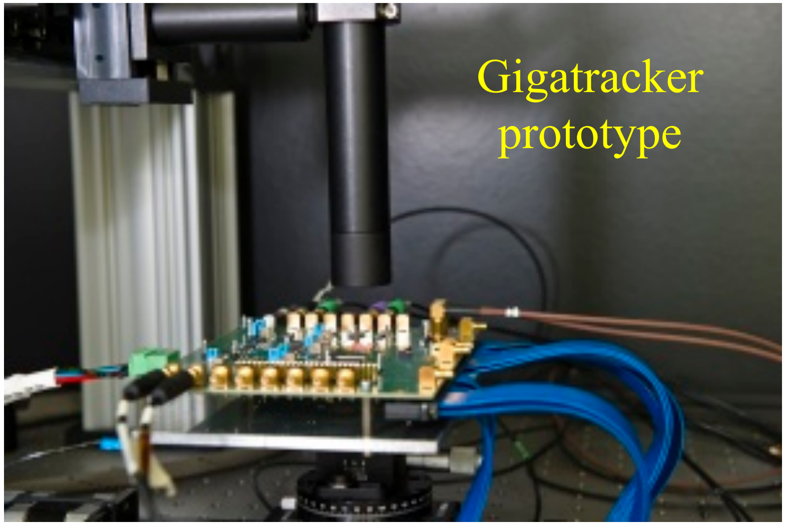
Decay	BR
$\mu^+\nu$ $(K_{\mu 2})$	63.5%
$\pi^+\pi^0$ $(K_{\pi 2})$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+\nu$ (K_{e3})	5.1%
$\pi^0\mu^+\nu$ $(K_{\mu 3})$	3.3%

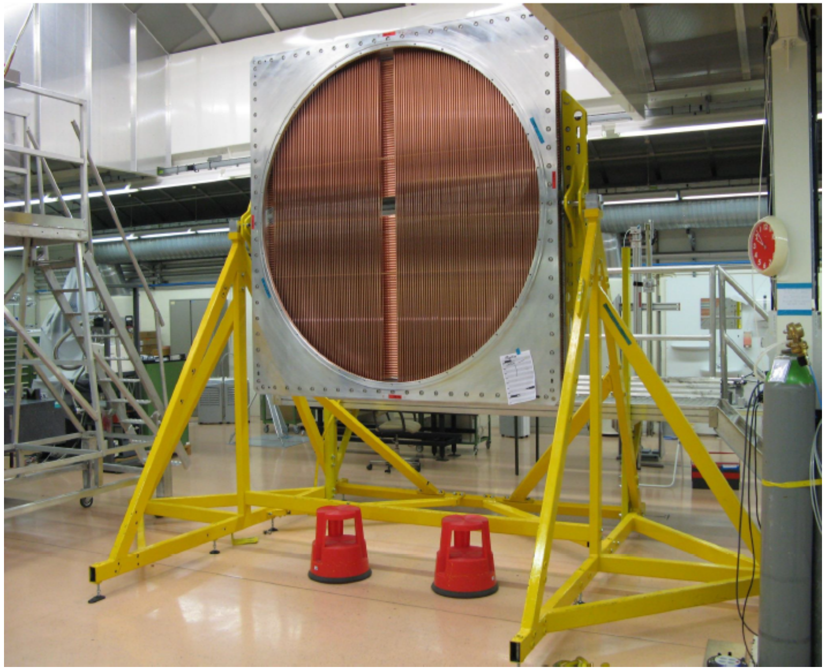
Tracking detectors



Gigatracker (800 MHz environment)

- measurement of time, coordinates and momentum of individual particles
- three Si-pixel station before the decay volume
- σ(t) ~ 150 ps on single track (test beam)

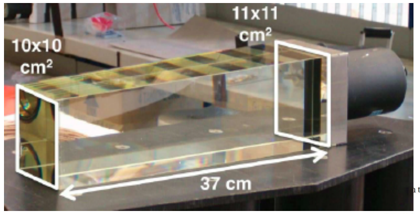


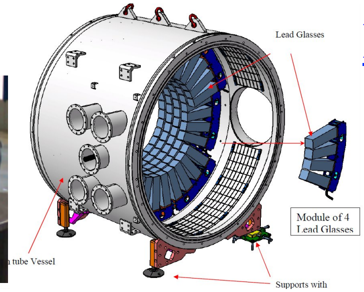


Straw chamber spectrometer

- measurement of coordinates and momentum of charged particles originating from decay
- 4 chambers + magnet
- $\sigma(P_\pi)/P_\pi \sim 0.3\% \oplus 0.007\% \times P_\pi$ (GeV/c)
- $\sigma(dX/dZ)/(dX/dZ) \sim 45\text{-}15$ μrad

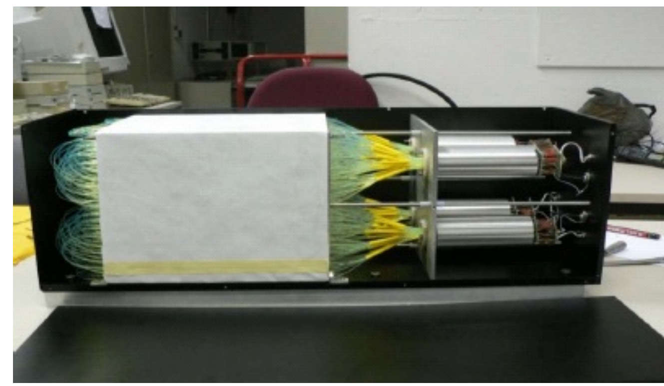
Vetos

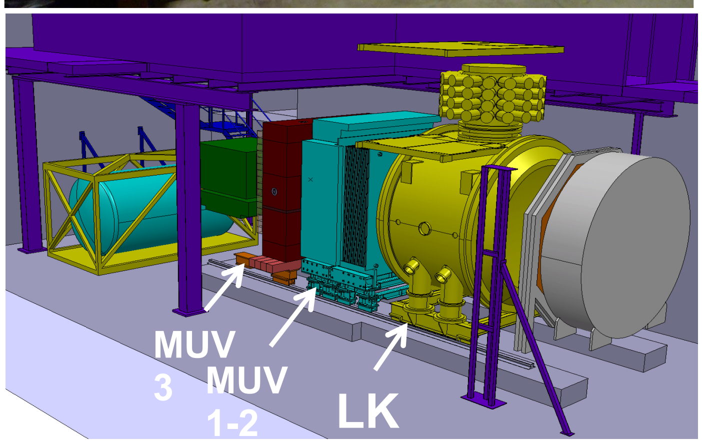




Photon Veto System - several subsystems, among them:

- Large angle (8.5-50 mrad) Lead glass blocks
  - Inefficiency $<10^{-4}$ for 100 MeV $< E_\gamma <$ 35 GeV
- (1- 8.5 mrad) Liquid Kripton Calorimeter
  - Inefficiency $<10^{-5}$ for $E_\gamma >$ 10 GeV
- Small angle (<1 mrad) “shashlyk” calorimeters
  - Inefficiency $<10^{-3}$ for $E_\gamma >$ 10 GeV





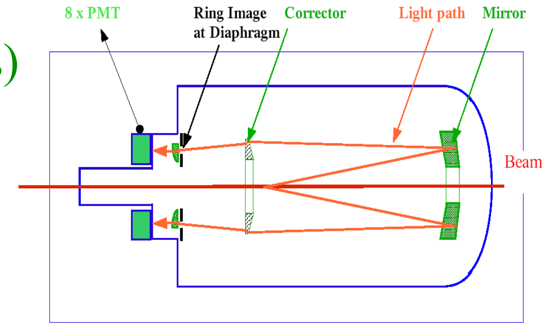
Muon detectors:

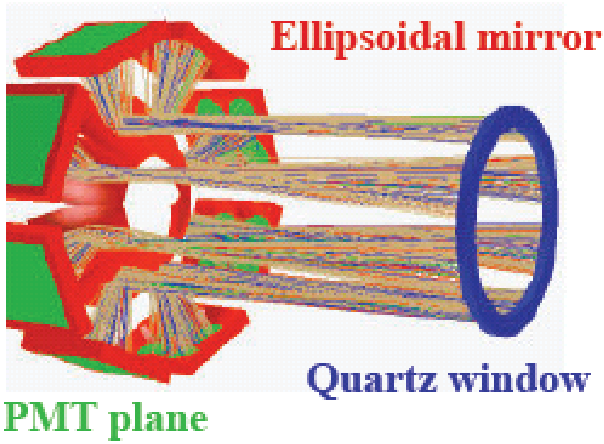
- 3 planes MUV 1,2,3 + iron
- MUV 1+MUV 2 reach a factor of 10^6 in muon rejection
- MUV 3 for trigger purposes

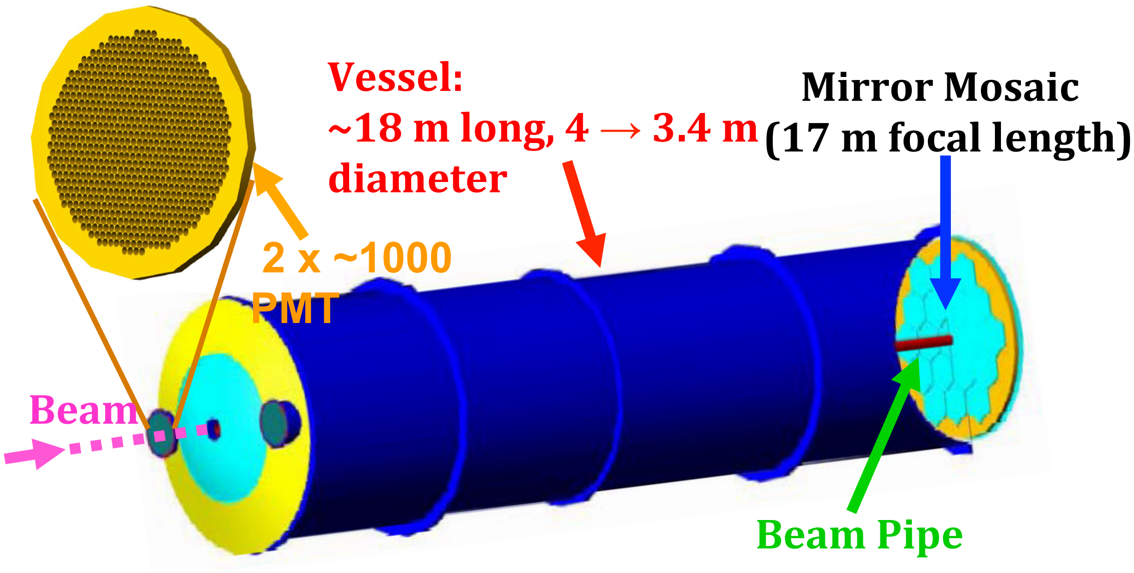
PID detectors

CEDAR - Differential Cherenkov counter

- Filled with Hydrogen gas
- Positive identification of Kaons in a 800 MHz hadron beam
- Excellent time resolution O(100 ps)
- Sustain rate O(MHz/mm^2)







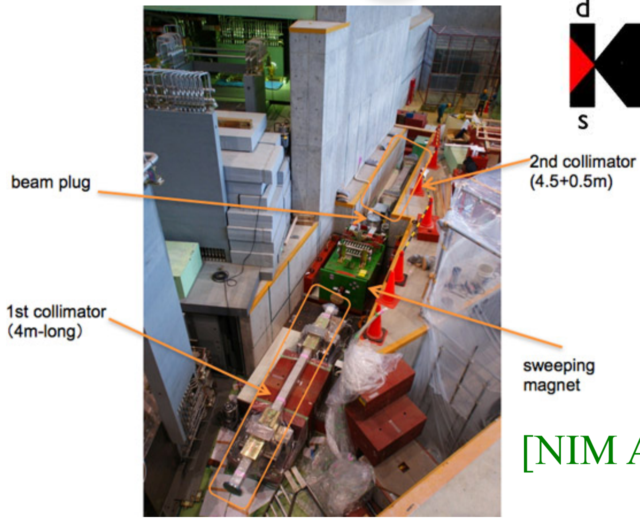
volume ~ 200 m^3

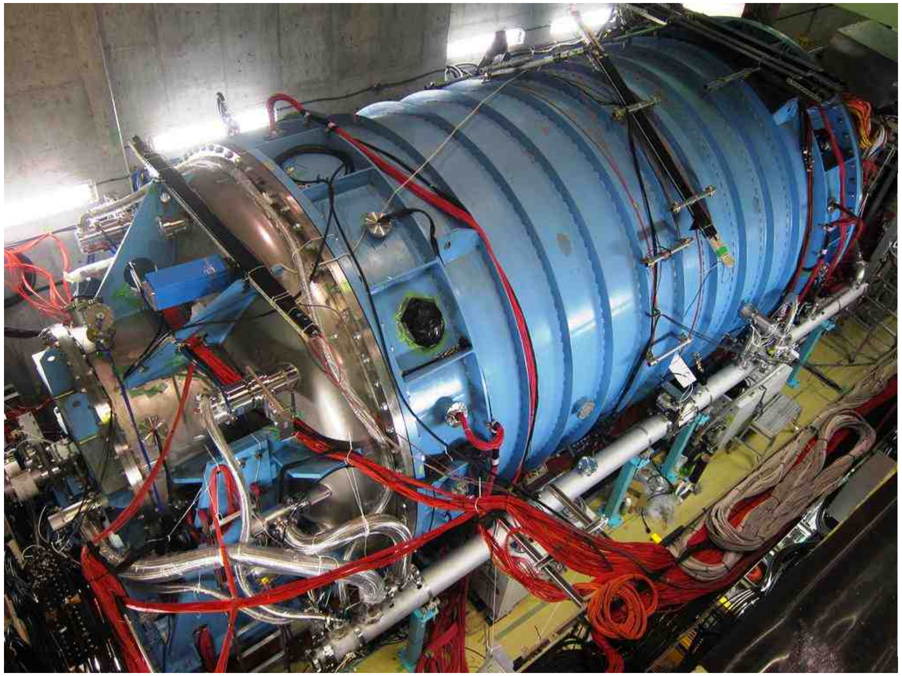
RICH – Ring Imaging Cherenkov counter:

- Filled with Neon at atm pressure
- Separate π-μ in 15 < p < 35 GeV/c with a μ suppression factor better than 5x10^{-3}
- Measure pion crossing time with a resolution < 100 ps
- Provide a L0 trigger for charged tracks

KOTO & ORKA

Koto @ JPARK and ORKA @ FNAL

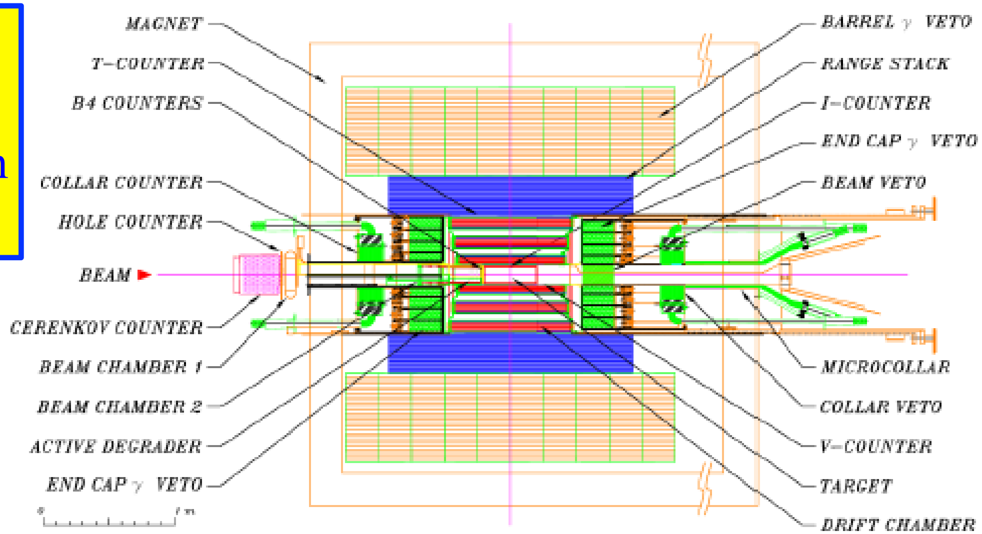




Beam line finalized and tested, first run starting now

[NIM A664 (2012) 264]

ORKA proposal @ FNAL:



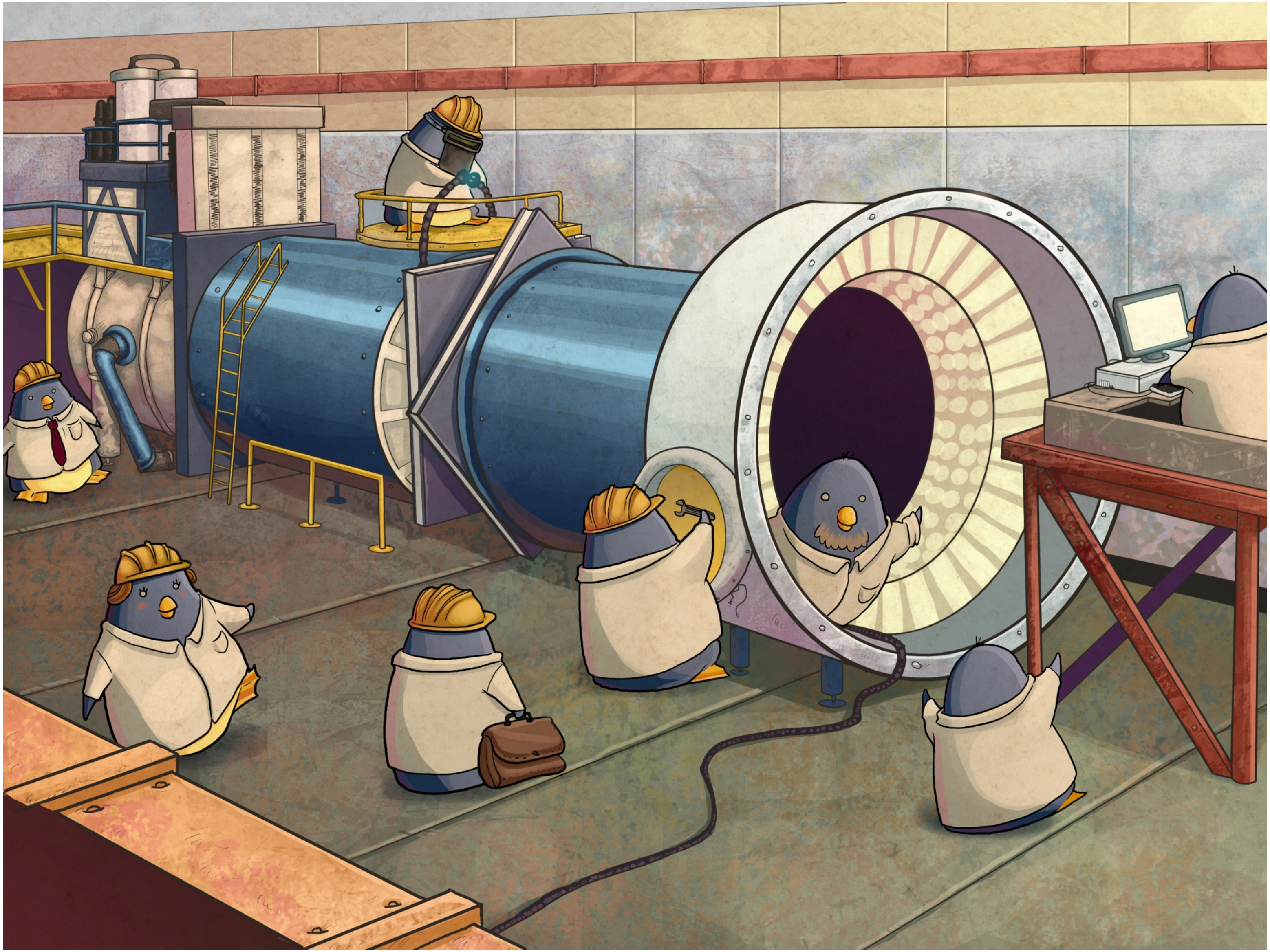
Goals	NA62 CERN	ORKA FNAL MI	Proj.X
Events/ yr	40	200	340
S/N	5	5	5
Precision	10%	5%	3%

Goals	KOTO * J-PARC	Proj.X
Events/yr	~1	"200"
S/N	~1	5-10
Precision		5%

* J-PARC plans a phase II to reach higher sensitivity.

…then OKA and TREK

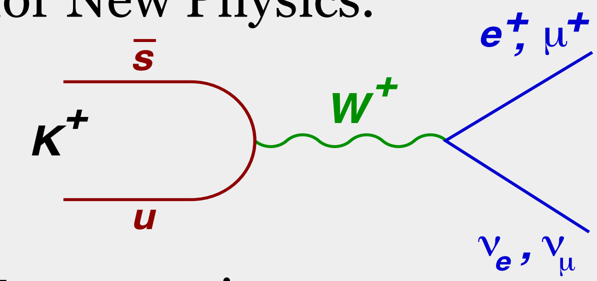
Summary: stay tuned on penguins!



SPARES

R_K measurement in NA62

A precise measurement of the ratio R_K of $K^{\pm}\rightarrow l^{\pm}\nu_l$ (K_{l2}) leptonic decays provides a stringent test of SM and indirect search for New Physics.



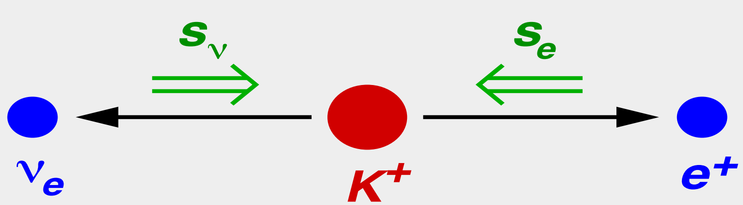
- Hadronic uncertainties cancel in the ratio $K_{e2}/K_{\mu2}$
- SM prediction: excellent sub-permille accuracy

R_K is sensitive to lepton flavour violation and its SM expectation:

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

Helicity suppression: f~10^{-5}

Radiative correction (few %) due to $K^+\rightarrow e^+\nu\gamma$ (IB) process, by definition included into R_K
[V.Cirigliano, I.Rosell JHEP 0710:005 (2007)]



Helicity suppression of R_K might enhance sensitivity to non-SM effects to an experimentally accessible level.

R_K^{SM} = (2.477±0.001)×10^{-5}

Phys. Rev. Lett. 99 (2007) 231801

Measurement strategy

(1) $K_{e2}/K_{\mu 2}$ candidates are collected concurrently:
- analysis does not rely on kaon flux measurement;
- several systematic effects cancel in the ratio (at first order);

(2) MC simulations used to a limited extent:
- Geometrical part of the acceptance correction and bkg estimation;

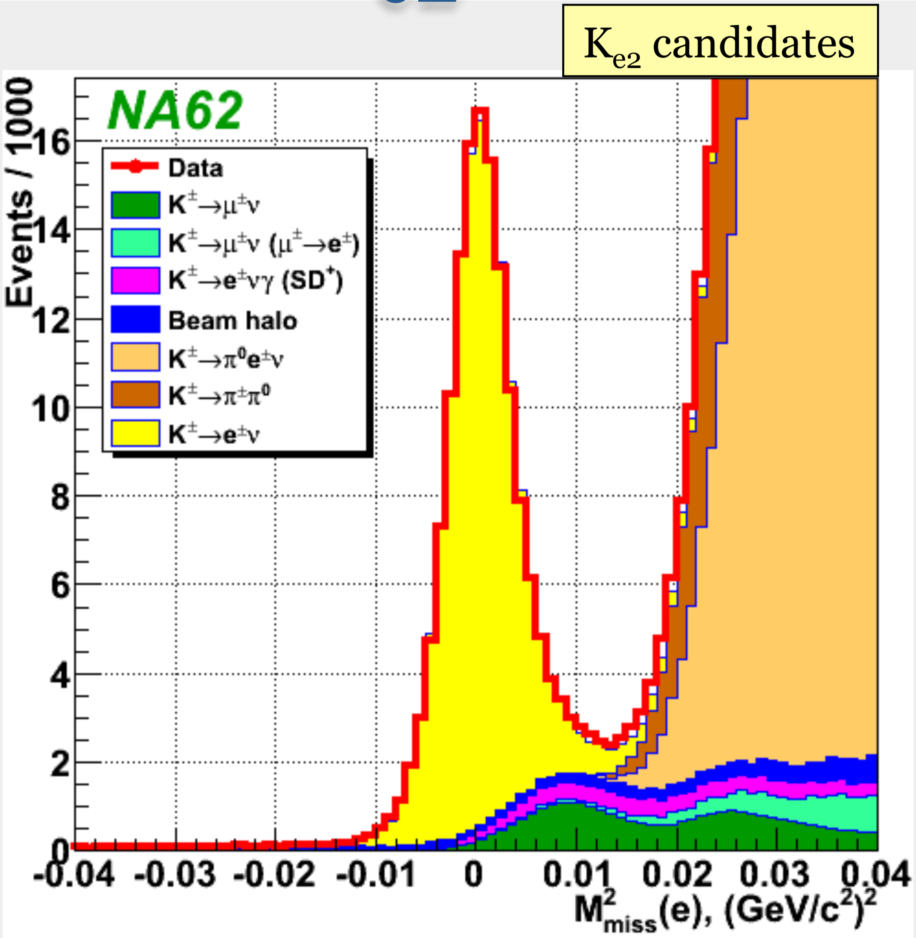
(3) PID, trigger, readout efficiencies and beam halo bkg measured directly from data;

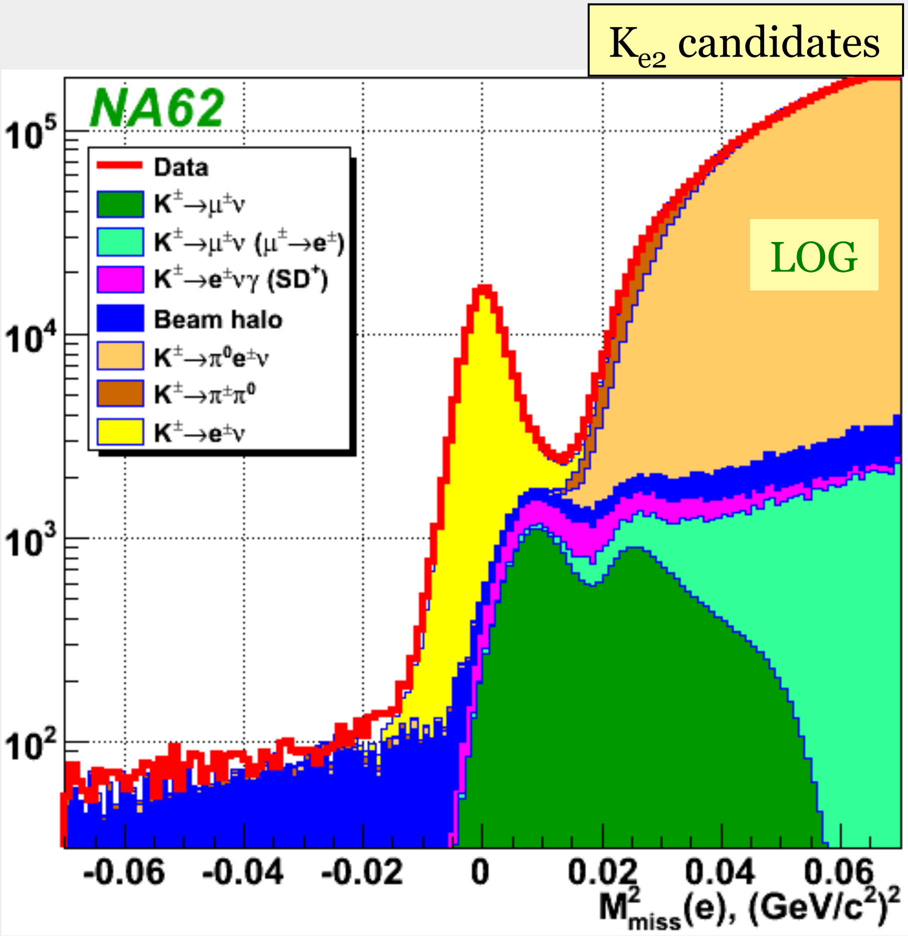
Counting experiment - analysis in 10 lepton momentum bins:
(due to strong momentum dependence of backgrounds and event topology)

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{f_\mu \cdot A(K_{\mu 2}) \cdot \varepsilon(K_{\mu 2})}{f_e \cdot A(K_{e2}) \cdot \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKR}}$$

Signal events — $N(K_{e2})$, $N(K_{\mu 2})$
Particle ID eff — f_μ, f_e
Trigger efficiency — ε
$K_{\mu 2}$ downscaling — D
Background events — N_B
Geometrical acceptance — A
Global LKr readout eff — f_{LKR}

K_{e2}: NA62 full data set





145,958 $K^{+}\to e^{+}\nu$ candidates.
Positron ID efficiency: (99.28±0.05)%.
B/(S+B) = (10.95±0.27)%.

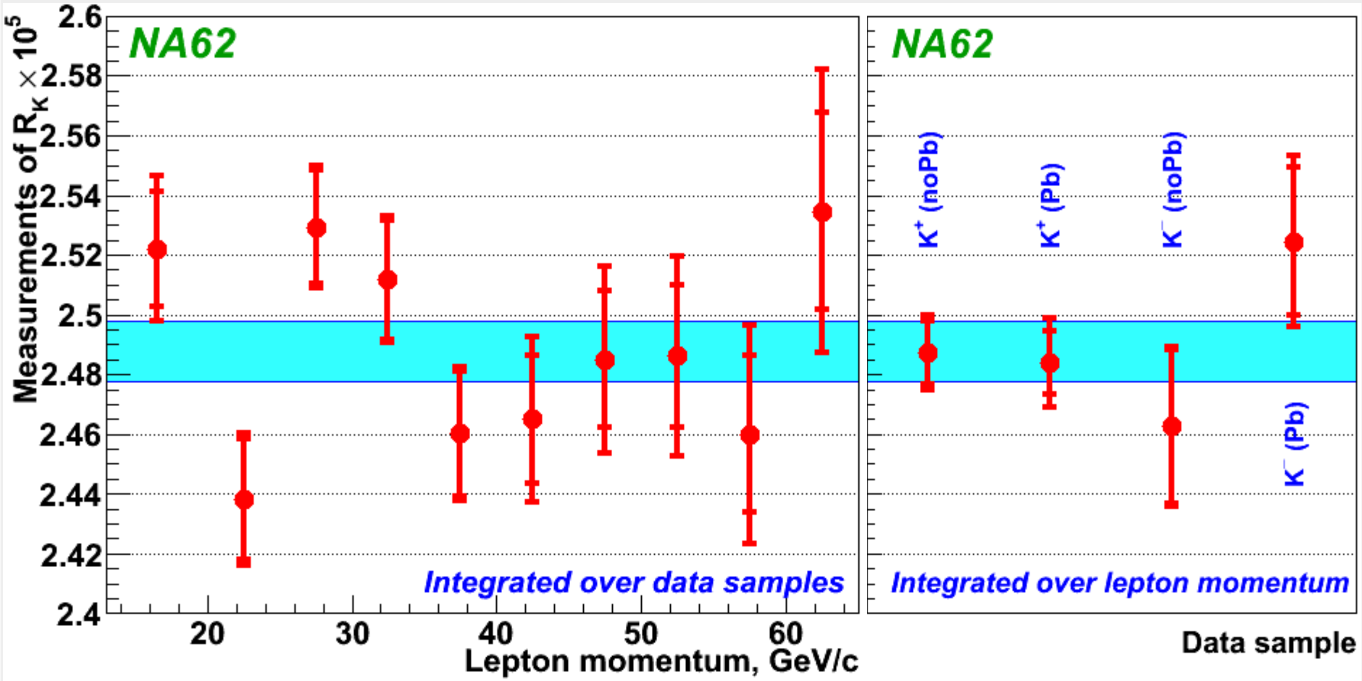
Proposal (CERN-SPSC-2006-033):
~ 150k candidates

cf. KLOE: 13.8K candidates (K^+ and K^-), ~90% electron ID efficiency, 16% bkg

NA62 result

$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$$
$$= (2.488 \pm 0.010) \times 10^{-5}$$

Fit over 40 measurements (4 data samples x 10 momentum bins) including correlations: $\chi^2/ndf=47/39$.



Independent measurements in lepton momentum bins

(systematic errors included, partially correlated)

NA62 result (40% data set): $R_K=(2.487\pm0.013)\times10^{-5}$ [PLB698 (2011) 105]

Uncertainties
0.4% tot precision

Source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$	0.004
BR($K_{e2\gamma}$ SD$^+$)	0.002
Beam halo	0.002
$K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$	0.003
Matter Composition	0.003
Acceptance	0.002
DCH alignment	0.001
Electron ID	0.001
LKr readout inef	0.001
1-track trigger	0.001
Total	**0.010**

Physics motivation

K_{l3} decays are described by **two form factors** $f_{\pm}(t)$, and the **matrix element** can be written as:

$$M = \frac{G_F}{2} V_{us} (f_+(t)(P_K + P_\pi)^\mu \bar{u}_l \gamma_\mu (1+\gamma_5) u_\nu + f_-(t) m_l \bar{u}_l (1+\gamma_5) u_\nu)$$

$t = q^2$ is the square of the four-momentum transfer to the lepton neutrino system

$f_-(t)$ can only be measured in $K_{\mu 3}$ decays because of $m_e << m_K$

$f_+(t)$ is the **vector form factor** and $f_0(t)$ the **scalar form factor** with:

$$f_0(t) = f_+(t) + \frac{t}{(m_K^2 - m_\pi^2)} f_-(t)$$

$f_+(0)$ cannot be measured directly, therefore the form factors are normalised to $f_+(0)$:

$$\bar{f}_+(t) = \frac{f_+(t)}{f_+(0)} \qquad \bar{f}_0(t) = \frac{f_0(t)}{f_+(0)}$$

Form Factor Parametrizations

Parametrizations using **physical quantities** are called **class 1** parametrizations. They depend on free parameters with a physical meaning.

Pole parametrization:

Assumes the exchange of vector and scalar resonances K* with spin-parity $1^-/0^+$ and masses m_V/m_S, $f_+(t)$ can be described by K*(892), for $f_0(t)$ no obvious dominance is seen:

$$\bar{f}_{+,0}(t) = \frac{m^2_{V,S}}{m^2_{V,S} - t}$$

Parametrizations without a **physical meaning** are called **class 2** parametrizations. They require more free parameters and are expansions in the momentum transfer.

Linear and quadratic parametrization:

$$\bar{f}_{+,0}(t) = \left[1 + \lambda_{+,0}\frac{t}{m^2_\pi}\right]$$ **Linear**

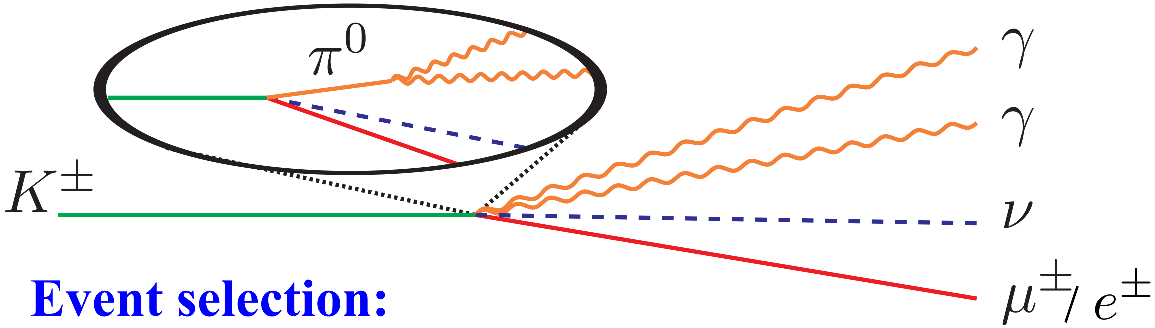
$$\bar{f}_{+,0}(t) = \left[1 + \lambda'_{+,0}\frac{t}{m^2_\pi} + \frac{1}{2}\lambda''_{+,0}\left(\frac{t}{m^2_\pi}\right)^2\right]$$ **Quadratic**

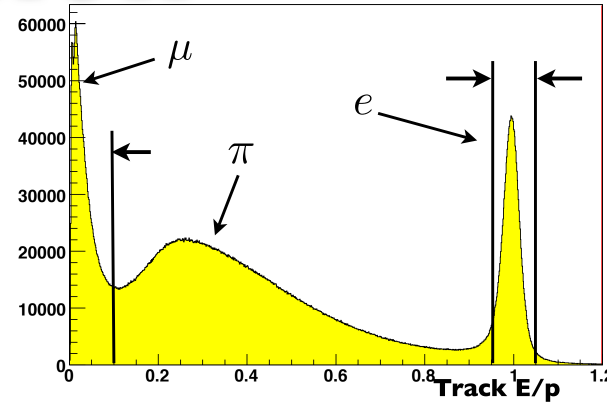
Correlations!

No sensitivity to λ''_0

$\bar{f}_0(t)$ linear

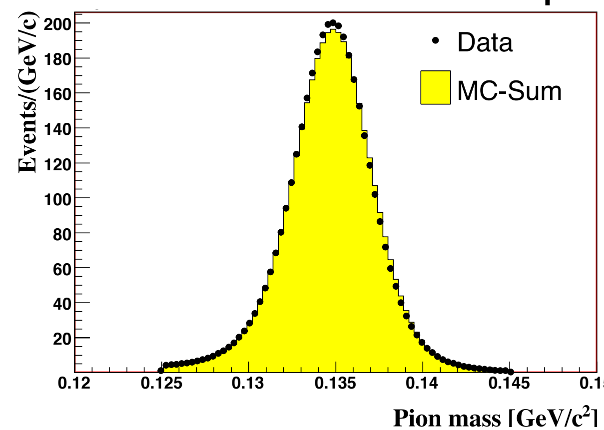
Event selection





Event selection:

- **1 good track**
  - Muon identified by muon veto and E/p
  - Electron identified by E/p
- **1 good $\pi^0 \rightarrow \gamma\gamma$**
  - Pion mass cut: $|m_{\gamma\gamma} - m^{PDG}(\pi^0)| > 10$ MeV



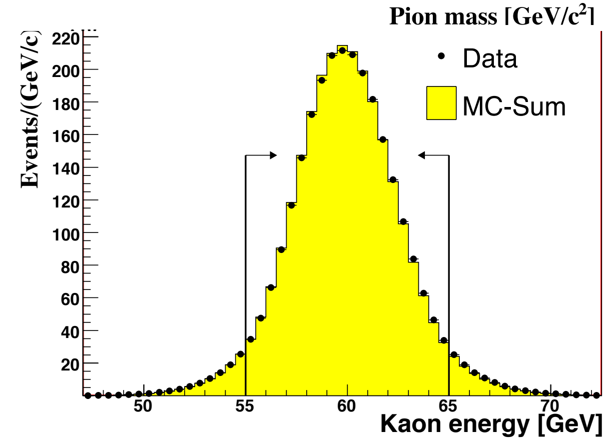
Event reconstruction:

- LKr clusters and muon track consistent in time
- Missing mass cut using $K^{\pm}$ hypothesis

$$M^2_{K_{l3}} = (P_K - P_l - P_{\pi^0})^2 < 10\ \text{MeV}^2$$

- Kaon energy reconstructed under the assumption of a missing undetected neutrino within the range of:

$$55\text{GeV} < E_{\pm} < 65\text{GeV}$$



2.5×10^6 $K^{\pm}_{\mu 3}$ **events selected**

4.0×10^6 $K^{\pm}_{e3}$ **events selected**

$\pi^+\pi^0$ background

To $K^{\pm}_{\mu3}$:

$K^{\pm} \rightarrow \pi^{\pm}\pi^0$ with $\pi \rightarrow \mu$ can fake the signal

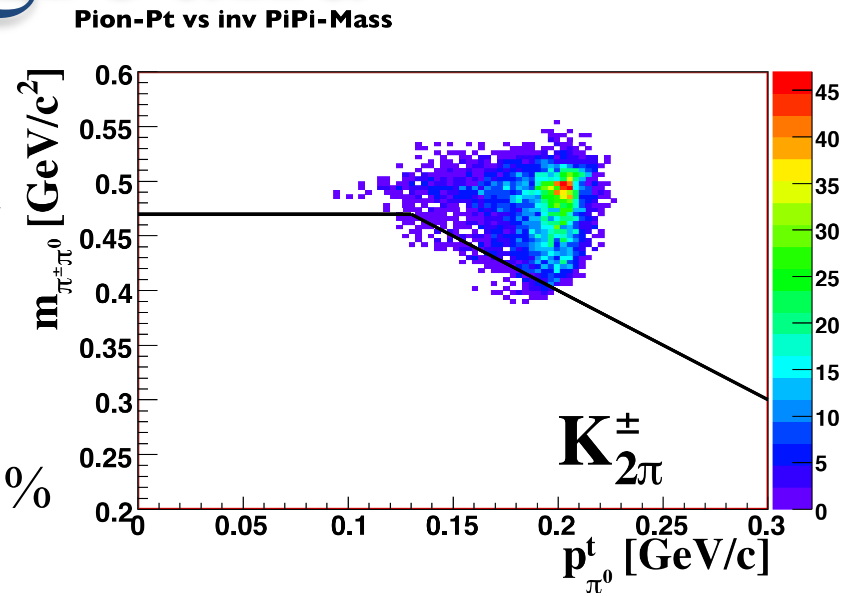
Without suppression, $K^{\pm} \rightarrow \pi^{\pm}\pi^0$ background at the level of 20%

Cut in the invariant $\pi^{\pm}\pi^0$ mass and the transverse momentum of the pion:

→ Background contamination reduced to 0.5%

→ about 24% of $K^{\pm}_{\mu3}$ events are lost

Background is well localized in the Dalitz plot



To $K^{\pm}_{e3}$:

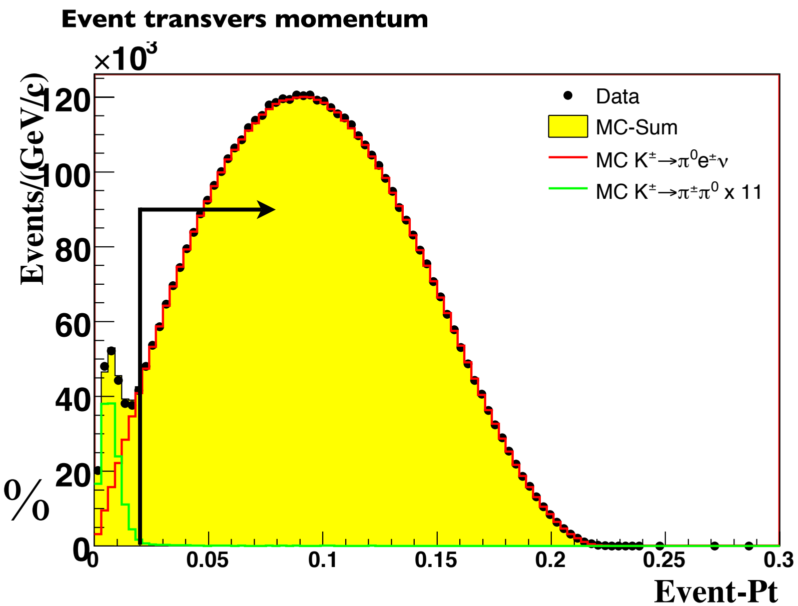
Pion with $E/P > 0.95$ can fake a $K^{\pm}_{e3}$ decay

Cut in the transverse momentum of the event:

$$p^T_{event} > 0.02 \text{ GeV/c}$$

→ Background contamination reduced to < 0.1%

→ about 3% of $K^{\pm}_{e3}$ events are lost



Radiative corrections

The K_{l3} decay rate including first order radiative corrections can be written as:

$$\Gamma_{K_{l3}} = \Gamma^0_{K_{l3}} + \Gamma^1_{K_{l3}} = \Gamma^0_{K_{l3}}(1 + 2\delta^{Kl}_{EM})$$

Simulation code provided by KLOE author C. Gatti, *EPJ C45 (2006) 417*

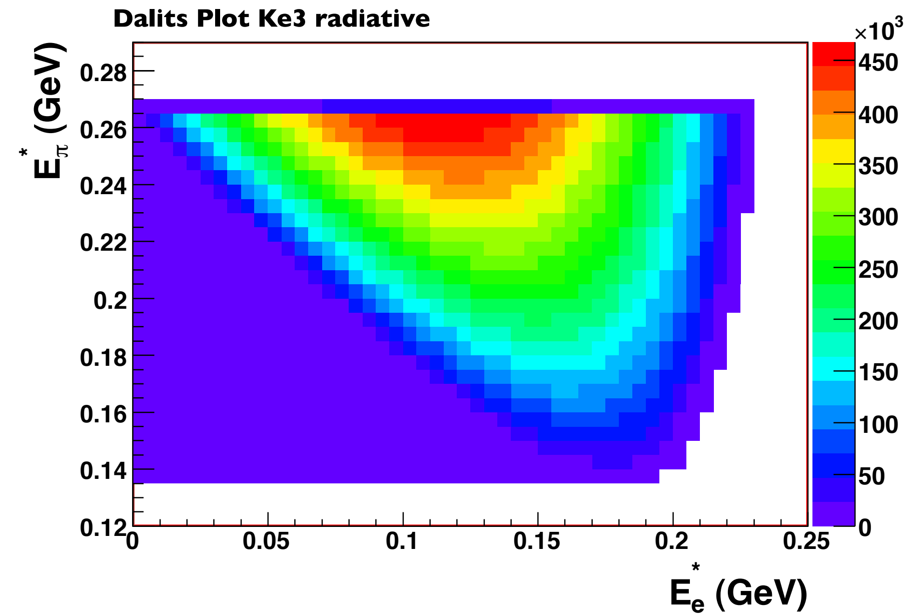
Parameters used for the normalization:

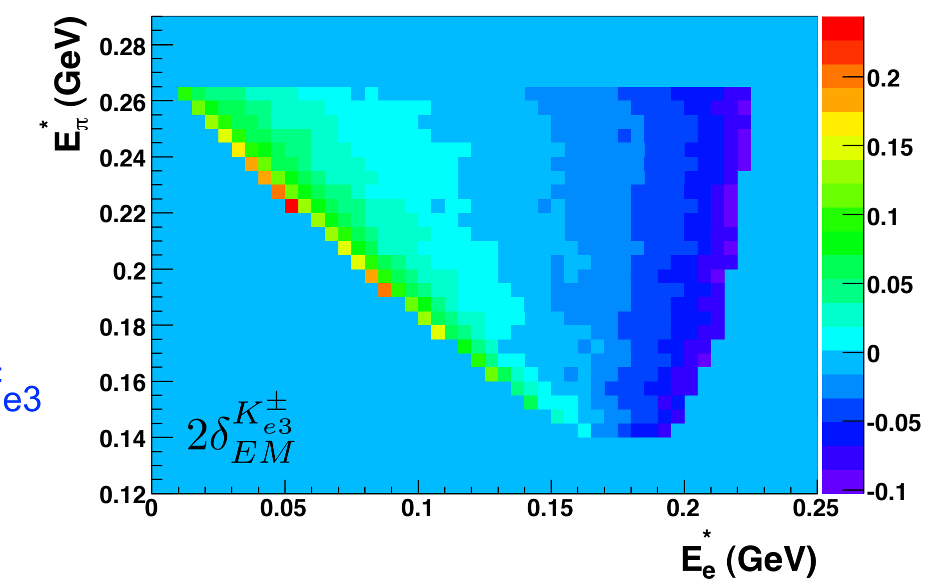
(JHEP 11 (2008) 006)

Mode	$\delta^{K_{l3}}_{EM}(\%)$
$K^{\pm}_{\mu3}$	0.008 ± 0.125
$K^{\pm}_{e3}$	0.050 ± 0.125

For $K^{\pm}_{e3}$ the effects on the acceptance are bigger with respect to $K^{\pm}_{\mu3}$

- ~10% effect on the Dalitz plot slope for $K^{\pm}_{e3}$
- Percent effect on slope for $K^{\pm}_{\mu3}$





Systematic checks

$K^{\pm}_{\mu 3}$	$\Delta\lambda'_+$	$\Delta\lambda''_+$ $\times 10^{-3}$	$\Delta\lambda_0$	Δm_V MeV/c^2	Δm_S
Kaon Energy	±0.1	±0.0	±0.3	±1	±8
Vertex	±1.0	±0.5	±0.1	±2	±7
Bin size	±0.8	±0.4	±0.7	±3	±10
Energy scale	±0.3	±0.1	±0.1	±0	±1
Acceptance	±0.2	±0.1	±0.3	±2	±5
$K_{2\pi}$ background	±1.7	±0.5	±0.6	±3	±0
2nd Analysis	±0.1	±0.1	±0.2	±2	±5
FF input	±0.3	±0.8	±0.1	±7	±3
Systematic	±2.2	±1.1	±1.0	±9	±16
Statistical	±3.0	±1.1	±1.4	±8	±31

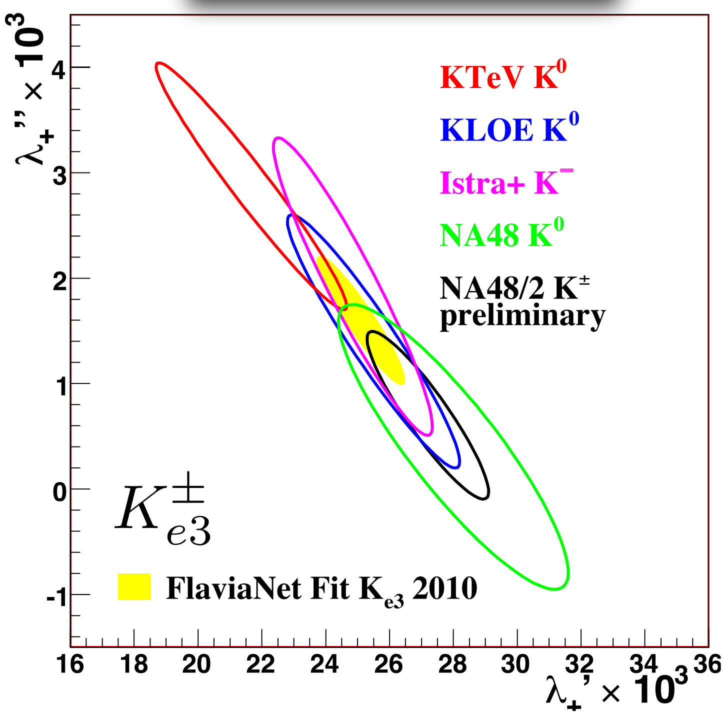
$K^{\pm}_{e3}$	$\Delta\lambda'_+$ $\times 10^{-3}$	$\Delta\lambda''_+$	Δm_V MeV/c^2
Kaon Energy	±0.3	±0.1	±6
Vertex	±0.2	±0.1	±0
Bin size	±0.0	±0.1	±2
Energy scale	±0.1	±0.0	±0
Acceptance	±0.2	±0.0	±3
2nd Ana	±0.9	±0.4	±1
FF input	±0.4	±0.0	±1
Sytematic	±1.1	±0.4	±7
Statistical	±0.7	±0.3	±3

$K^{\pm}_{\mu 3}$ is dominated by statistics, $K^{\pm}_{e3}$ is dominated by the systematics

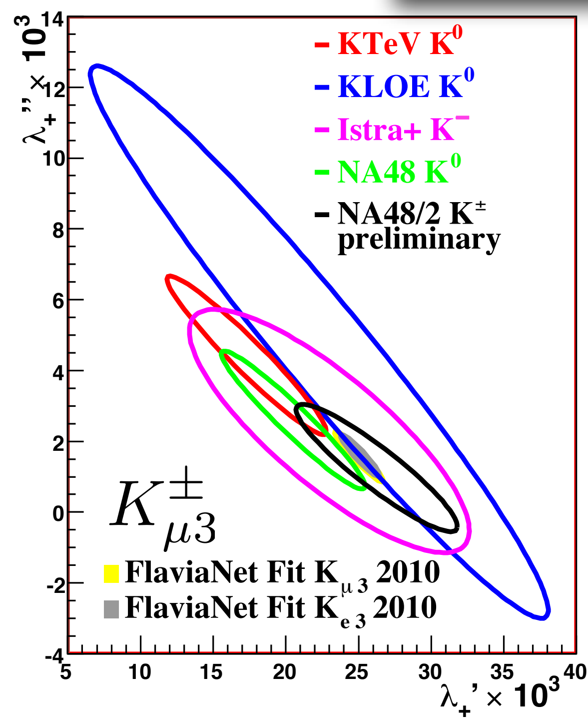
Preliminary results

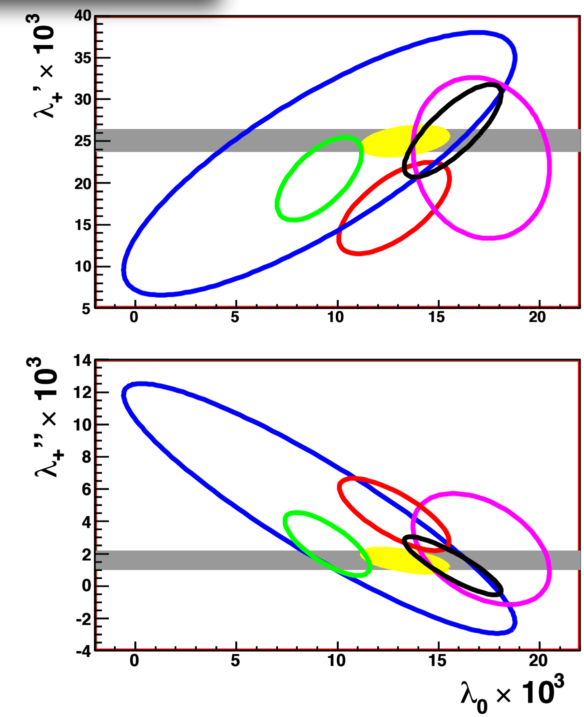
Quadratic $(\times 10^{-3})$	λ'_+	λ''_+	λ_0
$K^{\pm}_{\mu 3}$	$26.3 \pm 3.0_{stat} \pm 2.2_{syst}$	$1.2 \pm 1.1_{stat} \pm 1.1_{syst}$	$15.7 \pm 1.4_{stat} \pm 1.0_{syst}$
$K^{\pm}_{e3}$	$27.2 \pm 0.7_{stat} \pm 1.1_{syst}$	$0.7 \pm 0.3_{stat} \pm 0.4_{syst}$	
Pole $(\mathrm{MeV/c^2})$	m_V		m_S
$K^{\pm}_{\mu 3}$	$873 \pm 8_{stat} \pm 9_{syst}$		$1183 \pm 31_{stat} \pm 16_{syst}$
$K^{\pm}_{e3}$	$879 \pm 3_{stat} \pm 7_{syst}$		

68% Confidence level contours



68% Confidence level contours





Grossman-Nir bound

Grossman-Nir bound (1997)

- Since the two processes are determined by the imaginary part and the absolute value of the same coupling, a simple model-independent bound is obtained.

$$B(K_L \to \pi^0 \nu \bar{\nu}) < 4.4 B(K^+ \to \pi^+ \nu \bar{\nu})$$

Present experimental bounds

$B(K^+ \to \pi^+ \nu \bar{\nu})$	$B(K_L \to \pi^0 \nu \bar{\nu})$
$(1.47^{+1.30}_{-0.89}) \cdot 10^{-10}$	$< 2.1 \cdot 10^{-7}$
BNL E949	KEK E391a

The GN bound can be violated if lepton flavor violation exists.