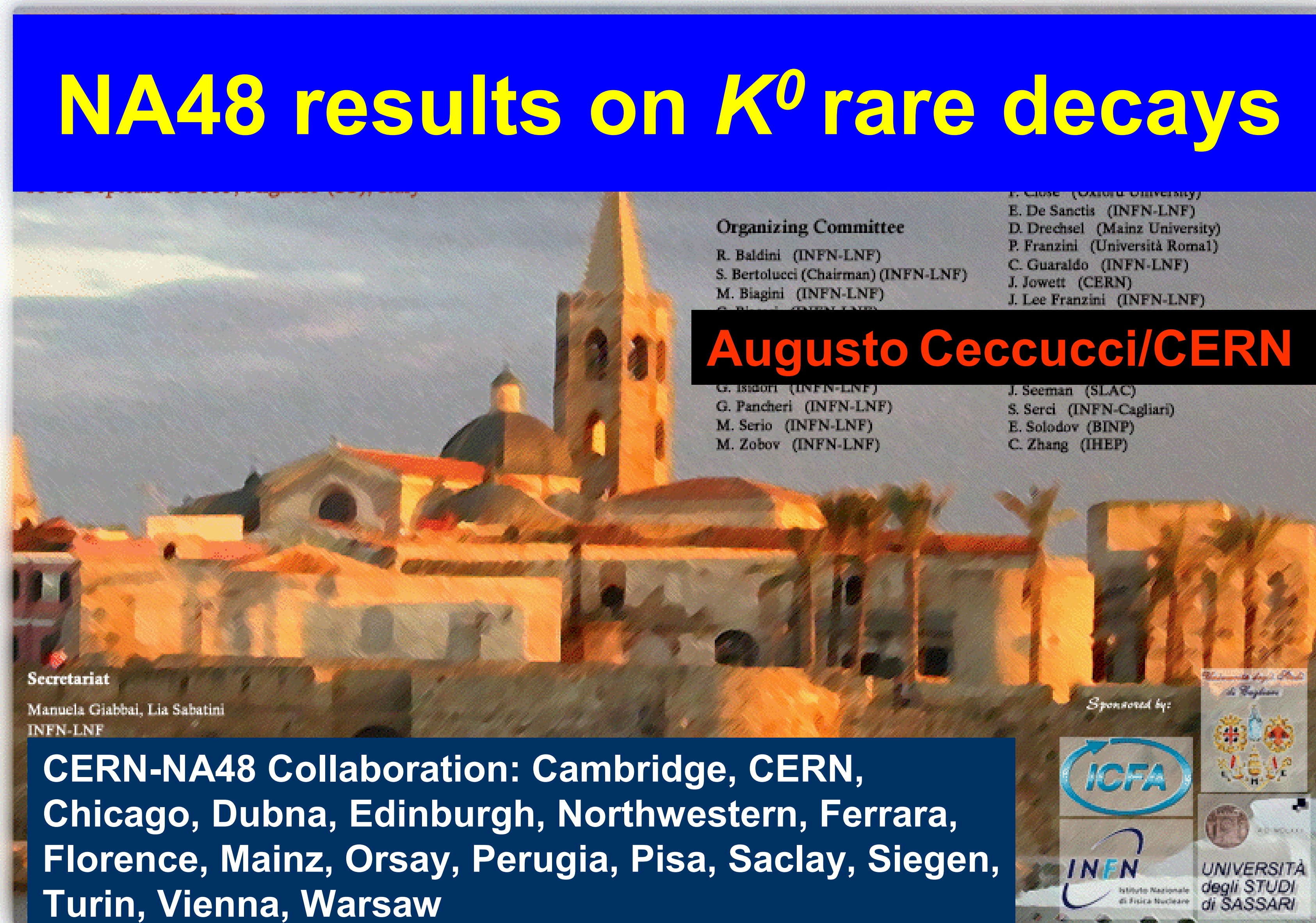
NA48 results on K^0 rare decays

Augusto Ceccucci/CERN



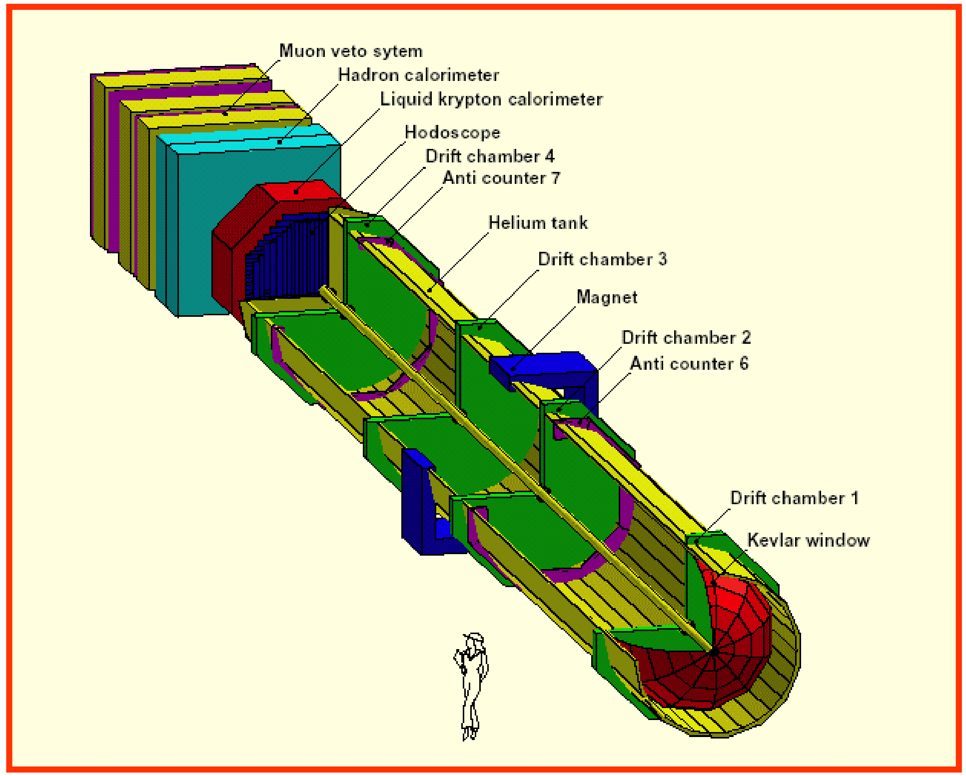
CERN-NA48 Collaboration: Cambridge, CERN, Chicago, Dubna, Edinburgh, Northwestern, Ferrara, Florence, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Turin, Vienna, Warsaw

Outline

- Testing SM with Rare Kaon Decays
  - $K_S \to \pi^0 ee$ 2002 data
- Other tests of CP and CPT symmetry
  - $K_{L,S} \to \pi\pi ee$ 1998-1999 data
  - $K_S \to 3\pi^0$ 2000 data
- Non-Leptonic decays
  - $K_{S,L} \to \gamma\gamma$ 2000 data
  - $K_{S,L} \to \pi^0\gamma\gamma$ 1998-1999 (K_L); 2000 (K_S)
- Outlook

NA48 Detector & Data Taking

NA48: ε'/ε	1997
ε'/ε	1998
ε'/ε	1999
K_L no spectrometer / NA48/1 K_S	2000
ε'/ε lower inst. intensity	2001
NA48/1: K_S	2002
NA48/2: $K^{\pm}$	2003

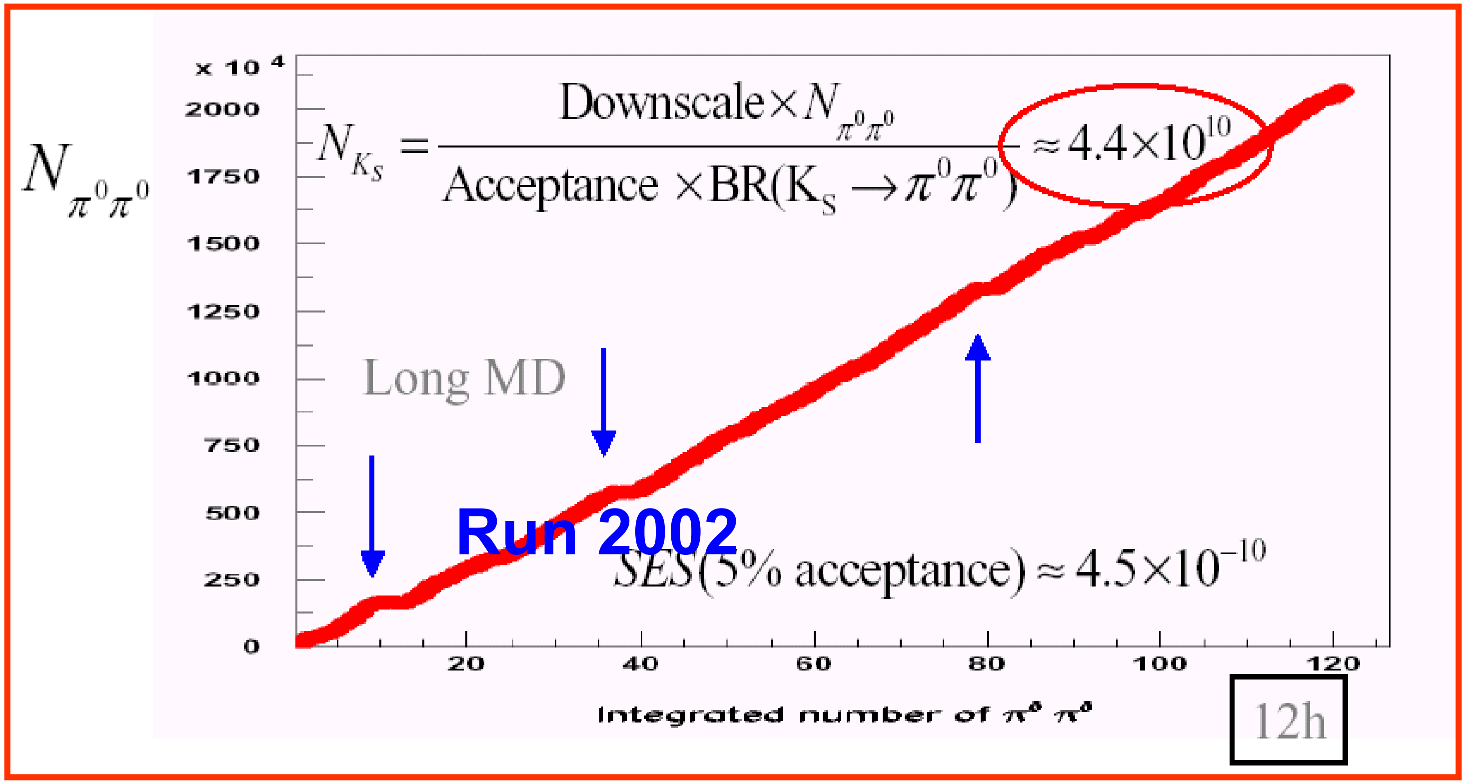


Kaons produced by 450(400) GeV protons from the CERN SPS on Be target:
E_K~110 GeV
FAR (K_L) beam ~ 120 m long
NEAR (K_S) beam ~ 6 m long

NA48/1

***K_S* and neutral hyperon decays**

- **Upgraded read out**
- **High intensity short neutral beam from the CERN-SPS**
- **Run in 2000 (only γs) and 2002**

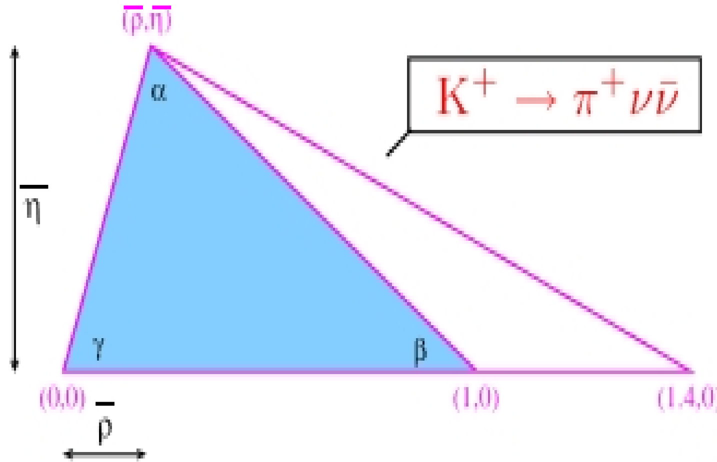


Kaon Rare Decays and the SM

CP-Violation

$K_L \rightarrow \pi^0 \nu\bar{\nu}$ **(holy grail)**

$$K_L \rightarrow \pi^0 e^+ e^- \left\{ \begin{array}{l} K_S \rightarrow \pi^0 e^+ e^- \\ K_L \rightarrow \pi^0 \gamma\gamma \\ K_L \rightarrow e e \gamma\gamma \end{array} \right.$$



$$K_L \rightarrow \mu^+ \mu^- \left\{ \begin{array}{l} K_L \rightarrow \gamma\gamma,\ K_L \rightarrow e^+ e^- \gamma \\ K_L \rightarrow e^+ e^- e^+ e^-,\ e^+ e^- \mu^+ \mu^- \end{array} \right.$$

J_{CP}=2×(Triangle Area) is the unique measure of CP-Violation in SM

$$J_{CP} = Im(V_{ud}^* V_{us} V_{ts}^* V_{td}) \sim \cos\theta_c \sin\theta_c \, Im\, \lambda_t$$

In the Wolfenstein parameterisation (λ, A, $\bar{\eta}$, $\bar{\rho}$):

$$Im\, \lambda_t = A^2 \lambda^5 \bar{\eta}, \qquad Re\, \lambda_t = A^2 \lambda^5 \bar{\rho}$$

Theory of $K_L \to \pi^0 ee$ $(\mu\mu)$

- **Complete re-analysis of the decay:**
  (Buchalla, D'Ambrosio, Isidori, hep-ph/0308008) ➡ BDI

- **Short Distance (Direct CP-Violation)**
  - **From Standard Model fit:** $Im\ \lambda_t = (1.36 \pm 0.12)\ 10^{-4}$ **(CKM)**
  - $B(K_L \to \pi^0 ee)_{CPV\text{-}dir} = (2.4 \pm 0.2) \times 10^{-12} \times (Im\ \lambda_t / 10^{-4})^2 =$

    $$(3.2 \pm 0.4) \times 10^{-12}$$

- **Indirect CP-Violation**
  - $BR(K_L \to \pi^0\ ee)_{CPV\text{-}ind} \sim 1/330\ BR(K_S \to \pi^0\ ee)$
  - **Direct and Indirect CP-Violating components interfere**

- **CP-Conserving contribution**
  - **Need model ind. 3 par. fit (Gabbiani, Valencia, PRD 64 2001)**
  - $BR_{CPC} < 3 \times 10^{-12}$ **(conservative, BDI)**
    - **They fix the 3 counterterms from** $K_L \to \pi^0 \gamma\gamma$ **and** $K_S \to \gamma\gamma$

Experiment: $K_L \to \pi^0 ee$ ($\mu\mu$)

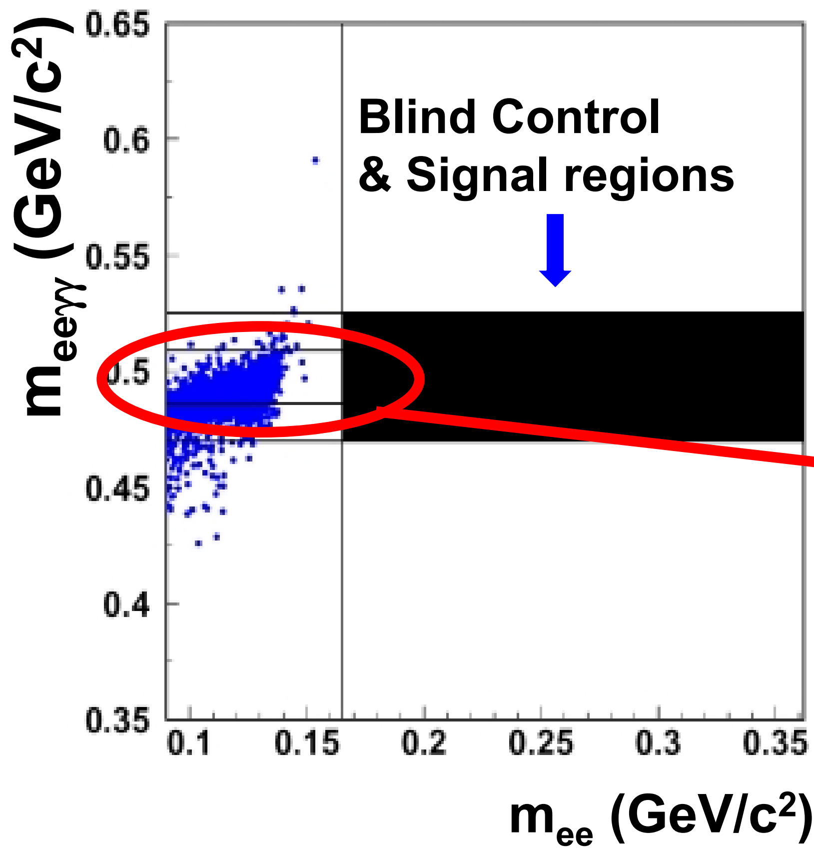
E799-II (KTeV)

Mode	Upper Limit 90% CL	Ref.
$K_L \to \pi^0 ee$	$< 5.1 \times 10^{-10}$	PRL86 (2001) 97 data
	$< 2.8 \times 10^{-10}$	Preliminary 97+99
$K_L \to \pi^0 \mu\mu$	$< 3.8 \times 10^{-10}$	PRL84 (2000)

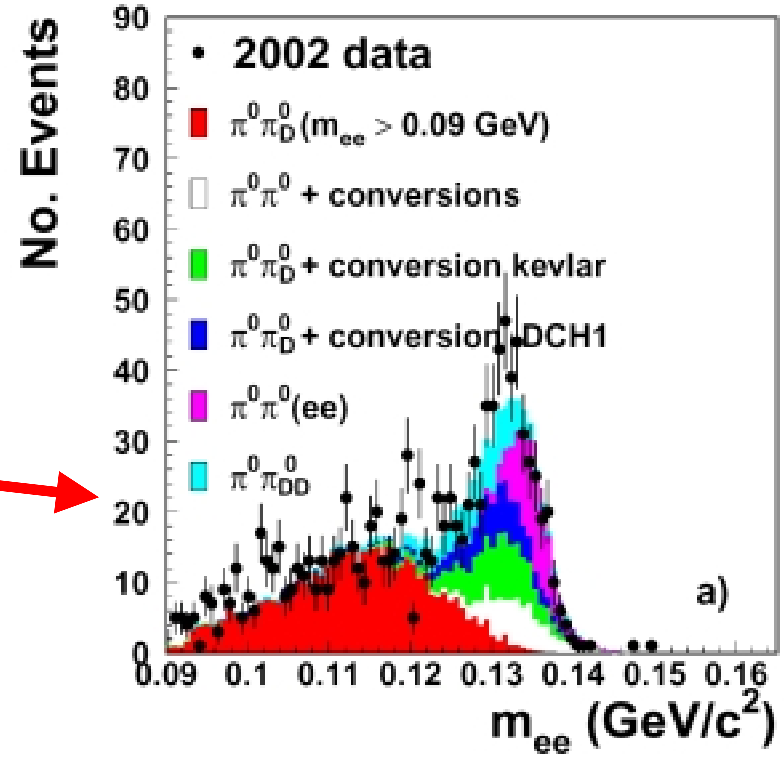
- **Irreducible background: $K_L \to ee(\mu\mu)\gamma\gamma$** *(Greenlee, 1990)*
  - Same final state as the signal, only $\gamma\gamma$ mass resolution and kinematics are available to suppress these backgrounds
  - To keep it to the ~1 event level the acceptance is quite reduced
  - Possible future searches will be background dominated

$K_S \rightarrow \pi^0 ee$

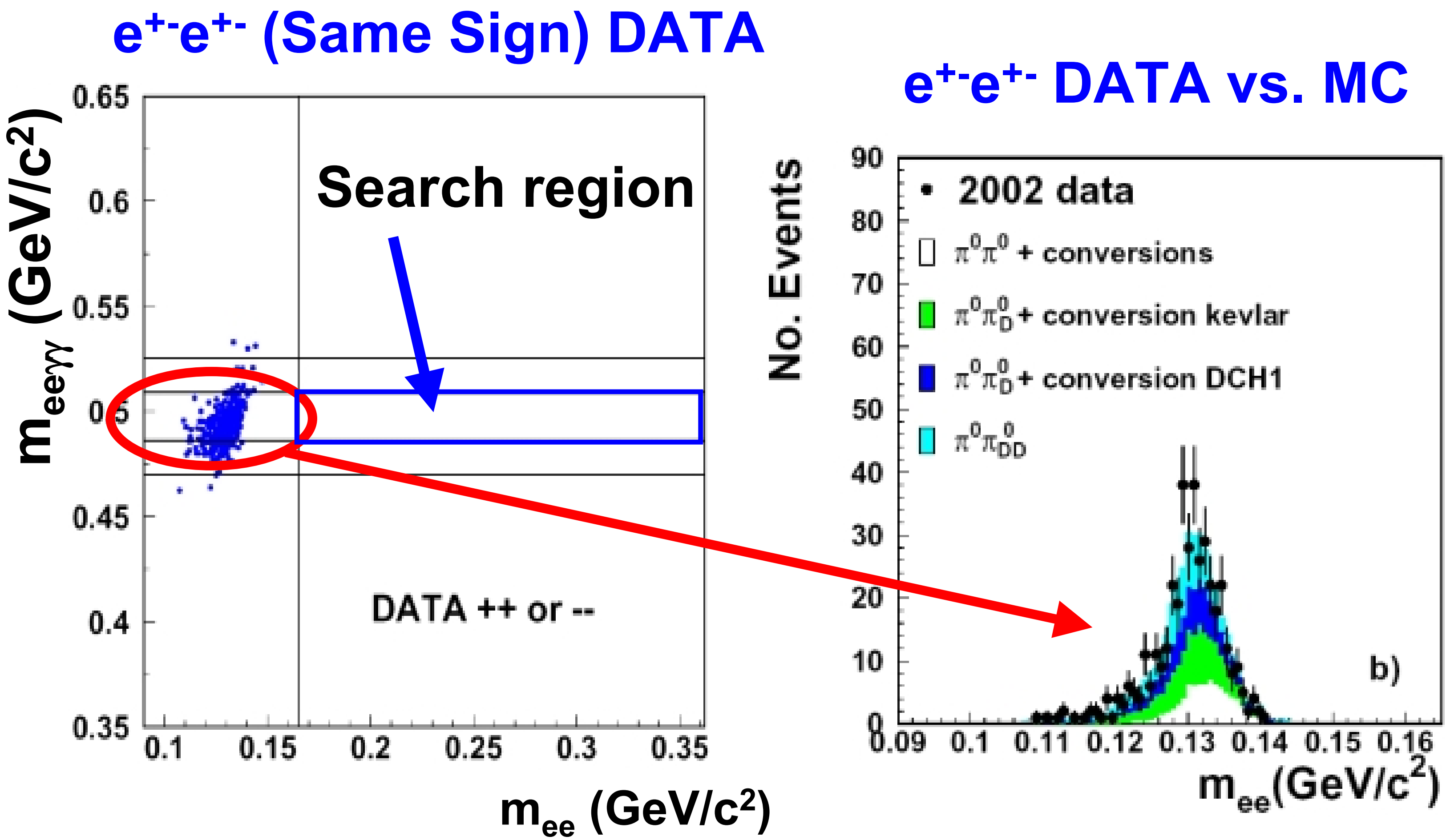
$e^{+-}e^{-+}$ (Odd Sign) DATA



$e^{+-}e^{-+}$ DATA vs. MC



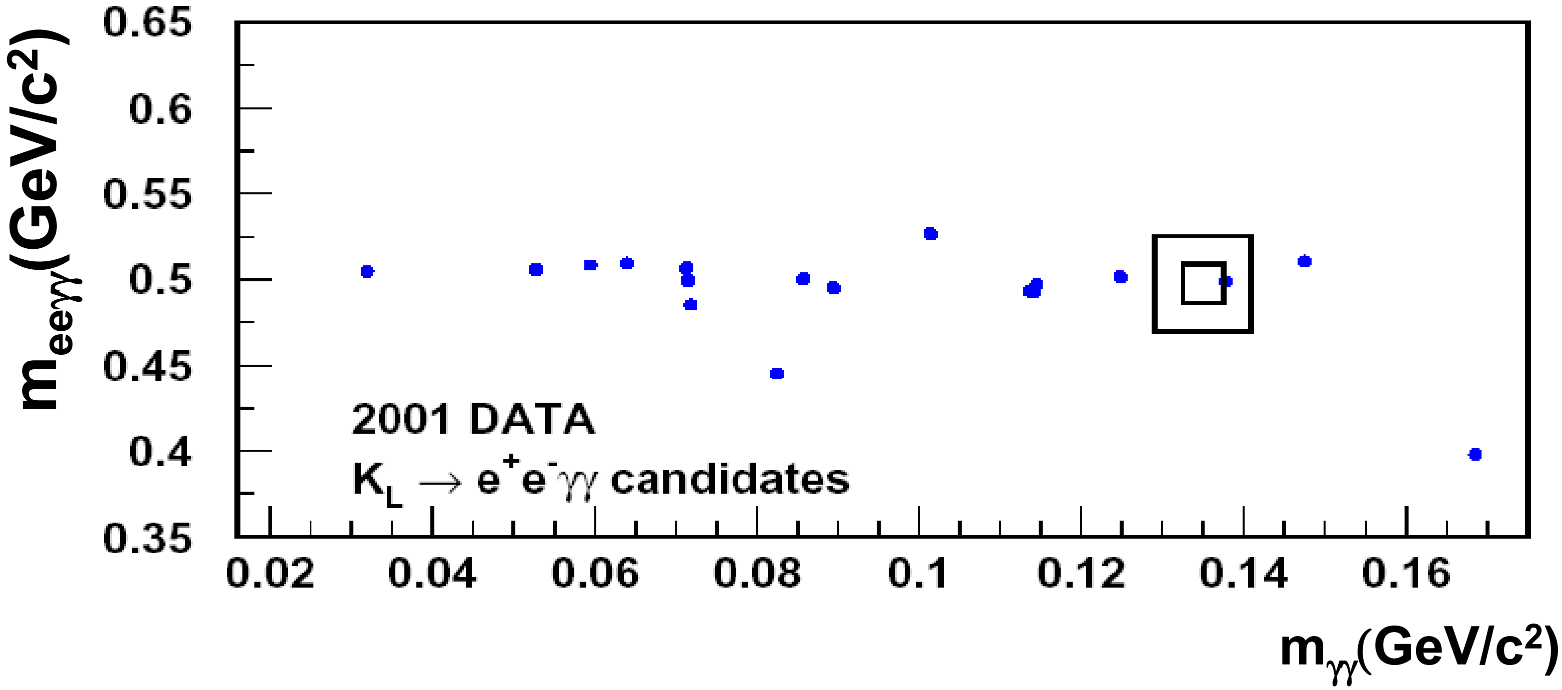
$K_S \to \pi^0 ee$



e+-e+- (Same Sign) DATA
e+-e+- DATA vs. MC
Search region
DATA ++ or --
m_eeγγ (GeV/c²)
m_ee (GeV/c²)
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.1
0.15
0.2
0.25
0.3
0.35
No. Events
2002 data
π0π0 + conversions
π0π0D + conversion kevlar
π0π0D + conversion DCH1
π0π0DD
b)
0
10
20
30
40
50
60
70
80
90
0.09
0.11
0.12
0.13
0.14
0.15
0.16

$K_S \to \pi^0\, ee$

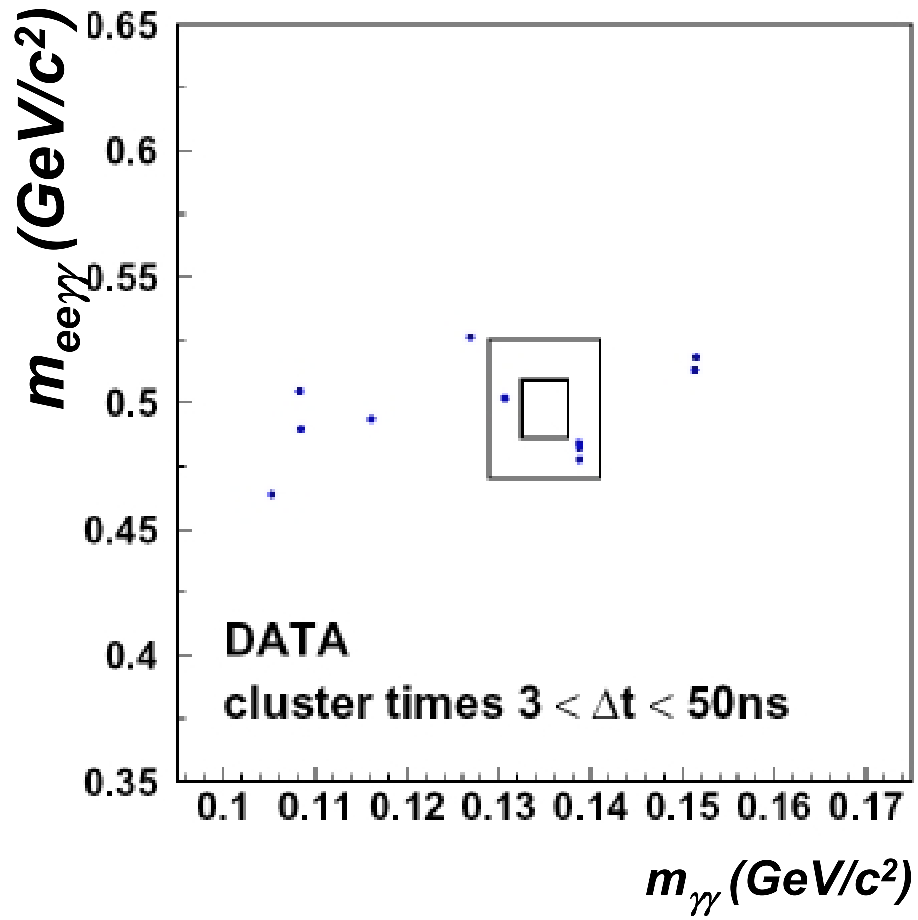
Background from $K_{L,S} \to ee\gamma\gamma$:
measured using NA48 K_L data from 2001
$N(K_L \to ee\gamma\gamma,\ 2001) \approx 10 \times N(K_{L,S} \to ee\gamma\gamma,\ 2002)$



$K_S \rightarrow \pi^0 ee$

Accidental backgrounds

- DC proton beam
- Read out window: ~ 200ns
- Use time side band to measure background from time-overlapping fragments from differ decays
- Major component:
  - $e\pi\nu + \pi^0\pi^0(\pi^0)$
  - Confirmed relaxing E/P cuts



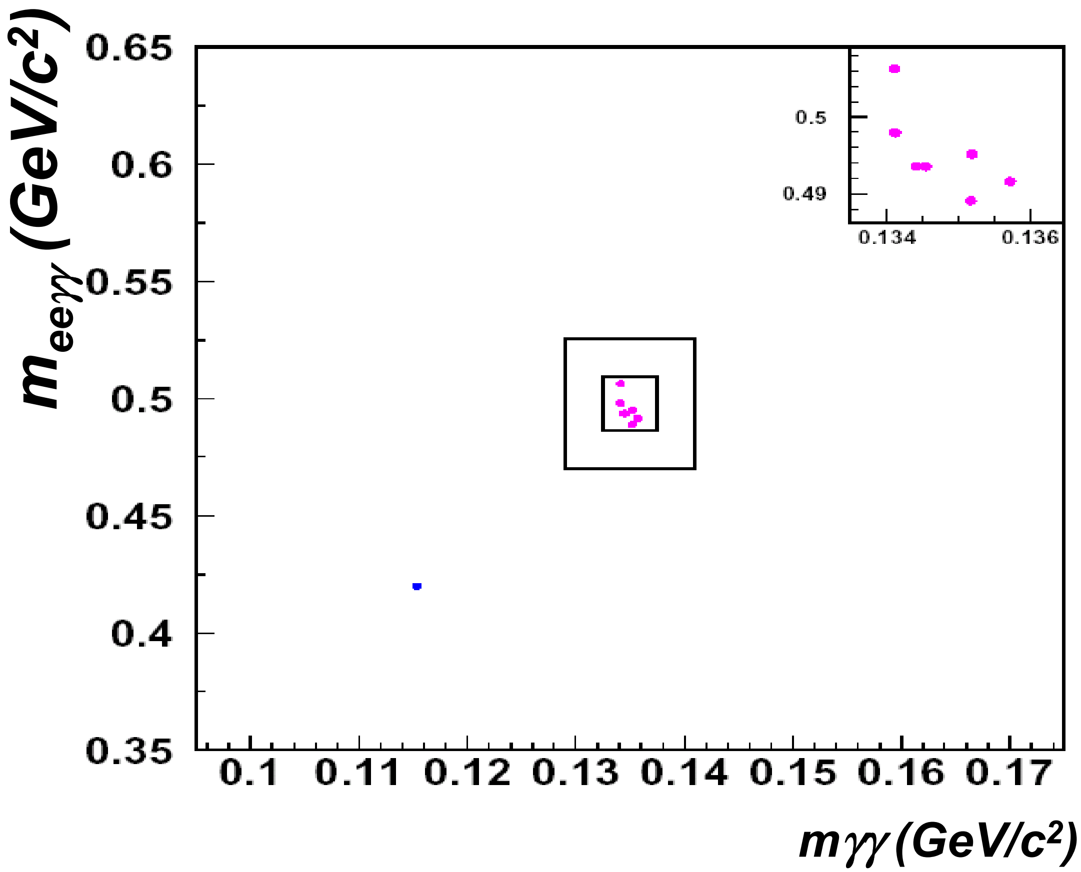
$K_S \rightarrow \pi^0\ ee$

SUMMARY OF BACKGROUNDS:

Source	Control Region	Signal region
$K_S \rightarrow \pi^0_D \pi^0_D$	0.03	<0.01
$K_{L,S} \rightarrow ee\gamma\gamma$	0.11	0.08
$\pi e \nu + 2\pi^0(\pi^0)$	0.19	0.07
Total	0.33	$0.15^{+0.10}_{-0.04}$

- **Many other sources investigated and found to be negligible (e,g neutral cascade decays)**
- **Blind analysis: Control and signal region remained masked until the study of the background was finished**

$K_S \to \pi^0 ee$



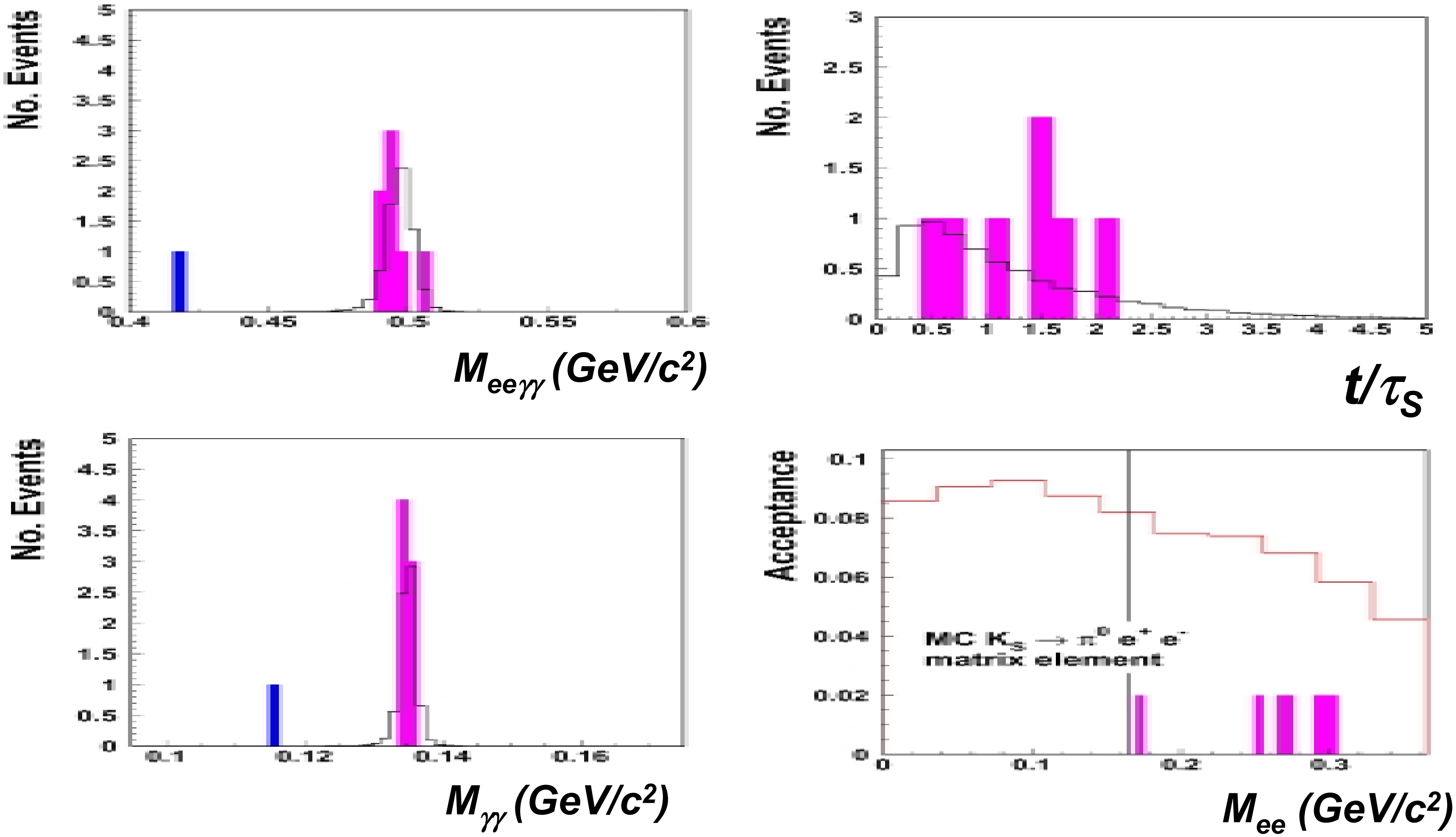
- **7 candidates in the signal region**

- **0 in control region**
- **Background 0.15**

The probability that all 7 events are background is ~10^{-10}

→ **First observation of $K_S \to \pi^0 ee$**

The 7 $K_S \to \pi^0 ee$ candidates



$K_S \to \pi^0 ee$

Accepted for publication by PLB

$BR(K_S \to \pi^0 ee, m_{ee} > 165\ MeV/c^2) = (3.0^{+1.5}_{-1.2}(stat) \pm 0.1(syst)) \times 10^{-9}$

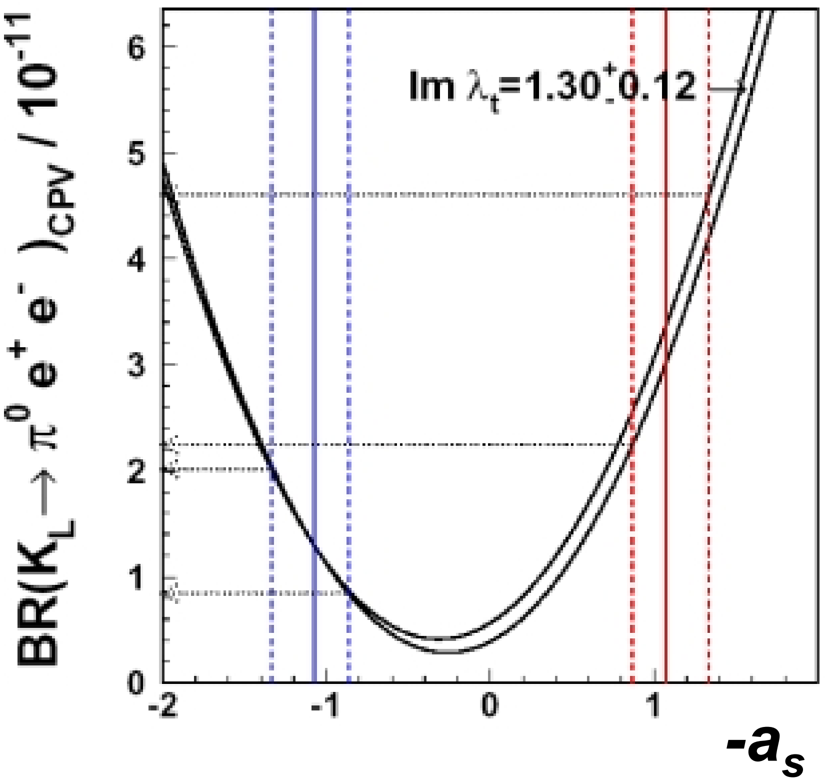
- Assuming vector interaction and unity form factor:

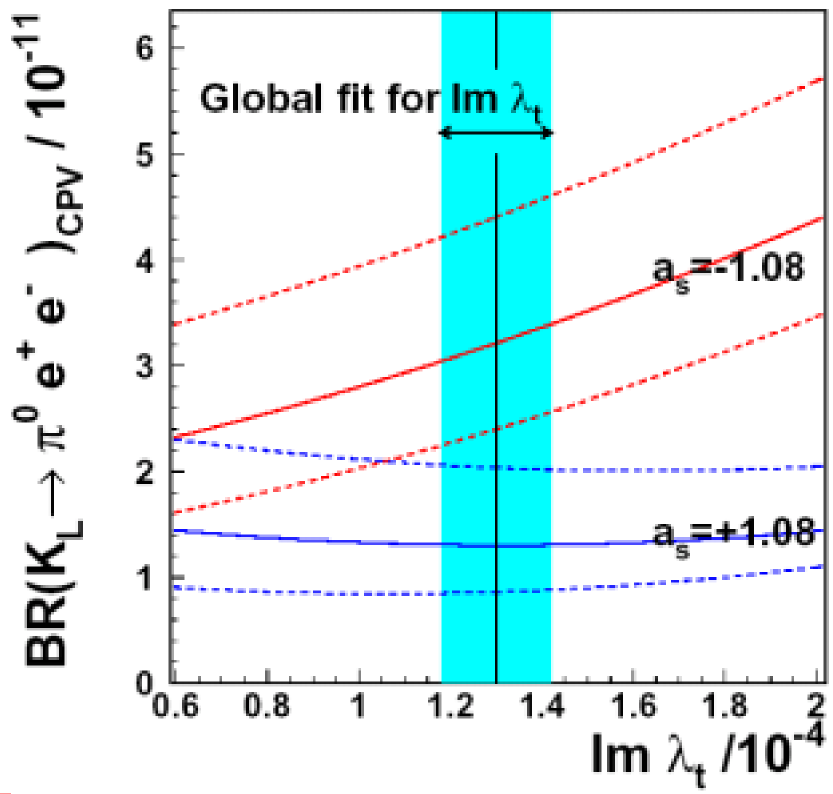
$BR(K_S \to \pi^0 ee) = (5.8\ ^{+2.8}_{-2.3}(stat) \pm\ 0.8(syst)) \times 10^{-9}$

  - In remarkable agreement with L. Sehgal prediction: $\sim 5.5 \times 10^{-9}$ NP B19 (1970)
  - In the notation of D'Ambrosio et al. JHEP 08 (1998 004):
  - $BR(K_S \to \pi^0 ee) \sim 5\,|a_s|^2$

$|a_s| = 1.06^{+0.26}_{-0.21}\ (stat) \pm 0.05\ (syst)$

Sensitivity to *Im* λ_t

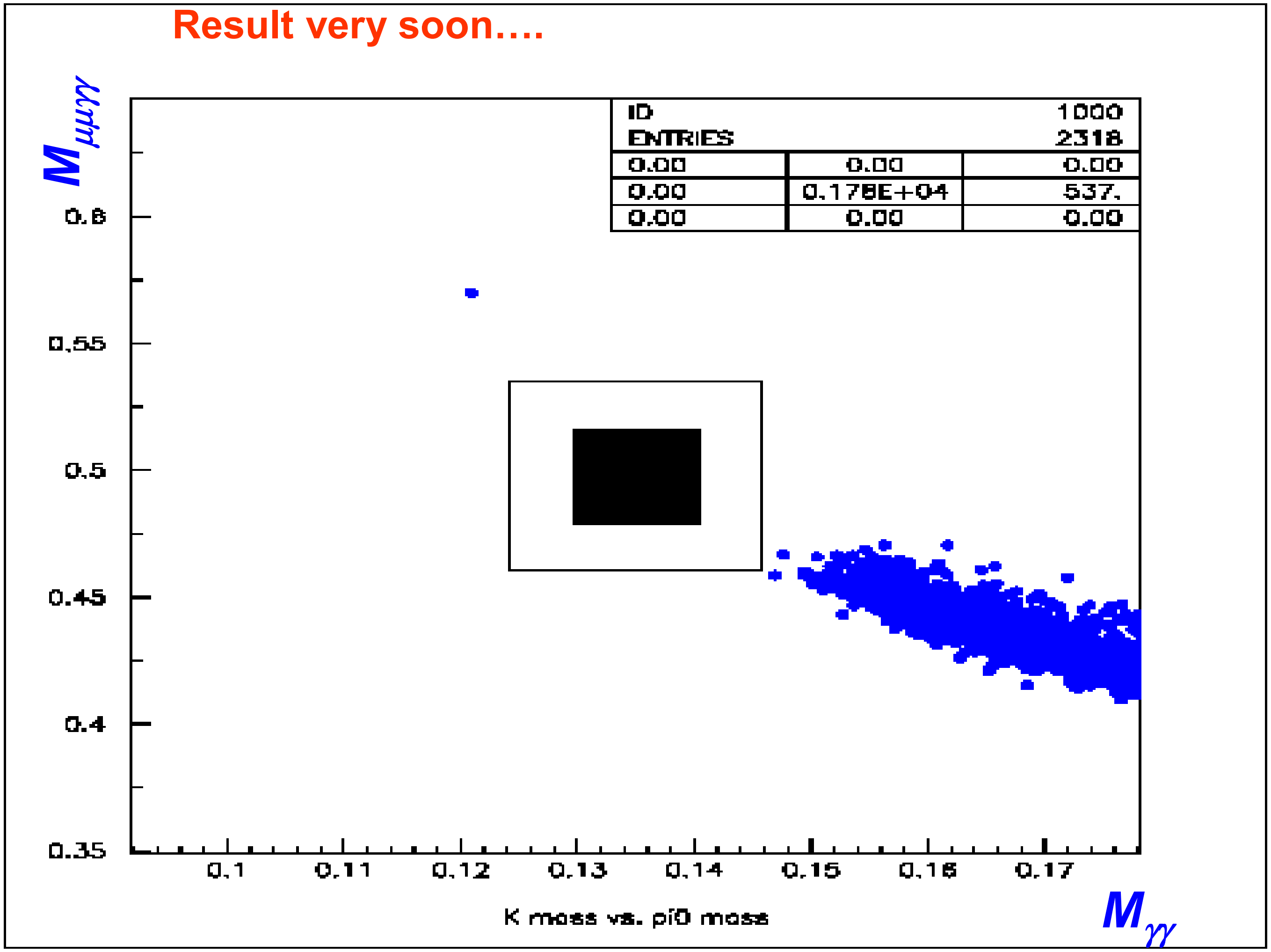




$$B(K_L \to \pi^0 e^+ e^-)_{CPV} \times 10^{12} \approx 15.3 a_s^2 - 6.8 a_s \frac{\mathrm{Im}(\lambda_t)}{10^{-4}} + 2.8 \left(\frac{\mathrm{Im}(\lambda_t)}{10^{-4}} \right)^2$$

IF the interference is constructive some sensitivity to *Im* λ_t is retained

$K_S \to \pi^0 \mu\mu$

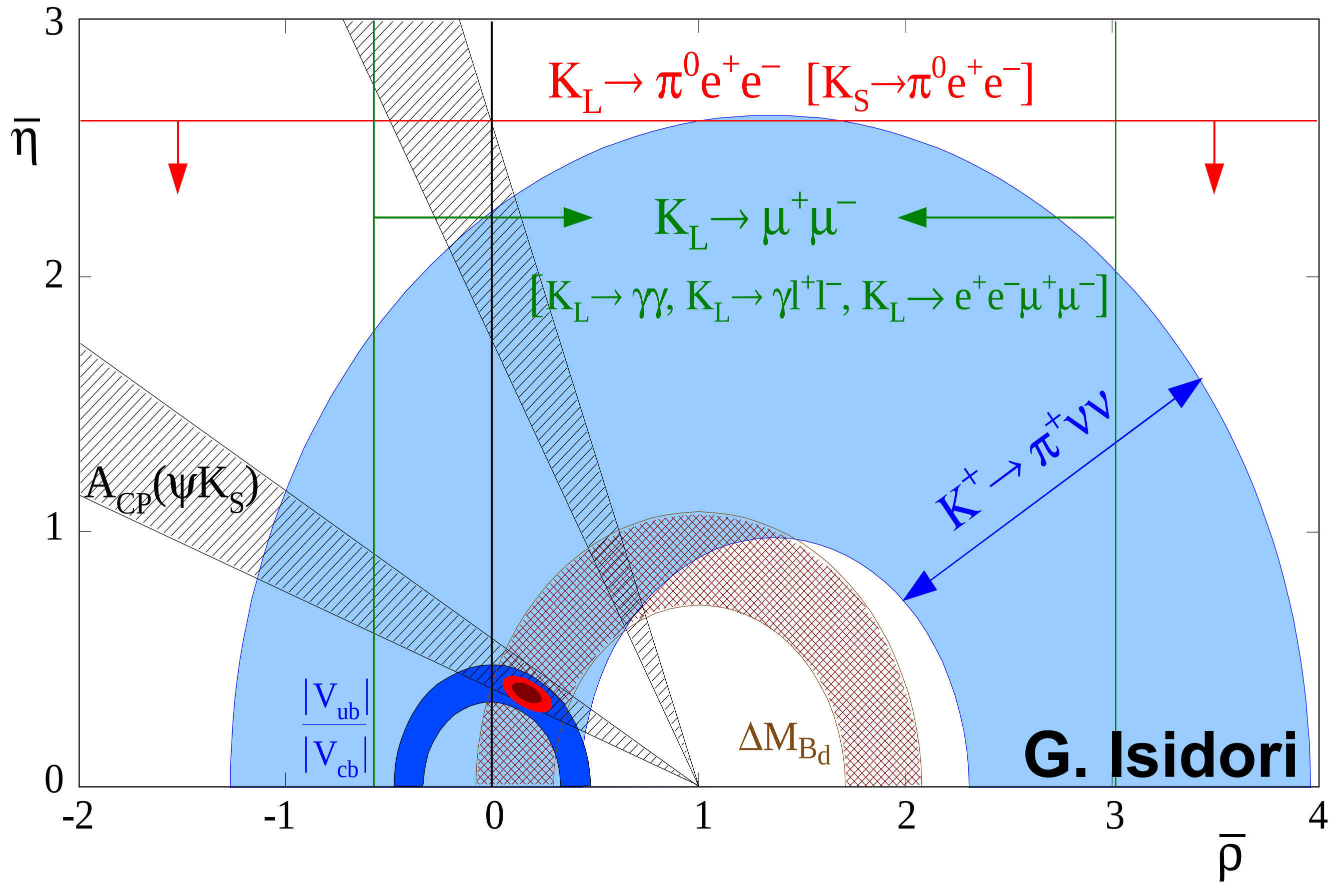


$K_L \to \pi^0 ee(\mu\mu)$ Perspectives

Admittedly aggressive Road Map

- **Detector $\sigma(\gamma\gamma)$ ×2**
  - Very ambitious, KTeV/NA48 already state of the art
- **K_S-K_L time dependent interference ×2**
  - Position experiment between 9 and 16 K_S lifetimes (hep-ph/0107046)
- **K_S-K_L time independent interference ×3**
  - Assume constructive interference (theoretically preferred)
- **Data Taking ×5**
  - Run in "factory mode". After all E799-II run only for a few months to collect ~7 × 10^{11} K_L decays
- **Beam intensity ×4**
  - Need ~10^{12} protons/sec, slowly extracted, high energy, DC
- **Tot ~ ×240 → sens~ ×15**
  - close the gap between current upper limit and SM
- **Where? When?**

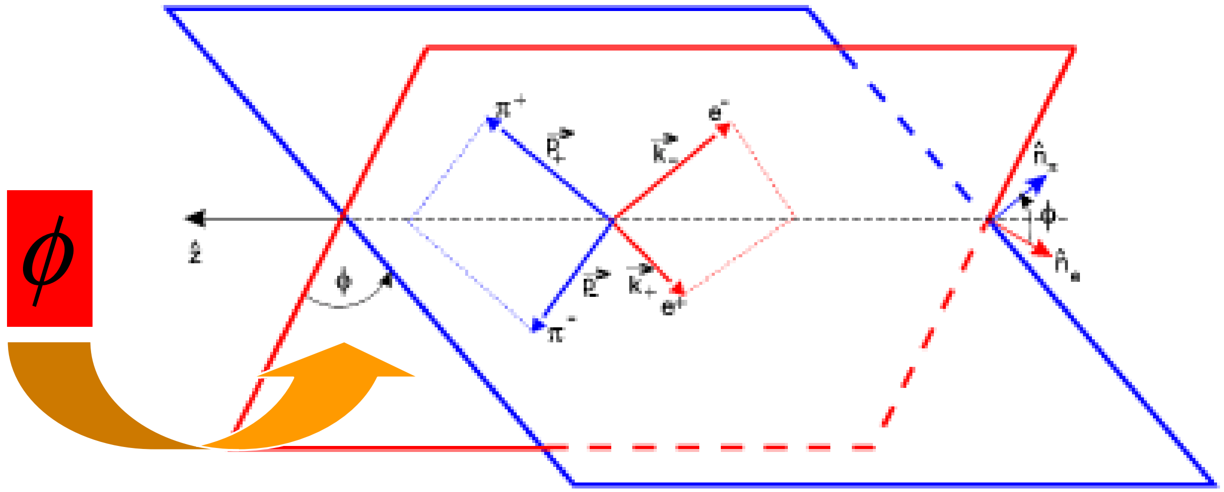
Current Status



STILL A LARGE WINDOW OF OPPORTUNITY EXISTS

Motivation for $K_L \to \pi\pi ee$ measurement

Interference between IB and DE in $K_L \to \pi\pi\gamma^*$ gives rise to CPV asymmetry in φ distribution



$$\frac{d\Gamma}{d\phi} = \Gamma_1 \cos^2\phi + \Gamma_2 \sin^2\phi + \Gamma_3 \sin\phi\cos\phi$$

CP-odd:

$$\mathbf{CP}\left[\sin\phi\cos\phi\right] = -\sin\phi\cos\phi$$

COUNT:

$$N_+ \equiv N(\cos\phi\sin\phi > 0)$$
$$N_- \equiv N(\cos\phi\sin\phi < 0)$$

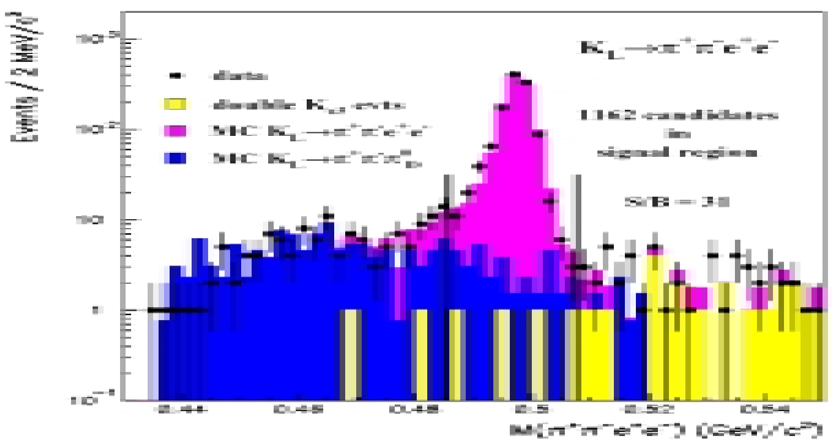
CALCULATE:

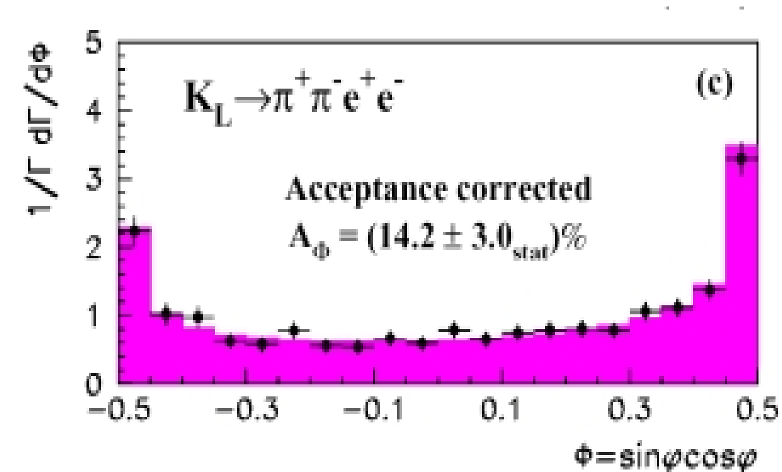
$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

←Predicted: 14%, BR=3.1·10^-7^.

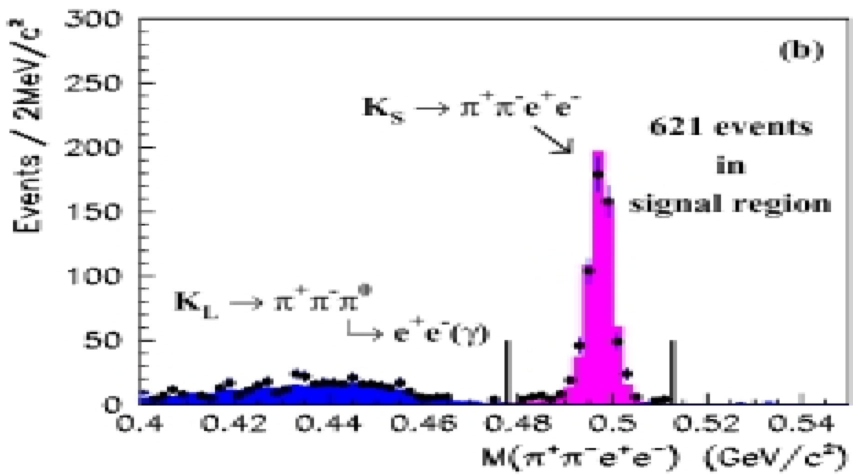
L.M.Sehgal, M.Wanniger, 1992

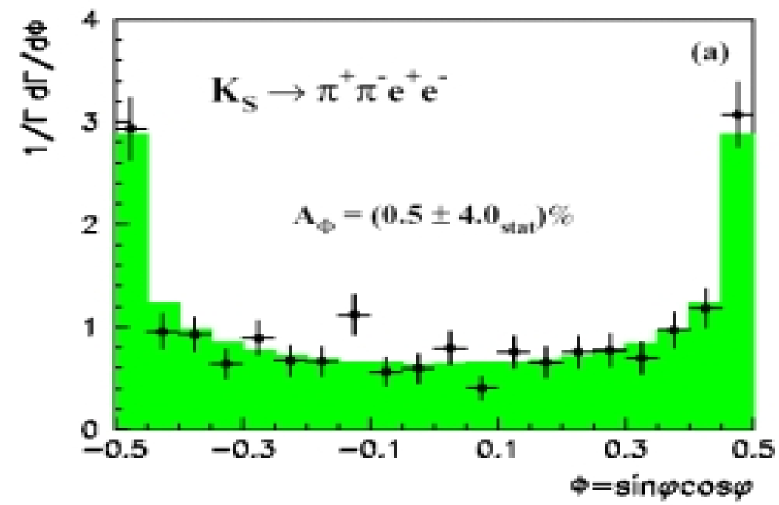
$K_{L,S} \rightarrow \pi\pi ee$





c.f. KTeV (prel): 13.3 ± 1.4 ± 1.0 %





$K_{L,S} \rightarrow \pi\pi ee$ branching ratios

The events are normalised to reconstructed Dalitz decays with the known BR = $(1.5 \pm 0.05) \times 10^{-3}$

K_L :

BR = $(3.08 \pm 0.09_{stat} \pm 0.15_{syst} \pm 0.10_{norm}) \times 10^{-7}$

= $(3.08 \pm 0.20) \times 10^{-7}$

K_S :

621 evts.

BR $_{1999}$= $(4.71 \pm 0.23_{stat} \pm 0.16_{syst} \pm 0.15_{norm}) \times 10^{-5}$

BR $_{1998}$= $(4.5 \pm 0.7_{stat} \pm 0.4_{syst}) \times 10^{-5}$

= $(4.69 \pm 0.30) \times 10^{-5}$

Used to estimate: $BR(K_L \rightarrow \pi\pi ee)_{IB} = (1.4 \pm 0.1) \times 10^{-7}$

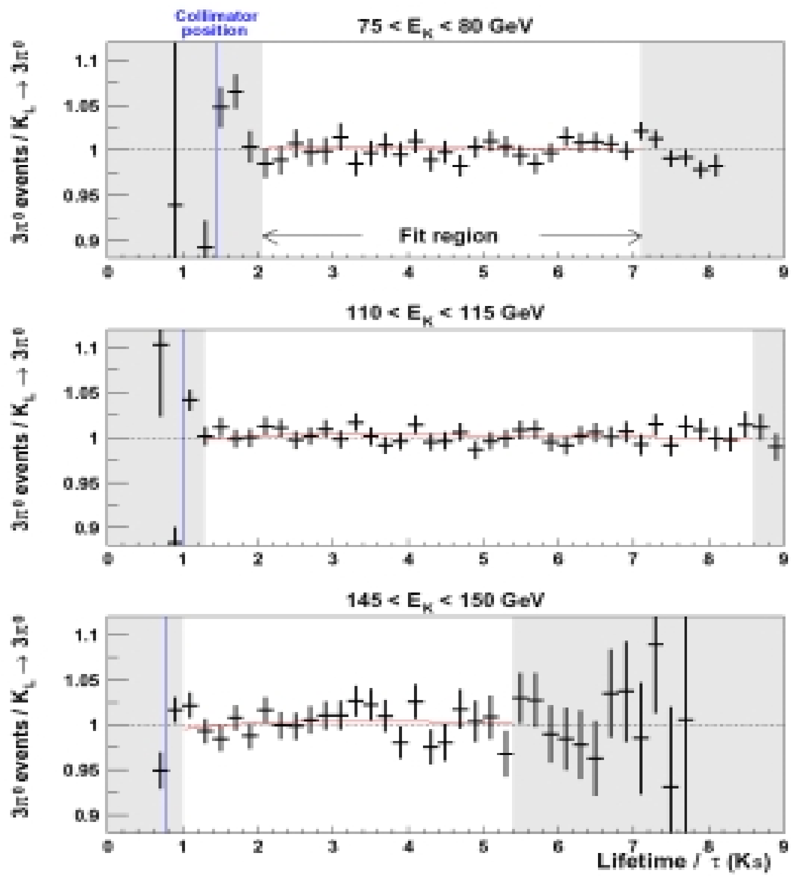
$K_S \to 3\pi^0$

$$\eta_{000} = \frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)}$$

CP-Violating

In SM $\eta_{000} \sim \varepsilon$

- **Near Beam**
  - **NA48/1 (2000) ~6.5 10^6 $3\pi^0$**
- **Far Beam:**
  - **NA48 2000 > 10^7 $K_L \to 3\pi^0$**
  - **To normalise the acceptance**
- **Analysis in bins of energy**

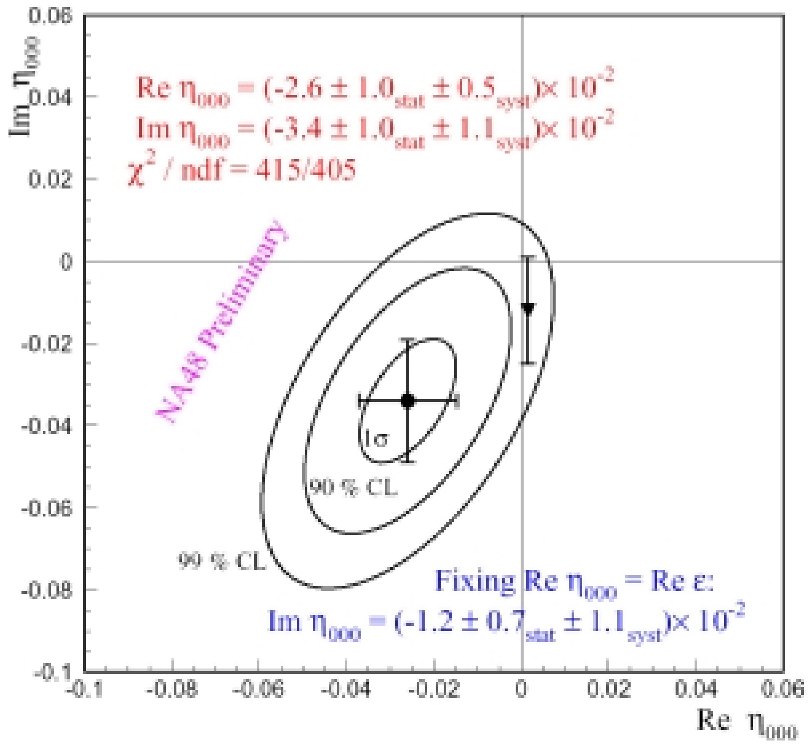


$$f(E,t) = \frac{NEAR}{FAR} =$$

$$A(E)\left[1 + |\eta_{000}|^2 e^{(\Gamma_L - \Gamma_S)t} + 2D(E)e^{\frac{1}{2}(\Gamma_L - \Gamma_S)t}\left(\mathrm{Re}\,\eta_{000}\cos\Delta mt - \mathrm{Im}\,\eta_{000}\sin\Delta mt\right)\right]$$

***D(E)* is the K^0 $\bar{K}^0$ dilution (from NA31)**

$K_S \to 3\pi^0$



CPT TEST: $K_L \sim (\varepsilon+\delta_{CPT})K_1 + K_2$

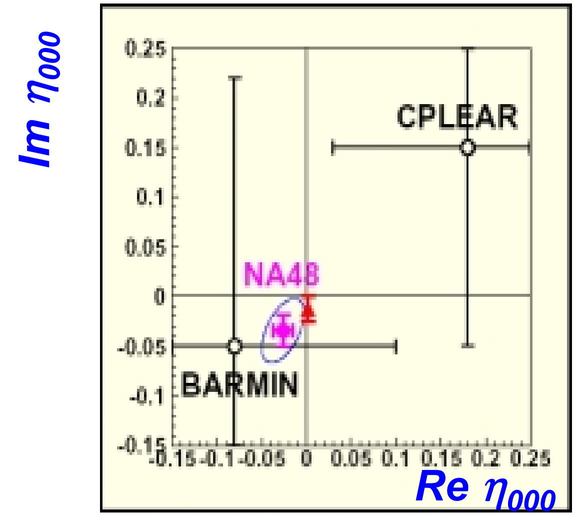
$K_S \sim K_1 + (\varepsilon-\delta_{CPT})K_2$

From the 2 parameter fit, using BS unitarity relation:

$\mathrm{Im}\ \delta_{CPT} = (-1.2 \pm 3.0) \times 10^{-5}$

Assuming CPT conservation in decay:

$M(K^0) - M(\overline{K^0}) = (-1.7 \pm 4.2) \times 10^{-19}\ GeV/c^2$

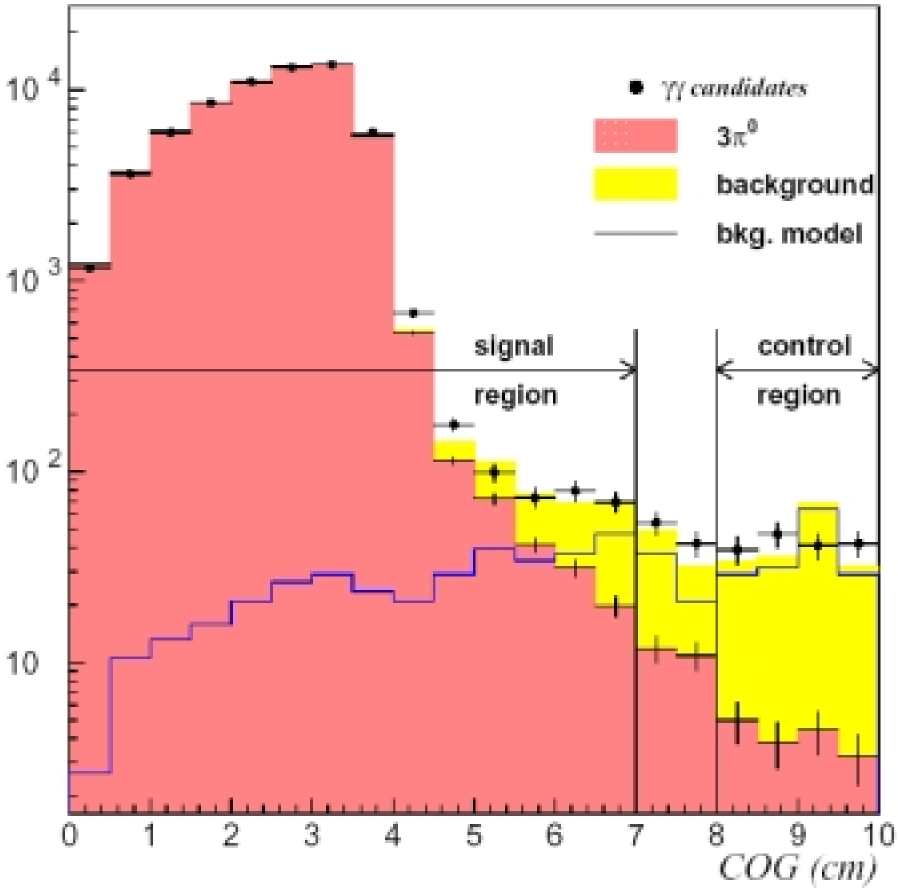


From one parameter fit:

$BR(K_S \to 3\pi^0) < 3.0 \times 10^{-7}$ 90%CL

$BR_{SM} \sim 3 \times 10^{-9}$

$K_L \to \gamma\gamma$

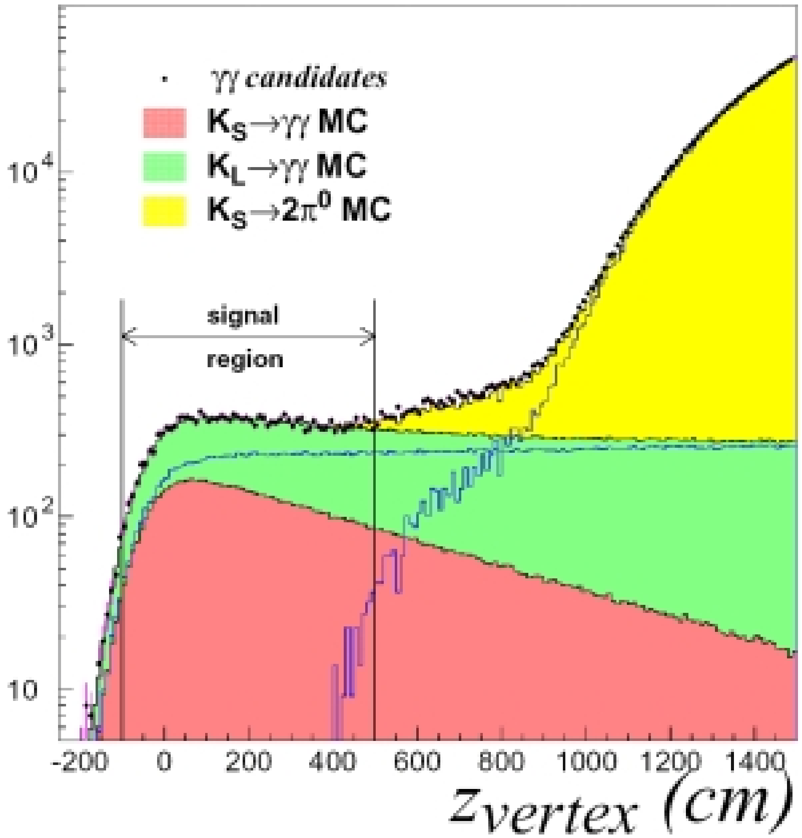


- **Data 2000**
  - sub-sample of K_L data
- **Background:**
  - Hadronic origin
  - 0.6 ± 0.3 %
- **Main systematics:**
  - calorimeter response for the acceptance calculation

$$\Gamma(K_L \to \gamma\gamma) / \Gamma(K_L \to \pi^0\pi^0\pi^0) = (2.81 \pm 0.01_{stat} \pm 0.02_{syst}) \times 10^{-3}$$

4 times better precision than PDG: $(2.77 \pm 0.08) \times 10^{-3}$

$K_S \rightarrow \gamma\gamma$

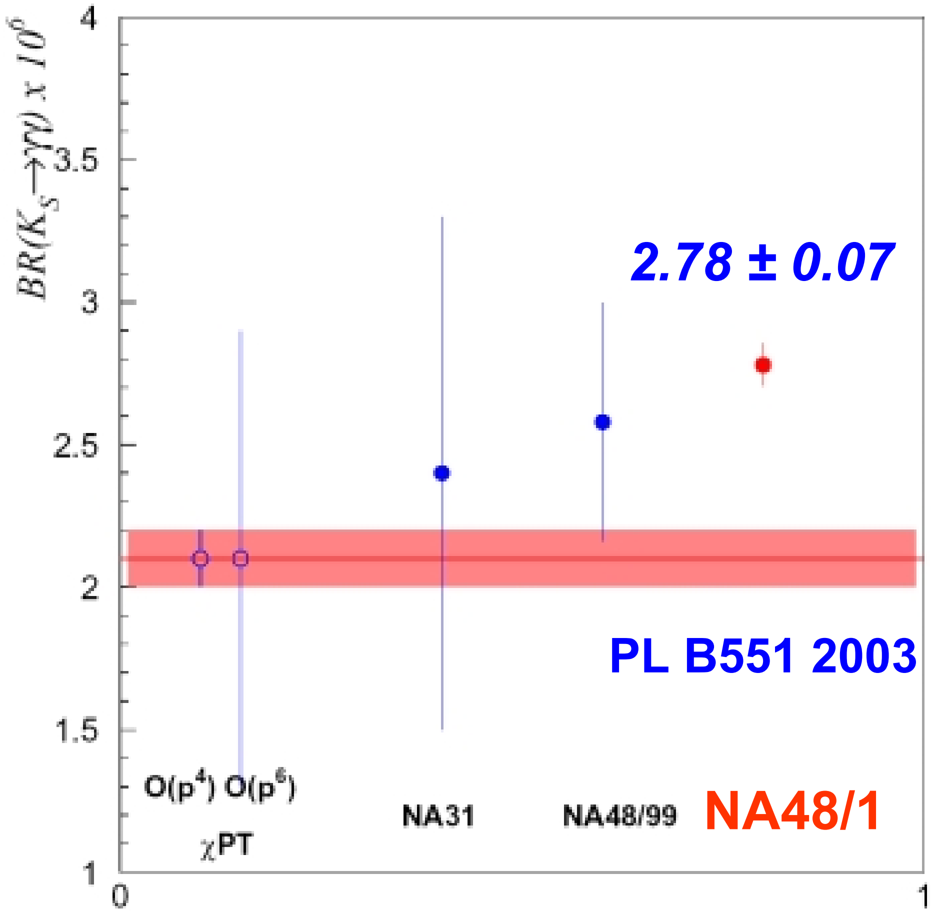


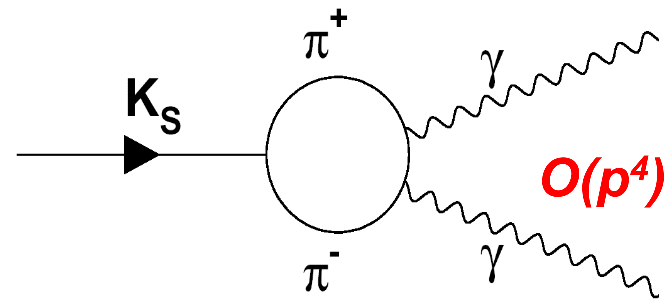
- **Impose m_K to compute decay vertex**
- **Background due to missing particles shifted downstream**
- **Keep short decay region (~5m)**
- **Total background ~ 4%**
- **Subtract $K_L \rightarrow \gamma\gamma$ measuring the $K_L \rightarrow 3\pi^0$ flux and using newly measured $BR(K_L \rightarrow \gamma\gamma)$**

$$BR\,(K_S \rightarrow \gamma\gamma) = (2.78 \pm 0.06_{stat} \pm 0.03_{syst} \pm 0.02_{ext}) \times 10^{-6}$$

PLB 551 (2003)

$K_S \rightarrow \gamma\gamma$ measurements





The NA48/1 result has an accuracy better than 3%

It differs by 30% from $O(p^4)$ prediction of CHPT

Used to fix one $O(p^6)$ counterterm:

$8m_K^2/F_\pi^2\, a_1 = 1.0 \pm 0.3$

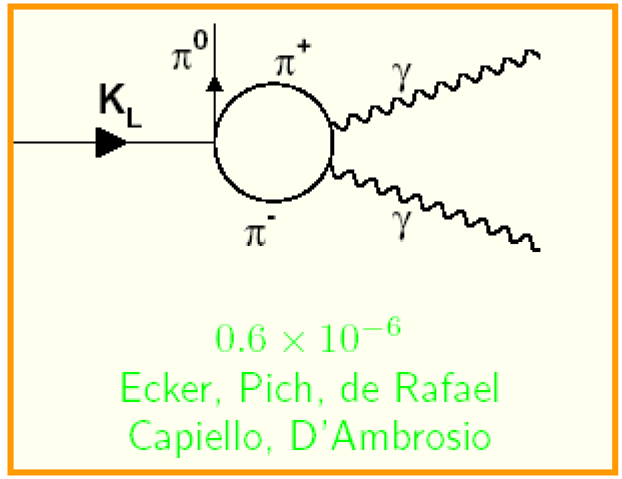
BDI (hep-ph/0308008)

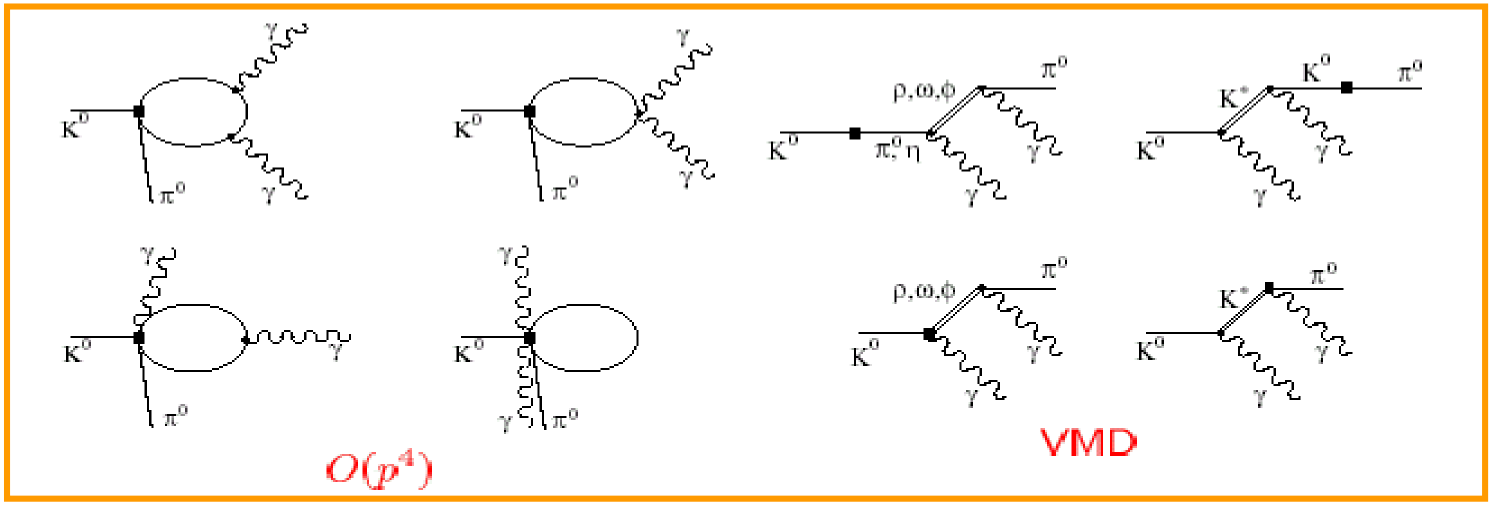
$K_L \to \pi^0\gamma\gamma$ decay

- Only 1/3 of the measured $K_L \to \pi^0\gamma\gamma$ rate is predicted by $O(p^4)$.

• The rate can be reproduced at $O(p^6)$ including vector mesons exchange.

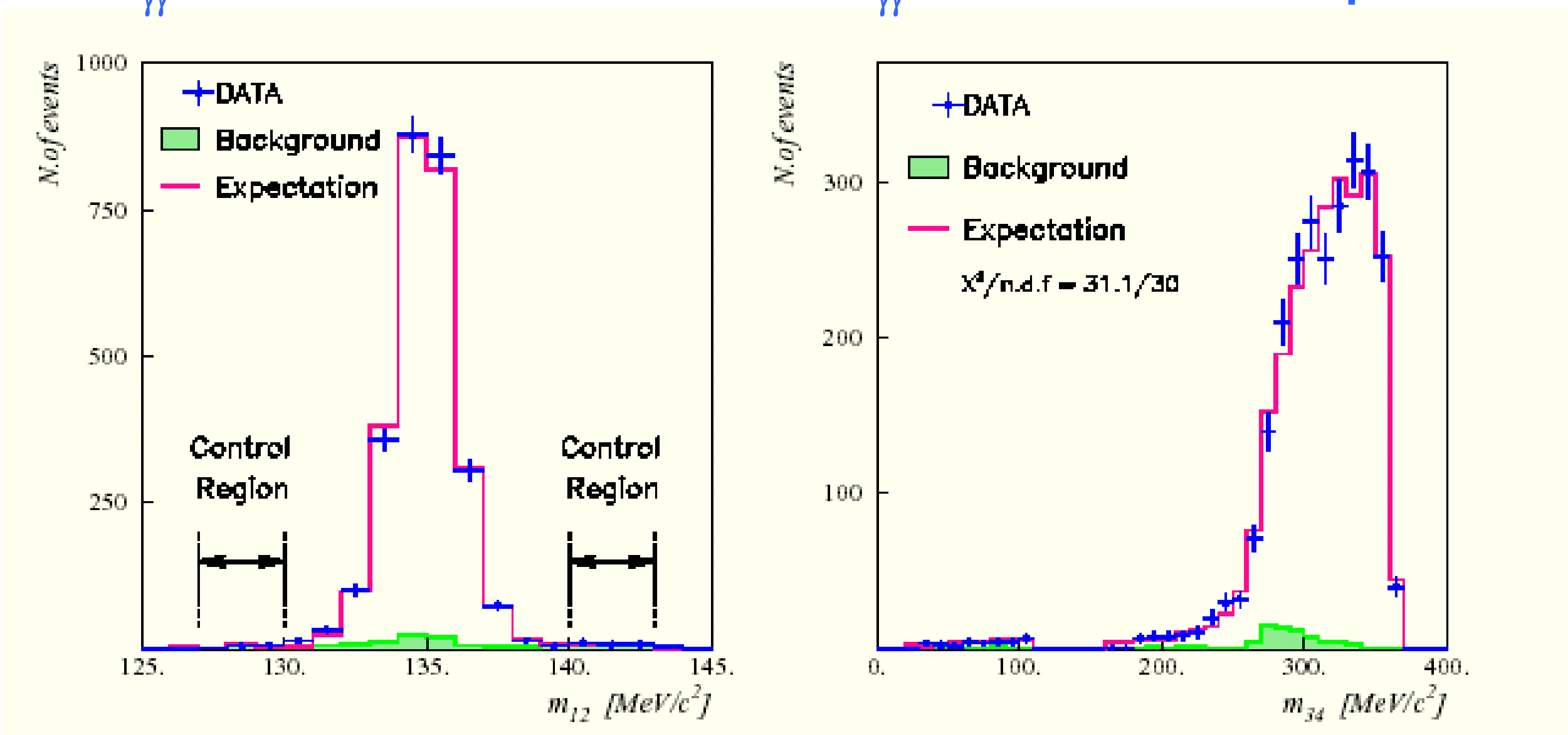
• The VMD contribution is parametrised by a_V , which has to be experimentally determinated.





$K_L \rightarrow \pi^0 \gamma \gamma$

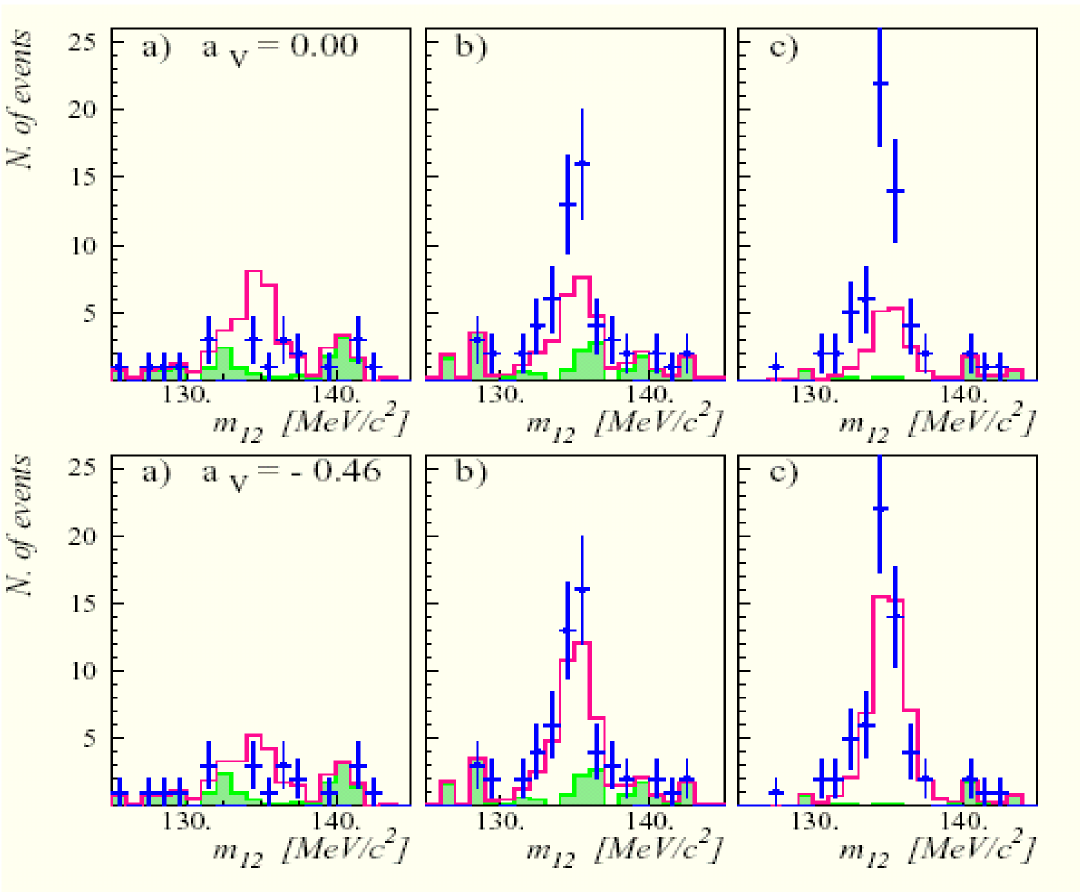
$m_{\gamma\gamma}$ for the π^0 candidates $\quad$ $m_{\gamma\gamma}$ for the two non- π^0 photons



$a_V = -0.46 \pm 0.03_{stat} \pm 0.04_{syst}$

$BR(K_L \rightarrow \pi^0 \gamma \gamma) = (1.36 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.03_{norm}) \times 10^{-6}$

$K_L \to \pi^0 \gamma \gamma$



$m_{34} \in$ [30-110] $m_{34} \in$ [160-240] $m_{34} \in$ [240-260]

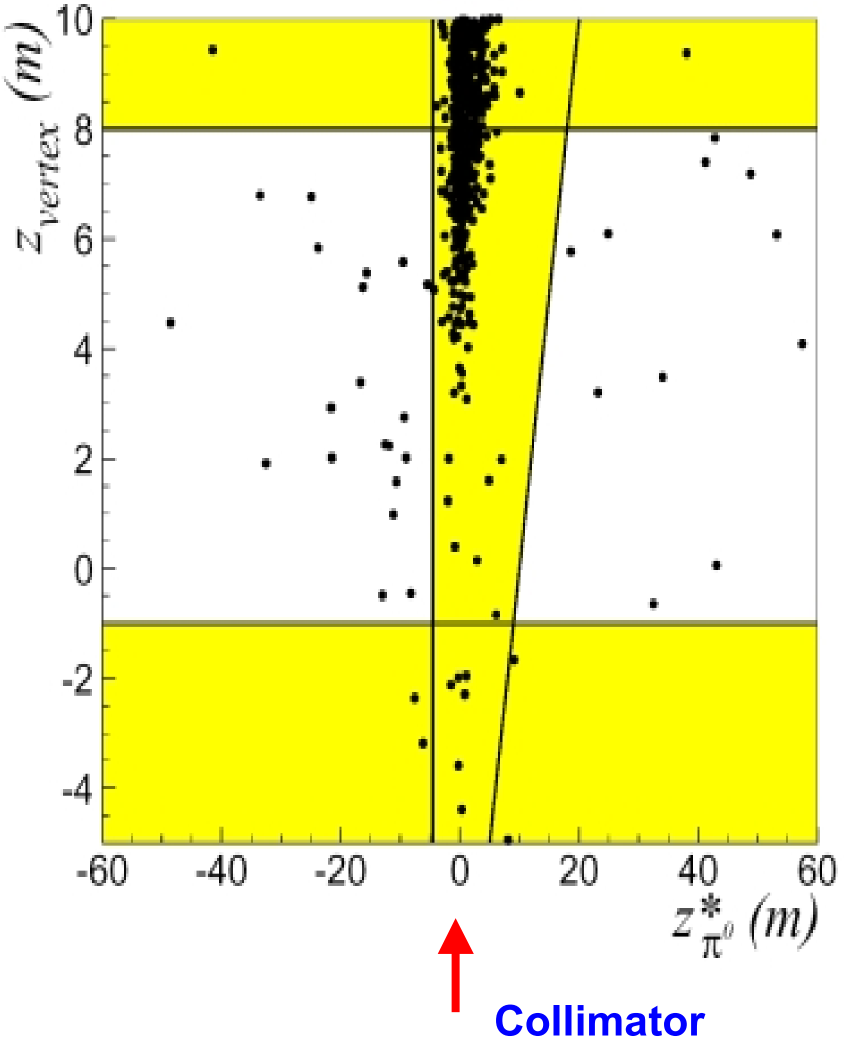
$\Rightarrow$ Implies very small CP conserving amplitude in $K_L \to \pi^0 e+e-$

KTeV results (PRL 83 (99) 917):

$$a_v = -0.72 \pm 0.05_{stat} \pm 0.06_{syst}$$
$$BR(K_L \to \pi^0 \gamma\gamma) = (1.68 \pm 0.07_{stat} \pm 0.08_{syst}) \times 10^{-6}$$

$K_S \rightarrow \pi^0\gamma\gamma$

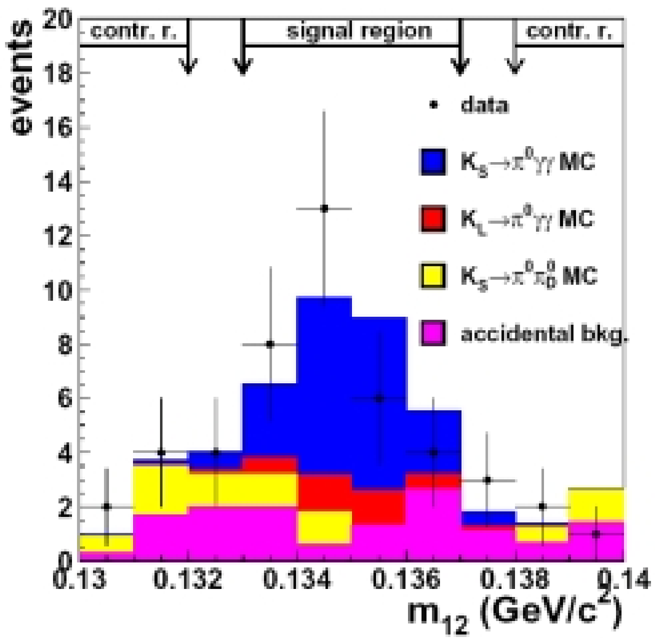
- The rejection of the Dalitz decays is complicated since no drift chambers were available during Y2K
- Fiducial region: -1↔8 m
- $Z^*_{\pi 0}$ = vertex reconstructed pairing 2 γ assuming π^0 mass
- Impose m_K to reconstruct decay vertex
- Events from Kaon decays with missing particles are reconstructed downstream

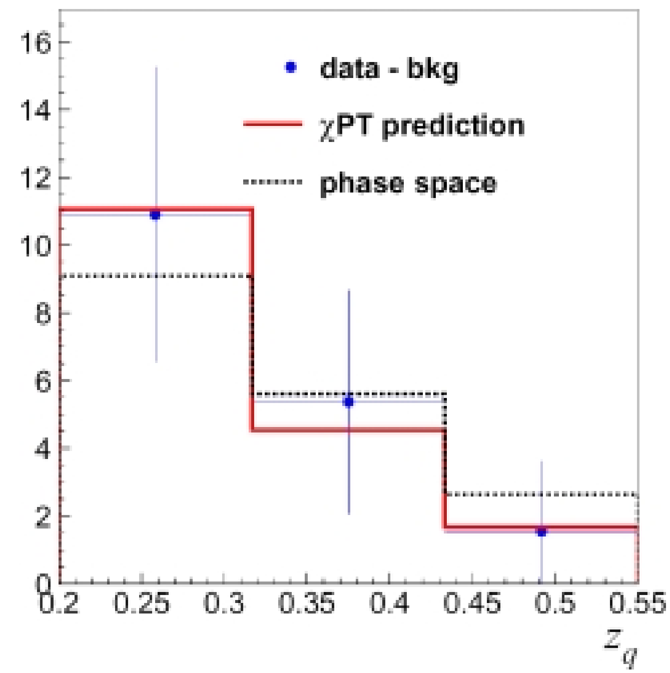


$K_S \rightarrow \pi^0 \gamma \gamma$

first observation

CERN-EP/2003-052 (hep-ex/0309022)





$Z_q = q^2/M_K^2$

$$BR(K_S \rightarrow \pi^0 \gamma\gamma, z_q > 0.2) = (4.9 \pm 1.6_{stat} \pm 0.9_{syst}) \times 10^{-8}$$

CHPT predicts (Ecker, Pich and De Rafael, PLB 189 1987):

$$BR(K_S \rightarrow \pi^0 \gamma \gamma)_{zq > 0.2} = 3.8 \times 10^{-8}$$

Outlook

- **NA48**
  - ε'/ε
    - **Experiment is complete:** Direct CP-violation demonstrated to >6 standard deviations **Re ε'/ε = 14.7 ± 2.2 × 10^{-4}**
  - **Rare K_L decays**
    - expects results on K_L Dalitz decays ($K_L \to ee\gamma$, $K_L \to eeee$) and *Ke4*
- **NA48/1**
  - Expect new results soon, in particular:
    - $K_S \to \pi^0 \mu\mu$ **(VERY SOON!)**
    - **Semi-leptonic Neutral Cascade decays**
- **NA48/2**
  - charged kaons (see Marco Sozzi's report)
- **NA48/3 ??**
  - CERN is currently the only place where high energy kaon beams could be employed to exploit:
    - **Very good energy resolution** (essential for $K_L \to \pi^0 ee$ ($\mu\mu$))
    - **Very good photon vetoing** (essential for $K \to \pi \nu\nu$)

Why study Rare Kaon Decays

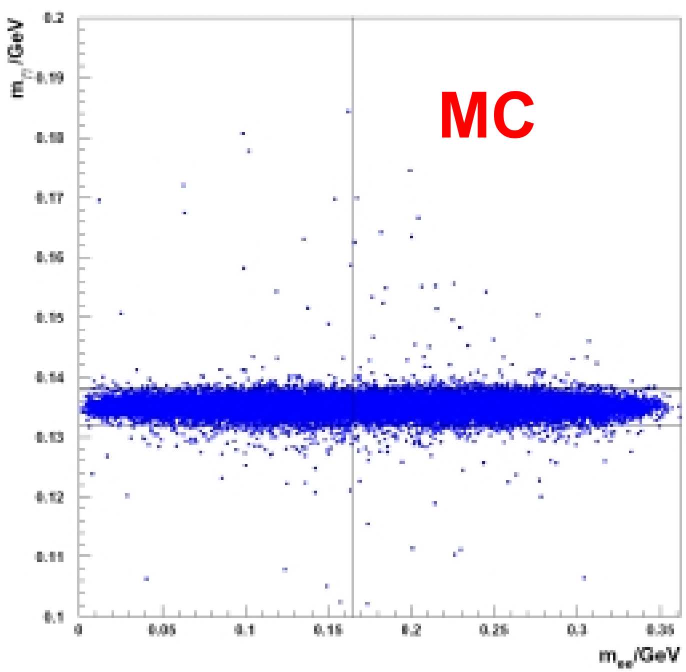
- Search for explicit violation of Standard Model
  - Lepton Flavour Violation (e.g. BNL-E865, BNL-E871)
- Probe the flavour sector of the Standard Model
  - FCNC (e.g. BNL-E787)
- Test fundamental symmetries
  - CP, CPT
- Study the strong interactions at low energy
  - Chiral Perturbation Theory

- I will give a review of recent results obtained by NA48 (K_L) and NA48/1 (K_S)
  - K_S rare decays ($BR \leq 10^{-8}$) start to be studied

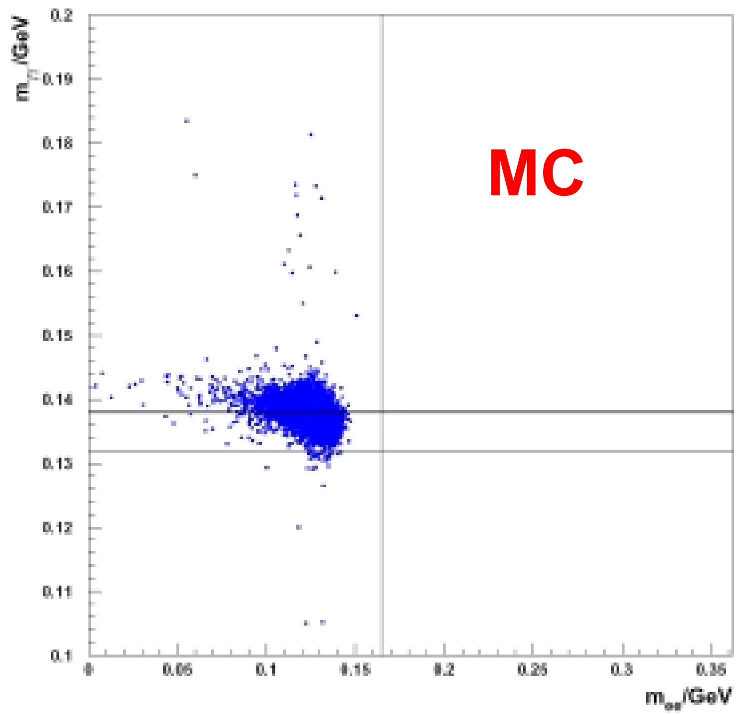
Spare Material

$K_S \rightarrow \pi^0\ ee$

$K_S \rightarrow \pi^0\ ee$



$K_S \rightarrow \pi^0\ \pi^0_D \rightarrow \gamma\gamma ee(\gamma)$



- **To reject the $K_S \rightarrow \pi^0\ \pi^0_D$ decays that may mimic $K_S \rightarrow \pi^0\ ee$ if a γ is lost, a cut $m_{ee} > 0.165\ GeV/c^2$ is applied**

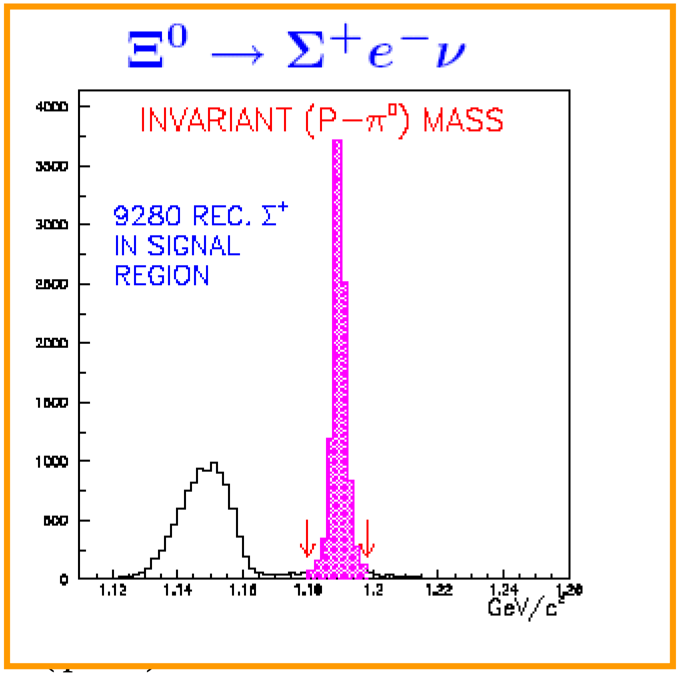
Chiral Perturbation Theory

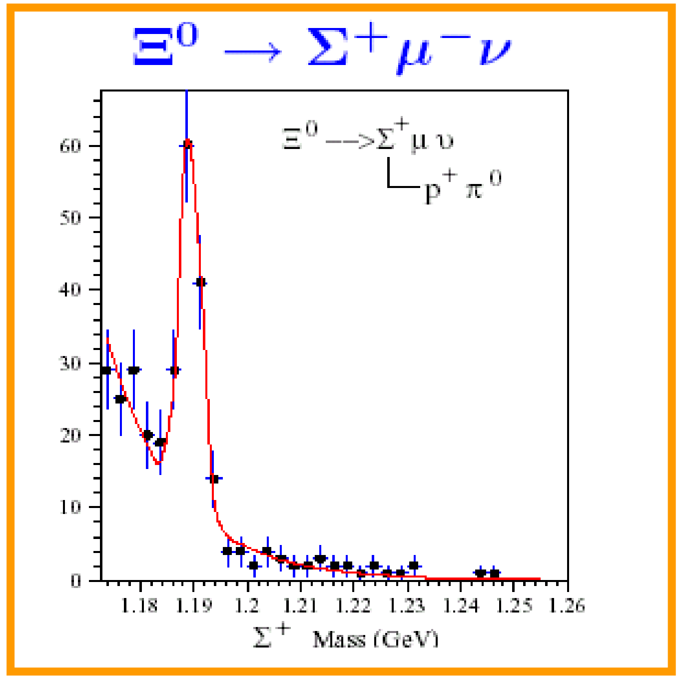
- ChPT is the effective field theory of the Standard Model at low energy (E <1 GeV region of non-perturbative QCD)
- Chiral symmetry of the QCD Lagrangian is spontaneously broken

$\Rightarrow$ degree of freedom of the theory are eight pseudoscalar Goldstone bosons (π, η, K)

- Processes described in perturbative expansion of momenta and masses
- Higher order boson loops are divergent, but compensated by counter-terms with (empirically determinated) effective couplings
- $K_{L,S} \to \pi^0 \gamma \gamma$, $K_{L,S} \to \gamma\gamma$ are good tools to probe ChPT

Ξ^0 beta decays : $\Xi^0 \rightarrow \Sigma l \nu$



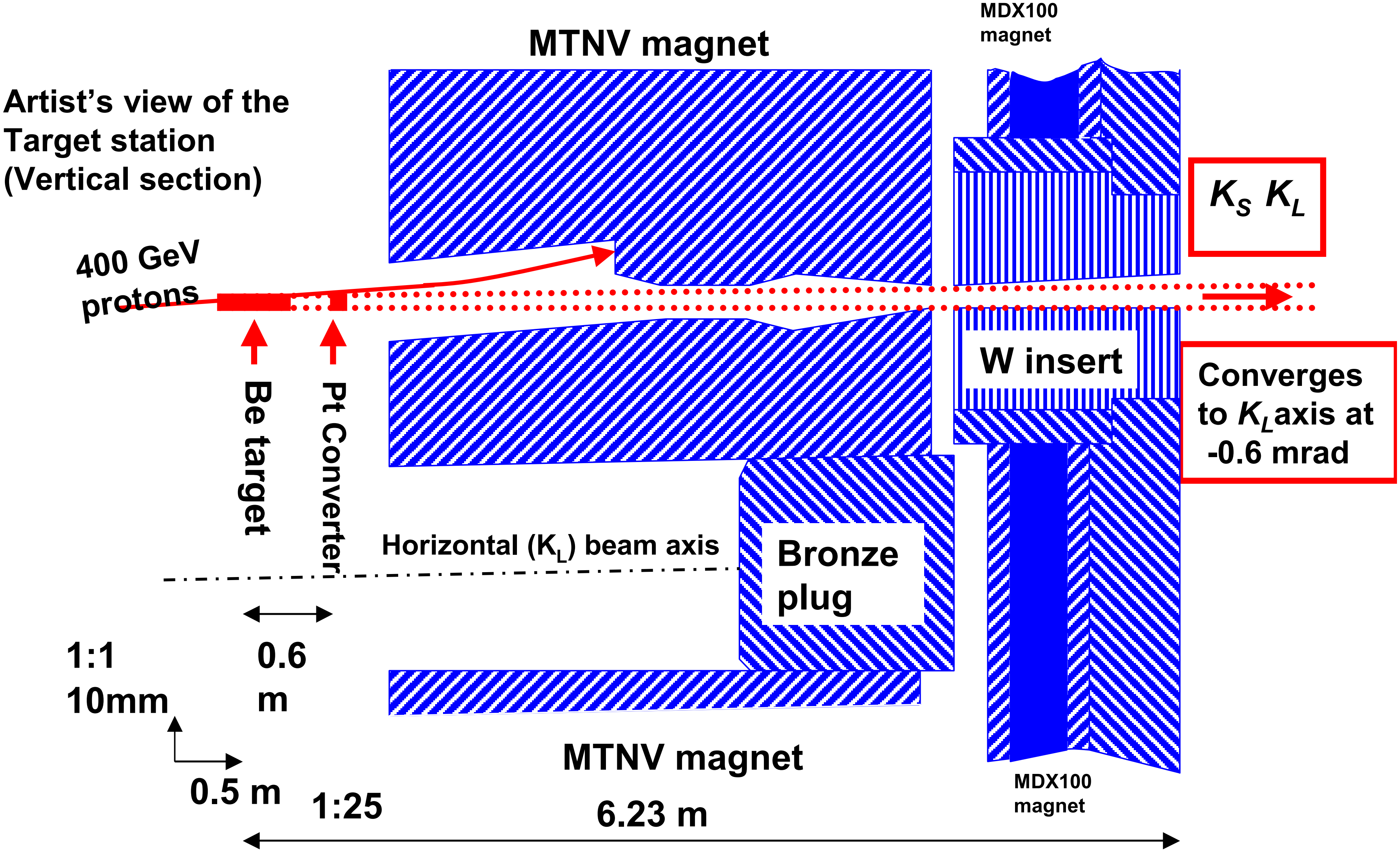


Study the rate and the form-factors (V_{us})

- **Run 2002 not optimized for hyperons**
- $\Xi^0 \rightarrow \Sigma e \nu$ **clean sample: Signal/Back ~ 40, ~9000 events after cuts**

  Currently published sample (KTeV): BR 176 evts, FF 487
- $\Xi^0 \rightarrow \Sigma \mu\nu$ **first experimental evidence**

CERN-NA48/1: High Intensity K_S



$K_L \to \pi^0 \gamma \gamma$

Rare process without a clear signature. Data from 1998 and 1999 ε'/ε runs.

- Background sources :
  - $K_L \to \pi^0 \pi^0$ with mis-reconstructed showers; m_{π^0} mass cut ; residual background evaluated from the tagged $K_S \to \pi^0 \pi^0$ events (0.16 ± 0.08) %
  - $K_L \to \pi^0 \pi^0 \pi^0$ with missing or overlapping showers; shower width cut and vertex position cut assuming background hypothesis; residual background evaluated from a MC sample of 3×10^9 events (2.74 ± 0.42) %
  - pile-up events e.g. two decays occuring within 3 ns; quantified from the tails of the R_{cog} distribution from good $\pi^0 \pi^0$ events (0.32 ± 0.21) %

NA48: all ε'/ε results

From 2001 data:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (13.7 \pm 2.5_{\mathrm{stat}} \pm 1.1_{\mathrm{syst,stat}} \pm 1.5_{\mathrm{syst}}) \times 10^{-4}$$

Combining with 97+98+99 result

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 1.6_{\mathrm{stat}} \pm 1.3_{\mathrm{syst,stat}} \pm 1.6_{\mathrm{syst}}) \times 10^{-4}$$

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 1.3_{\mathrm{stat}} \pm 1.0_{\mathrm{syst,stat}} \pm 1.5_{\mathrm{syst}}) \times 10^{-4}}$$

NA48 (2001): systematics on R

Table 1
Corrections and systematic uncertainties on the double ratio R (2001 data)

		in 10^{-4}	
$\pi^+\pi^-$ trigger inefficiency	+5.2	±3.6	(stat)
AKS inefficiency	+1.2	±0.3	
Reconstruction of $\pi^0\pi^0$	–	±5.3	
Reconstruction of $\pi^+\pi^-$	–	±2.8	
Background to $\pi^0\pi^0$	−5.6	±2.0	
Background to $\pi^+\pi^-$	+14.2	±3.0	
Beam scattering	−8.8	±2.0	
Accidental tagging	+6.9	±2.8	(stat)
Tagging inefficiency	–	±3.0	
Acceptance statistical	+21.9	±3.5	(stat)
Acceptance systematic	+21.9	±4.0	
Accidental activity intensity difference	–	±1.1	
Accidental activity illumination difference	–	±3.0	(stat)
K_S in time activity	–	±1.0	
Total	+35.0	±11.0	

Conclusions

- The field of kaon rare decays is **quite active**
- New experimental initiatives are **planned**
- Significant tests of the SM are to be expected **by the end of the decade**

High Energy Frontier ⟷ Rare Processes

SM Master Formula for ε'/ε

$$\frac{\varepsilon'}{\varepsilon} = e^{i\phi} \frac{G_F \omega}{2|\varepsilon| \mathrm{Re} A_0} \mathrm{Im}\lambda_t \left[\Pi_0 (1-\Omega_{IB}) - \frac{1}{\omega} \Pi_2 \right]$$

$$\omega = \frac{A(K_S \to \pi\pi, I=2)}{A(K_S \to \pi\pi, I=0)} \approx 0.045 \qquad \phi = \frac{\pi}{2} + \delta_2 - \delta_0 \approx 0^\circ$$

$$\Pi_0 = \frac{1}{\cos\delta_0} \sum_i y_i \mathrm{Re} \langle Q_i \rangle_0 \qquad \Pi_2 = \frac{1}{\cos\delta_2} \sum_i y_i \mathrm{Re} \langle Q_i \rangle 2$$

•1976 Ellis, Gaillard and Nanopoulos: **ε'/ε > 0 is expected in the CKM description**

•**Gluonic Pinguins can lead to large ε'/ε**

•**Large top mass → contribution of EW Pinguins leads to cancellations**

•Short distance physics is in the Wilson Coefficients y_i computed to NLO (Buras et al., Martinelli et al.)

•Low energy physics in the hadronic matrix elements Q_i: to be reliably calculated by lattice QCD WHEN?

•Current Predictions of ε'/ε in SM range from –4 to +40 $\times 10^{-4}$

CP-Violation in SM

A phase in the quark-quark current leads to CP-Violation (Kobayashi, Maskawa, 1973)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$N_g=2$ $N_{phase}=0$ $\Rightarrow$ No CP-Violation

$N_g=3$ $N_{phase}=1$ $\Rightarrow$ CP-Violation Possible

$$\sum_{i=u,c,t} V_{ij} V_{ik}{}^* = \sum_{i=u,c,t} V_{ji}{}^* V_{ki} = \delta_{jk}$$

6 unitarity relations (triangles in the complex plane)

$J_{CP}=2\times$(Triangle Area) Is the unique measure of CP-Violation in SM

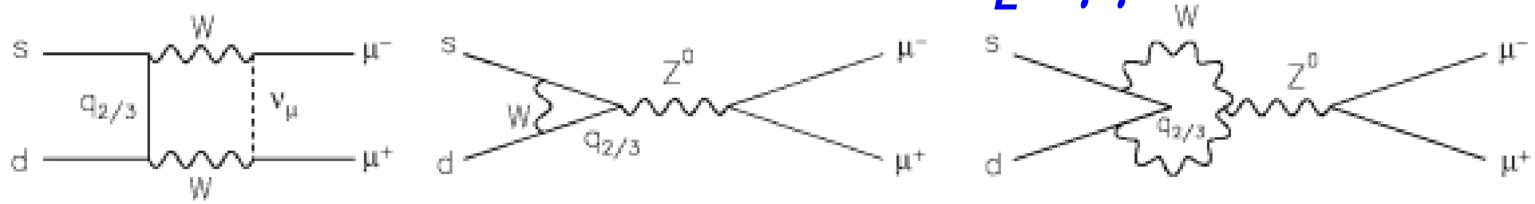
$$J_{CP} = \mathrm{Im}(V_{ud}^* V_{us} V_{ts}^* V_{td}) = \mathrm{Im}(\lambda_u^* \lambda_t) \sim \sin\theta_c \cos\theta_c \, \mathrm{Im}(\lambda_t)$$

Consistency of CKM picture

- **Paradigm shift:**
  - **Old question:** **(before the ε'/ε and $B \rightarrow J/\Psi K_s$ asymmetry measurements):**
    - **Is CKM the source of CP-violation?**
  - **New question:**
    - **Is CKM the only source of CP-violation?**
- **Decisive tests must have small theoretical errors**
  - **The opportunity is to compare information from *K* rare decays and *B* mesons**

Kaon Dalitz decays: Motivation

Short distance contributions to $K_L \rightarrow \mu\mu$ sensitive to *Re* λ_t

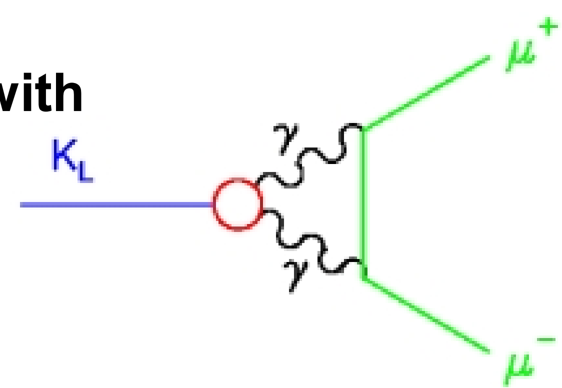


$$B_{SD}(K_L \rightarrow \mu\mu) = \frac{\tau_{K_L}}{\tau_{K^+}} \frac{\alpha^2 B(K_{\mu 2})}{\pi^2 \sin^4\theta_W |V_{us}|^2} |Y_c \,\mathrm{Re}\lambda_c + Y_t \,\mathrm{Re}\lambda_t|^2 = 1.51\times 10^{-9} A^4 (\rho_0 - \bar{\rho})^2$$

Buchalla & Buras 1994

Long distance contributions:

- **Absorptive part** ***(Im Aγγ)*** **is dominant (2 real photons)**
- **Dispersive part** ***(Re Aγγ)*** **depends on the** ***K-γ*γ(*)*** **form factors that can be studied with the Dalitz decays:**
  - **Is much less under control**
  - **Can interfere with the SD piece**



Form Factors $K\gamma^*\gamma^{(*)}$

- **BMS (Bergström, Massó, Singer, 1983)**

$$f(q^2,0)_{BMS} = 1 + (1 - 3.1\alpha_K^*)\frac{q^2}{m_\rho^2} + O((q^2)^2/m_\rho^4)$$

- **DIP (D'Ambrosio, Isidori, Portoles, 1997)**

$$f(q_1^2,q_2^2)_{DIP} = 1 + \alpha\left(\frac{q_1^2}{q_1^2 - m_\rho^2} + \frac{q_2^2}{q_2^2 - m_\rho^2}\right) + \beta\frac{q_1^2 q_2^2}{(q_1^2 - m_\rho^2)(q_2^2 - m_\rho^2)}$$

$$\alpha = -1 + (3.1 \pm 0.5)\alpha_K^*$$

$K_L \rightarrow \pi^0\ \nu\ \nu$ (reminder)

- Theoretical error ~2%:
  - Purely CP-Violating (Littenberg, 1989)
  - Totally dominated from t-quark
  - Computed to NLO in QCD (e.g. Buchalla Buras, 1999)
  - No long distance contribution SM~3 × 10^{-11}

- Experimentally: 2/3 invisible final state !!
- Best limit from KTeV using $\pi^0 \rightarrow ee\gamma$ decay

$BR(K^0 \rightarrow \pi^0 \nu\nu) < 5.9 \times 10^{-7}$ 90% CL

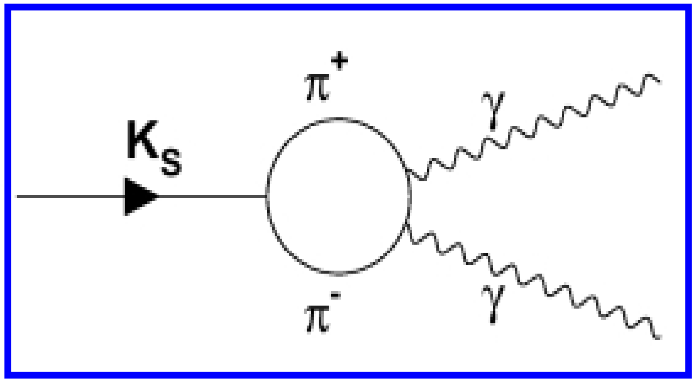
Still far from the model independent limit:

$BR(K^0 \rightarrow \pi^0 \nu\nu) < 4.4 \times BR(K^+ \rightarrow \pi^+ \nu\nu) \sim 7 \times 10^{-9}$

Grossman & Nir, PL B407 (1997)

NA48/1 $K_S \to \gamma\gamma$

- Decays into neutral final states : *$O(p^2) = 0$*



- $O(p^4)$ unambiguosly predicted by ChPT loop diagram to better than 5% without counter terms:
  Theory: *$BR(K_S \to \gamma\gamma, O(p^4))=2.1\ 10^{-6}$*

- Older NA48 measurement of $K_S \to \gamma\gamma$ branching ratio based on 2 days of test-run in 1999 with high intensity K_S :
  $(2.6 \pm 0.4) \times 10^{-6}$ PLB 493 (2000)

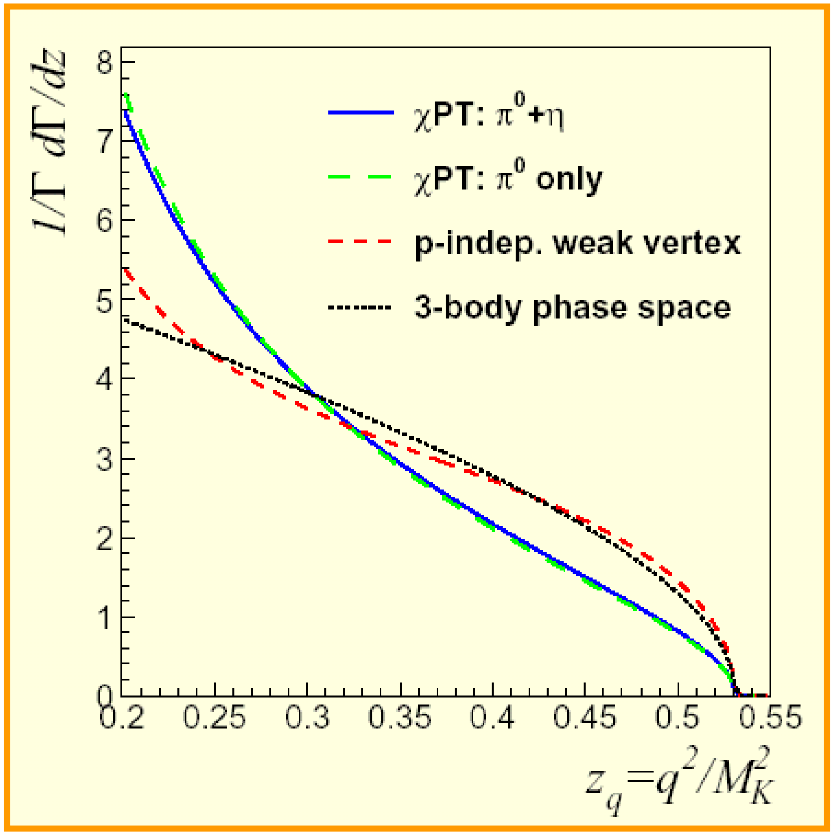
No indication of $O(p^6)$ contributions

NA48/1: $K_S \to \pi^0 \gamma \gamma$

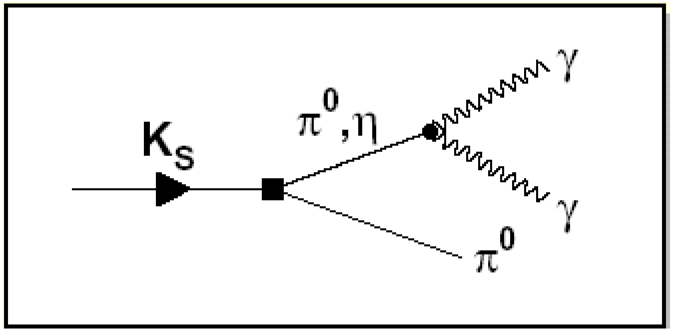
- **Previous limit (NA48):**

  BR($K_S \to \pi^0 \gamma \gamma$, $z_q > 0.2$) < 3.3×10^{-7} at 90% CL

- **ChPT predicts (Ecker, Pich, De Rafael - PLB 189 (1987)):**



BR($K_S \to \pi^0 \gamma \gamma$)$_{zq > 0.2}$ = 3.8×10^{-8}

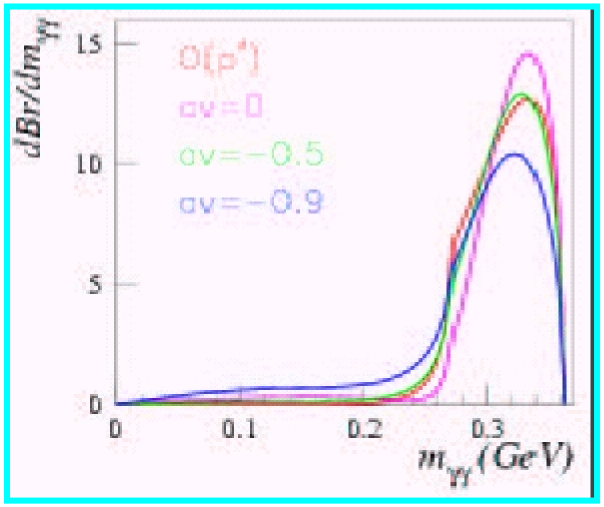


- **momentum dependence of the weak vertex**

→ **Chiral structure of the weak vertex can be tested from $z_q = (m_{34}/m_K)^2$ distribution**

$K_L \rightarrow \pi^0 \gamma \gamma$

The a_v can be extracted from the tail
$m_{\gamma\gamma} < 2\, m_{\pi 0}$

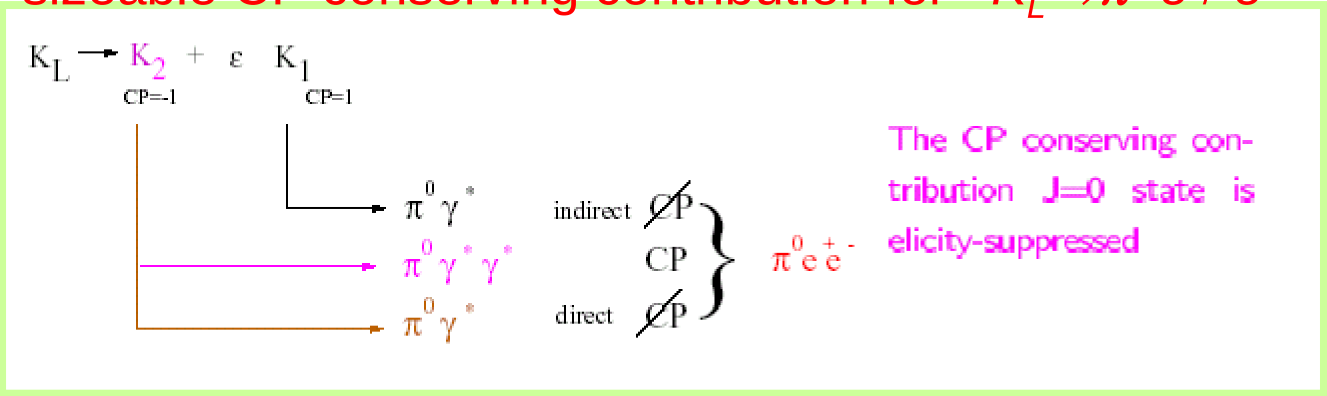


- **The a_v contribution leads to a CP conserving**
- **component to $K_L \rightarrow \pi^0\, e+\, e-$:**

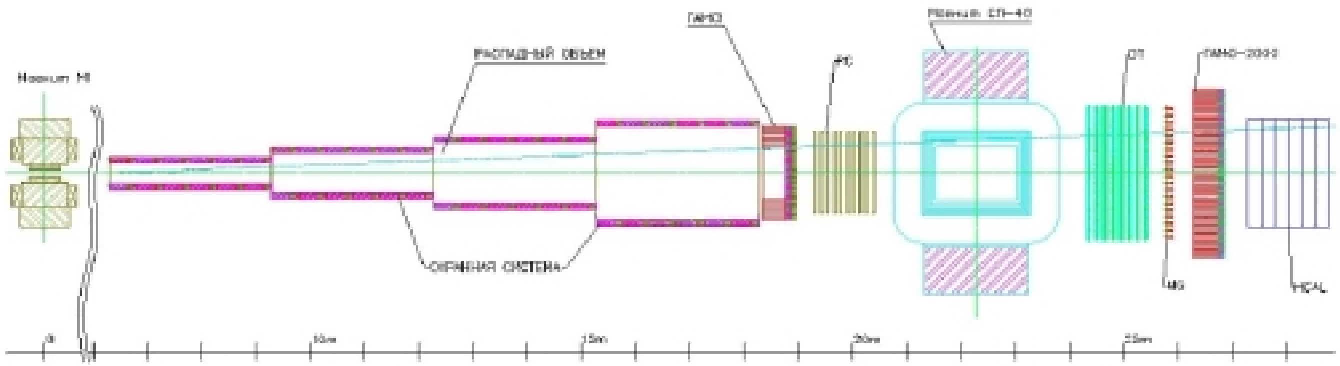
•BR($K_L \rightarrow \pi^0\, e+\, e-$)$_{CPC}$ = 1.24×10^{-12} for a_v = - 0.7
D'Ambrosio, Portoles NP B492 417

- The VMD mechanism could enhance the state J=2 for the two photons

⇨ sizeable CP conserving contribution for $K_L \rightarrow \pi^0\, e+\, e-$

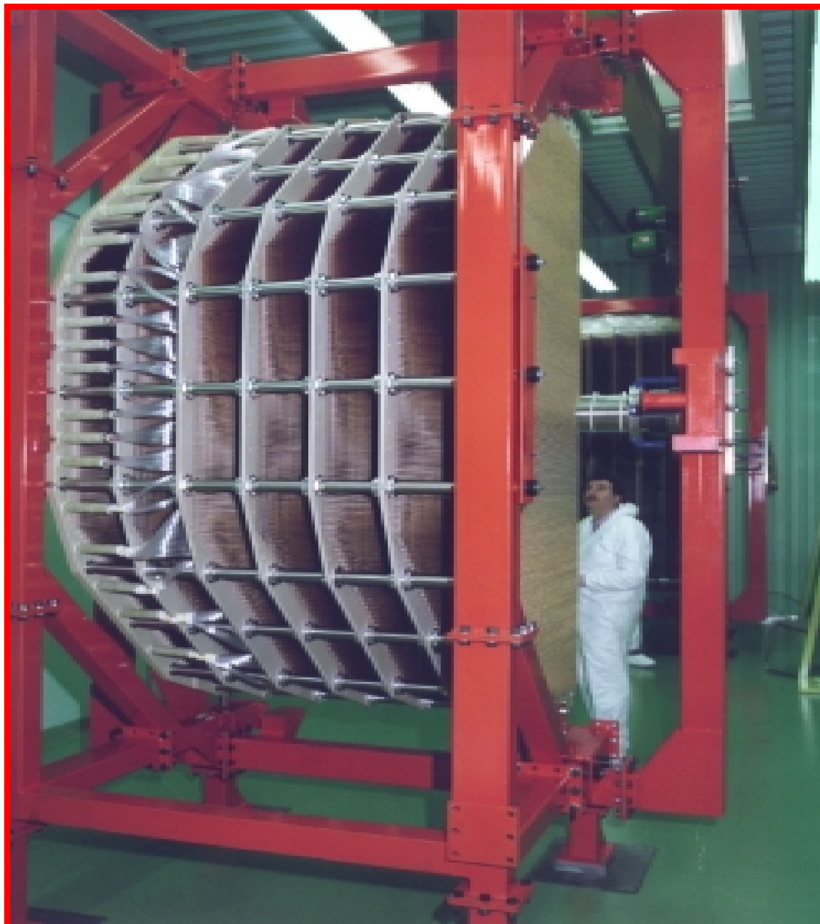


OKA @ Protvino - $K^{\pm}$

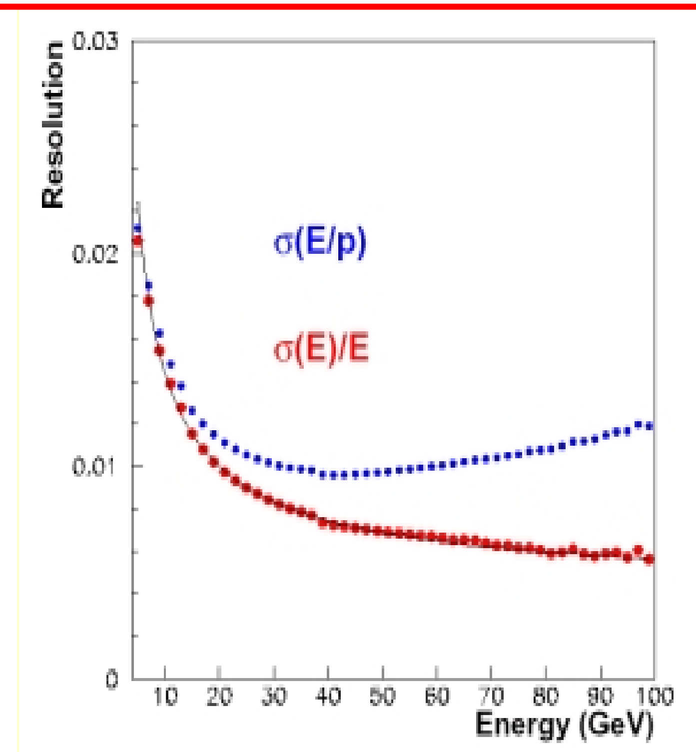


New RF-separated beam at U-70 PS in construction
15 GeV/c kaons, alternating K^+ or K^-
Magnetic detector evolved from ISTRA+, GAMS
In preparation, expected 2004
Measurement of 3π Dalitz plot asymmetries @ 1×10^{-4}
T-odd correlations, search for New Physics in K_{l2} decays

Liquid Krypton Calorimeter



9 m^3 of Lkr (13212 cells)
1.25 m deph (27 X_0)



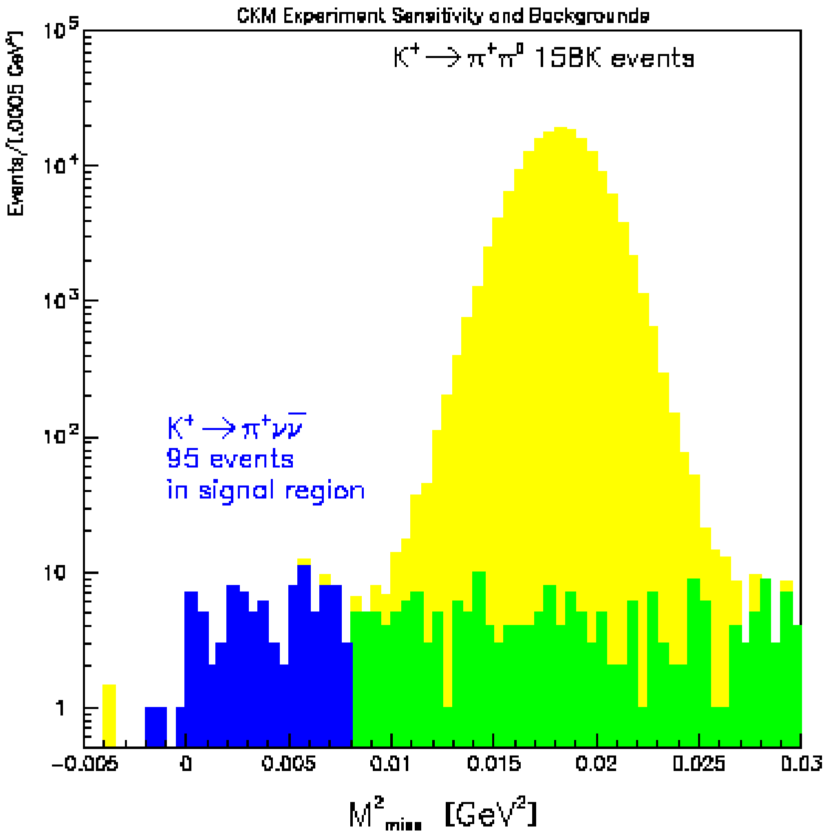
$\sigma(E)/E = 3.2\%/\sqrt{E} \oplus 9\ \%/E \oplus 0.42\%$

$\sigma(m_{\gamma\gamma})\sim 1\ MeV/c^2\ ; \sigma(t) \sim 600\ ps$

CKM@FNAL-MI (2009)

- **SCRF 13 cell cavity**
  - Built full size prototype
- **Photon vetoes**
  - Measured inefficiency for 1GeV γ: 5×10^{-6}
  - ×6 better than needed
- **Straw tubes**
  - Demonstrated operation in vacuum
  - Same preformance as in air
- **Simulation of "triggerless DAQ"**
- **Awaiting approval ratification by P5**

From CKM proposal



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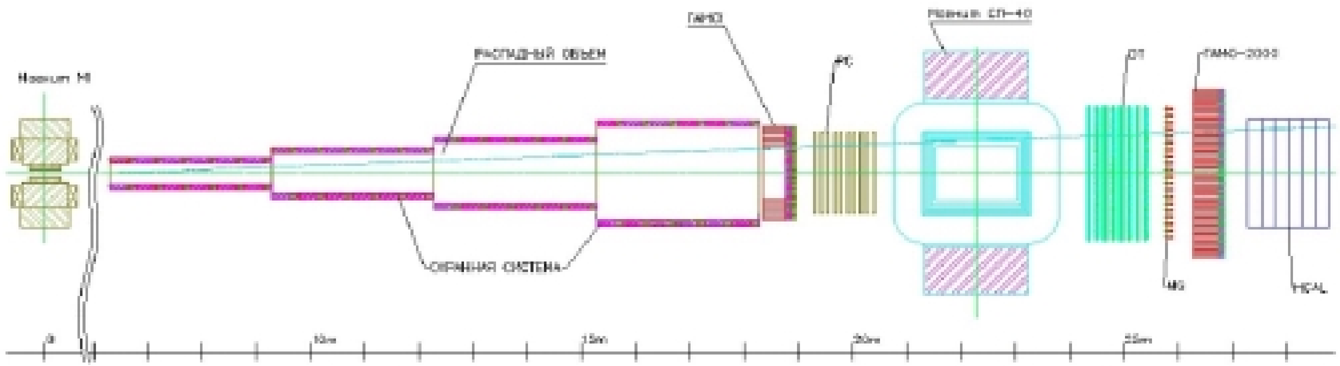

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