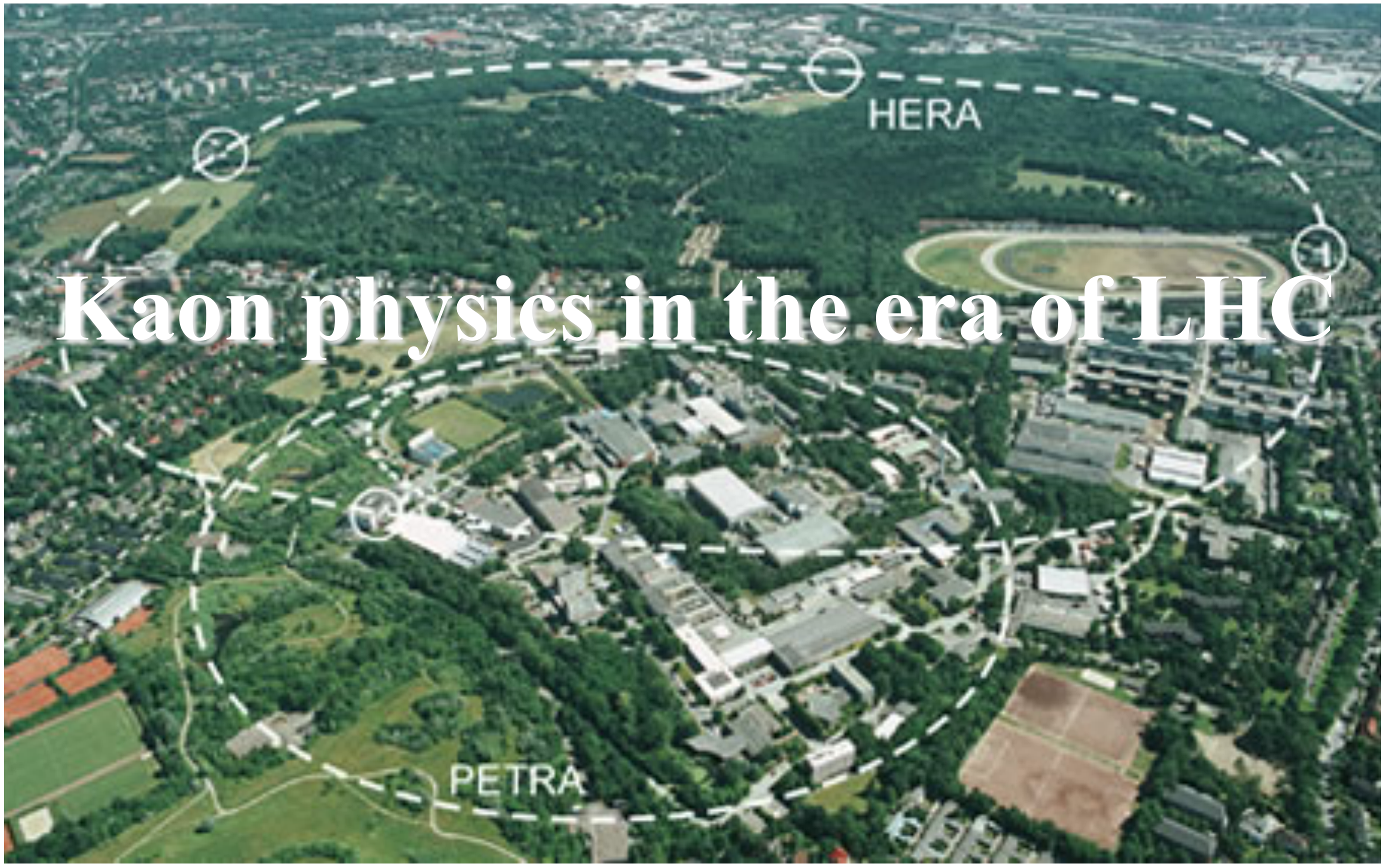
Kaon physics in the era of LHC



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Wednesday-Seminar in Zeuthen
DESY, Germany, 27th January, 2010

***member of the KLOE and NA62 collaborations**

Our physics – the landscape

Particle physics seems to be described by a simple and economical theory:

$$L_{SM} = L_{gauge}(A_a, \psi_i) + L_{Higgs}(\phi, A_a, \psi_i)$$

- **Natural**
- **Experimentally tested with high accuracy**
- **Stable with respect to quantum corrections**
- **Highly symmetric (gauge and flavor symmetries)**

- ***Ad hoc***
- **Necessary to explain data (presence of a non-symmetric vacuum)**
- **poorly tested in its dynamical form**
- **Not stable with respect to quantum corrections**
- **Determine the flavor structure of the model**

Our physics – the future goals

Particle physics seems to be described by a simple and economical theory:

$$L_{SM} = L_{gauge}(A_a, \psi_i) + L_{Symmetry\ Breaking}(\phi?, A_a, \psi_i)$$

Key problem addressed by high-P_T LHC experiments:

The dynamical structure of ew symmetry breaking mechanism
Is there a Higgs boson? Is it fundamental or composite?

But the "genuine" Higgs mechanism is not stable. Theory prejudices:

"the Higgs boson (if any) will not be alone;

A new sector @ TeV scale might show up, to stabilize the electroweak scale, $\langle\phi\rangle$ = 246 GeV" [Isidori, 2009 NA62 Physics workshop]

Key problem addressed by high-precision low-energy experiments:

Investigate the symmetry properties of the Higgs sector

Kaon physics – the landscape

Kaon is the lightest strange particle, studied since 60's to test fundamental properties of nature. The SM appears remarkably simple @ $E \sim M_K$:

$$L_{SM} = L_{QCD}(m_u=m_d, m_s) + L_{QED} + L_{IB}(m_u-m_d) + L_{ew}$$

- **Only 2 parameters in L_{QCD}: m_s and $m_d \sim m_u \sim (m_d+m_u)/2$**
- **L_{QED} and L_{IB} isospin-breaking: often neglected, but add 3rd parameter**
- **L_{ew} links to physics @ e.w. scale, breaks many symmetries: P, CP, flavor**

Kaons special role
- **weak decays**
- **theoretical cleanness**
- **short distance FCNC with the strongest SM suppression**
- **limited number of decay modes**

Kaons reach the highest sensitivities to CPT violation, QM tests and are competitive with B decays to test new physics in LFV or CPV transitions

First achievements: CPV

K^0's produced are stable for decay via QCD, $\overline{K^0}$-K^0 oscillation determined by 2nd order weak transitions (box diagrams)

$$|K_{S,L}\rangle \propto (1+\varepsilon_{S,L})\,|K^0\rangle + (1-\varepsilon_{S,L})\,|\overline{K}^0\rangle$$

CPT demands $\delta = \varepsilon_S - \varepsilon_L = 0$

CP implies $K_{S,L}$ have definite CP, so $\varepsilon = 0$

first CP violation effects first revealed from K decays to $\pi\pi$ (1964)

it is a tiny effect: $|\varepsilon| = (2.221 \pm 0.006) \times 10^{-3}$

Mixing studied with precision (in the past decade, data dominated by CPLEAR experiment)

Evidence of T violation in time evolution of strangeness-tagged kaon decays

Direct CPV: the ε'/ε saga

For deeper insight into CPV compare $K_{L,S} \to \pi\pi$ decay widths @ level of 10^{-4}

$$K_L \sim K_{odd} + \varepsilon K_{even}$$

"Direct" in decay process — ε' → $\pi\pi$

"Indirect" from asymmetric $K^0 - \overline{K}^0$ mixing → $\pi\pi$

$$\mathrm{Re}(\varepsilon'/\varepsilon) \approx \frac{1}{6}\left[\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_s \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_s \to \pi^0\pi^0)} - 1\right]$$

A new class of high-sensitivity experiments (NA31→NA48, E731→ KTeV)

kaons produced by proton interaction on fixed Be target

unprecedented fluxes, to collect >10^6 $K_L \to \pi^0\pi^0$

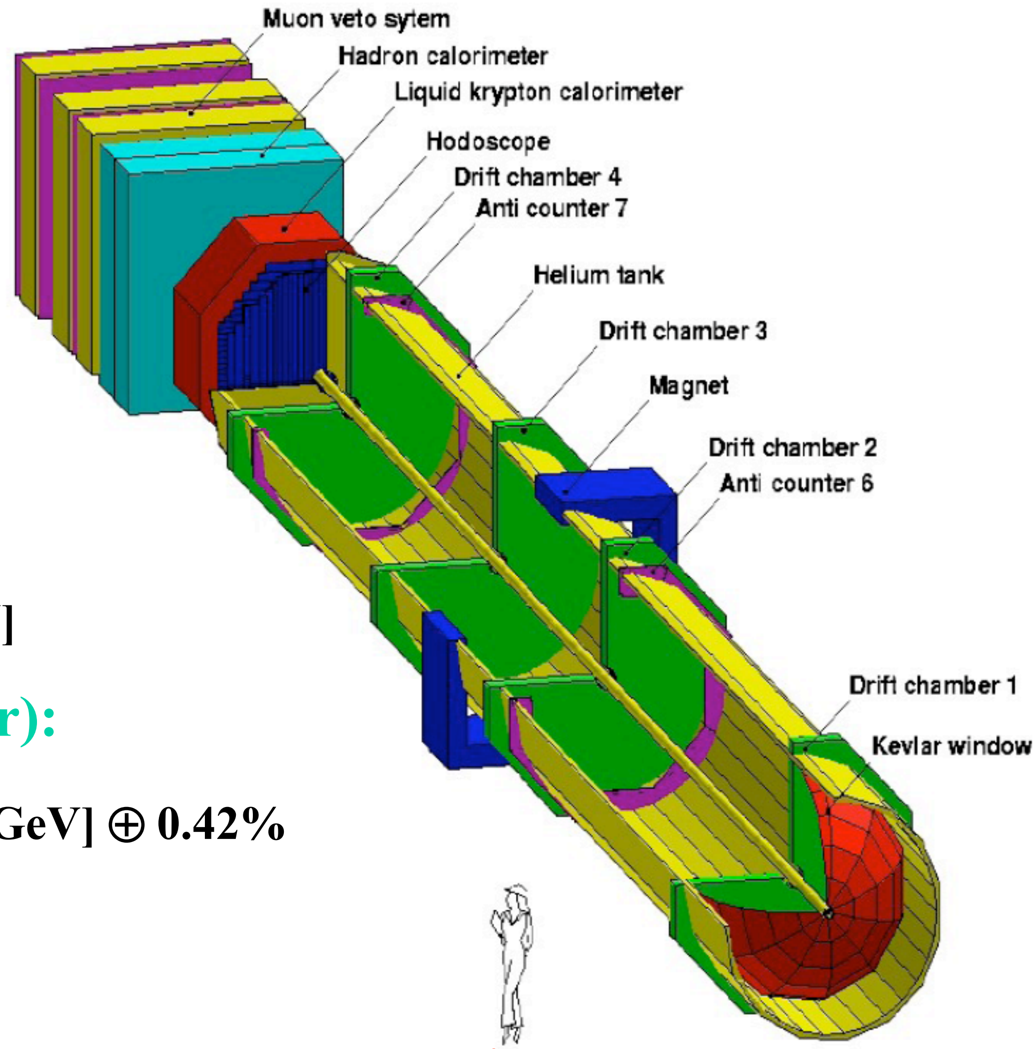
guarantee thorough control of systematics by careful setup design

The NA48 experiment

Enriched K_S beam: bend fraction of p beam via channelling crystal

Simultaneous K_L/"K_S" beams: assure K_S-K_L overlap in FV

Alternate analyzing magnet polarities during data taking



Magnetic spectrometer:

$$\sigma_p/p = 1.02\% \oplus 0.044\%\ p\ [\mathrm{GeV}]$$

Electromagnetic calorimeter (LKr):

$$\sigma_E/E < 3.2\% / \sqrt{E[\mathrm{GeV}]} \oplus 9\% / E[\mathrm{GeV}] \oplus 0.42\%$$

$$\sigma_{x,y}[\mathrm{mm}] = 0.42 / \sqrt{E[\mathrm{GeV}]} \oplus 0.6$$

Specific operations for high-intensity K_S beam and K^+K^- beams (NA48/2)

The KTeV experiment

Select enriched K_S beam from regenerator

Regularly alternate regenerator position during data taking

Magnetic Spectrometer:

$\sigma_p/p < 1\%$ for charged tracks, $p > 8$ GeV

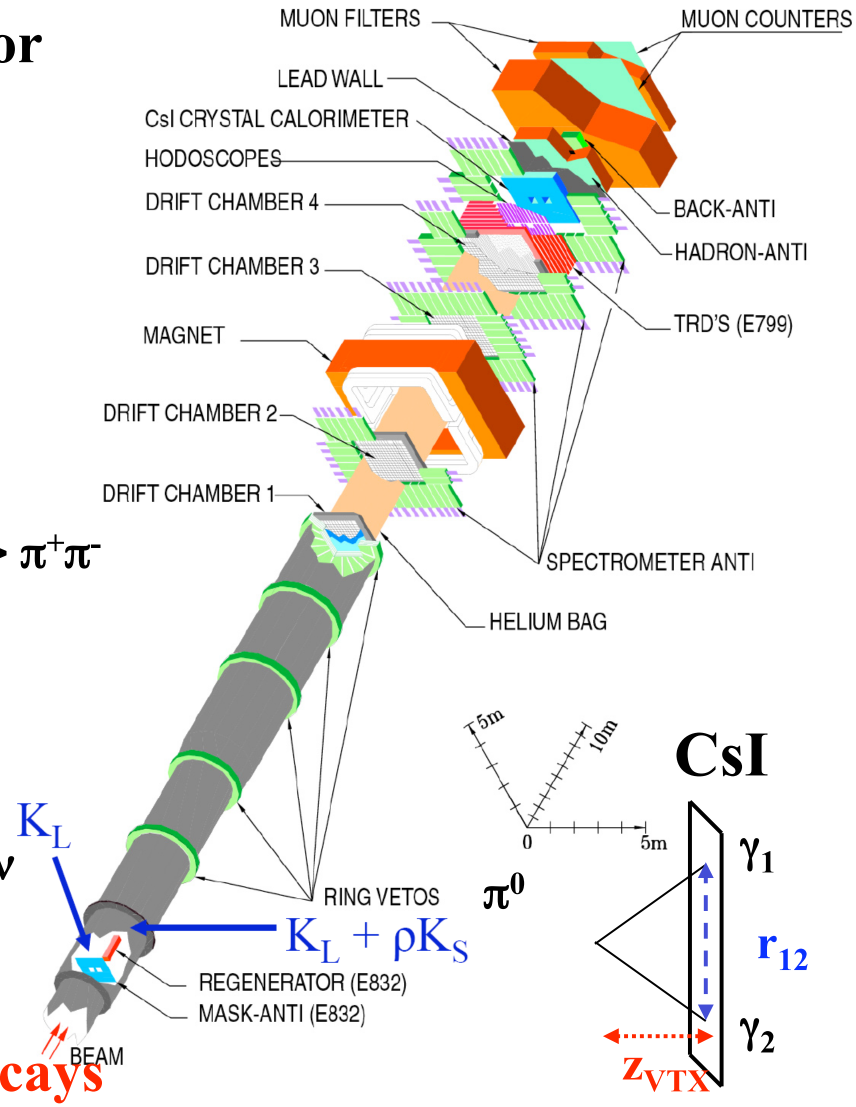
Momentum scale known < 0.01% from $K \rightarrow \pi^+\pi^-$

Electromagnetic calorimeter (CsI):

$\sigma_E/E < 1\%$ for $E_\gamma > 3$ GeV

Energy scale known to 0.05% from $K \rightarrow \pi e \nu$

Provide z_{VTX} from $\pi^0 \rightarrow \gamma\gamma$, $m_\pi^2 z \sim E_1 E_2 r^2_{12}$



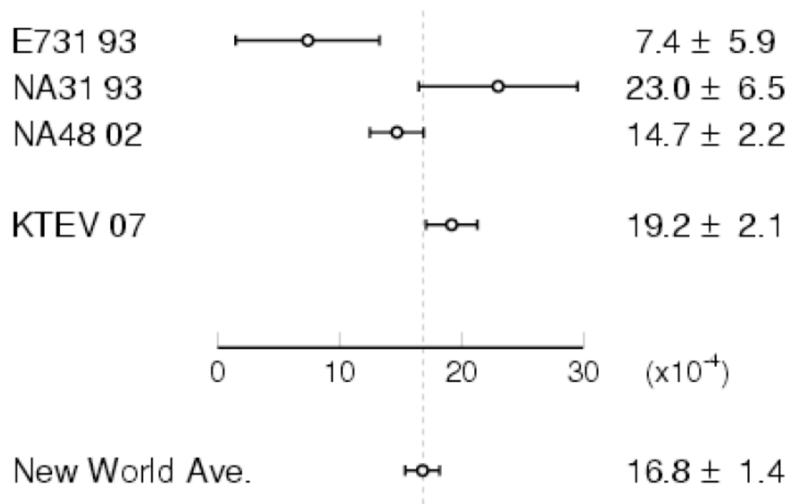
Unprecedented sensitivity for rare K_L decays

Final results for ε'/ε

Effort of ~ 20 years, ended only recently:

KTeV 2007: $R(\varepsilon'/\varepsilon) = (19.2 \pm 1.1_{stat} \pm 1.8_{syst})10^{-4}$

[KTeV 2003: $R(\varepsilon'/\varepsilon) = (20.7 \pm 1.5_{stat} \pm 2.4_{syst})10^{-4}$**, 50% of data]**



World average: $R(\varepsilon'/\varepsilon) = (16.8 \pm 1.4)10^{-4}$**, with a 13% CL**

ε'/ε as a test for new physics?

So called "superweak" theories predicting ε'/ε = 0 are ruled out

An accurate SM prediction of direct CPV in ππ decays is still missing:

$$\mathcal{H}^{(\Delta S=1)} = \frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \left\{ \sum_{i=1}^{10} \left[z_i(\mu) - \frac{V_{td}}{V_{ts}^*} \frac{V_{us}^*}{V_{ud}} y_i(\mu) \right] Q_i \right\}$$

yes, easily related to CKM elements, Re(ε'/ε) ∝ Im($V_{td}V_{ts}$*)

obtain Wilson coefficients (z_i, y_i) as a function of CKM elements, of the masses of heavy degrees, of the gauge couplings

but, difficult to precisely evaluate K--ππ ΔS=1 hadronic elements @ low energy: use non perturbative QCD for the Q_i's, but a dangerous cancellation occurs: e.m. ↔ QCD penguins

A future task for lattice, RBC/UKQCD collaborations are working

"20% result within 3 years for ε'/ε and ΔI=1/2 rule!" [N. Christ (RBC), KAON2009]

If so, it will provide stringent CKM test and will probe for new physics (see later on)

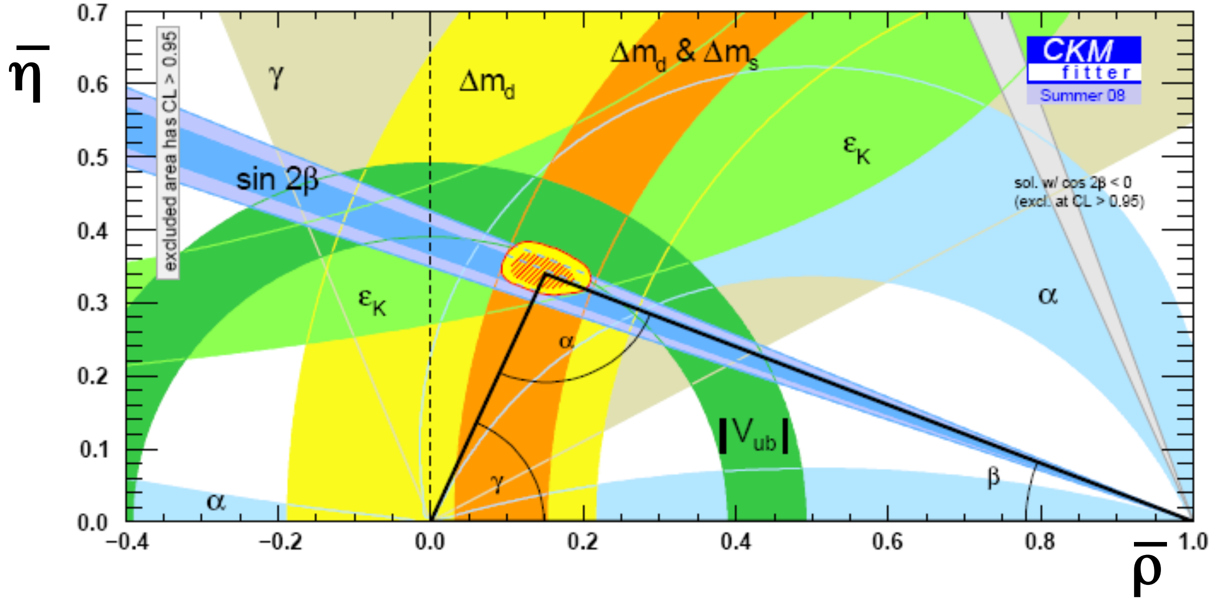
CPV comparing K and B mesons

Significant progress in time for knowledge of ε_K, now better than 3 per mil!

from $|\varepsilon_K| = (2.284 \pm 0.014)10^{-3}$ [PDG04] to $|\varepsilon_K| = (2.221 \pm 0.006)10^{-3}$

the SM prediction relates ε_K to $\bar{\rho}$ and $\bar{\eta}$ parameters of CKM matrix:

$|\varepsilon_K| = C_1\, B_K\, V_{cb}^{\,2}\, \eta\, [C_2 + C_3\, V_{cb}^{\,2}\, (1-\rho)]$, where C_i uncertainty is negligible



Past uncertainty dominated by contribution from B_K parameter and V_{cb}

CPV, K vs B mesons: lattice improvements

The "bag parameter" B_K is the QCD matrix element of a 4-quark operator,

$$B_K = \frac{\langle \overline{K_0} | \mathcal{O}_{LL} | K_0 \rangle}{\frac{8}{3} f_K^2 M_K^2} \quad \mathcal{O}_{LL} = (\bar{s}d)_L (\bar{s}d)_L$$

Recent lattice calculations significantly improved [Sachrajda, NA62PW 2009]

now exact flavor symmetry and good chiral symmetry are achieved by DWF technique

discretization error reduced, results closer to continuum limit

RBC/UKQCD collaboration new result, 5% error, B_K = 0.720(39)

used by PDG 09 review, ~10% difference PDG07: B_K = 0.79(4)(9)

This result confirmed by Aubin et al. 09, B_K = 0.724(8)(28), with 4% error

Averaging to be done with care [P. Boyle @ KAON 2009, Lelluch @ LATTICE 08]

a FLAVIANET group is devoted to Lattice result averaging (FLAG)

CPV: K vs B mesons and V_{cb}

V_{cb} limiting present impact of ε_K on UT fits:

Parametric uncertainty for ε_K scales as $\sigma(|V_{cb}{}^4|)$

- **expected value from UT inputs from B physics: $|\varepsilon_K| = (1.78 \pm 0.25)10^{-3}$**
- **~2σ difference wrt experimental value [Buras, Guadagnoli, Lunghi, Soni]**
- **agreement changes if V_{cb} from exclusive decays 38.6(1.1) wrt inclusive 41.54(73)**

Would be easy to find new physics explanations…

Kaons and unambiguous new physics signals

… for the moment, better to discuss NP unambiguous signatures:

1. CPT violation: foreseen in extra-dimensions, impossible to conceive in SM

2. Violation of quantum mechanics: foreseen in certain quantum gravity models

3. Direct search for lepton flavor violation: channels forbidden/ultra rare in SM

Dedicated experimental designs to reach ultimate sensitivities:

1. Precise measurement of main channel widths (τ's, BR's) and charge asymmetries

2. Production of coherent KK pairs

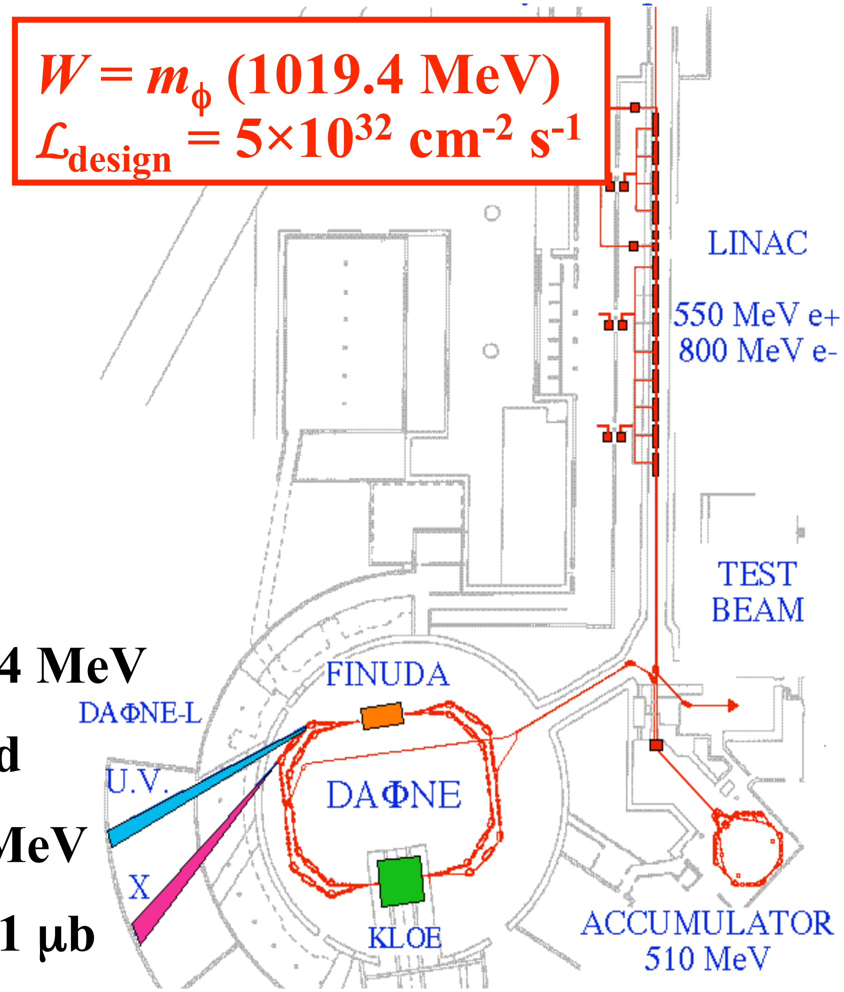
3. Fixed target experiments: huge statistics, stringent veto and PID, dedicated triggers

For 1. and 2. → KLOE

For 3. → Fixed target experiments

An independent approach to K physics: KLOE

Precision physics benefits of independent approaches: the KLOE experiment



Collisions at cm energy around m_ϕ: **$\sqrt{s} \sim$ 1019.4 MeV**

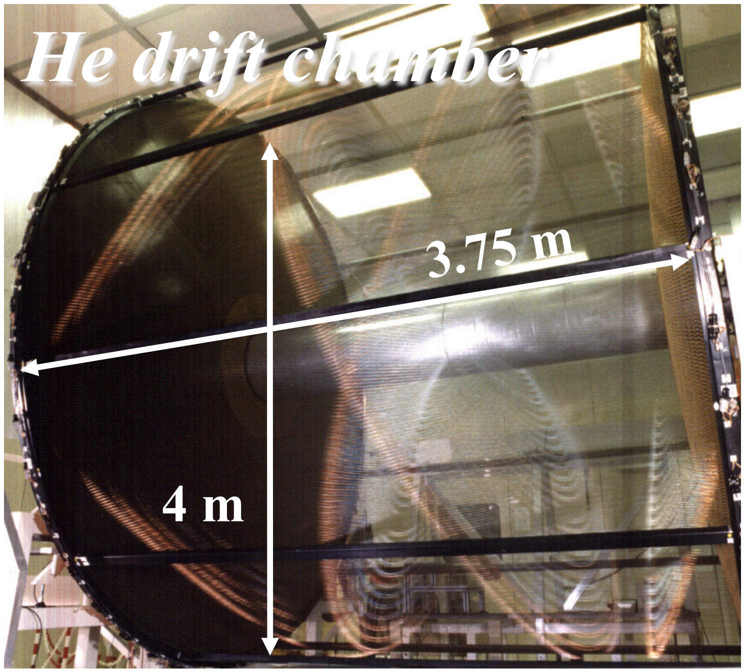
Angle between the beams @ IP: **$\alpha \sim$ 12.5 mrad**

Residual laboratory momentum of ϕ: **$p_\phi \sim$ 13 MeV**

Cross section for ϕ production @ peak: **$\sigma_\phi \sim$ 3.1 μb**

The KLOE detector

Large cylindrical drift chamber + lead/scintillating-fiber calorimeter + superconducting coil providing a 0.52 T field



σ_p/p	**0.4 %** (tracks with $\theta > 45°$)
σ_x^{hit}	**150 μm (xy), 2 mm (z)**
σ_x^{vertex}	**~1 mm**

σ_E/E	**5.7% /$\sqrt{E(\mathrm{GeV})}$**
σ_t	**54 ps /$\sqrt{E(\mathrm{GeV})} \oplus$ 50 ps** (relative time between clusters)
$\sigma_L(\gamma\gamma)$	**~2 cm** (π^0 from $K_L \to \pi^+\pi^-\pi^0$)

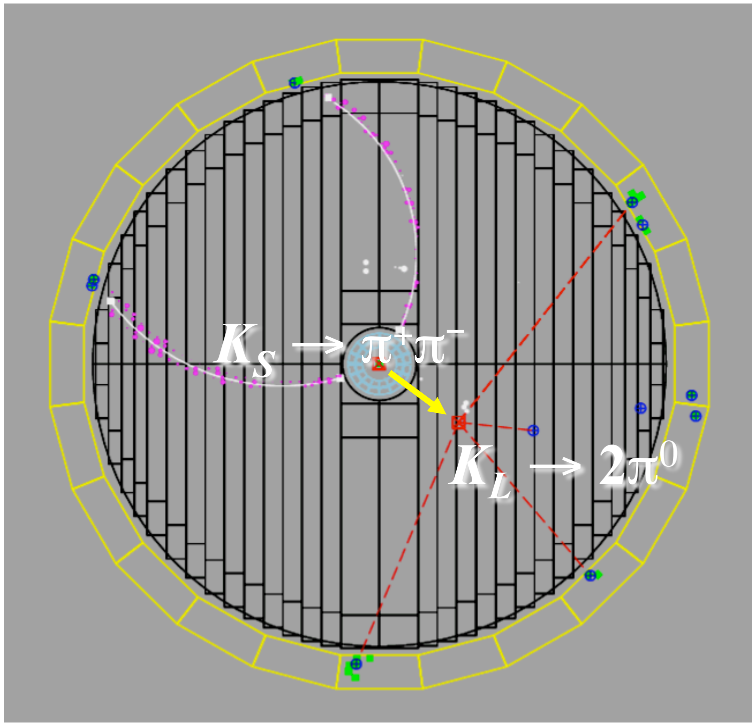
Kaon physics at KLOE

KK pairs emitted ~back to back, p ~ 110 MeV

Identification of $K_{S,L}(K^{+,-})$ decay (interaction) tags presence of $K_{L,S}(K^{-,+})$

Almost pure $K_{L,S}$ and $K^{+,-}$ beams of known momentum + PID (kinematics & TOF):

- **Access to absolute BR's**
- **Precise measurements of K_{Le3} from factors and K_L, K^+ lifetimes (acceptance ~0.5 τ_L, τ_+)**



Above points crucial for V_{us} determination

CPT symmetry test from Kaons

The most stringent test of CPT symmetry comes from kaon decays

Diagonal states for t evolution:

$$|K_{S,L}\rangle = \frac{1}{\sqrt{2\left(1+|\varepsilon_{S,L}|\right)}}\left[\left(1+\varepsilon_{S,L}\right)|K^0\rangle \pm \left(1-\varepsilon_{S,L}\right)|\overline{K}^0\rangle\right]$$

δ = ½ (ε_S-ε_L): CPT violation in mixing,

$$\delta = \frac{1}{2}\frac{\left(m_{\overline{K}^0} - m_{K^0}\right) - (i/2)\left(\Gamma_{\overline{K}^0} - \Gamma_{K^0}\right)}{\Delta m + i\Delta\Gamma/2}$$

Probability conservation implies a unitarity constraint (Bell-Steinberger)

Output

$$\left(\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L}+i\tan\phi_{SW}\right)\left(\frac{\Re\epsilon - i\Im\delta}{1+\epsilon^2}\right) = \frac{1}{\Gamma_S-\Gamma_L}\Sigma_f A_L(f)A_S^*(f)$$

$$\Delta m = m_L - m_S$$

$$\Delta\Gamma = \Gamma_S - \Gamma_L$$

$$\phi_{SW} = \arctan\left(2\Delta m/\Delta\Gamma\right)$$

Experimental inputs

Advantage of K^0 system: **sum over all final states, but only few ($\pi\pi$, $\pi\pi\pi$, and $\pi l\nu$) give significant contribution**

Impact of new data on CPT test: KLOE

With KLOE data, improved CPT violation test:

Precise measurement of BR($K_S \to \pi\pi$), $K_S \to \pi l \nu$ charge asymmetry, UL for $K_S \to 3\pi^0$

After CPLEAR measurements (2001)

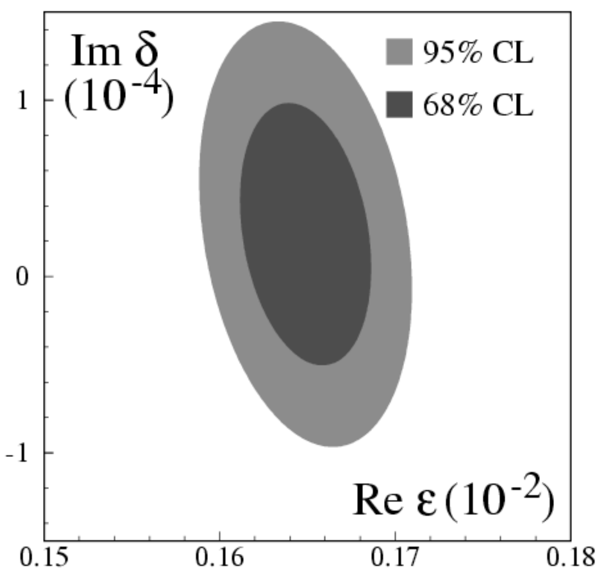
$$\mathrm{Re}(\epsilon) = (164.9 \pm 2.5) \times 10^{-5}$$

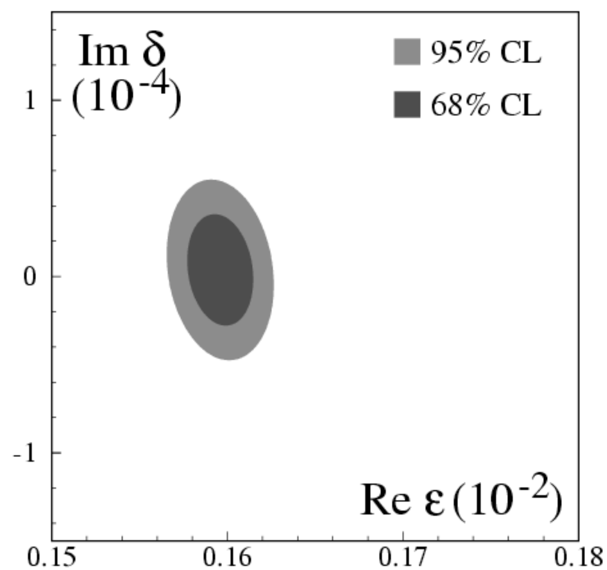
$$\mathrm{Im}(\delta) = (\ 2.4 \pm 5.0) \times 10^{-5}$$

After KLOE measurements (2006)

$$\mathrm{Re}(\epsilon) = (159.6 \pm 1.3) \times 10^{-5}$$

$$\mathrm{Im}(\delta) = (\ 0.4 \pm 2.1) \times 10^{-5}$$





Impact of new data on CPT test: KTeV

Further improvement from KTeV in 2008:

New measurement of Arg($K_L \to \pi\pi$ / $K_S \to \pi\pi$) = ϕ^{+-} = 43.8(6) [KTeV 08]
As precise as previous world average ϕ^{+-} = 43.4(7) [PDG 06]

	CPLEAR 01	KLOE 06	PDG 08	KTeV 08
Re ε ($\times 10^5$)	164.9±2.5	159.6±1.3	161.2±1.6	161.2±1.6
Im δ ($\times 10^5$)	2.4±5.0	0.4±2.1	-0.6±1.9	-0.1±1.4
Comment	$K \to \pi l \nu$ vs proper time	$K_S \to \pi l \nu$, $\pi\pi$ UL($K_S \to 3\pi^0$)	Better treatment of CPLEAR data	New ϕ^{+-}
$M_K - M_{\underline{K}}$, 10^{-19} GeV	3.3 ± 7.0	0.5 ± 3.0	-0.9 ± 2.6	-0.1 ± 2.0

Limit on ΔM obtained assuming $\Gamma_K = \Gamma_{\overline{K}}$ (no CPTV in decay): $| M_K - M_{\overline{K}} | / M_K < 4\ 10^{-19}$
Compare with: $| M_B - M_{\overline{B}} | / M_B < 10^{-14}$ and $| M_p - M_{\overline{p}} | / M_p < 10^{-9}$

Test of quantum mechanics coherence

Study t evolution of KK decays into ππ–ππ final states, unique at ϕ factory

Test QM coherence: $I(\Delta t) \propto e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2(1-\zeta_{S,L})\, e^{-(\Gamma_S+\Gamma_L)|\Delta\tau|/2} \cos(\Delta m \Delta t)$

$K_{S(L)} \rightarrow \pi^+\pi^-$ at t_1 ⟵ ϕ ⟶ $K_{L(S)} \rightarrow \pi^+\pi^-$ at t_2

$K_S K_L$ pairs produced from ϕ decays:

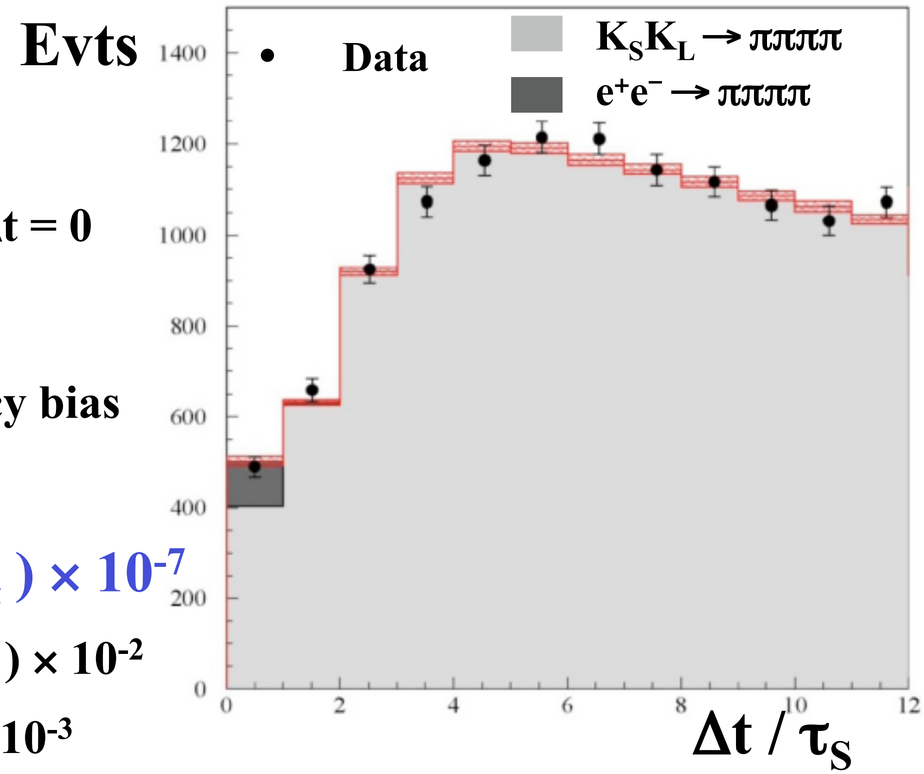
- antisymmetric, 1^{--} state
- for a ππ-ππ decay expect no events for $\Delta t = 0$

Fit observed distribution including:

- resolution effects and selection efficiency bias
- regeneration on beam pipe material

KLOE final: $\zeta_{00} = (1.4 \pm 9.5_{stat} \pm 3.8_{syst}) \times 10^{-7}$

- Compare with B system: $\zeta_{00} = (2.9 \pm 5.7) \times 10^{-2}$
- Compare with quantum optics, $\sigma(\zeta_{00}) \sim 10^{-3}$

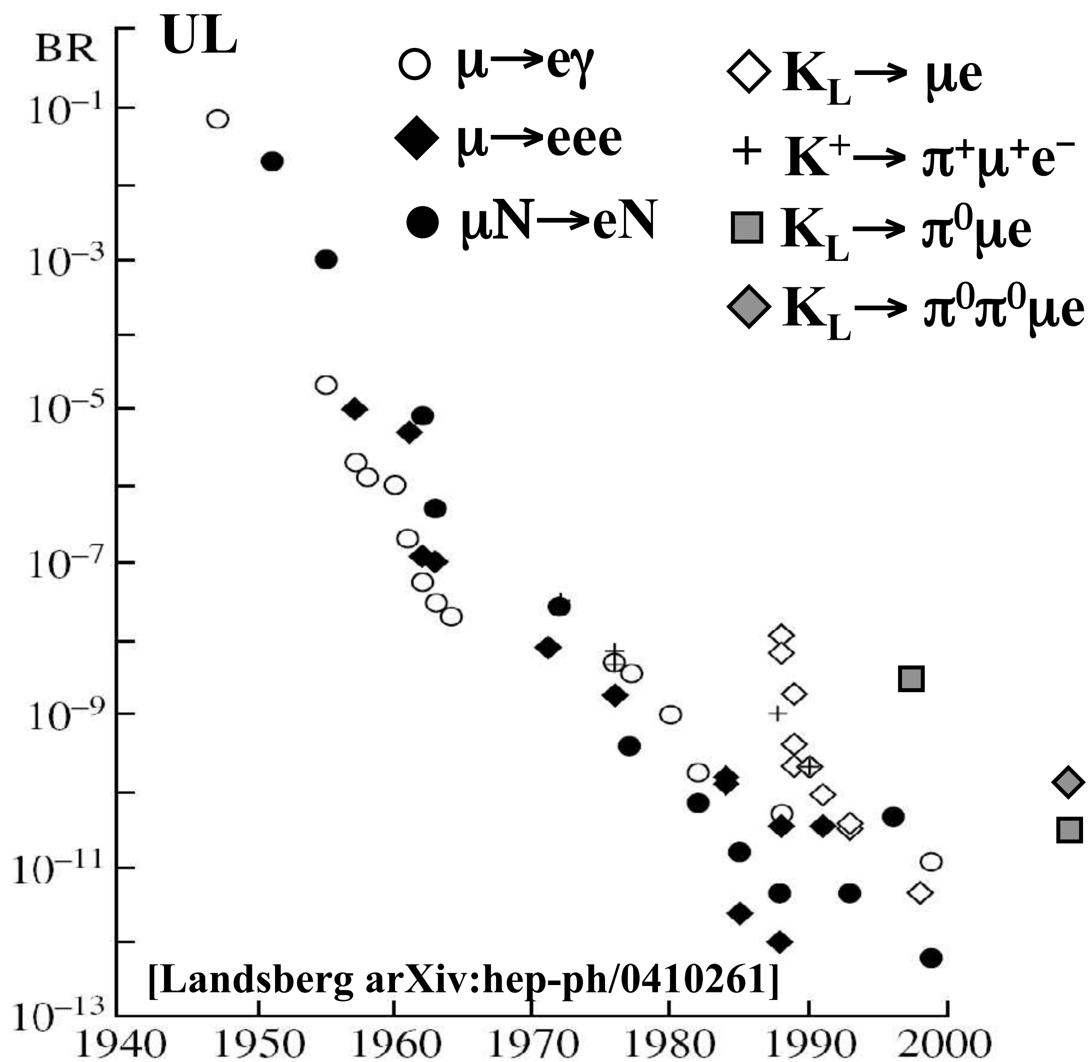


Searches for unambigous NP signals: LFV

Huge efforts along the years to isolate signals from LFV transitions, which are forbidden/ ultra rare in the SM

Cfr. also $\tau \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to lll$ modes [see P. del Amo Sanchez, PIC 2009]

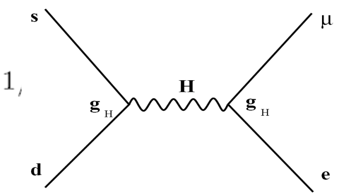
Sensitivity roughly increased by 2 order of magnitudes per decade



Direct searches for LFV with kaons

Searches motivation: tests for tree-level LFV amplitudes possible in Technicolor, SUSY, …

E.g., horizontal bosons in extended TC: $M_H \approx 85 \text{ TeV} \left[\frac{10^{-11}}{B(K^+ \to \pi^+\mu^+e)}\right]^{1/4}$



Activity still alive, results continue to come (cfr. new KTeV limits):

$K_L \to \mu e$ (10^{-11})

- 22 PRL 63 (1989) 2181, BNL E791
- 3.9 PRL 70 (1993) 1049, BNL E791
- 3.3 PRL 70 (1993) 1049, BNL E791
- 9.4 PR D51 (1995) 2061 KEK E137
- 0.5 PRL 81 (1998) 5734 BNL E871

$K_L \to \pi^0\mu e$ (10^{-11})

- 620 PL B432 (1998) 230, FNAL E799
- 7.6 PRL 100 (2008) 131803, FNAL KTeV

$K_L \to \pi^0\pi^0\mu e$ (10^{-11})

- 17 PRL 100 (2008) 131803, FNAL KTeV

$K^+ \to \pi^+\mu^+e^-$ (10^{-11})

- 2.1 PRL 64 (1990) 165, BNL E777
- 0.39 PRL 85 (2000) 2450, BNL E865
- 0.21 PR D72 (2005) 012005, BNL E865
- 0.13* PR D72 (2005) 012005, BNL E865

*E865 combined

$K_L \to \mu^\pm\mu^\pm e^\mp e^\mp$ (10^{-11})

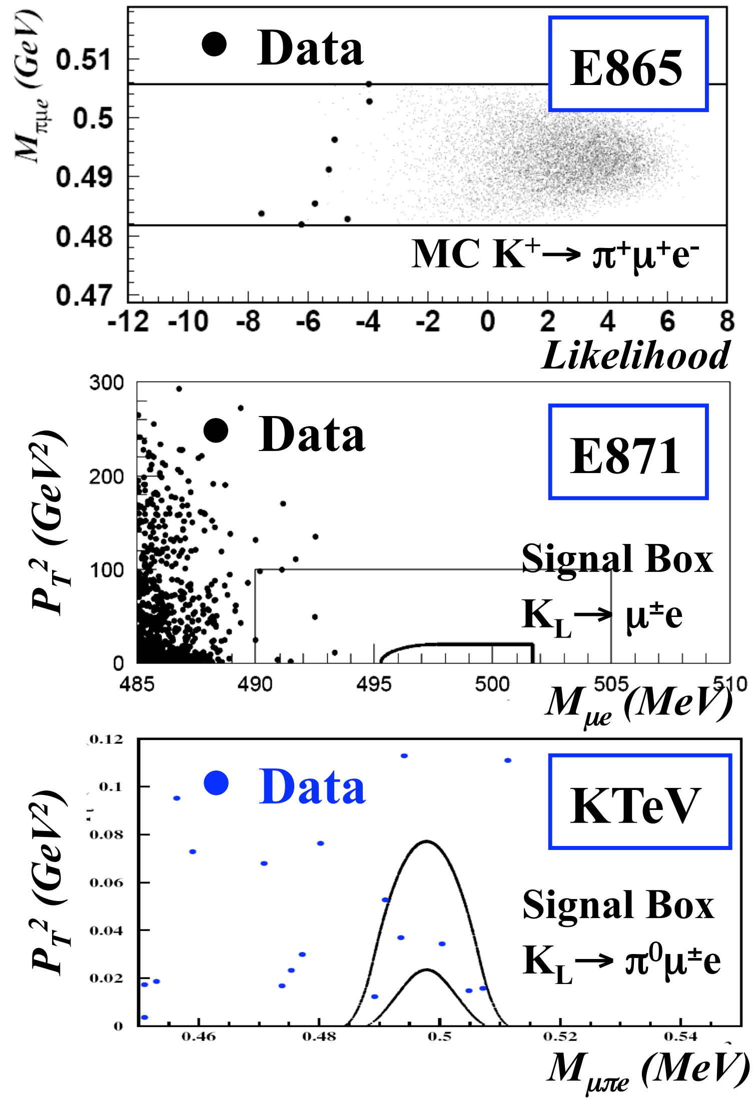
- 610 PRL 76 (1996) 4312, FNAL E799
- 12 PRL 87 (2001) 111802, FNAL KTeV
- 4.1 PRL 90 (2003) 141801, FNAL KTeV

Direct search for LFV

World kaon data dominated by results from fixed target experiments

Results generally dominated by statistics collected

Would need higher fluxes to improve by relevant factors



Direct search for LFV – results and lessons

SM extensions with < ~100 TeV mediator masses ruled out by exp, with some model dependence (Technicolor, SUSY)

Outcome might have been regarded as disappointing, but allowed focus to be put on new possibilities:

- **Presence of NP effects in loop amplitudes**
- **Seek deviations in processes suppressed in the SM**
- **Precision physics of medium, rare and not-so-rare processes**

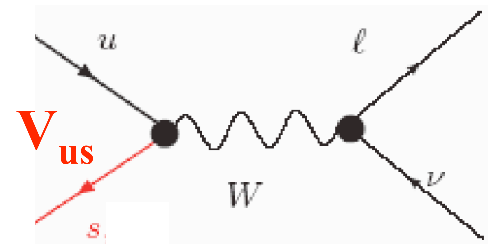
Golden modes: leptonic & semi-leptonic widths in the SM, predicted @ % level or better, accounting for radiative & isospin-breaking corrections

Kaon decay studies are very well suited to match required precisions:

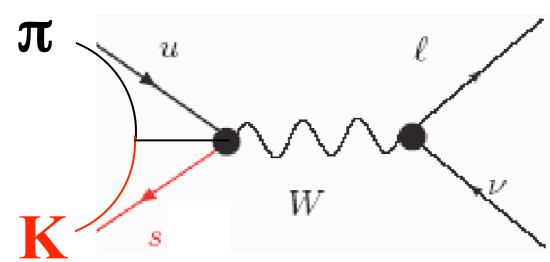
- **Experiments with clean environment, low level of background**

Kaon decays with leptons: precise predictions

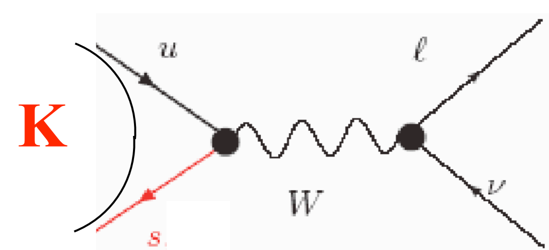
$K \to l\nu$ (K_{l2}) and $K \to \pi l\nu$ (K_{l3}) decay observables linked to the wanted short distance physics with <u>independent</u> theoretical uncertainty:



For K_{l3} decays, Ademollo-Gatto theorem dictates ~~SU~~(3) terms appear at 2nd order in $f^{+}_{K\pi}(0)$



$K_{\mu 2}/\pi_{\mu 2}$: f_K/f_π uncertainty reduced from latest lattice results



NP test from (semi)leptonic K decays

Measurements of $K \to \pi l\nu$, $l\nu$ decays can shed light on NP BSM

Precise determination of V_{us} from BR's for $K \to \pi l\nu$, ff slopes, etc.:

allows most precise test of unitarity of the CKM matrix

translates into a severe constraint for many NP models

Test of SM from $\Gamma(K_{\mu 2})/\Gamma(\pi_{\mu 2})$:

probes NP RH contributions to charged weak currents

probes H^+ exchange in every SM extension with 2 Higgs doublets

LF violation test from $\Gamma(K_{e2})/\Gamma(K_{\mu 2})$ (most recent results):

sensitive to NP effects, which might be at % level wrt SM prediction

Interest in V_{us} measurement with kaons

In SM, universality of weak coupling dictates:

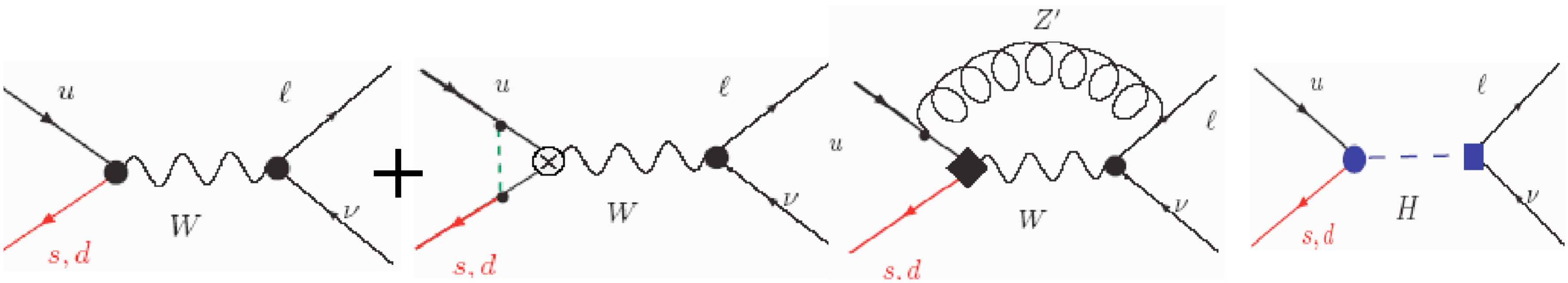
$$G_F^2\,(|V_{ud}|^2 + |V_{us}|^2) = G^2(\text{from } \mu \text{ lifetime}) = (g_w/M_w)^2\ [V_{ub}\ \text{negligible}]$$

One can test for possible breaking of one of the two conditions:

CKM unitarity: is $(|V_{ud}|^2 + |V_{us}|^2) = 1$?

coupling universality: is $G_F^2\,(|V_{ud}|^2 + |V_{us}|^2) = G^2(\text{from } \mu \text{ lifetime})$?

New physics extensions of the SM can indeed break coupling universality:



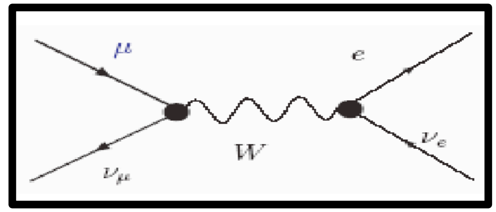
SM + NP $\propto G_F^2\,|V_{uq}|^2\,(1 + a\,M_W^2/M_{NP}^2)^2$, naively $a_{tree} \sim 1$, $a_{loop} \sim g^2_W/16\pi^2$

Interest in V_{us} measurement with kaons

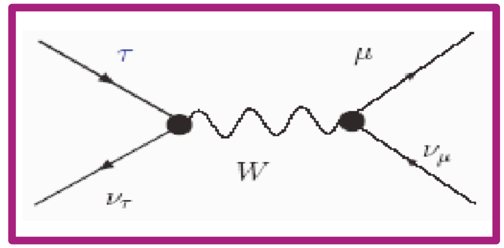
A measurement of $G_{CKM} = G_F\,(|V_{ud}|^2 + |V_{us}|^2)$ with error @ 0.5%

- **is sensitive to tree masses $M_{NP} \sim 10$ TeV and to loop masses $M_{NP} \sim 1$ TeV**
- **is competitive with ew precision tests:**

$G_F = 1.166371(6) \times 10^{-5}$ GeV^{-2} ←



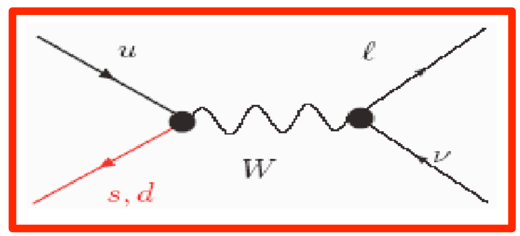
$G_\tau = 1.1678(26) \times 10^{-5}$ GeV^{-2} ←



$G_{ew} = 1.1655(12) \times 10^{-5}$ GeV^{-2} ←

$\alpha_{em} + M_W + s_W$
[ew precision tests]

$G_{CKM} = 1.16xx(04) \times 10^{-5}$ GeV^{-2} ←



V_{us} from semileptonic kaon decays

Master formula: $\Gamma(K_{l3(\gamma)}) = |V_{us}|^2 \, |f_+^{K^0\pi^-}(0)|^2 \, \frac{G_F^2 \, m_K^5}{128\pi^3} S_{\rm EW} \, C_K^2 \, I_{K\ell} \, (1 + \delta_K^\ell)$

Theoretical inputs:

- **$f_+(0)$**, FF @ zero momentum transfer: theoretical calculation
  Recent result from UKQCD/RBC, 07 prel.: **$f_+(0) = 0.964(5)$**
- **$\delta^\ell_K = 2(\Delta_K^{SU(2)} + \Delta^\ell_K{}^{em})$**, I-breaking + em effects:
  Recent χPt results: $\Delta_{K+}^{SU(2)} = +2.9(4)\%$, $\Delta^\ell_K{}^{em} =$

	K0	K+
$\ell = e$	+0.50(11)%	+0.05(13)%
$\ell = \mu$	+0.70(11)%	+0.01(12)%

- S_{EW}, short distance correction (=1.0232), $C_K = 1$ ($2^{-½}$) for K^0 (K^+) decays

Experimental inputs:

- **$I^\ell_K = I(\{\lambda_+\},\{\lambda_0\},0)$**, phase space integral, **λ_+, λ_0** → t-dependence of vector, scalar ffs
- **$\Gamma_{K\ell3(\gamma)}$**, semileptonic decay width evaluated from γ-inclusive BR and lifetime
- **m_K**, appropriate kaon mass

Recent measurements for all relevant inputs: BR's, τ's, ff's

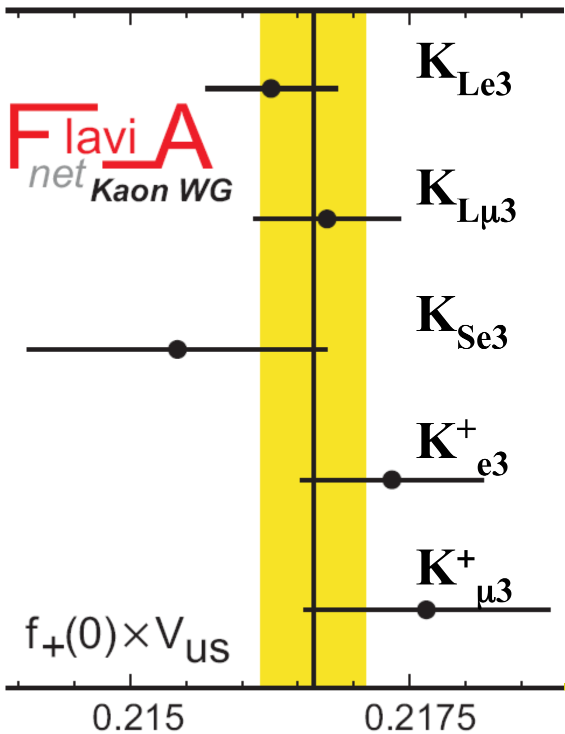
Vus from Kl3 decays

World data for K_L, $K^+ \rightarrow \pi l \nu$ BR's quite satisfactory, determined by experiments with very different techniques:

- **KLOE @ DAΦNE e^+e^- collider (tagged $K_{L,S}$, $K^{+,-}$ from ϕ decays)**
  - **absolute branching ratios for K_L, K^+, and K_S**
- **NA48 @ CERN (intense K^0,K^+ beams from SPS proton beam)**
  - **ratio of BR's for K_L and $K^{+,-}$**
- **KTeV @ Fermilab (intense K_L beam from Tevatron proton beam)**
  - **ratio of K_L BR's**
- **ISTRA+ @ IHEP, Protvino**
  - **ratio of K^-_{l3} BR's**

Experimental status of Kl3 BR's - world data

From: $$\Gamma(K_{\ell 3(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3} C_K S_{\rm ew} |V_{us}|^2 f_+(0)^2 I_K^\ell(\lambda_{+,0}) \left(1 + \delta_{SU(2)}^K + \delta_{\rm em}^{K\ell}\right)^2$$



	$f_+(0) \times \lvert V_{us}\rvert$	Error,%	Contributions to % error: BR	τ	δ	I^l_K
K_{Le3}	0.2164(6)	0.26	0.09	0.19	0.11	0.09
$K_{L\mu3}$	0.2170(6)	0.29	0.10	0.18	0.11	0.15
K_{Se3}	0.2156(13)	0.62	0.60	0.03	0.11	0.09
K^+_{e3}	0.2174(8)	0.38	0.26	0.13	0.25	0.09
$K^+_{\mu3}$	0.2177(11)	0.51	0.40	0.13	0.25	0.15
	0.21660(5)	0.22	$P(\chi^2/ndf) = 2.83/4 = 59\%$			

Results for $f_0 V_{us}$ from Kl3 decays

1. Agreement of $f_+(0)V_{us}$ for K^+ and K^0 is a brilliant success in calculating Isospin-breaking and e.m. corrections @ few 10^{-3}:

2.81(38)% found vs 2.9(4)% [Kastner-Neufeld 08] or 2.36(22)% [Cirigliano 07 χPt $O(p^4)$]

2. For each K charge state of K_{l3} decays, can test e / μ universality:

$$r_{\mu e} = \frac{(R_{\mu e})_{\rm obs}}{(R_{\mu e})_{\rm SM}} = \frac{\Gamma_{\mu 3}}{\Gamma_{e3}} \cdot \frac{I_{e3}\,(1+\delta_{e3})}{I_{\mu 3}\,(1+\delta_{\mu 3})} = \frac{g_\mu^2}{g_e^2}$$

Results satisfy universality:

$g_\mu^2/g_e^2 = 1.0050(44)$

Cfr. with test from $\tau \to l\nu\nu$ decays, sharing the same theoretical scenarios:

$g_\mu^2/g_e^2 = 1.0005(41)$ [PDG08]

Precision from K's comparable to that from τ's

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

Can also get $|V_{us}/V_{ud}|$ from K,π → μν widths [Marciano PRL93 231803,2004]**:**

$$\frac{\Gamma(K\to\mu\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))} = \frac{m_K\left(1-\frac{m_\mu^2}{m_K^2}\right)^2}{m_\pi\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2}\frac{|V_{us}|^2}{|V_{ud}|^2}\frac{f_K^2}{f_\pi^2}\frac{1+\frac{\alpha}{\pi}C_K}{1+\frac{\alpha}{\pi}C_\pi}$$

Theoretical inputs:

structure-dependent e.m. correction $\mathbf{1+\alpha/\pi\,(C_K-C_\pi) = 0.9930(35)}$ **[Marciano PRL93 (2004), Cirigliano Rosell JHEP 0710 (2007)]**

form factor ratio $\mathbf{f_K/f_\pi = 1.189(7)}$ **[MILC-HPQCD collaboration, arXiv:0706.1726]**

Experimental inputs:

$m_{K,\pi,\mu}$, $BR(K_{\mu 2}, \pi_{\mu 2})$, $\tau_{K,\pi}$ very accurate: $\mathbf{BR(K_{\mu 2}) = 0.6366(17)}$ **[KLOE PLB632, 2006]**

Obtain: $|V_{us}/V_{ud}| = 0.2322(15)$

V_{us}/V_{ud} from $K_{\mu 2}$ vs V_{us} from Kl3

Use $f_+(0) = 0.9644(49)$ [UKQCD-RBC arXiv: hep-lat/0702026] and fit:

1) $|V_{us}/V_{ud}| = 0.2323(15)$ from $K_{\mu 2}/\pi_{\mu 2}$
2) $|V_{us}| = 0.2237(13)$ from K_{l3}
3) $|V_{ud}| = 0.97424(22)$ from $0^+ \rightarrow 0^+$ nuclear β decays [Towner & Hardy CIPANP 2009]

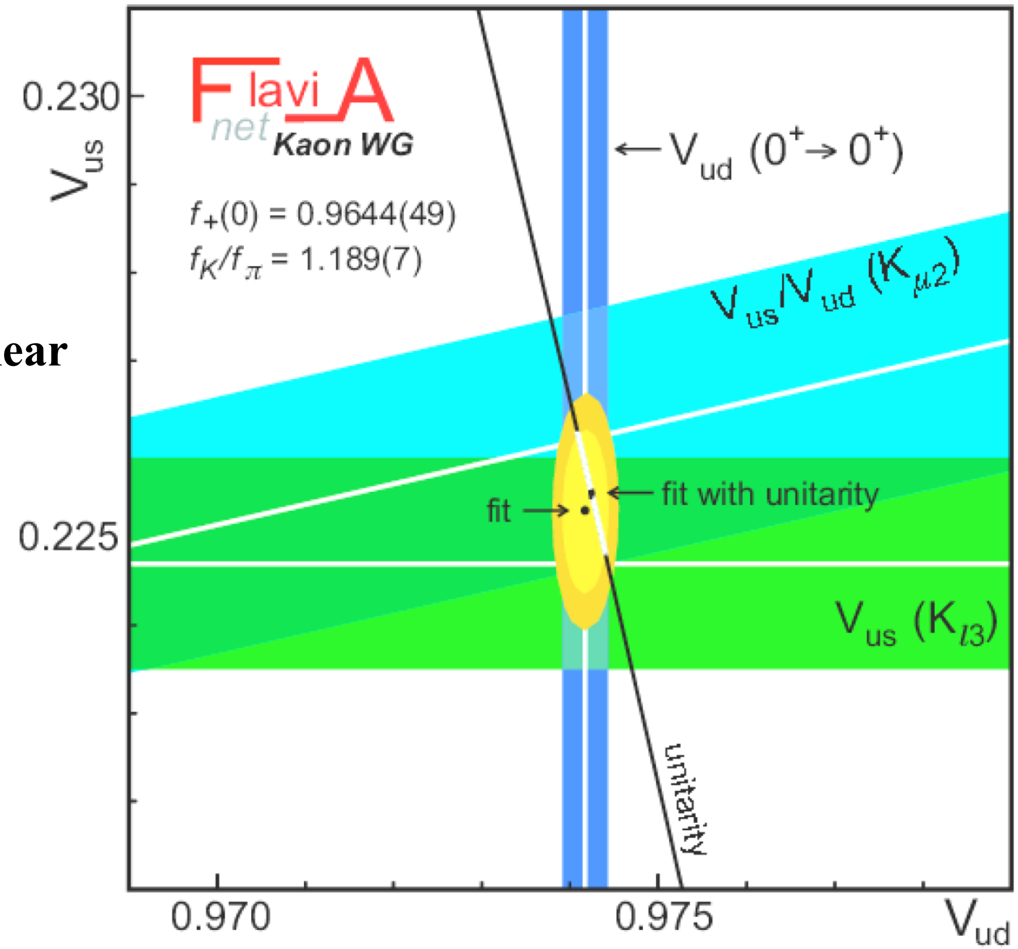
Obtain:

$|V_{ud}| = 0.97425(23)$ & $|V_{us}| = 0.2254(9)$
$P(\chi^2=0.6/1) = 44\%$

$\Delta = 1-|V_{ud}|^2-|V_{us}|^2 = (1 \pm 6)\times 10^{-4}$

Fit with unitarity constraint:

$V_{us} = 0.2254(7)$, $P(\chi^2=0.6/2) = 74\%$

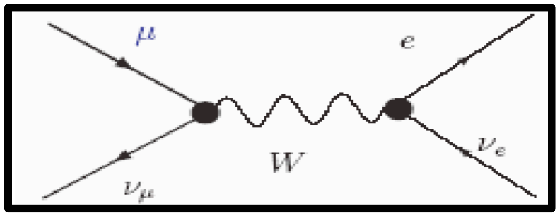


Total accuracy of 0.3%

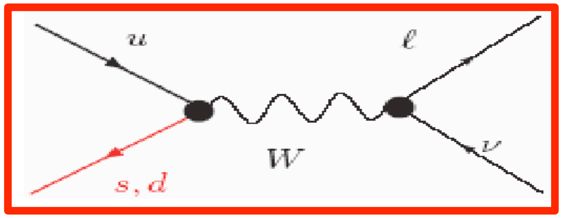
Weak coupling universality test

Agreement between weak couplings from K decays and from μ lifetime:

$G_F = 1.166371(6)\times10^{-5}\ \mathrm{GeV}^{-2}$ ←



$G_{CKM} = 1.16620(40)\times10^{-5}\ \mathrm{GeV}^{-2}$ ←



Agreement at this level of accuracy implies observation of short distance radiative corrections at ~40 σ level [Marciano-Sirlin]:

$2\ \alpha/\pi \log M_Z/M_\rho + \ldots \sim 2.5\%$

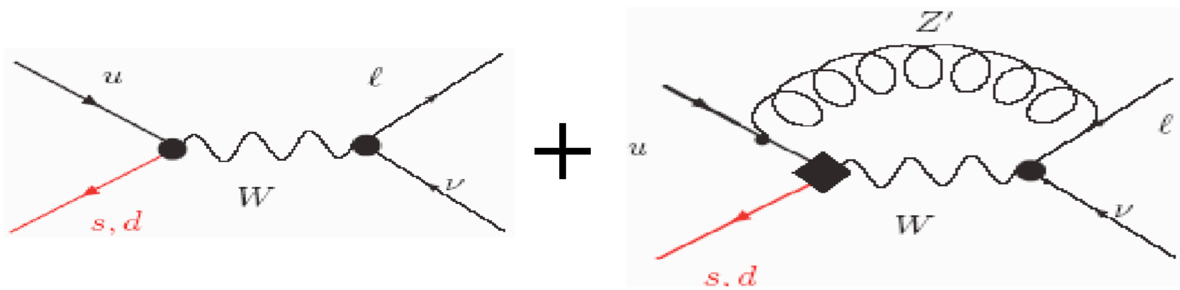
Might be able to extract from this: $M_Z = (90 \pm 7)$ GeV!

Weak coupling universality test: BSM

Agreement between weak couplings from K and from μ constraints NP

In SO(10) Z_χ boson [Marciano]:

$$G_F = G_{CKM} \left[1 - 0.007 \times 8/3 \times \ln(M_{Z'}/M_W)/(M_{Z'}^2/M_W^2 - 1) \right]$$



Implies: $M_{Z'} > 750$ GeV @ 95% CL

Weak coupling universality test: BSM

In non-universal gauge interaction model, a tree level contribution from a Z' boson breaking unitarity might be present [K. Y. Lee PRD 76, 117702 2007]

Assume different couplings of 1^{st}-2^{nd} lepton generation (g_l) and 3^{rd} (g_h):

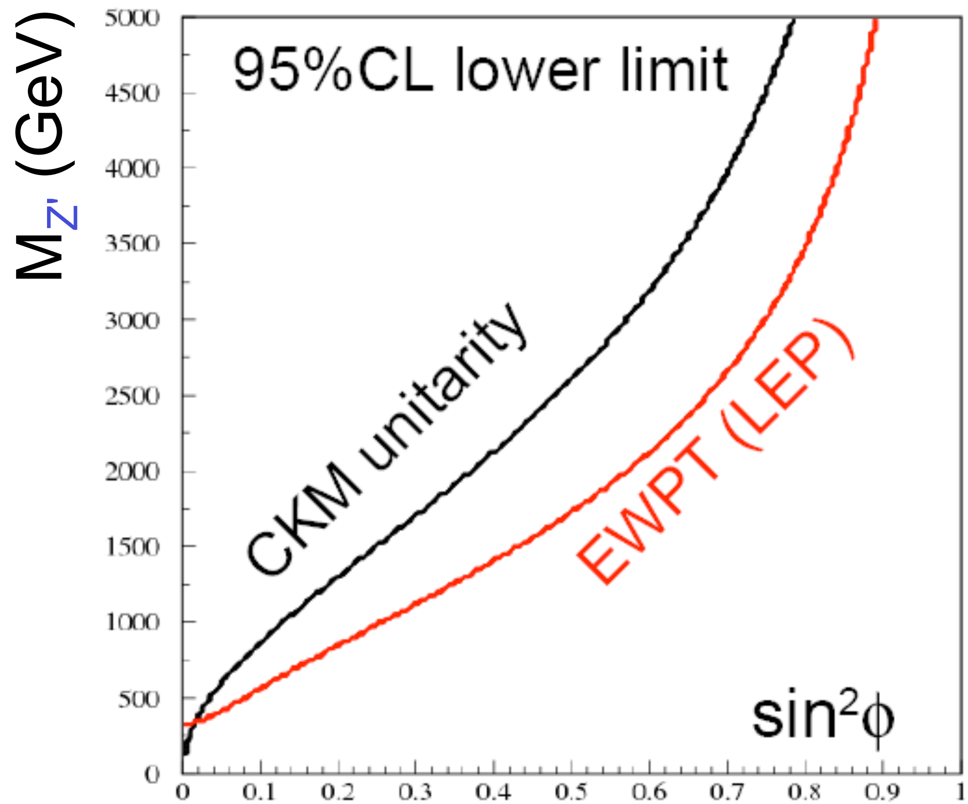
$g_l = e/\sin\theta_w \cos\phi$

$g_h = e/\sin\theta_w \sin\phi$

$g' = e/\cos\theta_w$

θ_w is the weak mixing angle

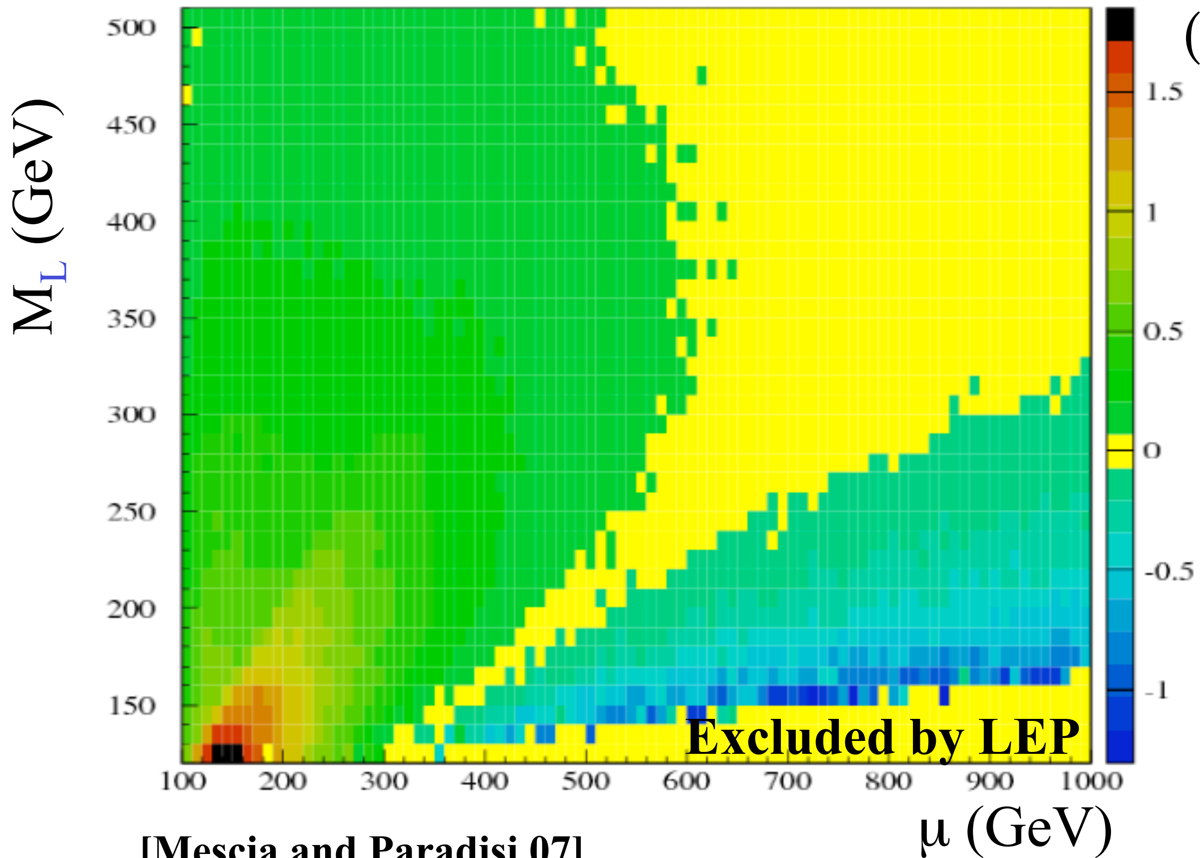
ϕ is the mixing angle between $SU(2)_l$ and $SU(2)_h$



This gauge structure might appear in extended technicolor models

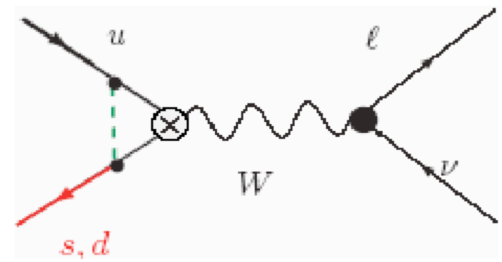
Weak coupling universality test: MSSM

Scanning over MSSM parameter space, unitarity is sensitive to the squark-slepton mass difference **[R. Barbieri 85, K. Hagiwara et al. 95, A Kurylov 00]**



[Mescia and Paradisi 07]

$(1 - V_{ud}^2 - V_{us}^2)^{½} \times 10^4$



Present error 0.3%

Need to improve error by ×2 to really have an impact here

A model-independent analysis of K data

From the unitarity constraint $\Delta = (1\pm6)\ 10^{-4}$ can constrain new physics:

naively, if $\Delta_{NP} \approx M_W^2/\Lambda_{NP}^2$, then $\Lambda_{NP} > O(\text{TeV})$

Model "independent" approach: effective lagrangian + symmetries

World @ O(100 GeV), Buchmuller-Wyler 86, Leung et al. 86

World @ O(1 GeV), Cirigliano et al. 09

Did we knew that from collider bounds? [Han, Skiba PRD 71:075009 05]

model-independent analysis of 237 measurements from HEP data

fit 21 NP parameters

obtain $\Delta_{NP} = (-4.7\pm2.9)\ 10^{-3}$

Kaon data improves by a factor of 5 on HEP data

If new physics is flavor-blind or with minimal flavor violation, can state:

$\Lambda_{NP} > 11$ TeV @ 90% CL

[Cirigliano, Gonzalez-Alonso, Jenkins arXiv:0908.1754, 2009]

$K_{\mu 2}$ again – Sensitivity to NP

In two Higgs doublet models (MSSM, too), exchange of H^+ provides an additional scalar current, which might contribute sizeably wrt to SM:

$$\frac{\Gamma(K \to \ell\nu)}{\Gamma_{SM}(K \to \ell\nu)} \cong \left| 1 - \frac{m_{K^+}^2}{M_{H^+}^2}\left(1 - \frac{m_d}{m_s}\right)\frac{\tan^2\beta}{1+\epsilon_0 \tan\beta}\right|$$

[Hou PRD48 (1992) 2342, Isidori-Paradisi]

NP effect is suppressed for π_{l2} wrt K_{l2}, so NP might appear in $Kl2$ / $\pi l2$, predicted in the SM to be:

$$\frac{\Gamma(K^{\pm}_{\ell 2(\gamma)})}{\Gamma(\pi^{\pm}_{\ell 2(\gamma)})} = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi}\left(\frac{1 - m_\ell^2/m_K^2}{1 - m_\ell^2/m_\pi^2}\right)^2 \times (1+\delta_{\text{em}})$$

NP test from comparing V_{us}/V_{ud} from $M \to l\nu$ with $V_{us}(K_{l3})/V_{ud}(0^+ \to 0^+)$:

$$\left|\frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})}\right| \overset{?}{=} \left| 1 - \frac{m_{K^+}^2}{M_{H^+}^2}\left(1 - \frac{m_d}{m_s}\right)\frac{\tan^2\beta}{1+\epsilon_0 \tan\beta}\right|$$

$K_{\mu 2}$ – Sensitivity to NP

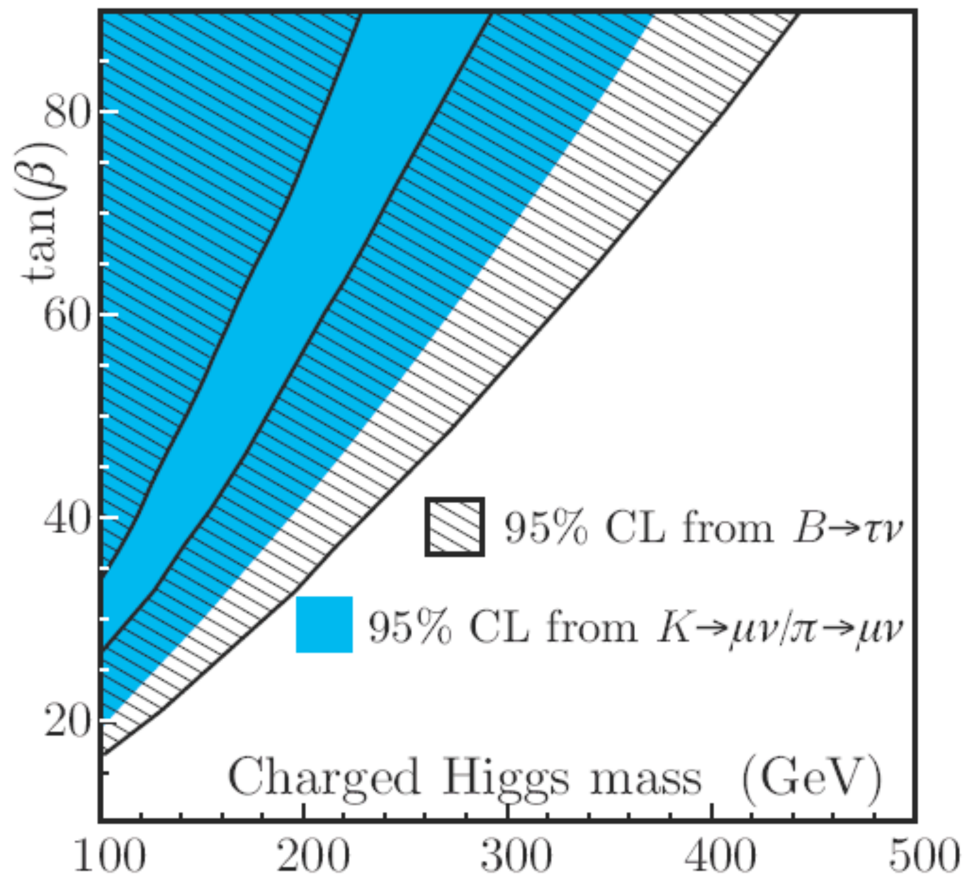
Result is: $$\left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})} \right| = 1.004(7)$$

NP sensitivity from K→ μν ~ as that from BR(B → τν) = 1.73(35)×10^{-4}

For Belle and Babar updates and a combined fit in 2-Higgs doublet models, see P. Del Amo Sanchez, PIC2009

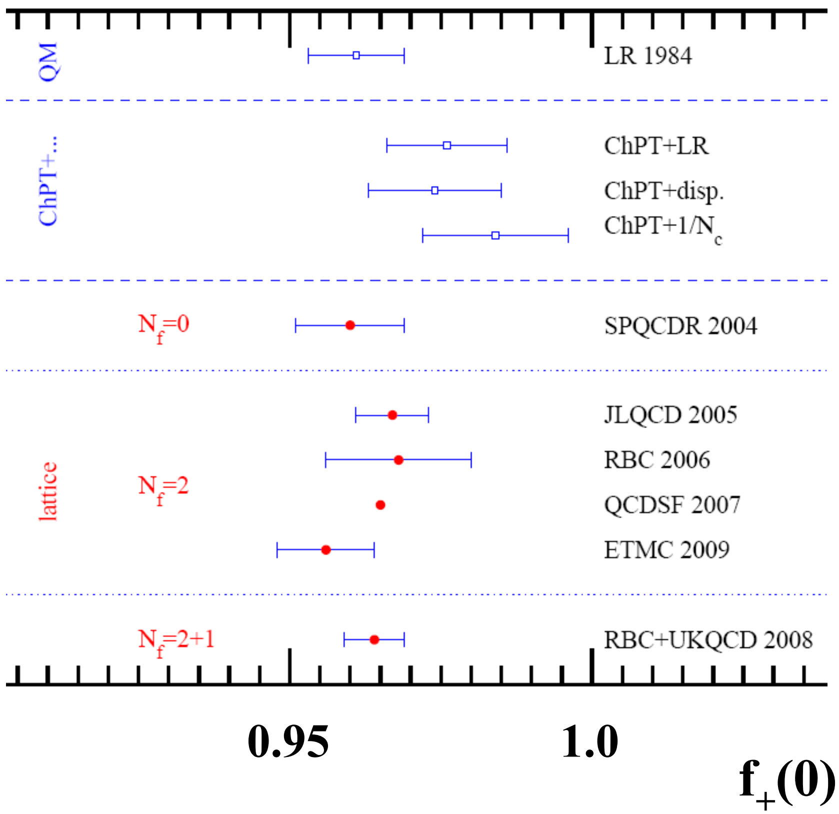
Error dominated by theoretical uncertainties in form factors

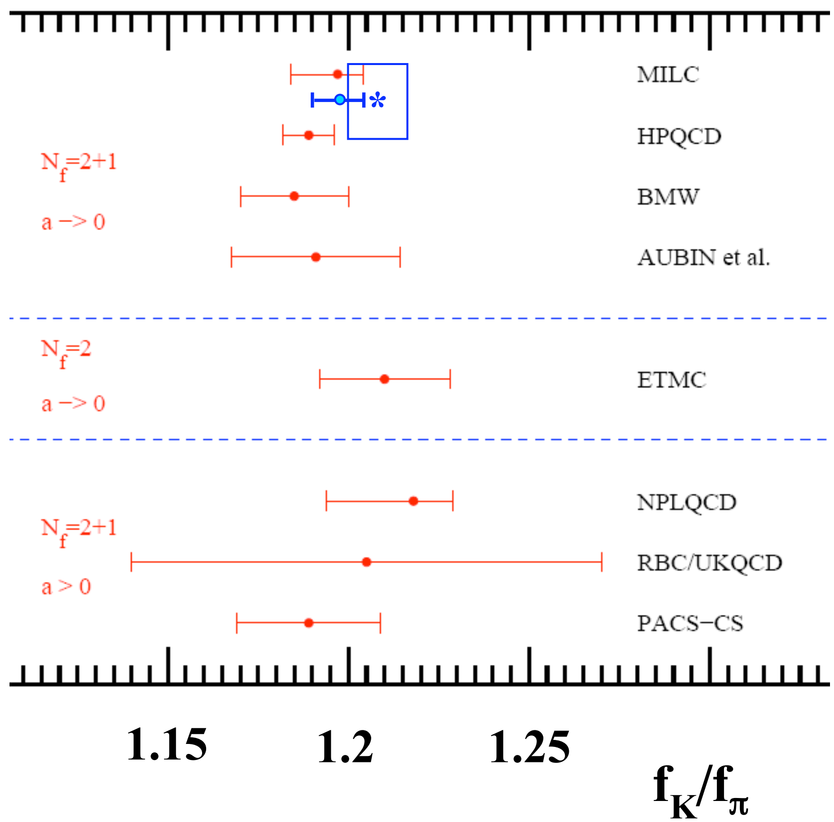
Test competitive with expected sensitivity from 10fb^{-1} ATLAS data, following gg/gb → t(b) H$^+$, H$^+$ → τν



Form factor evaluation: progress from lattice

Lattice produced solid results with recent improvements…





***Preliminary from MILC09, cfr Heller @ CHIRAL09**

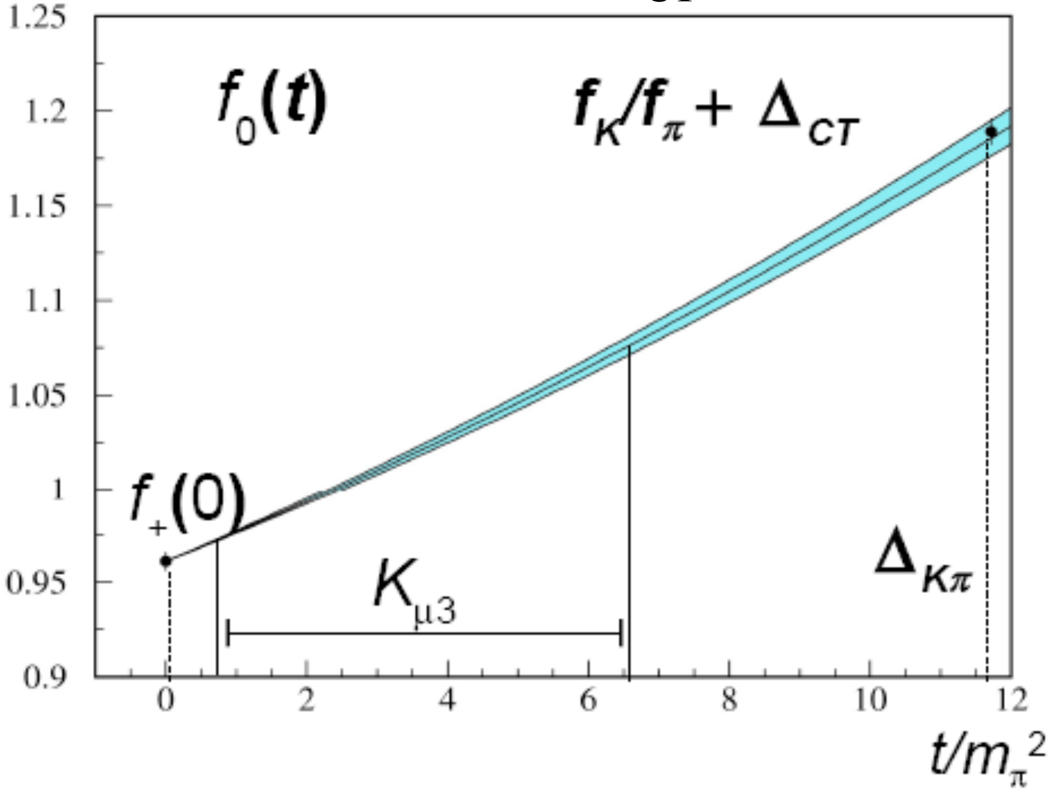
…but other tools are available to validate these calculations

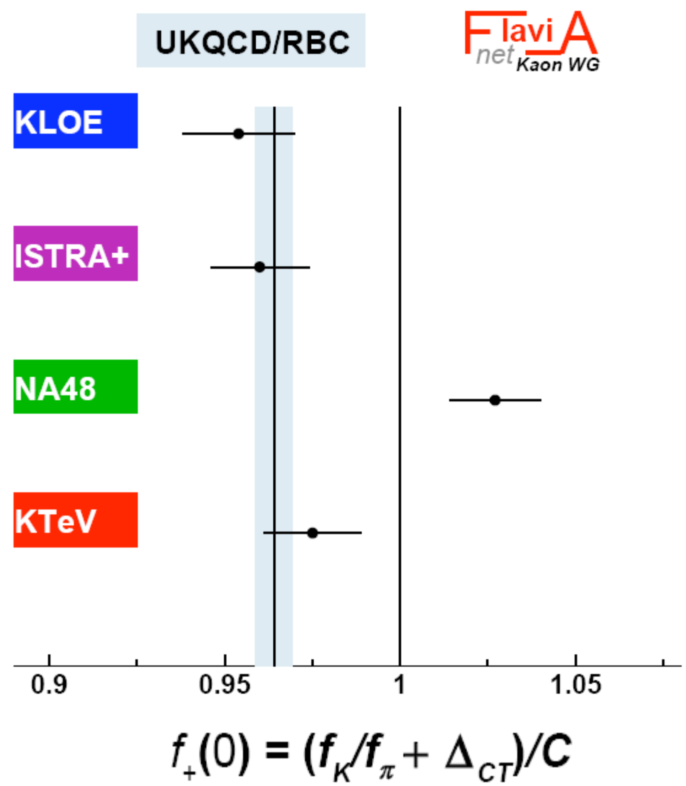
Form factor evaluation: progress from lattice

Dispersive parametrization of $f_0(t)$ from Kμ3 + Kπ scattering data

relate value in the Callan-Treiman point to f_K/f_π [Stern et al., Pich et al.]

The correction needed, Δ_{CT} = (-3.5±8) 10^{-3}, is evaluated in p-QCD





Perspectives: info from τ decay + theory improvements possible

New-physics potential of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$

SM prediction w 0.04% precision, benefits of cancellation of hadronic uncertainties (no f_K): $R_K = 2.477(1) \times 10^{-5}$ [Cirigliano Rosell arXiv:0707:4464]

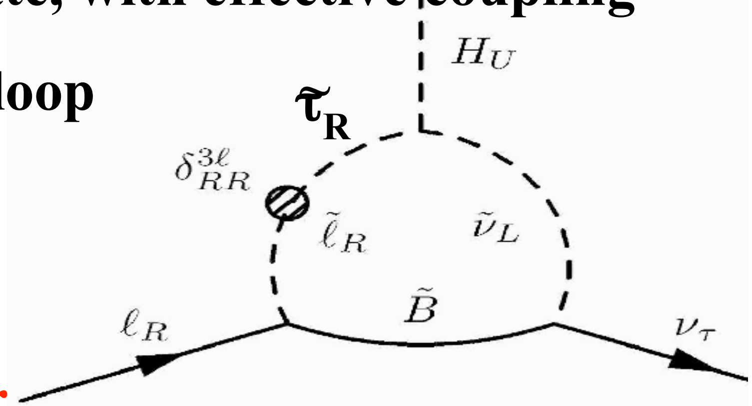
Helicity suppression can boost NP [Masiero-Paradisi-Petronzio PRD74 (2006) 011701]

In R-parity MSSM, LFV can give 1% deviations from SM:

$$R_K^{LFV} \simeq R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_H^4} \right) \left(\frac{m_\tau^2}{m_e^2} \right) |\Delta_R^{31}|^2 \tan^6\beta \right]$$

NP dominated by contribution of $e\nu_\tau$ final state, with effective coupling

$$l H^\pm \nu_\tau \rightarrow \frac{\mathbf{g_2}}{\sqrt{2}} \frac{\mathbf{m_\tau}}{\mathbf{M_W}} \mathbf{\Delta_{13}}$$ **, from loop**



Present exp. accuracy on R_K @ 6%

New measurement of R_K can be very interesting, if error is pushed @ 1% or better

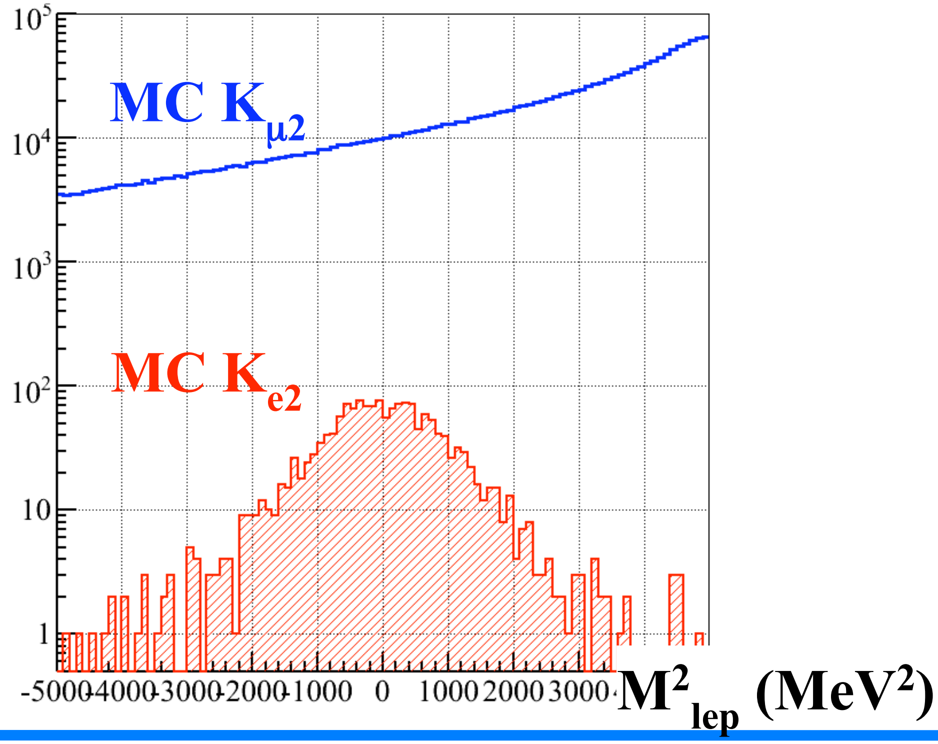
Analysis of $K_{e2}/K_{\mu2}$ @ KLOE - basic principles

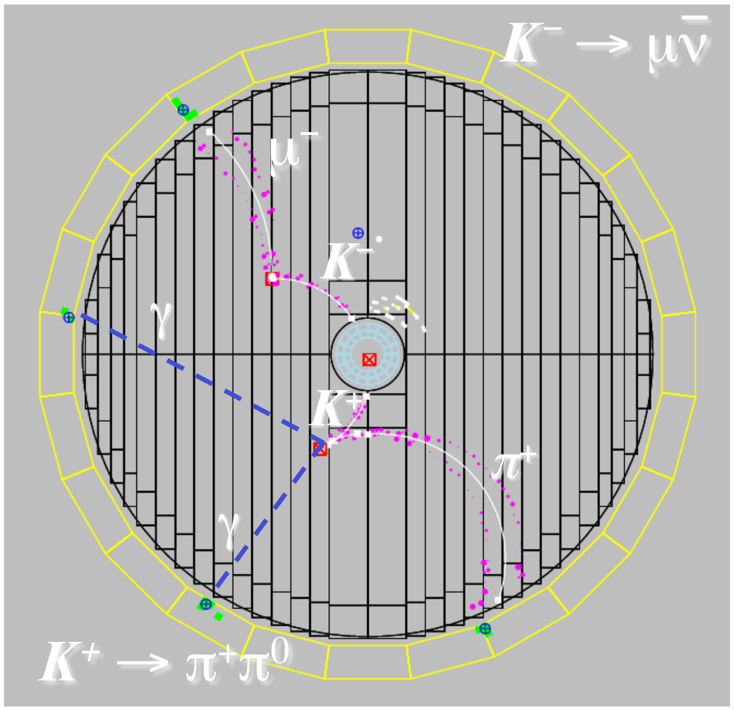
KLOE integrated ~2.5 fb^{-1} of data & BR(K_{e2})~10^{-5}: expect < ~4×10^4 events

Perform direct search for K_{e2} and $K_{\mu2}$, no tag: gain ×4 of statistics

Select 1-prong kinks in DC, K track from IP & secondary P > 180 MeV

Exploit tracking of K and secondary: assuming m_ν=0 get M^2_{lep}



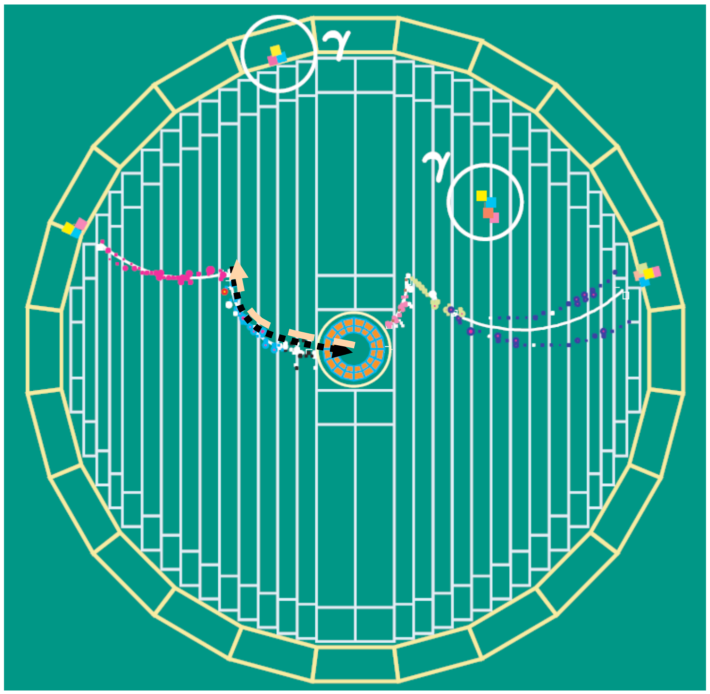


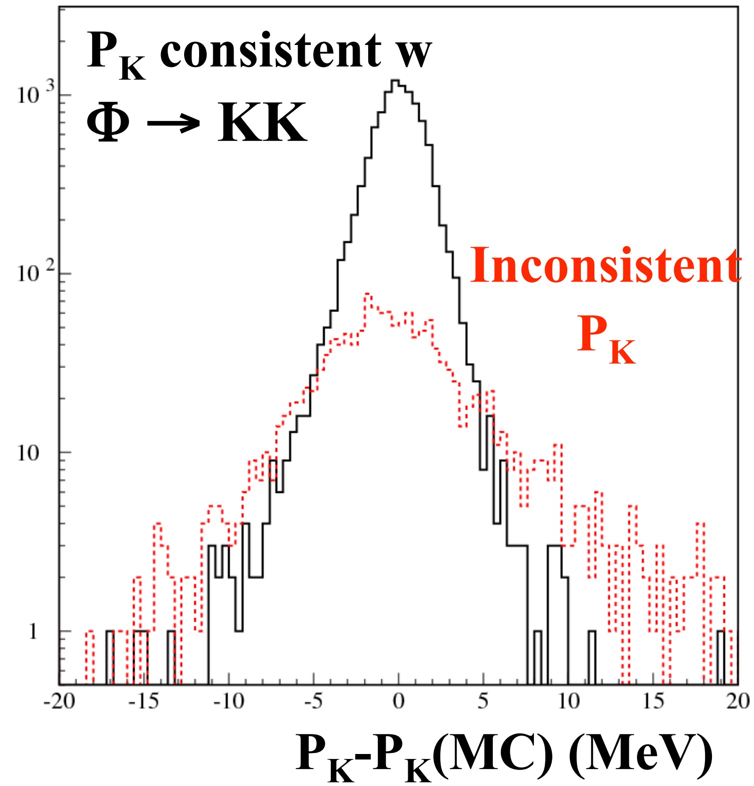
R_K analysis @ KLOE, kinematic selection

Rule of the game: reject Kμ2 by 10^4, with Ke2 efficiency of O(50%)…

Background composition: Kμ2 events with bad P_K, bad P_l reconstruction

Apply quality cuts for K and exploit Φ → KK two-body kinematics

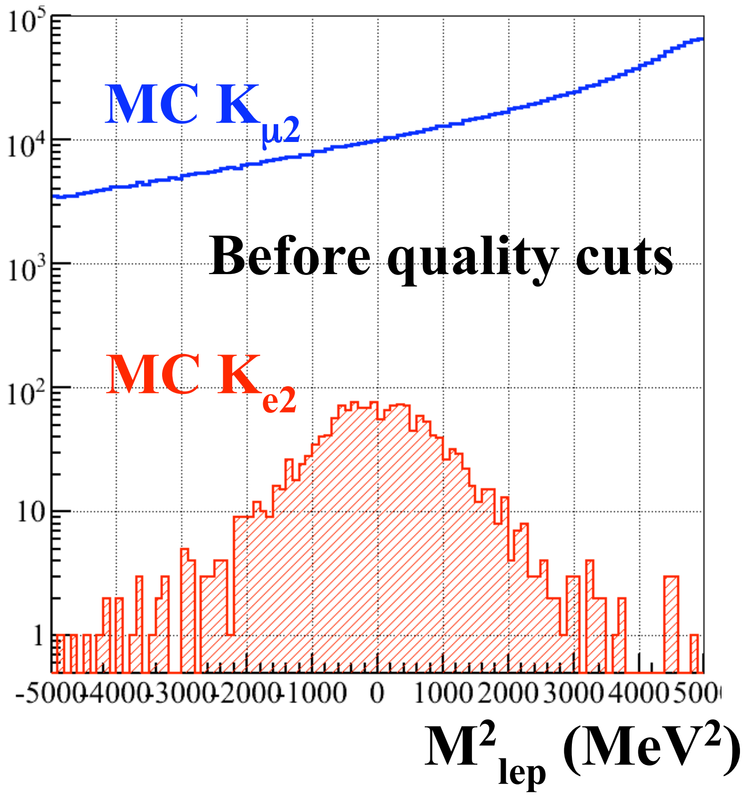


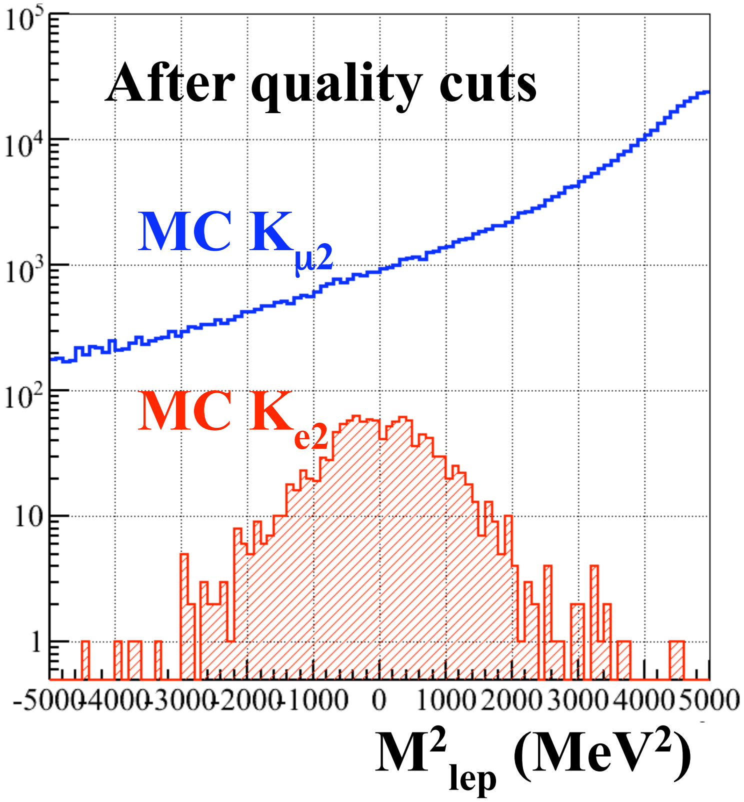


R_K analysis @ KLOE, quality criteria

$M_{lep}^2 = f(P_K, P_l, \cos\theta) \rightarrow$ a-priori error δM_{lep}^2 is scaled by opening angle

Achieve cancellation in Ke2/Kμ2 efficiencies, applying cosθ trailing cuts





Total efficiency ~ 33% at this level: select ~60% of Ke2 decaying in FV

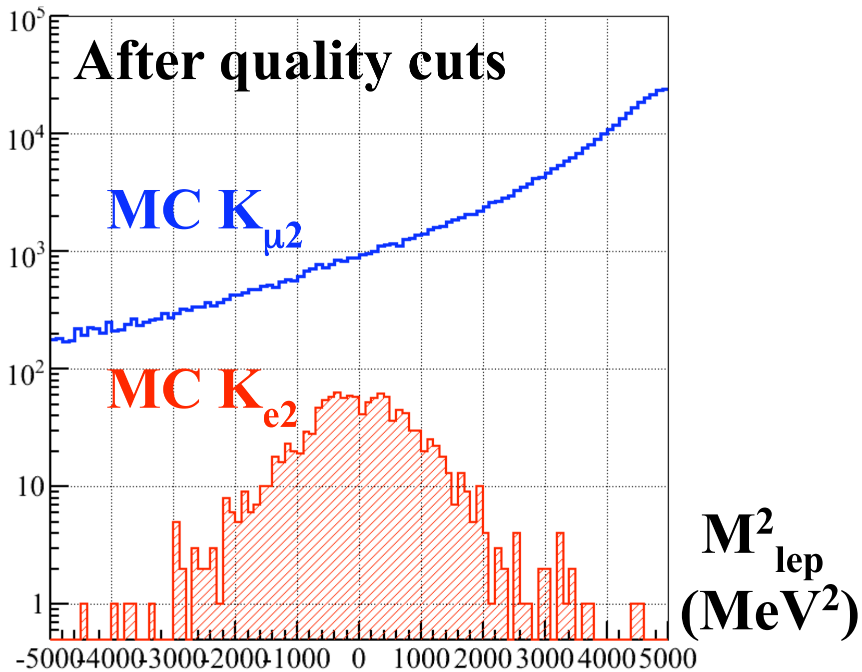
Analysis of R_K @ KLOE, electron identification

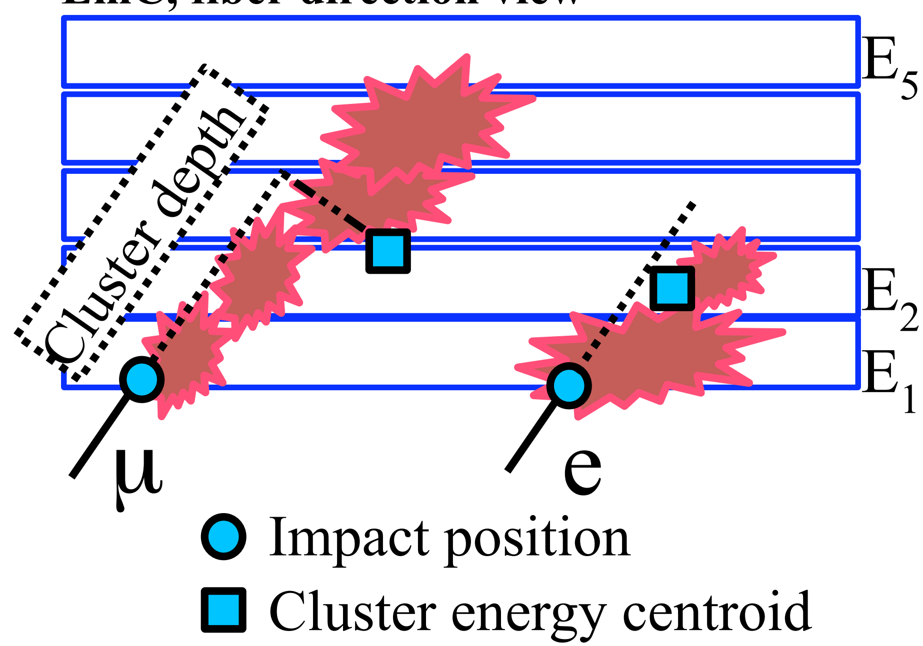
Apply quality cuts, enough to count $K_{\mu 2}$, not for K_{e2} (still Bkg ~ 10×Sig)

Further rejection for K_{e2}: extrapolate track to EmC, select closest cluster

PID exploits EmC granularity: energy deposits E_k into 5 layers in depth

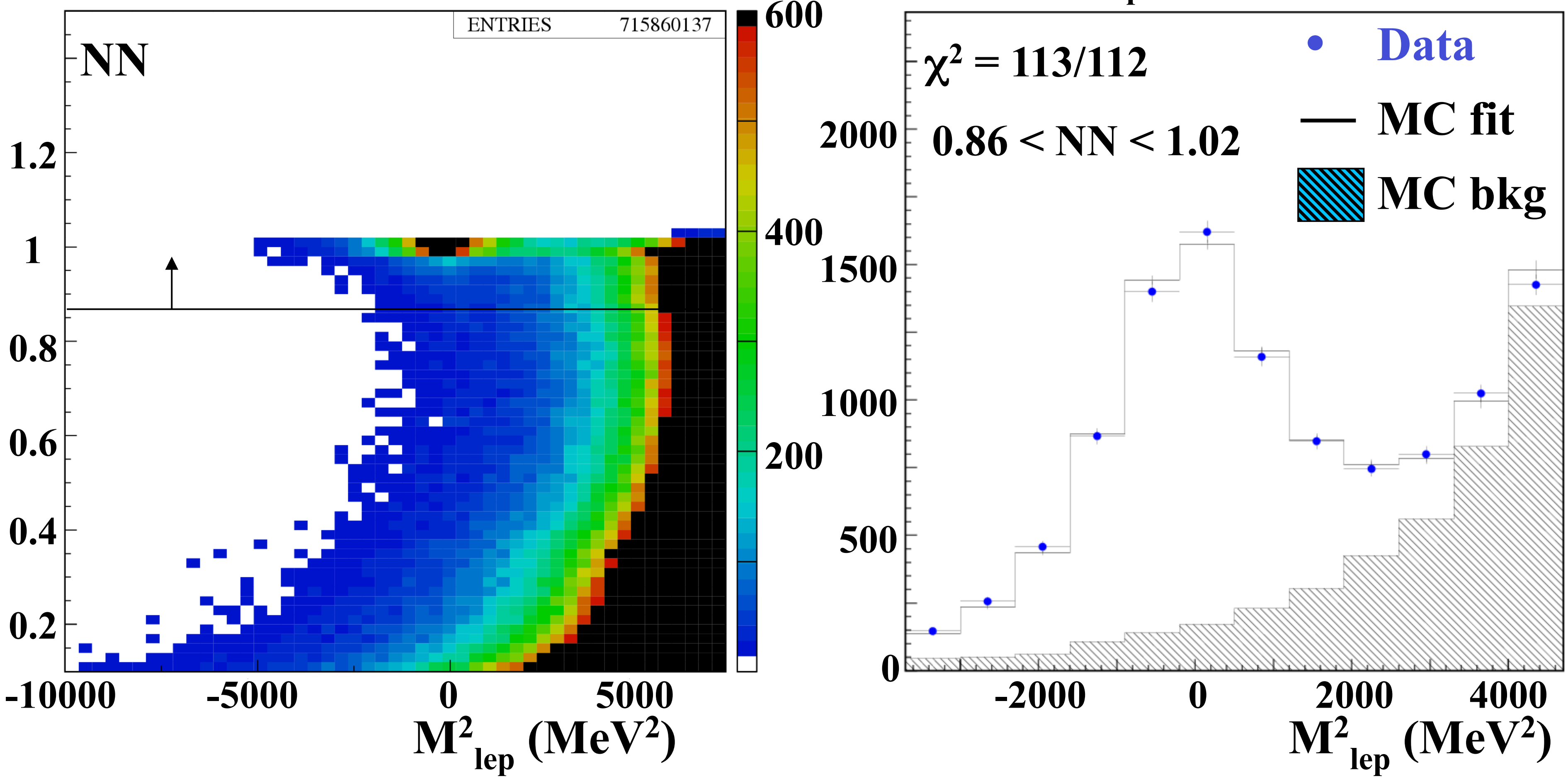
Combine cell-level information into a single NN variable





R_K analysis, fitting for Ke2 counting

Two-dimensional binned likelihood fit in the NN- M^2_{lep} plane



Count in entire statistics: NKe2(e^+) = 7060(98), NKe2(e^-) = 6750(97)

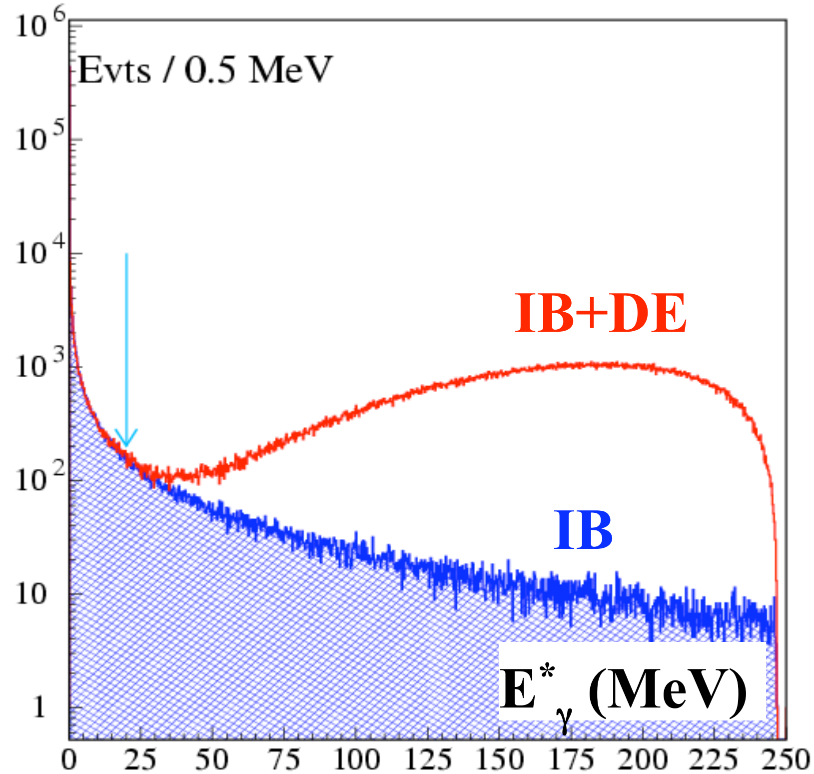
R_K @ KLOE – Radiative corrections

To match theory, has to count IB only

Expect DE ~ IB , but we poorly know

δDE/DE ~ 15%

- **Fit using IB+DE, count IB by considering as "signal" events those with E^*_γ<10 MeV**
- **Correct for IB tail, ε^{IB} = 95.28(5)**
- **Repeat fit varying DE by its 15% uncertainty, get 0.45% error…**



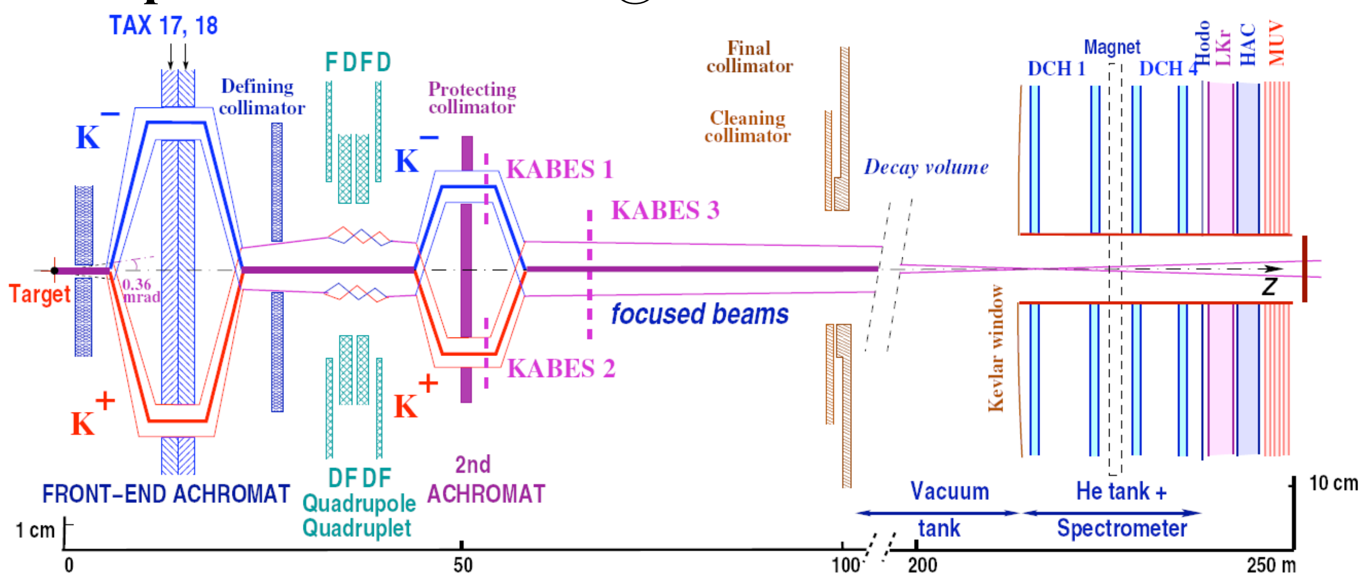
…too bad. Perform a dedicated analysis to measure DE, 4% accuracy:

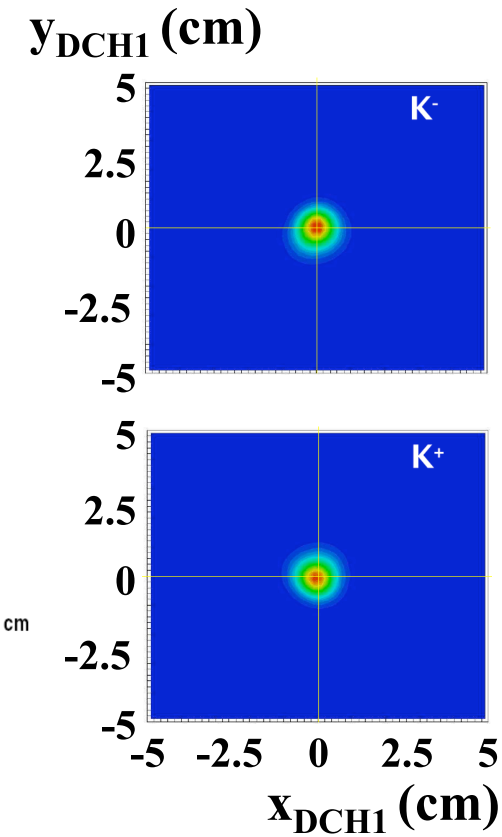
- **Explicitly detect radiated photon**
- **Fair agreement of DE/IB with expectation from theory, χPt O(p^4)**

RK in the NA48/2 experiment

NA48/2: unseparated, simultaneous $K^{\pm}$ highly collimated beams, designed to precisely measure $K^{\pm} \rightarrow \pi^{+,0}\pi^{-,0}\pi^{\pm}$ dalitz-plot density

- **p_K ~ 60 GeV, σ_p ~ 3 GeV (3.8% p-bite)**
- **spot of ~ 5 mm width @ DCH1 entrance**





Track decay products with 4 DCH's:

- **$P_{\perp}$ kick of 121 MeV after DCH2**
- **σ_p/p ~ 1.02% ⊕ 0.044% p [GeV]**

Analysis of Ke2/Kμ2 at NAxx

Scintillator hodoscope:

- **establish event time (σ~150 ps), initiate trigger**

LKr calorimeter: efficient vetoing, e.m. energy resolution

- **$\sigma_E/E = 3.2\%/\sqrt{E[GeV]} \oplus 9\%/E[GeV] \oplus 0.42\%$**
- **$\sigma_{x,y} = 4.2mm/\sqrt{E[GeV]} \oplus 0.6$ mm, granularity of ~13,000 2×2 cm^2 cells**

Hadron calorimeter, Muon veto system

Analysis starting samples:

K_{e2} trigger: 1 track (hodoscope) & 1-track activity in DCH's & E_{LKr} > 10 GeV

$K_{\mu 2}$ trigger: 1 track (hodoscope), downscaled

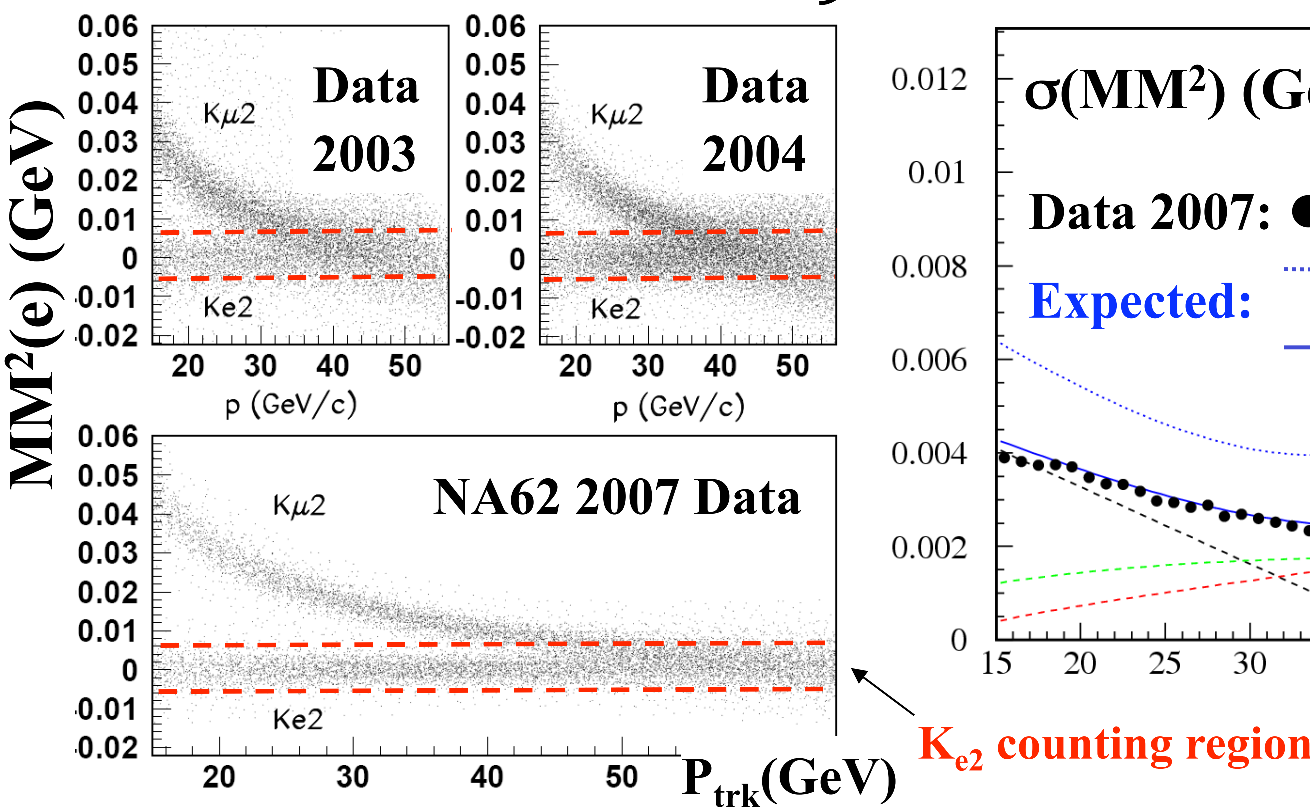
First useful data in 2003-4 NA48/2 runs, two preliminary results for R_K …

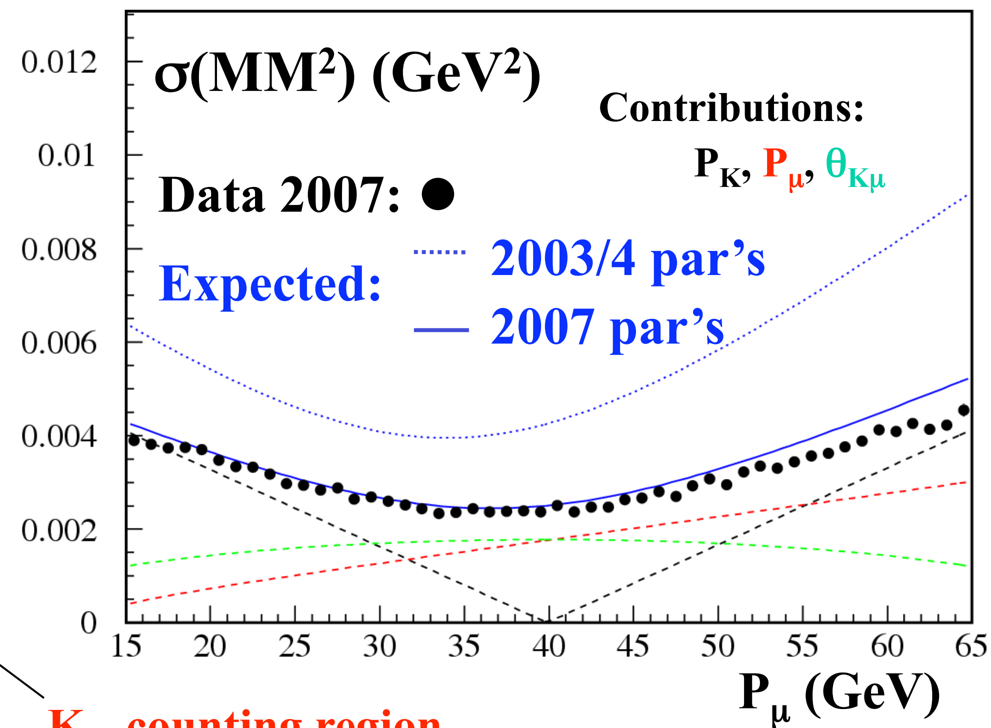
Analysis of Ke2/Km2 at NA62 – 2007 data

…then design of NA62 run optimized for Ke2/Kμ2; major parameters tuned:

- **P_K: ~60 GeV → ~75 GeV**
- **Momentum bite: 3.8% → 2.5%**

MM² resolution improved
Better separation for Ke2 and Kμ2





Analysis of Ke2/Kμ2 at NA62: μ background

Electron PID by LKr: $0.95 < E_{cl}/P_{trk} < 1.10$ guaranteeing rejection by $\sim 10^6$!

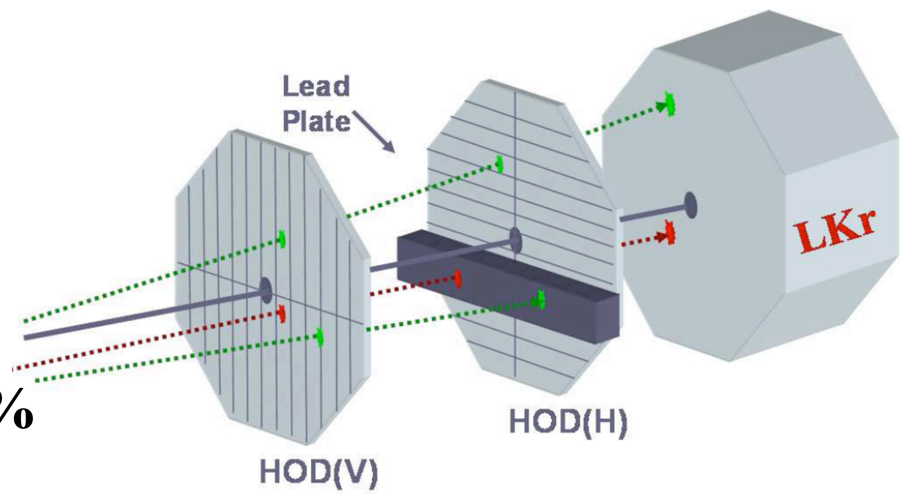
But: check probability for μ's to fake e's [$O(10^{-6})$] by directly measuring it:

- **Subsample of data taken with Pb wall between HOD's**
- **Use HOD pulse heights to select μ's (pure @ $<10^{-7}$) with MIP energy loss in Pb**

Evaluate 6.28(17)% Kμ2 bkg to Ke2, error dominated by sample statistics

Ke2γ Direct-Emission background suppressed by photon-veto w LKr

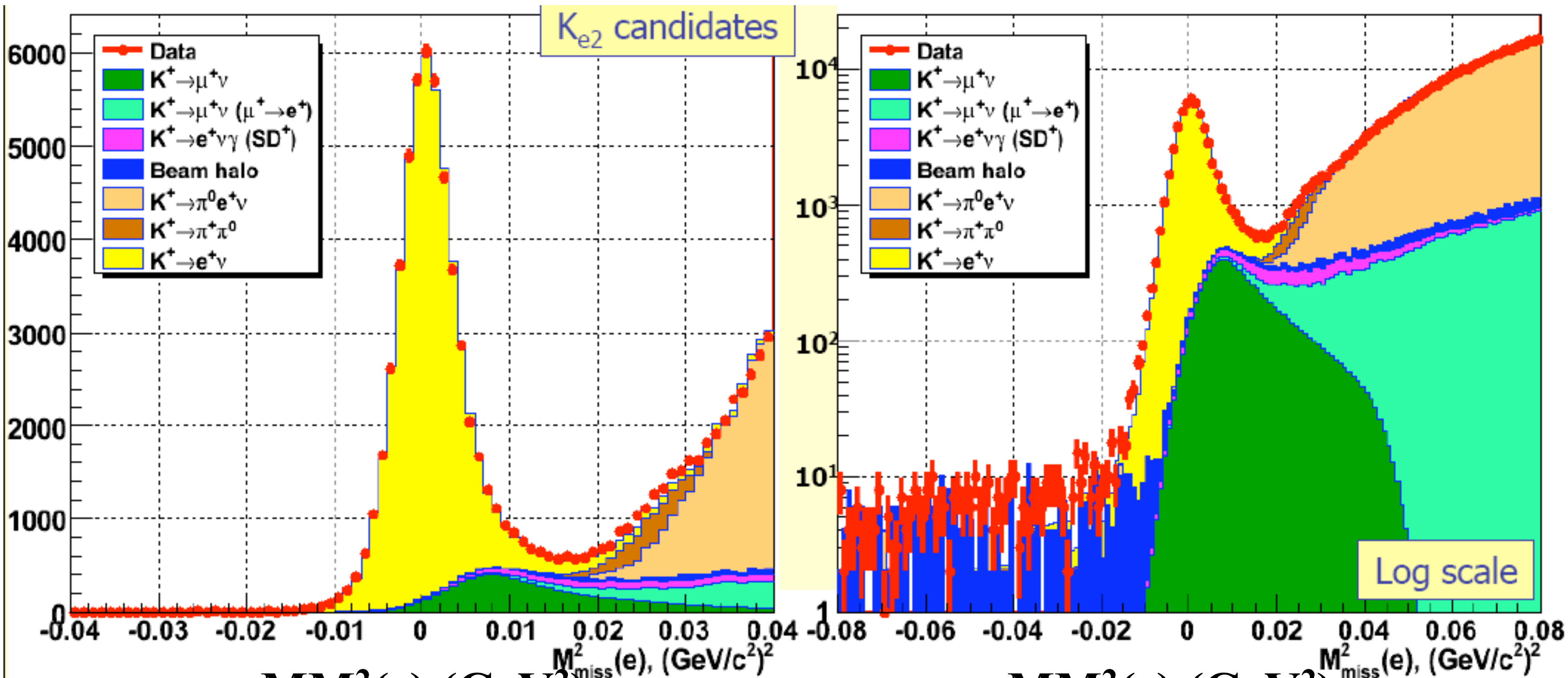
Total background to Ke2: 8.03(23)%



Analysis of Ke2/Km2 at NA62

Data taking lasted 4 months: the world largest data set of Ke2, > 100 Kevts

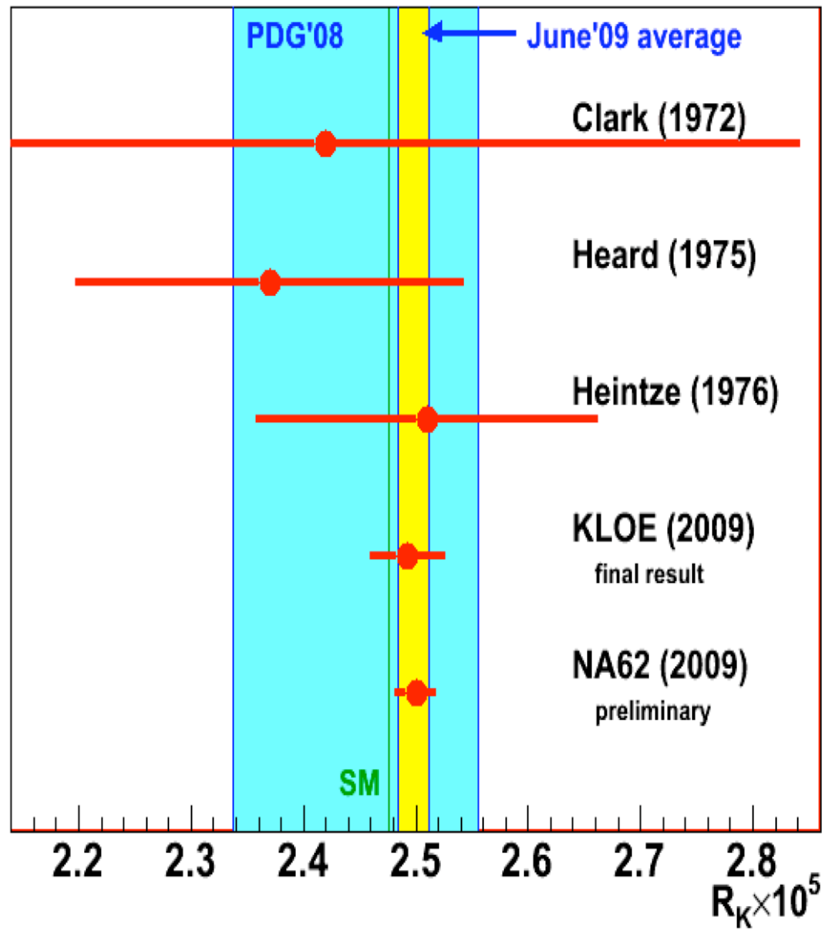
Preliminary result presented in 2009 from 51089 candidates



$MM^2(e)$ (GeV^2) **$MM^2(e)$ (GeV^2)**

Presenting new results for R_K (2009)

Experiment	KLOE	NA62
Ke2's on tape	30 k	100 k
Kin. Rejection	10^3 @ ε ~ 60%	10^3—1, p_{lep} in 20—60 GeV
e/μ rejection	10^3	3—1.5 10^5, p_{lep} in 20—60 GeV
Bkg to Ke2	16%	8%
Ke2g (SD)	Include as bkg Dedicated mmt.	Suppress in analysis
Ke2 counts	14 k	50 k
$R_K \times 10^5$	2.493(25)(19)	2.500(12)(11)
Total error	1.3%	0.64%
Status	Final result	Preliminary



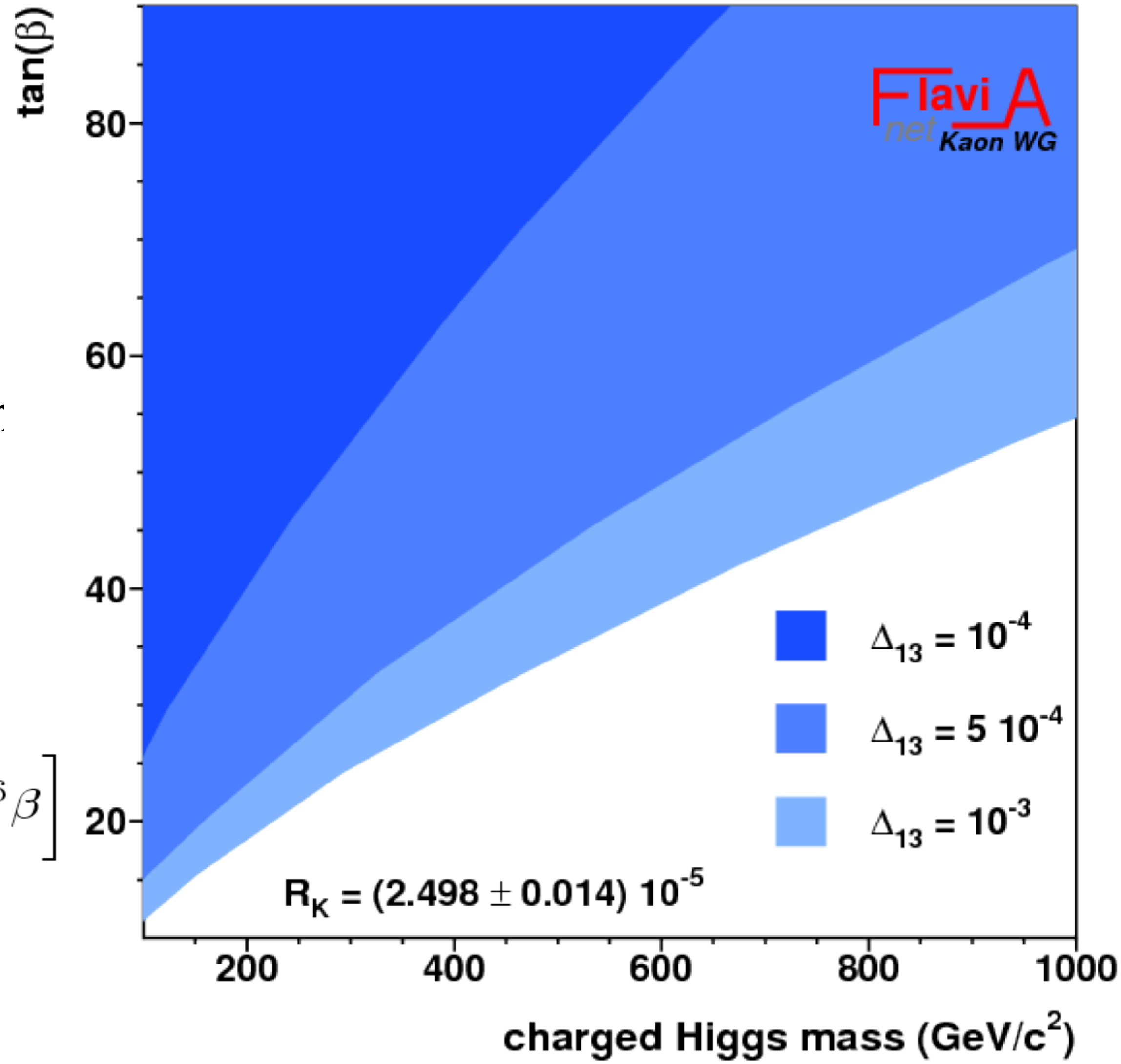
NP search from 2009 R_K results

New World Average:
R_K = 2.493(14) 10^{-5}

Compare with SM:
R_K = 2.477(1) 10^{-5}

Test NP from LFV transition
in R-parity SUSY:

$$R_K^{LFV} \simeq R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_H^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right) |\Delta_R^{31}|^2 \tan^6\beta \right]$$



The present and future of K physics

Sensitivity to new physics from the TeV scale reduced by small mass

Approach for the present and future of K physics:

1. **push at the limit accuracy of fundamental tests:**

   Violation of CPT symmetry [KLOE-2]

   Test presence of QM decoherence in KK evolution [KLOE-2]

   Measure T symmetry violation from μ polarization in $K \to \pi\mu\nu$ [TREK @ JPARC]

2. **study processes suppressed in SM, detect NP in loop transitions:**

   Improve on R_K = Ke2/Kμ2, in the near [KLOE-2], mid-term [NA62] future

   $K^+ \to \pi\nu\nu$: from present evidence [E787/949] to O(10%) BR mmt [NA62]

   $K_L \to \pi\nu\nu$: from present limits [KEK391a] to future mmt [E14 @ JPARC]

Old and new experiments to reach the sensitivity frontier

The KLOE-2 project

Dafne upgrade in luminosity, with new crabbed waist scheme

- **goal is an increase by × 5 with relatively low cost and minor modifications**
- **first test successful on Dafne**

KLOE-2 project

- **Phase 0: resume data taking @ end 2009: minimal upgrade, get 5 fb^{-1}, i.e., aim at integrating ×2 of present statistics**
- **Phase 1: full KLOE upgrade, start after 2011 to integrate > 20 fb^{-1}**

Physics goal

- **Neutral K interferometry: CPTV, QM violations**
- **LFV studies, rare KS decays**
- **η,η' physics, $\gamma\gamma$ physics**
- **$\sigma(ee \to$ hadrons) at low q^2 and μ anomaly**

Detector upgrade

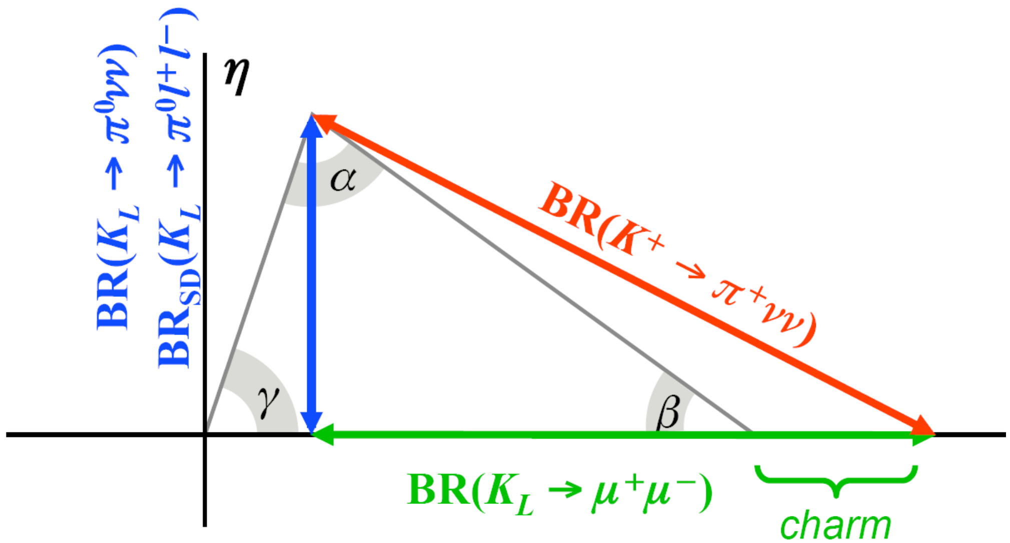
- **Insertion of an inner tracker**
- **Tagging system for $\gamma\gamma$ physics**
- **Increase read out granularity of EmC**
- **FEE maintenance and upgrade**
- **Computing and networking upgrades**

Golden K modes

FCNC processes dominated by Z penguin and box diagrams

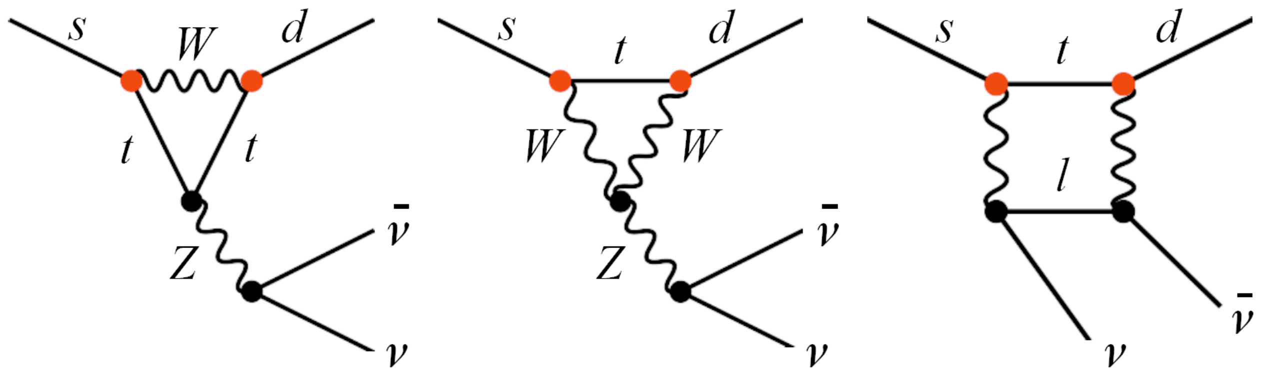
Can give direct information on CKM matrix elements:

- **No long distance contributions fron processes with intermediate γ's**
- **Hadronic matrix elements can be obtained from BR's of leading K decays**
- **$K_L \to \pi^0 \nu\nu$ is nearly pure CPV**



	Γ_{SD}/Γ	Irreducible theory err. (amp)	SM BR
$K_L \to \pi^0 \nu\nu$	>99%	1%	3×10^{-11}
$K^+ \to \pi^+ \nu\nu$	88%	3%	8×10^{-11}
$K_L \to \pi^0 e^+ e^-$	38%	15%	3.5×10^{-11}
$K_L \to \pi^0 \mu^+ \mu^-$	28%	30%	1.5×10^{-11}

SM prediction for $K \to \pi\nu\nu$



SM prediction [Buras et al., Mescia and Smith, Brod and Gorbahn]

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right] = 8.5(7) \times 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 = 2.6(4) \times 10^{-11}$$

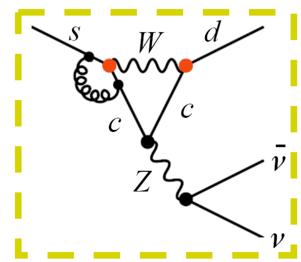
, where $x_q \equiv m_q^2/m_W^2$ **and**

$$\lambda = V_{us}, \quad \lambda_c = V_{cs}^* V_{cd}, \quad \lambda_t = V_{ts}^* V_{td}$$

Loops favor top contribution

Hadronic matrix elements from BR(Ke3) via isospin rotation:

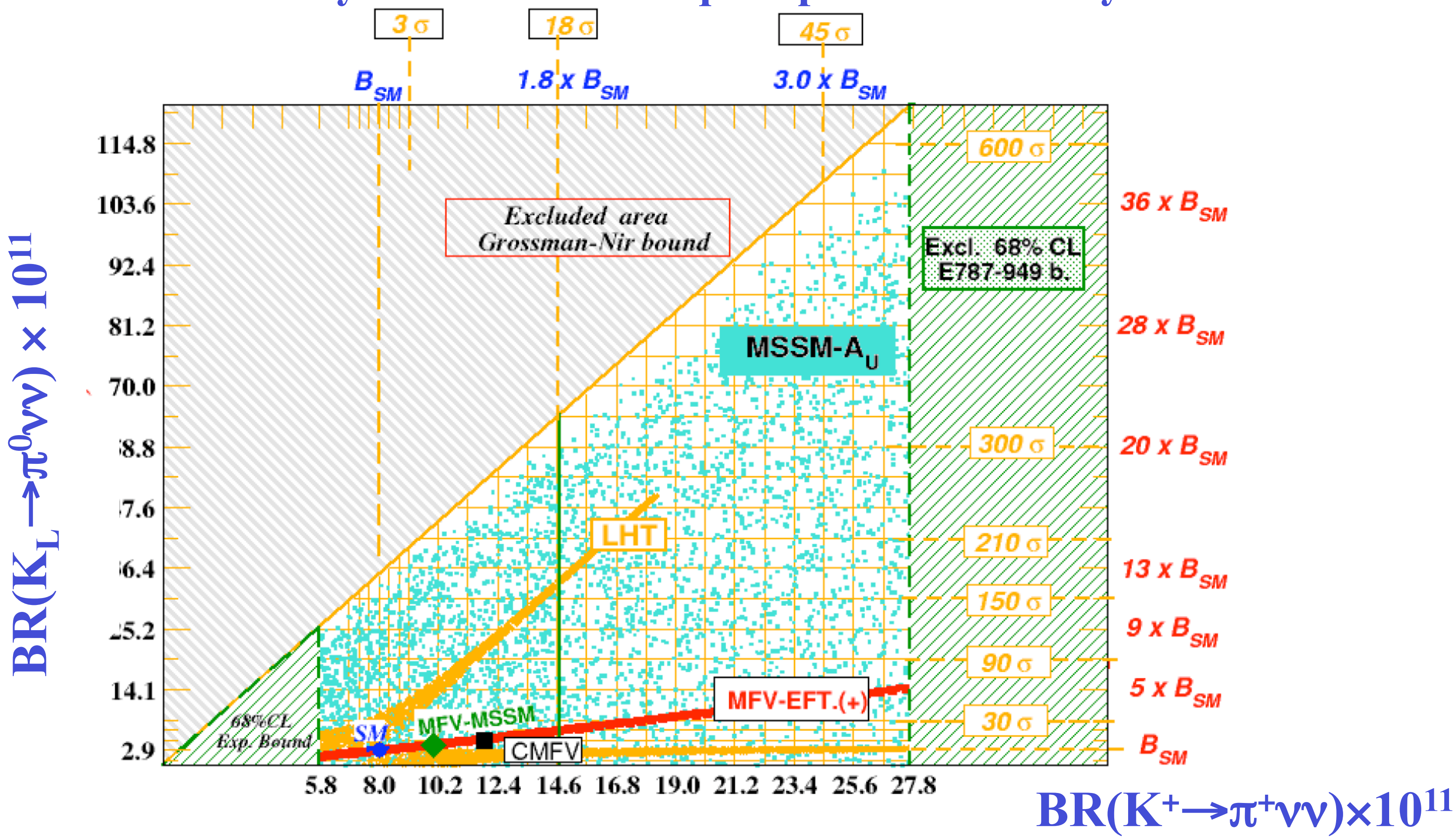
$$\kappa_+ = r_{K^+} \frac{3\alpha^2\,\mathrm{BR}(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \lambda^8$$



Charm contribute to theory error: non-parametric error 7% for K^+ vs 3% for K_L

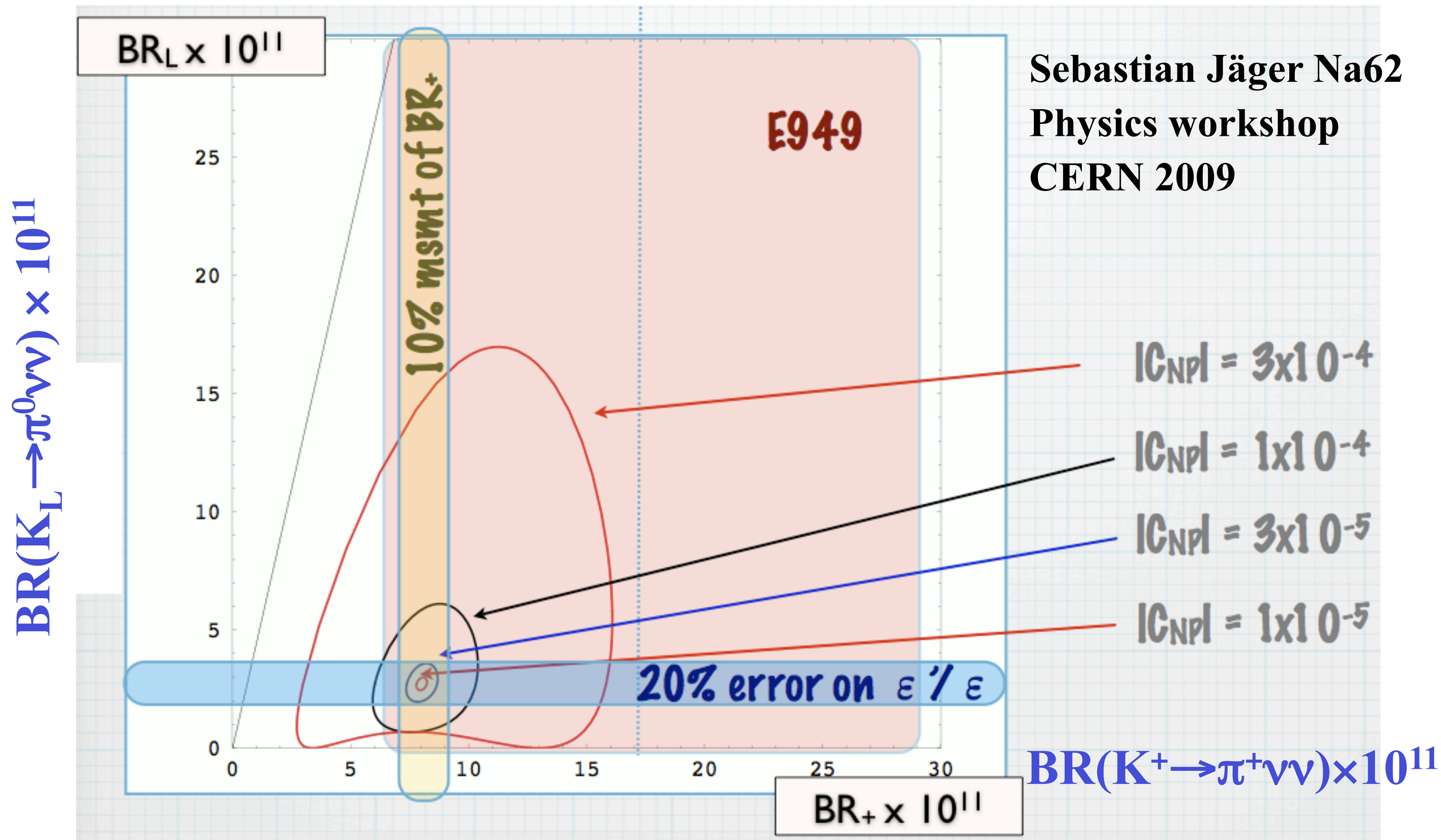
SM prediction for $K \to \pi\nu\nu$ and NP

Deviations from SM by more than 10% quite possible in many NP models



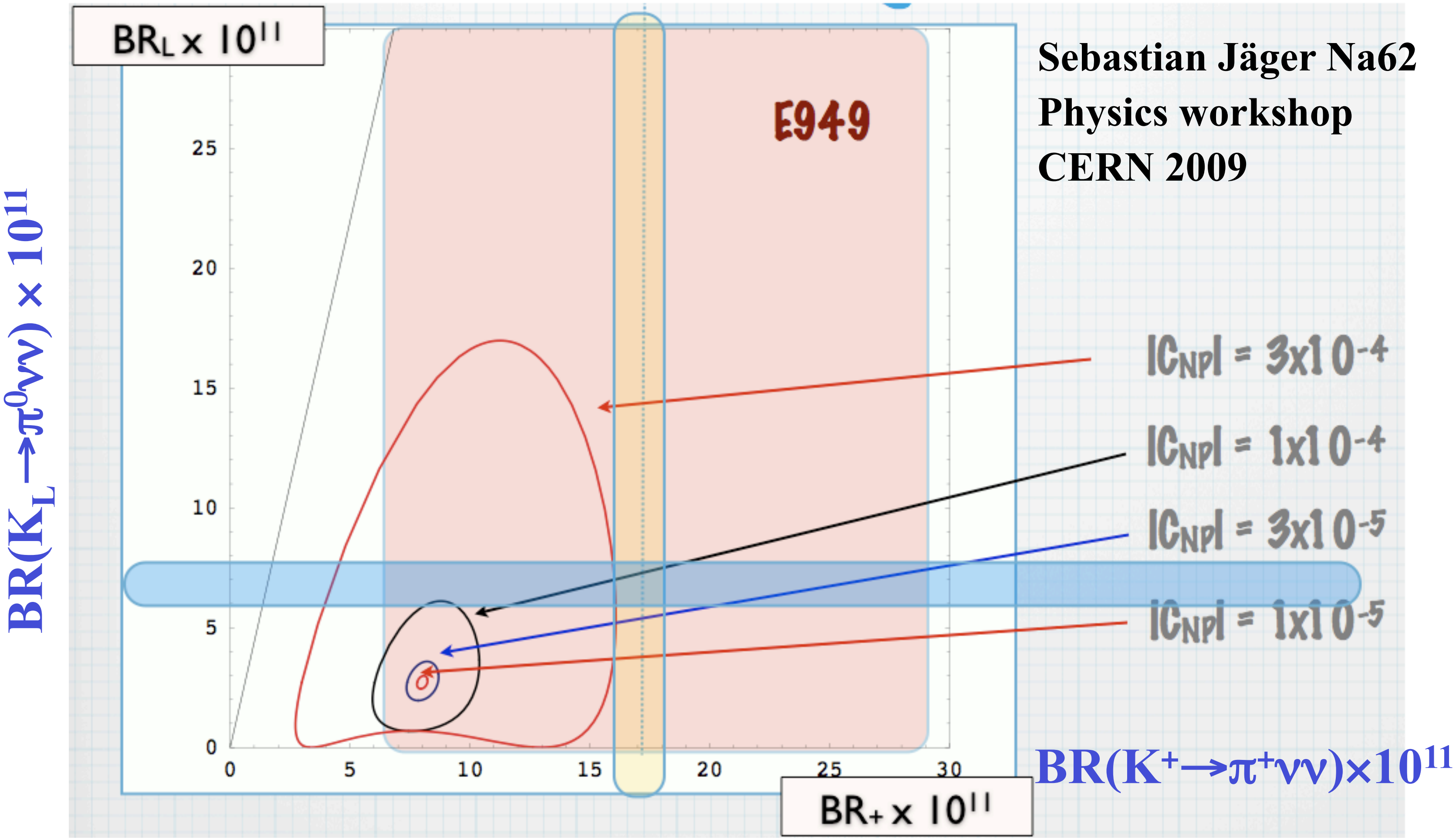
SM prediction for K → πνν and NP

Exciting possibilities from theory improvements for ε'/ε



SM prediction for K → πνν and NP

Exciting possibilities from theory improvements for ε'/ε



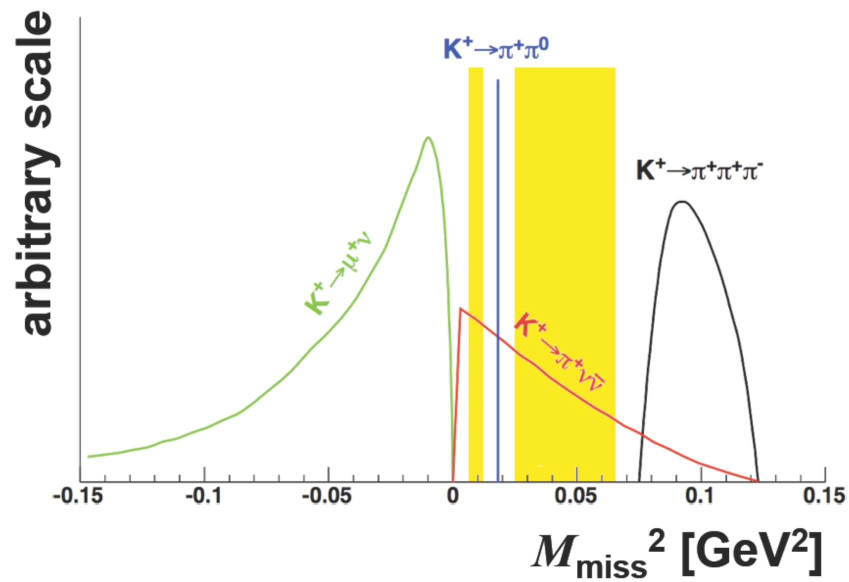
Sebastian Jäger Na62 Physics workshop CERN 2009

Experimental methods for $K^+ \rightarrow \pi\nu\nu$

Main backgrounds to $K^+ \rightarrow \pi^+\nu\nu$:

- **$K^+ \rightarrow \mu\nu$ with π ID for μ**
  need excellent PID, especially μ/π
- **$K^+ \rightarrow \pi\pi^0(\gamma)$ with γ's lost**
  need excellent γ vetoes

Kinematic rejection for 2 body →

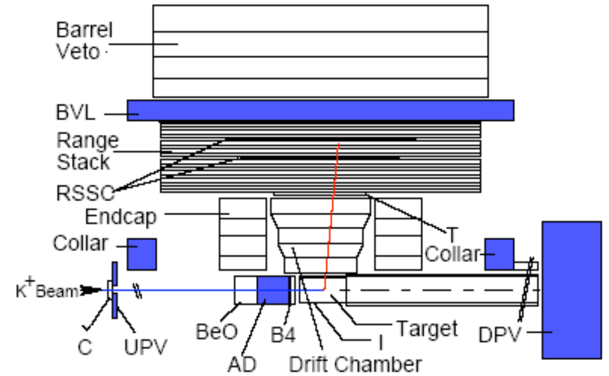


To reach 10^{-12}, PID & vetoes also reject unclosed bkg (K_{l3}, K_{l4}, …)

	Stopped K^+	Decay in flight
Kinematics	K^+ at rest	Must track K^+
Photon vetoes	Low-energy photons	High-energy photons
PID	Range π-μ-e decay chain	Advanced Cerenkov counters Muon detectors

Fixed target approach: E949 @ AGS

The entire AGS beam of 65 x 10^{12} (Tp/ spill) at a momentum of 21.5 GeV/c was delivered to the E949 K^+ production target



Duty Factor: 2.2 s / 5.4 s ~ 40%

1 interaction length Pt target

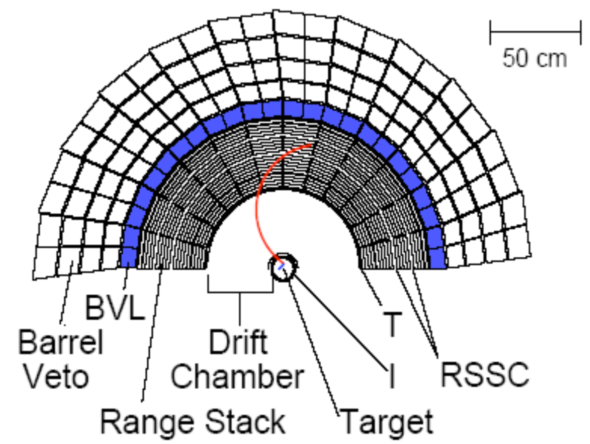
Before separators: 500 π : 500 p : 1 K

After separators: Purity K:π ~ 3--4 : 1

Incoming 710 MeV/c K^+ identified by Č and slowed down by BeO and Active Degrader

~27% K^+ stopped in the target (1.6 MHz)

Tracking in 1 T solenoid field

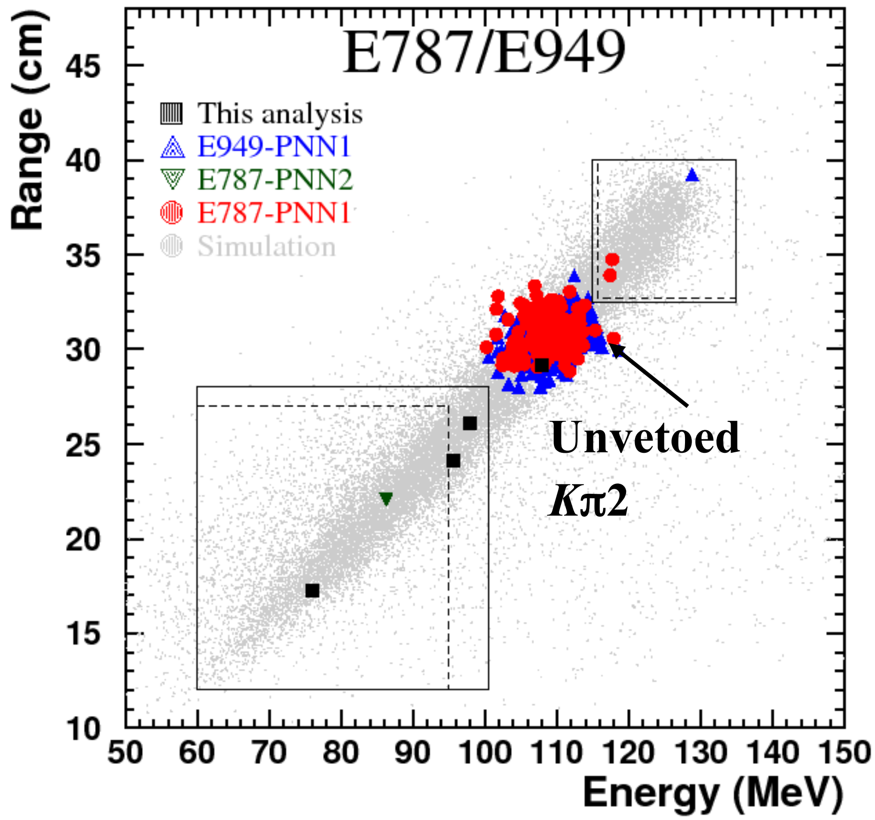


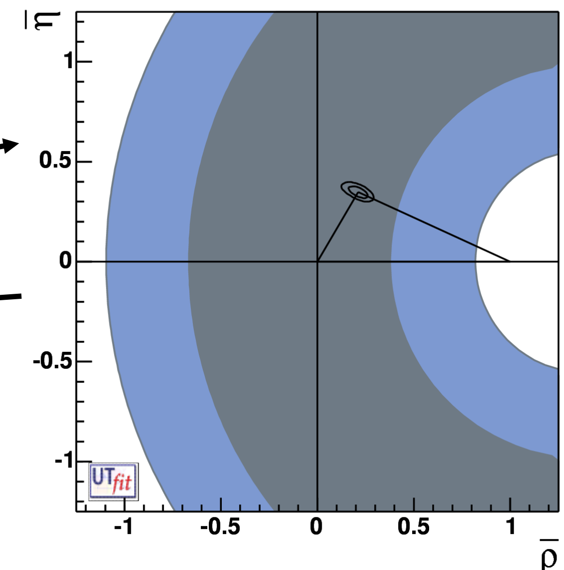
π^+ identification:
- **Delayed Coincidence**
- **Range**
- **Energy**
- **Momentum**
- **Detect entire $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ chain**

Final results from E787/E949 (2008)

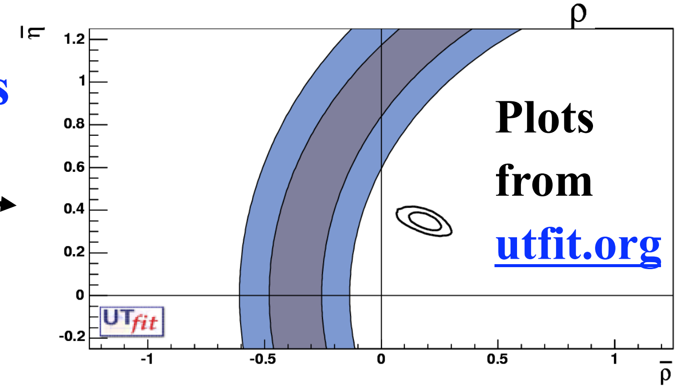
Combined results, from E787 (1995-8 runs) & E949 (12-weeks run in 2001)

$BR(K^+ \to \pi^+\nu\nu) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$





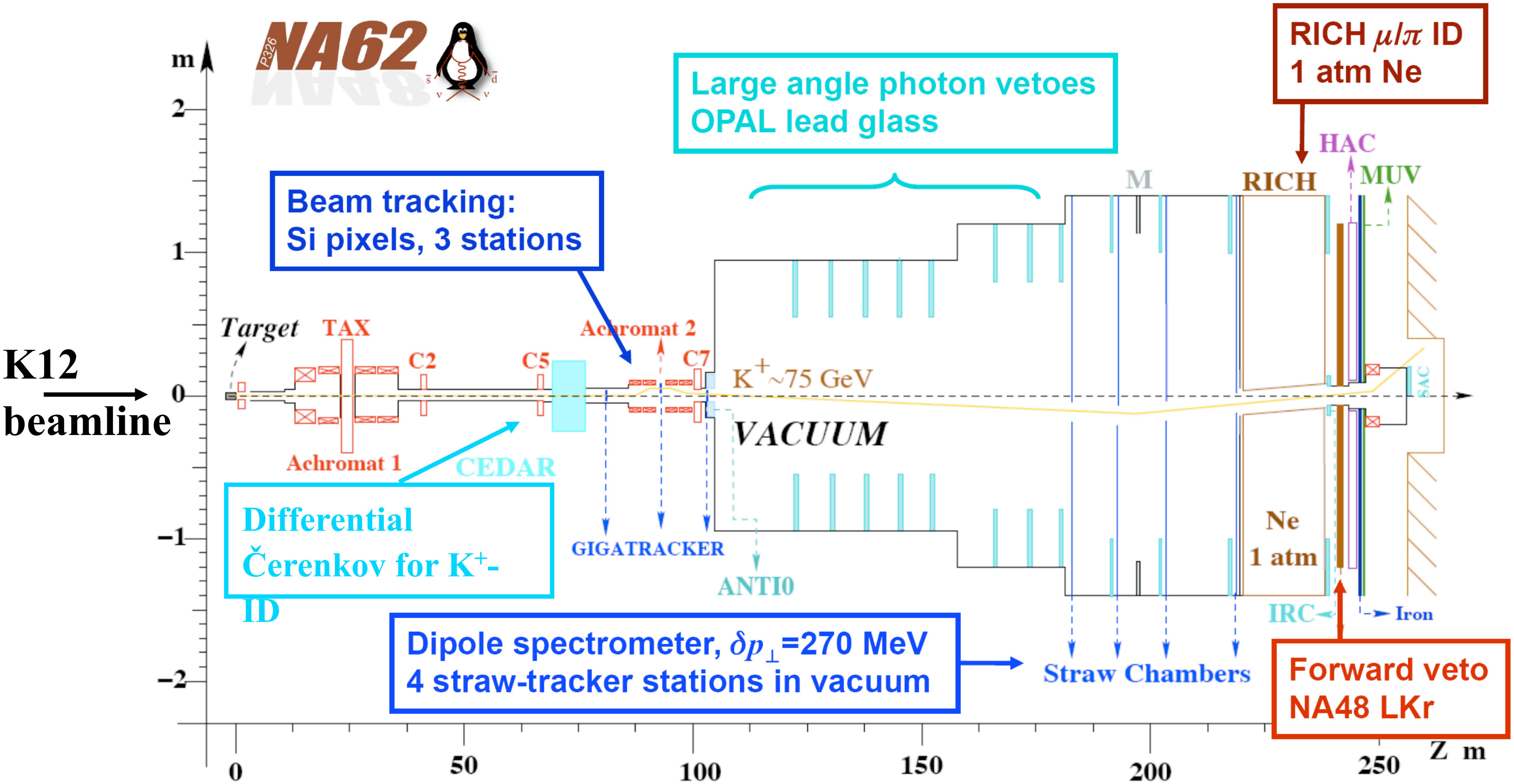
Same central value, 100 evts



Prob. all 7 obs. evts are bkg~10^{-3}

Prospects for upgrade @ FNAL Project X

The in-flight approach: NA62 @ CERN



400 GeV SPS primary proton beam → unseparated 75 GeV K⁺ beam

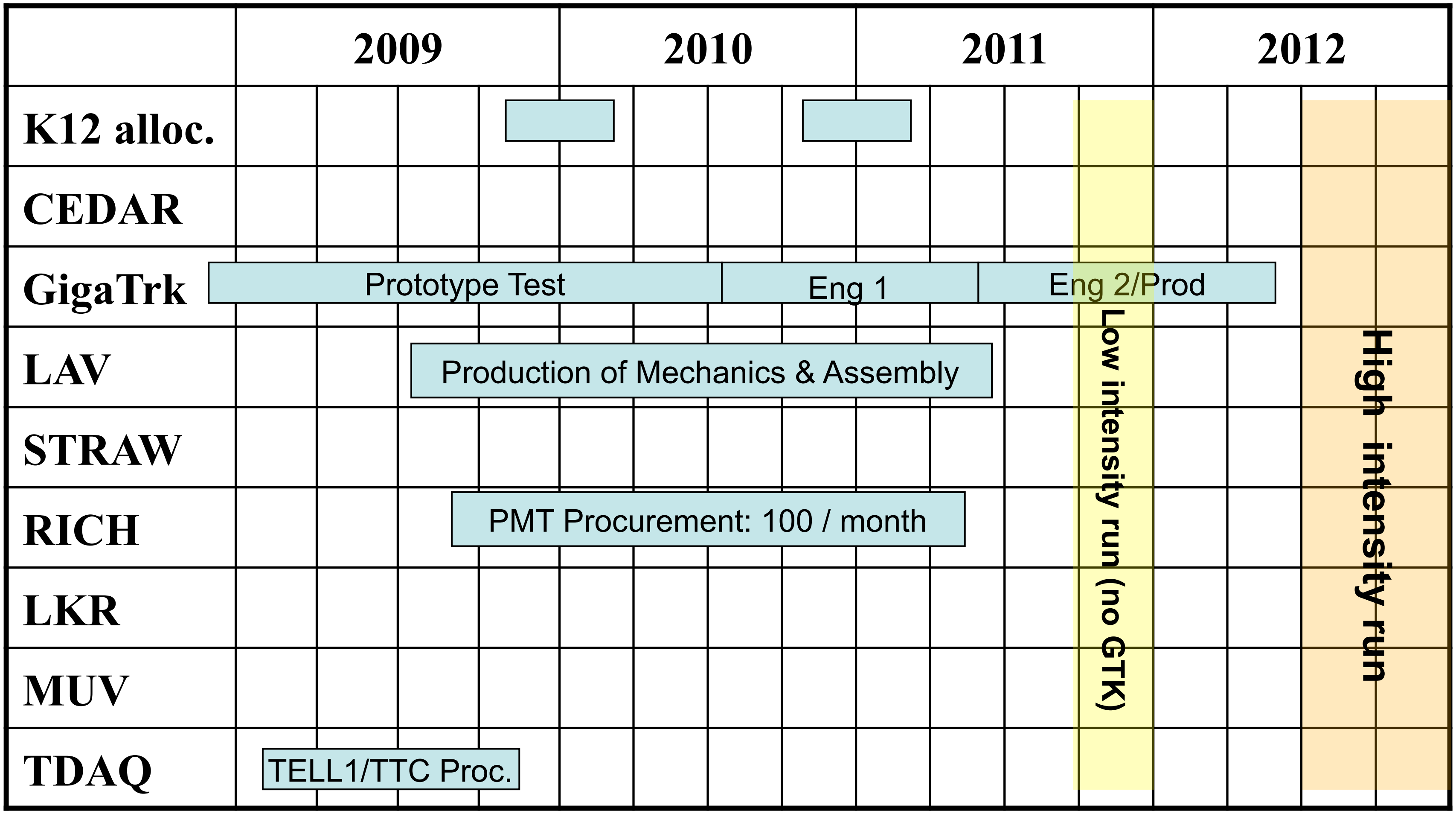
750 MHz beam → 50 MHz K+ → 6 MHz decay in 60-m fiducial volume

NA62 expected sensitivity

Decay Mode	Events
Signal: $K^+ \to \pi^+\nu\nu$ *[flux = 4.8×10^12 decay/year]*	55 *evt/year*
$K^+ \to \pi^+\pi^0$ *[$\eta_{\pi 0}$ = 2×10^-8 (3.5×10^-8)]*	4.3% (7.5%)
$K^+ \to \mu^+\nu$	2.2%
$K^+ \to e^+\pi^+\pi^-\nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+ \to \pi^+\pi^0\gamma$	~2%
$K^+ \to \mu^+\nu\gamma$	~0.7%
$K^+ \to e^+(\mu^+)\,\pi^0\nu$, others	negligible
Expected background	≤13.5% (≤17%)

year & running efficiency defined from NA48 story: ~100 days/year, 60% overall efficiency

NA62 timescale



The hardest job: $K^0 \rightarrow \pi^0 \nu\nu$

Search for "π^0 + nothing", pencil K_L beam:
vtx from γ directions + TOF

E391a @ 12 GeV KEK PS [See Hideki Morii PIC09]

Run I: Feb - Jul 2004

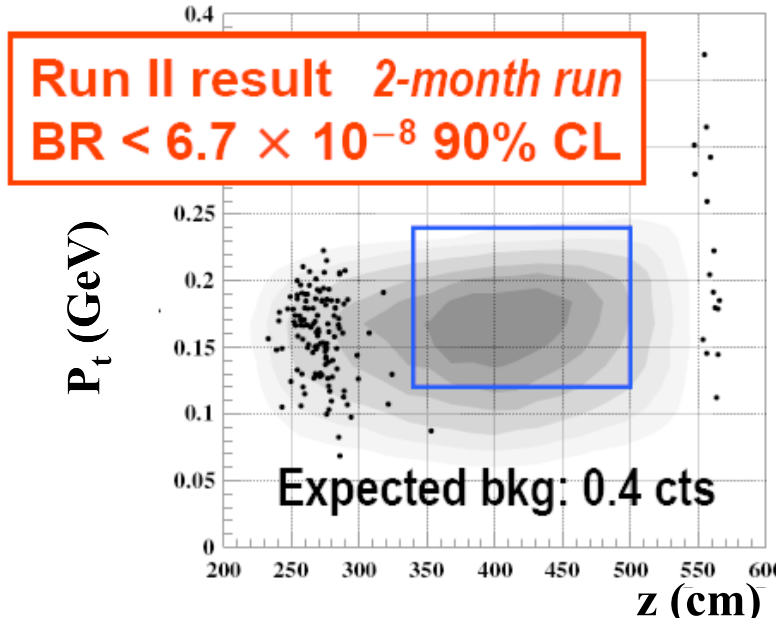
Run II: Feb - April 2005 (1.4×10^{18} POT)

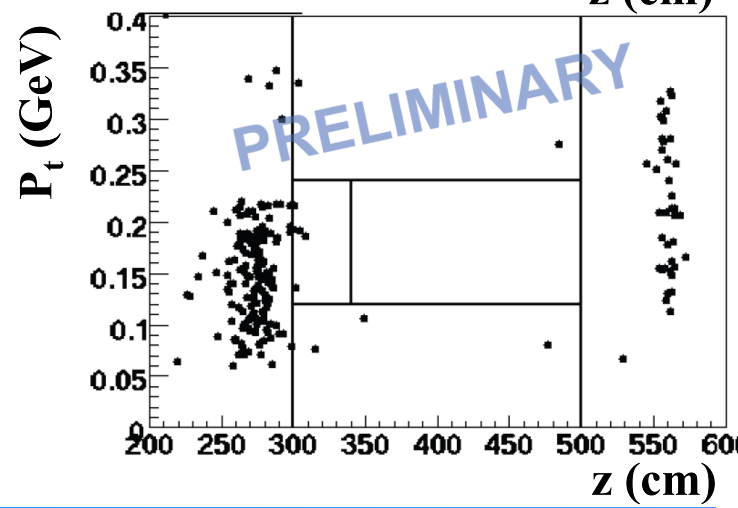
Neutron halo background

Run III: Nov - Dec 2005 (~70 % of Run II)

***$B(K_L \rightarrow \pi^0 \nu\nu) < 6.8\ 10^{-8}$* @ 90% CL (prelim. 09)**

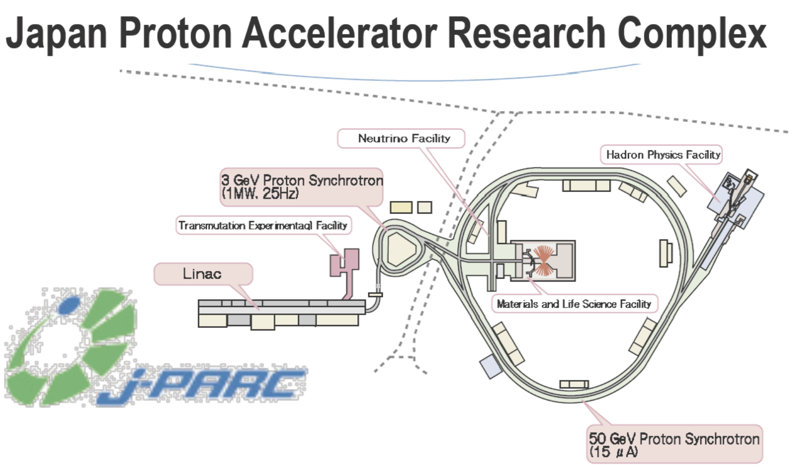
Run II—Run III combination under way





The future for $K^0 \to \pi^0 \nu\nu$, K^0TO

E391a seen as a preparation for KOTO (E14 @ J-Parc) [see T. Masuda, PIC 2009]




Satellite image, 16 July 2009

Wrt E391a: ×10 K_L beam, ×10 acceptance, ×10 running time

30 GeV primary beam

20-m K1.1 beamline

- **Core/halo, $10^{-4} \to 10^{-5}$**
- **Neutron/K_L, $40 \to 7$**

Schedule:

2009, construction & survey of beamline

2010, construction of CsI calorimeter & engenireeing run

2011, 1st physics run: 3-7 SM evts/ 3 years

Possible upgrades: 100 SM evts

Conclusions – kaon physics alive and kicking

Kaons pushing fundamental principles at severe test:

- **CPV, CPTV, and QM decoherence at state-of-art**
- **Progress from lattice, expect results will constrain more severely CKM fits soon**

Recent K decay mmts greatly improve knowledge of gauge coupling:

- **Effective coupling measured @ 0.2% (!), thus constraining many NP scenarios**

New and interesting tests of NP from two-body decay studies:

- **Sensitivity to NP from $K_{\mu2}/\pi_{\mu2}$: complementary wrt & competitive with $B \to \tau\nu$**
- **Golden LFV observable, R_K: KLOE final @ 1.3%, NA62 prel. @ 0.6% error**

The future: NP test from decays w clean theoretical signatures, $K \to \pi\nu\nu$

Sound theoretical basis, prediction @ % level

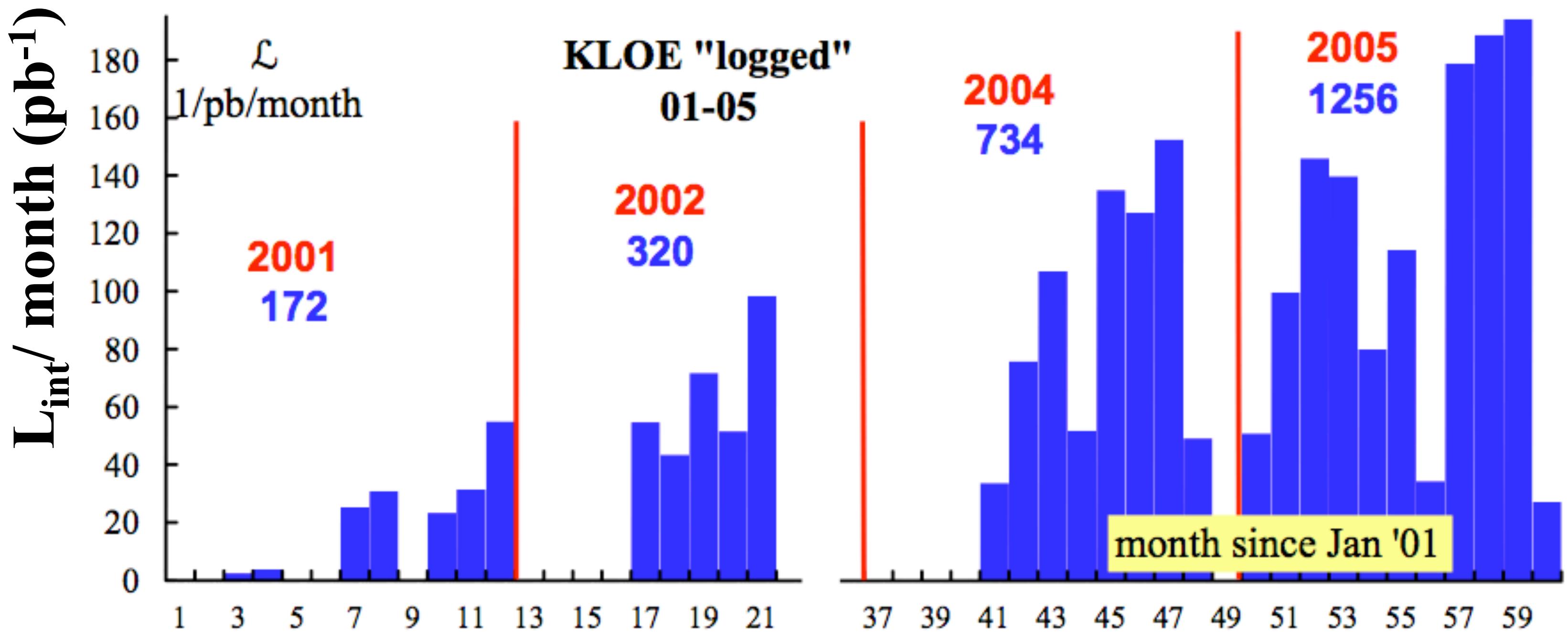
Sensitive to extremely high NP scales: 10% BR $\Rightarrow$ NP sensitivity up to TeV

A new experimental challenge, to compete with/complement LHC data

Additional information

Overview of KLOE data

Data taking for KLOE experiment, years 2001-2005, now run completed



2001−5: ~2.5 fb^{-1} integrated @ $\sqrt{s}$=M(ϕ), yielding ~2.5 × 10^9 K_SK_L pairs

Maximum peak luminosity, 2.5 10^{32} cm^{-2} s^{-1}

The TREK experiment @ J-parc

Physics goal: measurement of transverse μ polarization in $K \to \pi\mu\nu$ decays

In SM, $P_T = \frac{\sigma_\mu \cdot (p_{\pi^0,\gamma} \times p_{\mu^+})}{|(p_{\pi^0,\gamma} \times p_{\mu^+})|}$ **~ 10^{-7}: P_T in 10^{-3}—10^{-4} implies T-violating NP**

Stopped K-beam, upgraded E246 detector

- **Muons polarization measured as forward-backward asymmetry**

Aim at improving E246 limit $P_T < 5\ 10^{-3}$ by ×50

Beam ×30, detector acceptance ×10, syst $\times 10^{-1}$:

- **Improved μ polarimeter: measure energy and direction of emitted e^+, better alignment**
- **Finer segmentation of active target**
- **Better tracking, improve rejection of $K_{\pi 2}$ bkg**
- **New APD readout for CsI calorimeter**

2009: R&D + ask for budget, 2012-13: start run