Latest Results from NA48 on K_L and K_S CP Violating Related Rare Decays

On behalf of NA48 Collaboration

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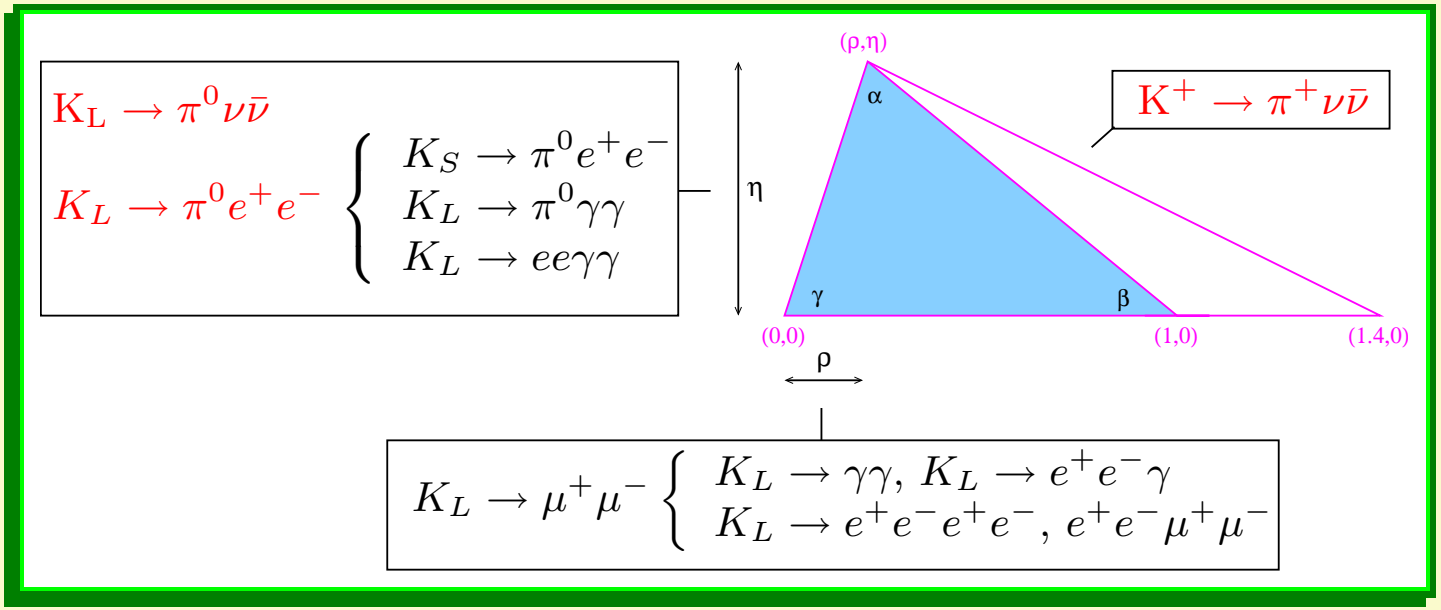
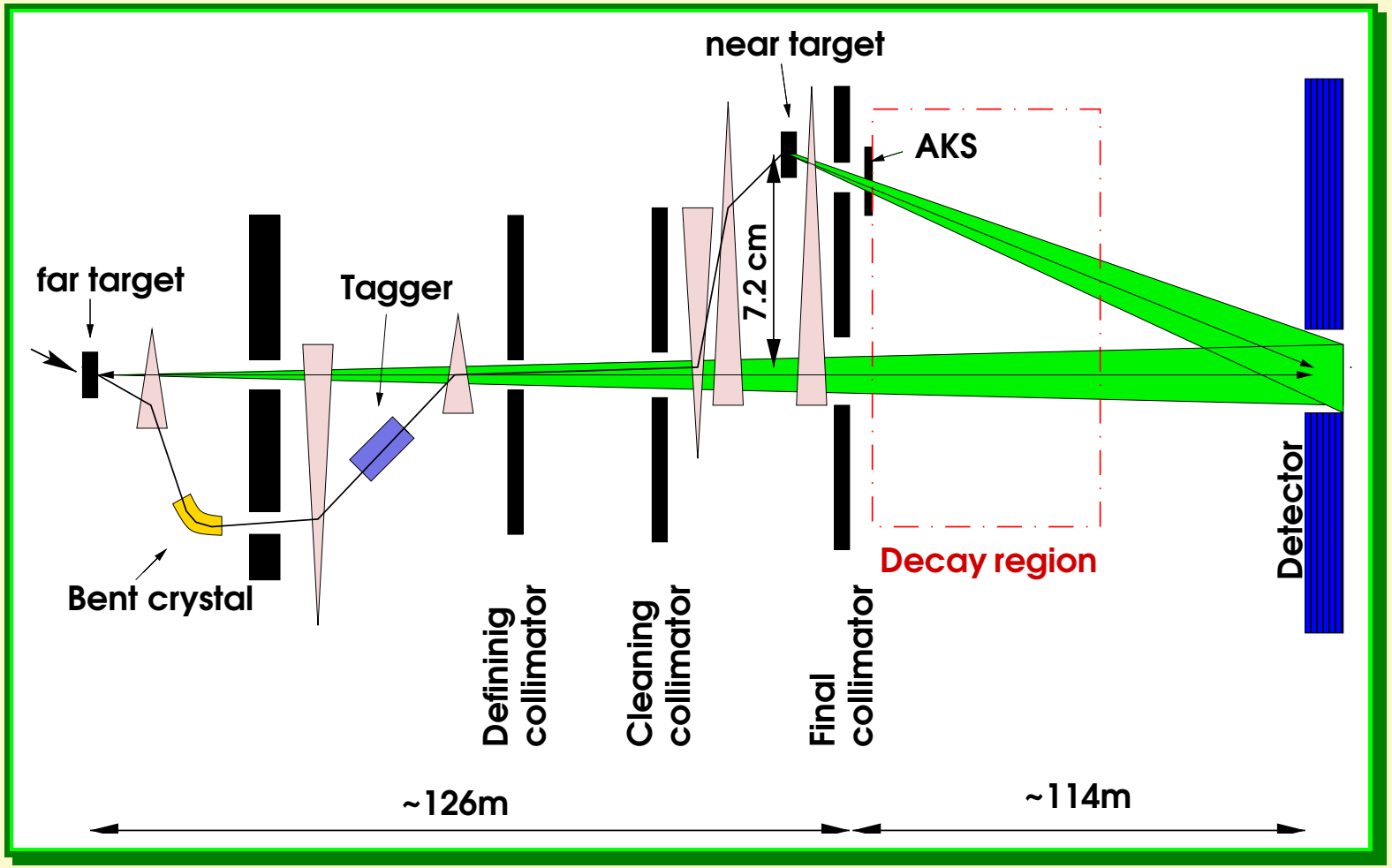
Particle Physics and Cosmology , Australia



- Results on χPT:
  - $K_{L,S} \to \pi^0\gamma\gamma$
  - $K_{L,S} \to \gamma\gamma$
- Results on indirect CP-violation:
  - $K_L \to e^{\pm}\pi^{\mp}\nu_e$ not so rare...
- Results that are input for direct CP-violation:
  - $K_S \to \pi^0 e^+e^-$
  - $K_S \to \pi^0\mu^+\mu^-$
- Future:
  - V_{us}: Kaons & Hyperons
  - Direct CP: $K_{\pm}$ charged asymmetries

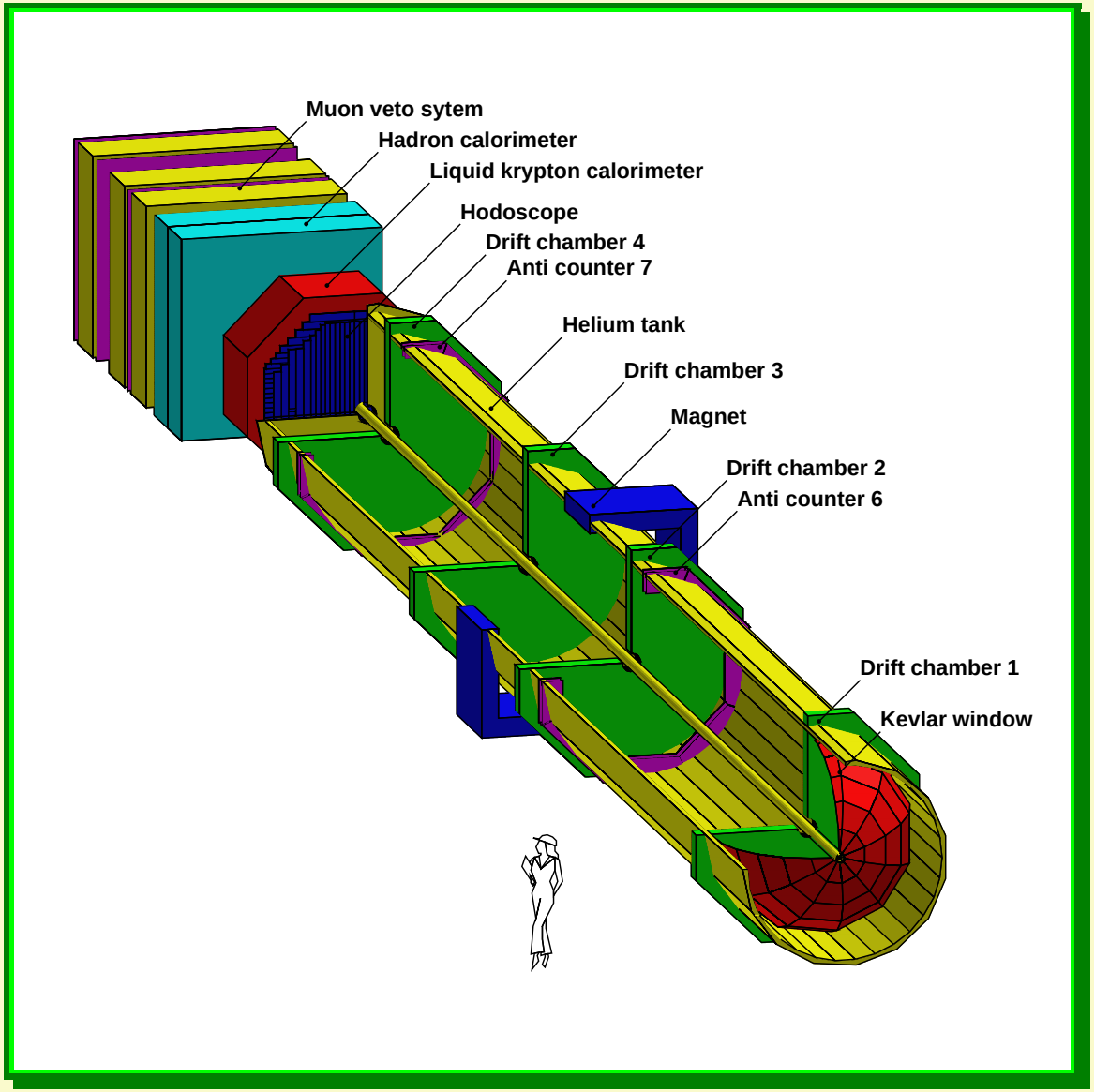
Simultaneous K_L and K_S Beam Line

Used for $Re(\epsilon'/\epsilon)$ measurement until 2001



2002 data-taking used only the K_S target

Detector


Muon veto sytem
Hadron calorimeter
Liquid krypton calorimeter
Hodoscope
Drift chamber 4
Anti counter 7
Helium tank
Drift chamber 3
Magnet
Drift chamber 2
Anti counter 6
Drift chamber 1
Kevlar window

Overview of NA48 runs

1997
$K_L + K_S$
ϵ'/ϵ

1998
$K_L + K_S$
ϵ'/ϵ
(K_L decays)

1999

$K_L + K_S$	K_L	HI K_S
ϵ'/ϵ	K_{e3}	K_S decays
K_L decays	$K_{\mu 3}$	

2000 (no spectrometer)

K_L	η	HI K_S
ϵ'/ϵ checks	checks	K_S decays
K_L decays		

2001
$K_L + K_S$
ϵ'/ϵ
($K_{L,S}$ decays)

2002
HI K_S
$K_S, Hyperon$ decays

2003

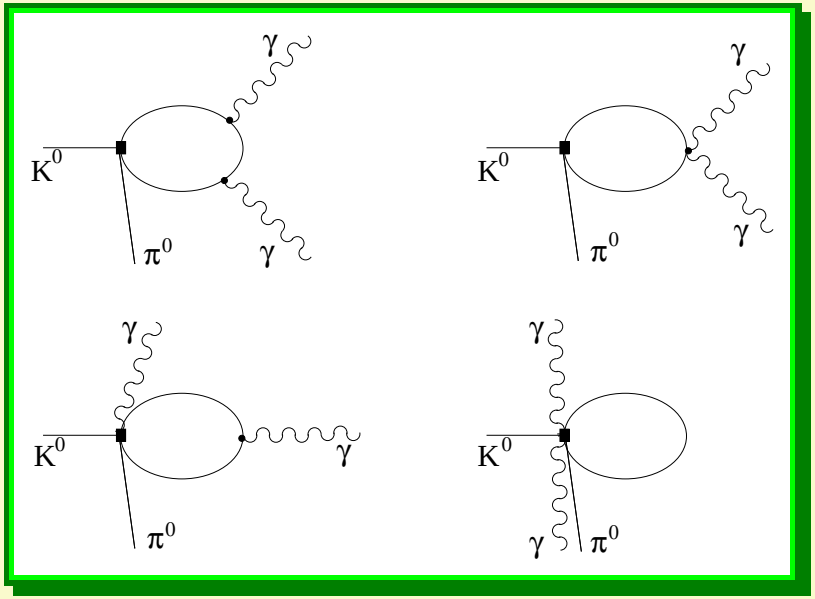
Dual $K^{\pm}$	Dual K^+
3π assymetry	$K_{e3}, K_{\mu 3}$

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

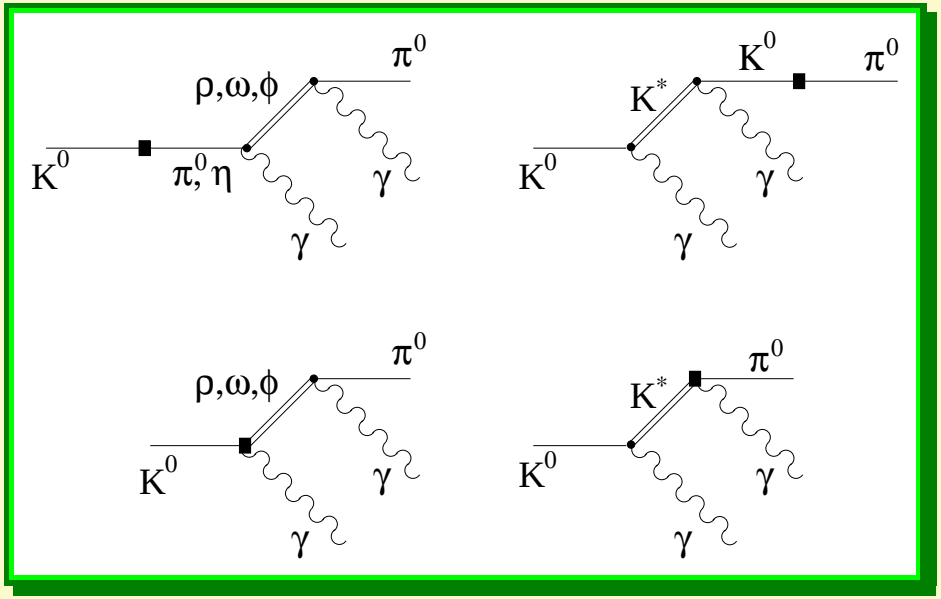
Decay amplitudes

- χPT, $\mathcal{O}(p^4)$ prediction: $BR \sim 0.6 \cdot 10^{-6}$ (Only $\sim$1/3 of the experimentally observed rate)
- $\mathcal{O}(p^6)$: rate and $m_{\gamma\gamma}$ spectrum well reproduced by VMD mechanism (a_v coupling constant).
- a_v allows CPC component of $K_L \to \pi^0 e^+ e^-$ to be predicted.

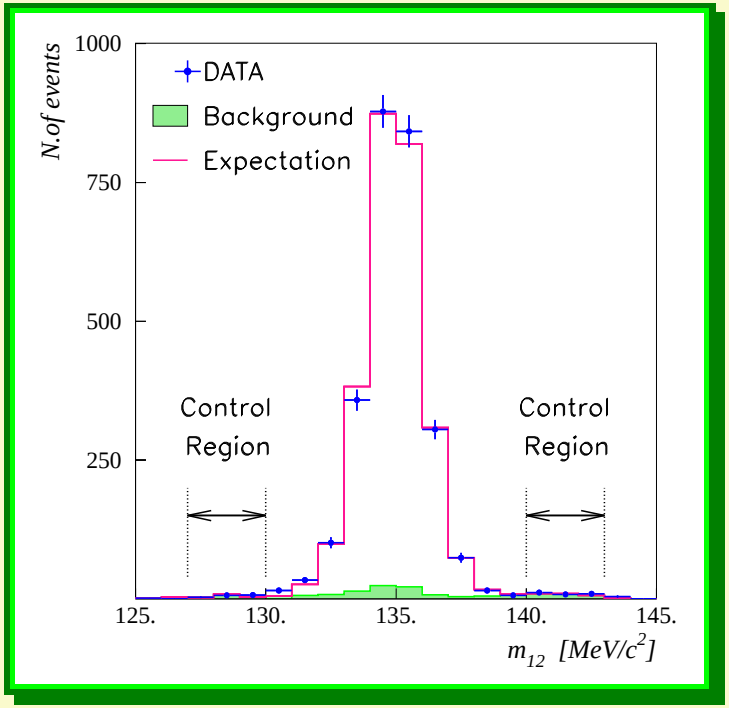
$\mathcal{O}(p^4)$

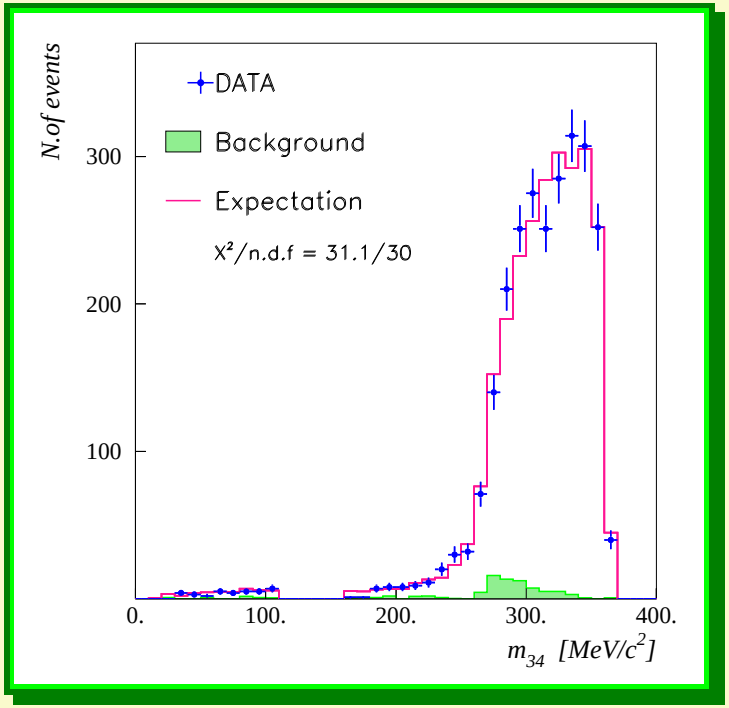


VMD



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





- 1998-1999 Data.
- **2558** $K_L \to \pi^0\gamma\gamma$ selected events $(132 < m_{1,2} < 138$ MeV/c$^2)$.
- Background:
  - $K_L \to 2\pi^0$: $(0.16 \pm 0.08)\%$
  - $K_L \to 3\pi^0$: $(2.74 \pm 0.42)\%$
  - **Pile-up**: $(0.32 \pm 0.21)\%$

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

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

- Main source of systematics:
  - Monte Carlo, Acceptance, Background.

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

- Normalization channel: $K_L \to \pi^0\pi^0$
- Main source of systematics:
  - Acceptance, a_v.

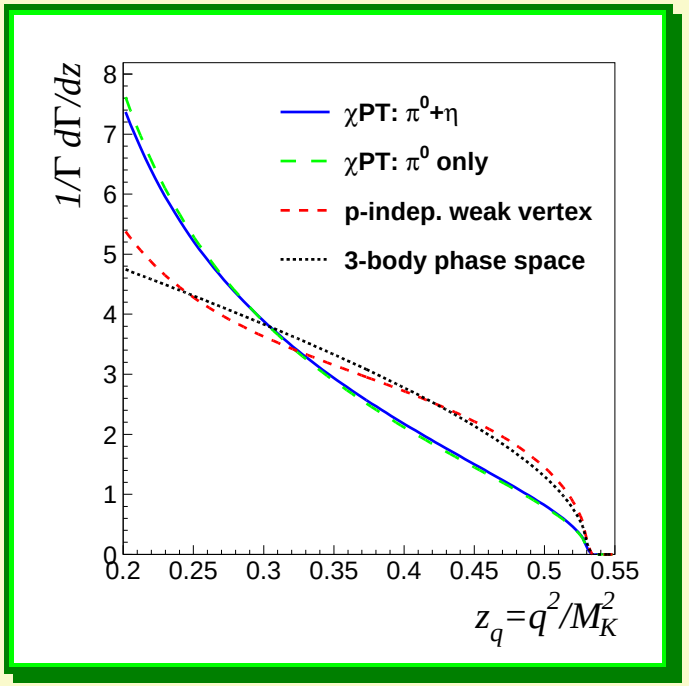
$$BR(K_L \to \pi^0 e^+ e^-)|_{CPC} = \left(4.7^{+2.2}_{-1.8}\right) \cdot 10^{-13}$$

$K_S \to \pi^0\gamma\gamma$: Physics

χPT prediction

- $BR(K_S \to \pi^0\gamma\gamma)_{z_q>0.2} = 3.8 \cdot 10^{-8}$
  (Ecker, Pich, De Rafael 1987)

- Chiral structure of the weak vertex from $d\Gamma/dq^2$ distribution.



Measurement

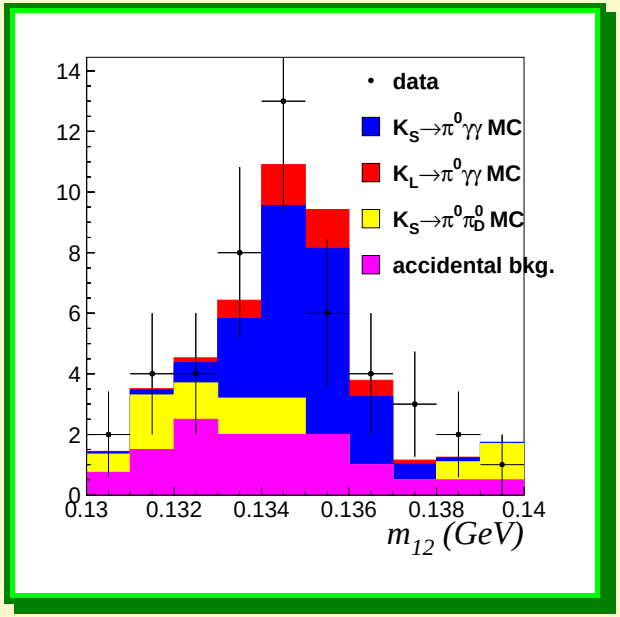
- Data from 2000 near-target run.
- Background:
  - **Accidental** → Timing
  - $K_S \to \pi^0\pi^0$ → Kinematics
  - $\Xi^0 \to \Lambda\pi^0 \to n\pi^0\pi^0$ → Kinematics
  - $K_L \to \pi^0\gamma\gamma$ → Irreducible

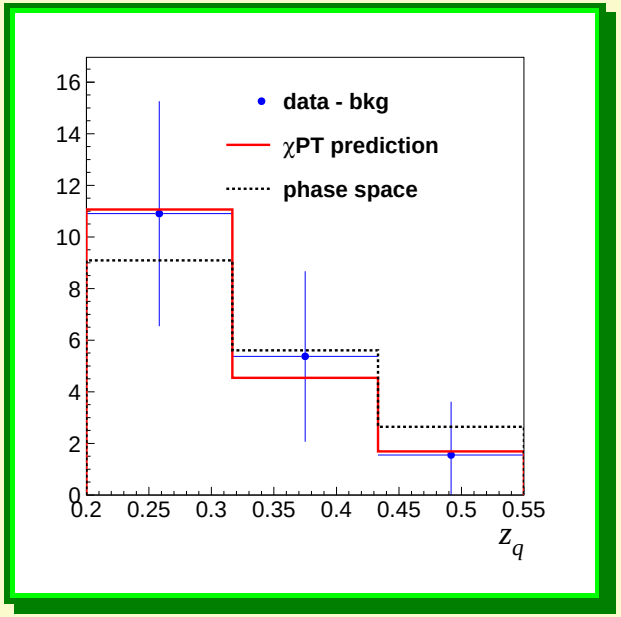
$K_S \to \pi^0\gamma\gamma$: Result (Preliminary)

31 signal candidates

Systematic Effects

Source	Events
Accidental	7.4 $\pm$2.4
$K_S \to \pi^0\pi^0$	2.4 $\pm$1.2
$K_L \to \pi^0\gamma\gamma$	3.8 $\pm$0.0
Acceptance	$\pm$0.7





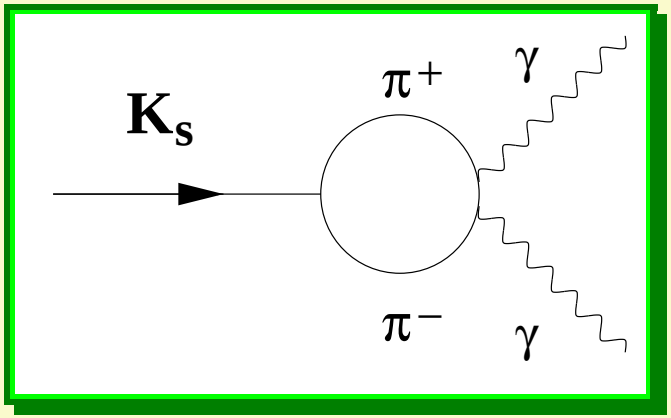
Result $BR(K_S \to \pi^0\gamma\gamma) = (4.9 \pm 1.6_{stat} \pm 0.8_{syst}) \cdot 10^{-8}$

PRELIMINARY

$K_S \to \gamma\gamma$: Physics

Decay Amplitude

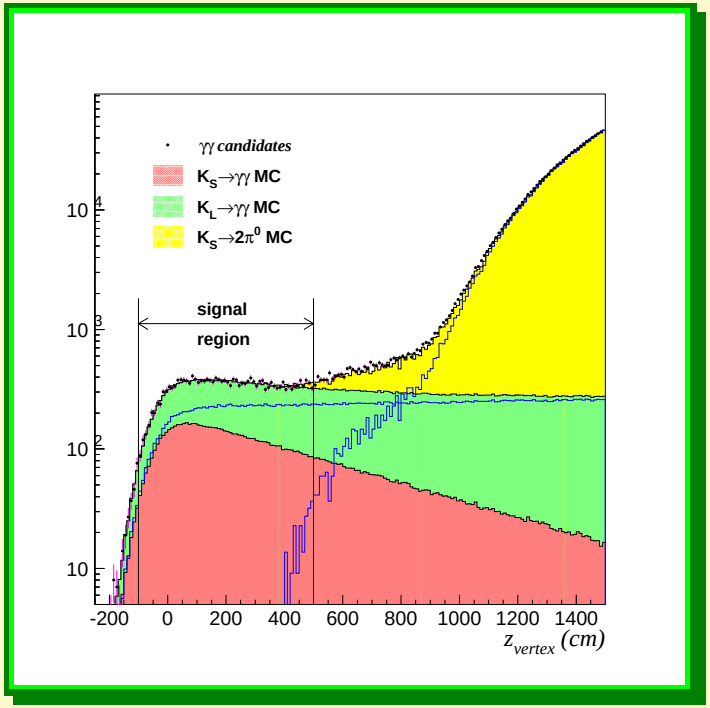
- χPT $\mathcal{O}(p^4)$ prediction: $BR = 2.1 \cdot 10^{-6}$ (D'Ambrosio, Espriu, Goity)

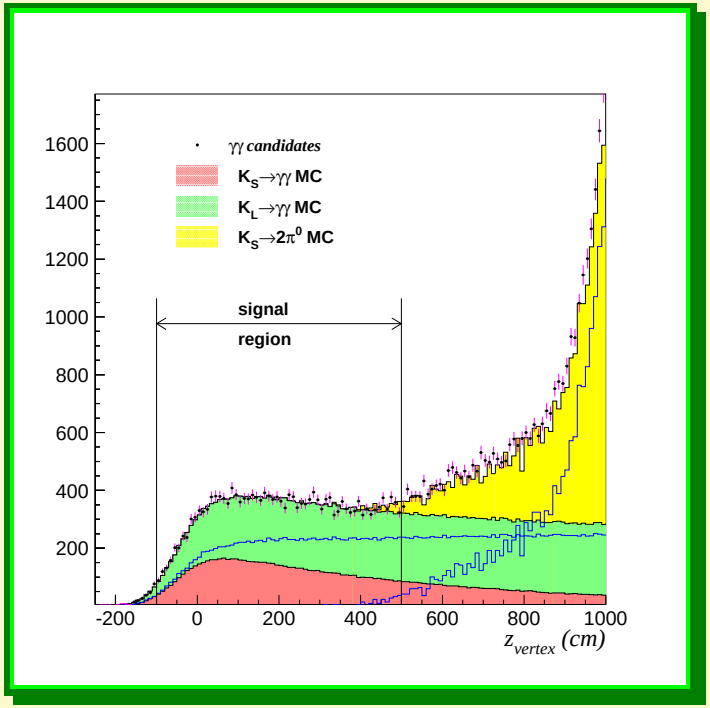


Measurement

- Data from 2000 near-target run.
- Main background sources:
  - $K_S \to \pi^0\pi^0$ ⟹ Cut on z vertex
  - $K_L \to \gamma\gamma$ ⟹ Irreducible
- Other backgrounds:
  - hadronic bckg., accidental $\gamma\gamma$ pairs $(2.1 \pm 0.7\%)$
  - residual $K_S \to \pi^0\pi^0$ $(2.1 \pm 0.4\%)$, Dalitz decays $(1.5 \pm 0.3\%)$.

$K_S \to \gamma\gamma$: Analysis





K_L flux from $K_L \to 3\pi^0$ (2000 far-target data):

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

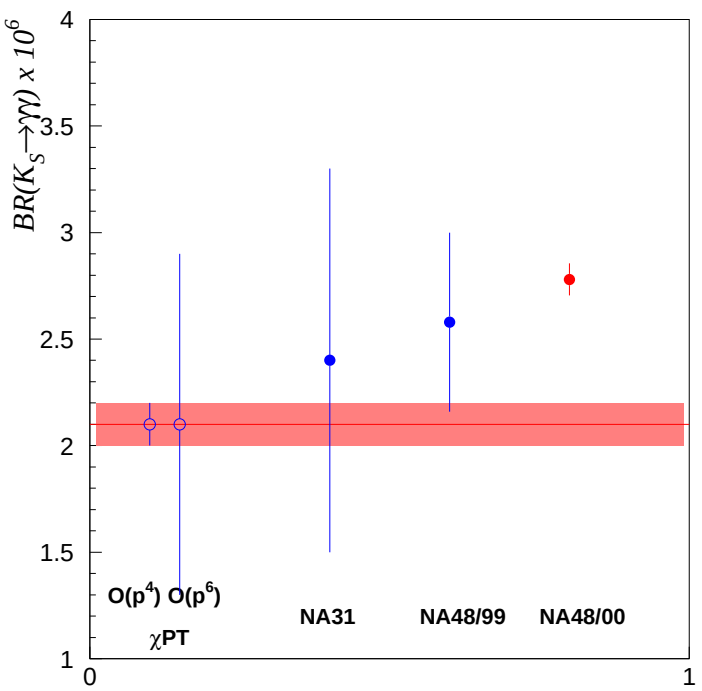
PDG: $(2.77 \pm 0.08) \cdot 10^{-3}$

Normalization to $K_S \to \pi^0\pi^0$ decay rate

$K_S \to \gamma\gamma$: Result

7461±172 signal candidates

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



30% difference from $\mathcal{O}(p^4)$ χPT prediction.

Indication of a large $\mathcal{O}(p^6)$ contribution.

$K_L \to e^{\pm}\pi^{\mp}\nu_e$

$$\delta_e \equiv \frac{BR(K_L \to e^+\pi^-\bar{\nu}_e) - BR(K_L \to e^-\pi^+\nu_e)}{BR(K_L \to e^+\pi^-\bar{\nu}_e) + BR(K_L \to e^-\pi^+\nu_e)} = \frac{2\Re e(\epsilon)}{1+|\epsilon|^2}$$

- CPT invariance.
- $\Delta S = \Delta Q$.

Measurement:

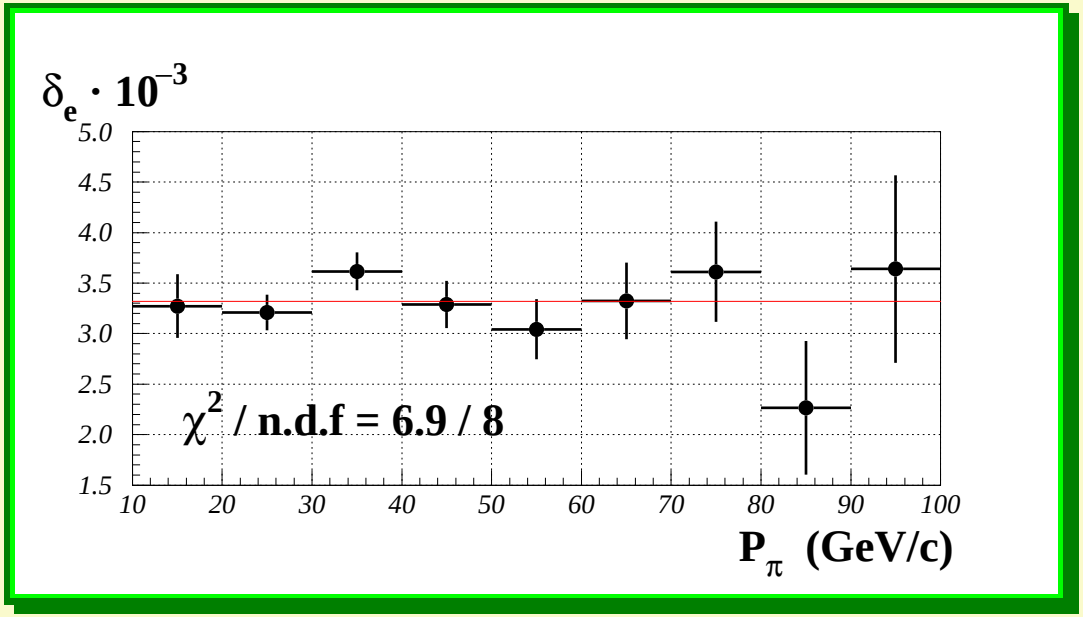
- 2001 Data.
- $\delta_e = \frac{N(K^+_{e3}) - N(K^-_{e3})}{N(K^+_{e3}) + N(K^-_{e3})}$.
- $e - \pi$ identification by $E(LKr)/p$.
- Selected Events $\sim 2.1 \cdot 10^8$ ($\sim 10^8$ per B orientation mode).
- Statistical Error $\sim 7 \cdot 10^{-5}$.

$K_L \to e^{\pm}\pi^{\mp}\nu_e$: Analysis (Preliminary)

Systematic Effects

- Fake asymmetry from particle interactions
- Data control samples:
  - $K_L \to \pi^+\pi^-\pi^0$
  - $K_S \to \pi^+\pi^-$
- Corrections track momentum dependent

Source	(10^{-5})
Trigger	$+25.7 \pm 5.8$
Pion ID	-16.7 ± 2.4
Punch-through	-1.9 ± 2.3
Acceptance	± 2.0
$K_L - K_S$ Inter	± 0.4
Accidentals	± 0.4
Background	± 0.3



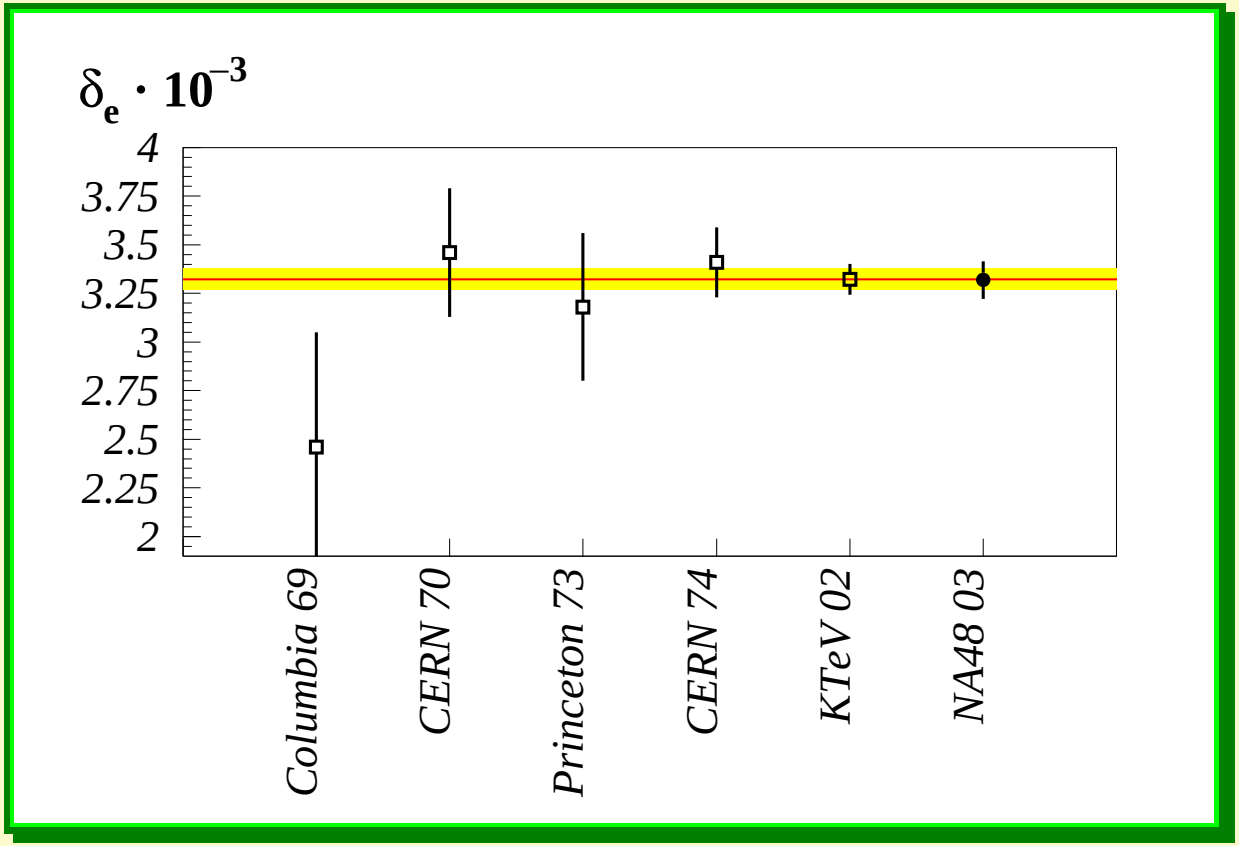
$K_L \to e^{\pm}\pi^{\mp}\nu_e$: Result (Preliminary)

$$\delta_e = (3.319 \pm 0.070_{stat} \pm 0.068_{syst}) \cdot 10^{-3}$$

PRELIMINARY

- Average over magnetic field orientations (l-r fake asymmetry suppressed).

World average: $\delta_e = (3.323 \pm 0.055) \cdot 10^{-3}$



Conclusions on results from 1997-2001 data

$K_L \to \pi^0\gamma\gamma$ Phys.Lett. B 536 (2002) 229-240

- $a_v = -0.46$.
- Negligible CPC contribution to $K_L \to \pi^0 e^+ e^-$.

$K_S \to \pi^0\gamma\gamma$ Preliminary

- First measurement of Branching Ratio.

$K_{L,S} \to \gamma\gamma$ Phys.Lett. B 551 (2003) 7

- Precise measurement of the $\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0)$.
- Large $\mathcal{O}(p^6)$ contribution to $BR(K_S \to \gamma\gamma)$.

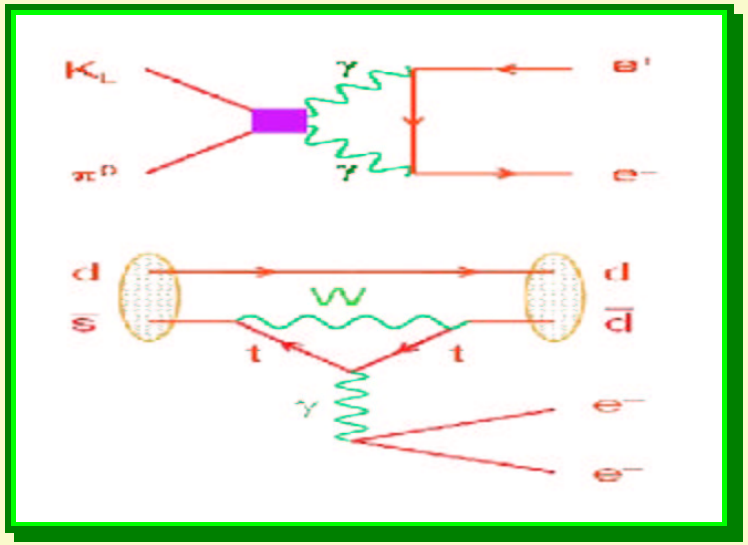
$K_L \to e^\pm \pi^\mp \nu$ Preliminary

- Competitive charge asymmetry measurement.

$K_L \to \pi^0 e^+ e^-$ has three components

Current limit: $BR(K_L \to \pi^0 ee) < 5.1 \times 10^{-10}$ [KTeV PRL 86 397]

- Direct CP violation: Given by η or $\Im(\lambda_t)$
  - $\Im(\lambda_t) = \eta A^2 \lambda^5 \quad \lambda_t = V_{ts}^* V_{td}$
  - $\Im(\lambda_t) = (1.30 \pm 0.12) \times 10^{-4}$
    [Kettell, et al, hep-ph/0212321]
    $BR(K_L \to \pi^0 ee)|_{CPD} \sim few \times 10^{-12}$
- Indirect CP violation:
  - $BR(K_L \to \pi^0 e^+ e^-)|_{CPI}$
    $= |\epsilon|^2 (\frac{\tau_L}{\tau_S}) BR(K_S \to \pi^0 e^+ e^-)$
- CP conserving: Given by $BR(K_L \to \pi^0 \gamma\gamma)$
  - $BR(K_L \to \pi^0 e^+ e^-)|_{CPC}$
    $= \left(0.47^{+0.22}_{-0.18}\right) \cdot 10^{-12}$



- Interferance between the Direct/Indirect CP violating components will depend on the size of the a_s coupling.

Can we measure a_s? $\Rightarrow$ $BR(K_S \to \pi^0 e^+ e^-) = 5 \times 10^{-9} |a_s|^2$

First Observation of $K_S \to \pi^0 e^+ e^-$

$\Rightarrow$ CERN-EP Seminar – June 10, 2003

4.2$\times 10^{10} K_S$ decays in the fiducial volume in 89 days.

Significant contributions to the background in the signal region :

Source	control region	signal region
$K_S \to \pi^0_D \pi^0_D$	0.03	0.007
$K_L \to ee\gamma\gamma$	0.11	0.075
$(\pi^\pm e^\mp \nu) + (\pi^0 \pi^0 (\pi^0))$	0.19	0.069
Total background	0.33	0.15

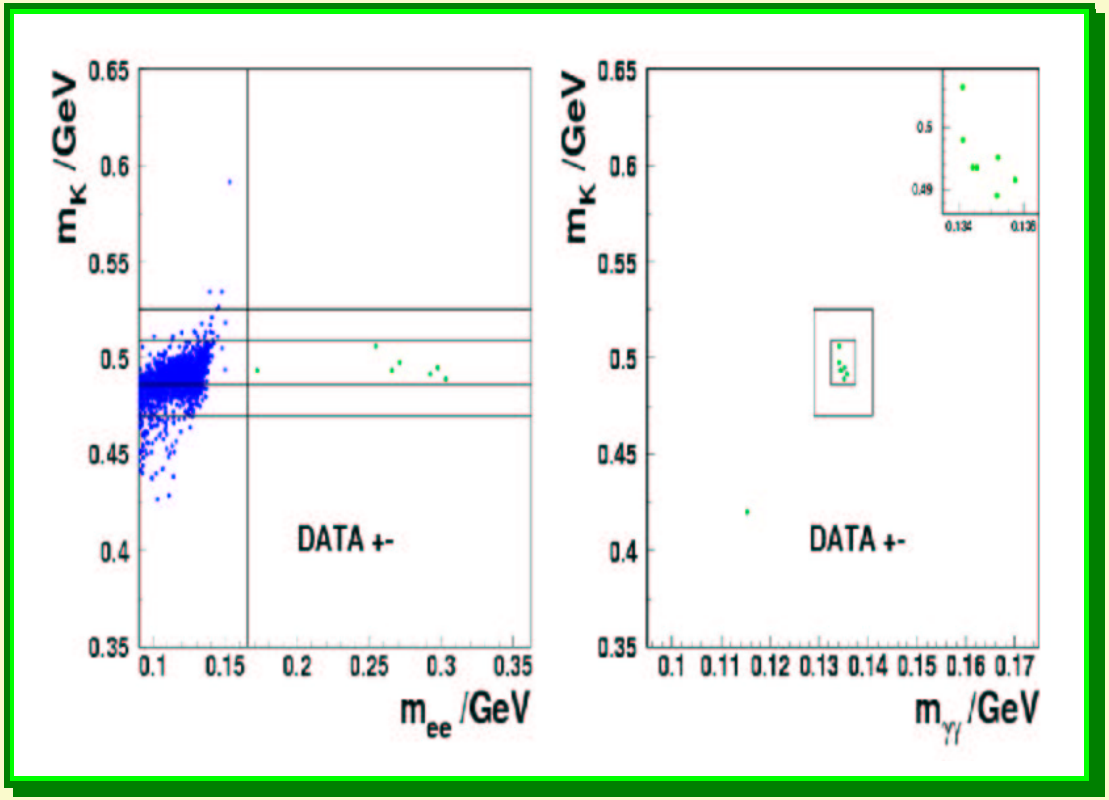
Total background in the signal region is $0.15^{+0.05}_{-0.04}$ event

To be compare to the K_L enviroment: KTeV 2 events with 1.1 background

First Observation of $K_S \to \pi^0 e^+ e^-$

$$BR(K_S \to \pi^0 e^+ e^-) = \left(5.8^{+2.8}_{-2.3}\right) \cdot 10^{-9}$$

PRELIMINARY



χ_{PT} prediction: $BR(K_S \to \pi^0 e^+ e^-) = 5 \times 10^{-9} |a_s|^2 \Rightarrow |a_s|_{theory} = 0.1 - 10$

Preliminary measurement of $|a_s|^2$: $|a_s|^2 = 1.08^{+0.26}_{-0.21}$

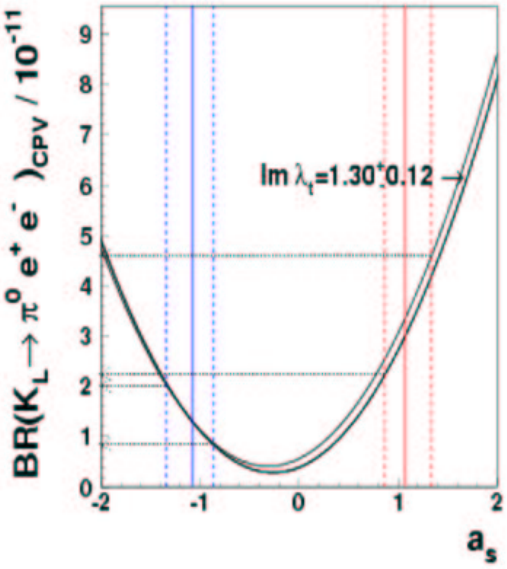
PRELIMINARY

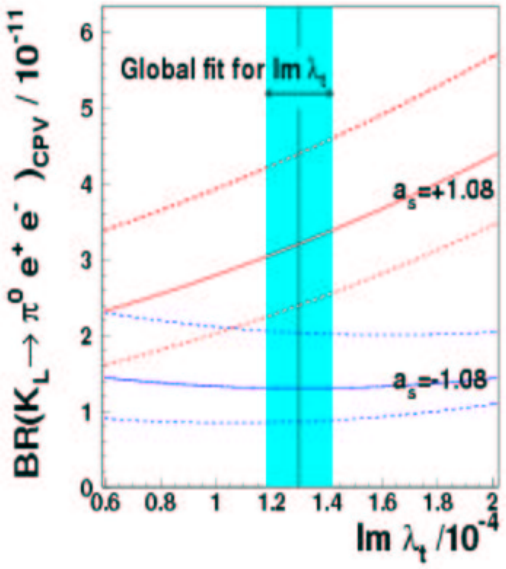
Implications for $K_L \to \pi^0 e^+ e^-$

Measurement of $|a_s|$ allows $\mathrm{BR}(K_L \to \pi^0 e^+ e^-)$ to be predicted as a function of $\mathcal{I}m(\lambda_t)$ to within a sign ambiguity :

$$BR(K_L \to \pi^0 e^+ e^-)_{CPV} = \left(15.3 a_s^2 \pm 6.8 \frac{\mathcal{I}m(\lambda_t)}{10^{-4}} |a_s| + 2.8 \left(\frac{\mathcal{I}m(\lambda_t)}{10^{-4}}\right)^2\right) \times 10^{-12}$$

	indirect	interference		direct	
$BR(K_L \to \pi^0 e^+ e^-)_{CPV} =$	17.7	$\pm$ 9.5	$+$	4.7	$\times 10^{-12}$



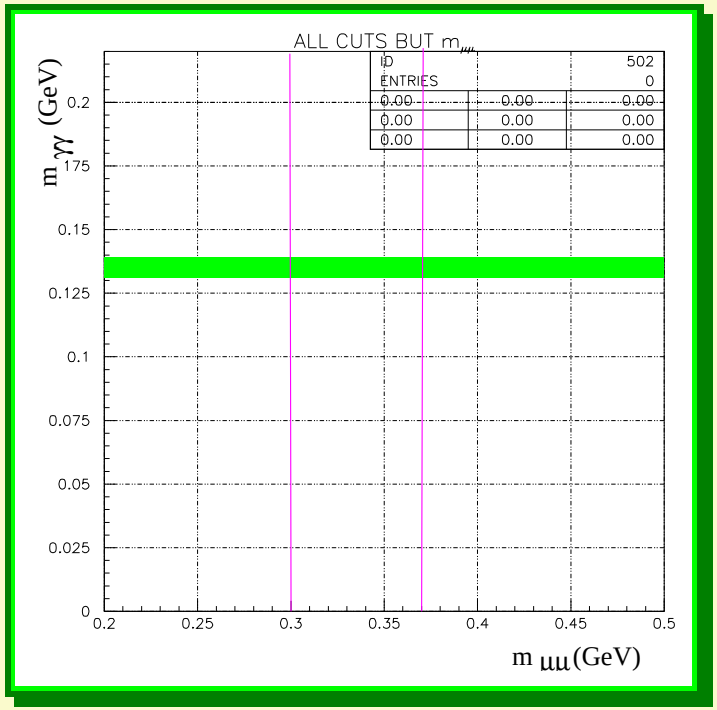


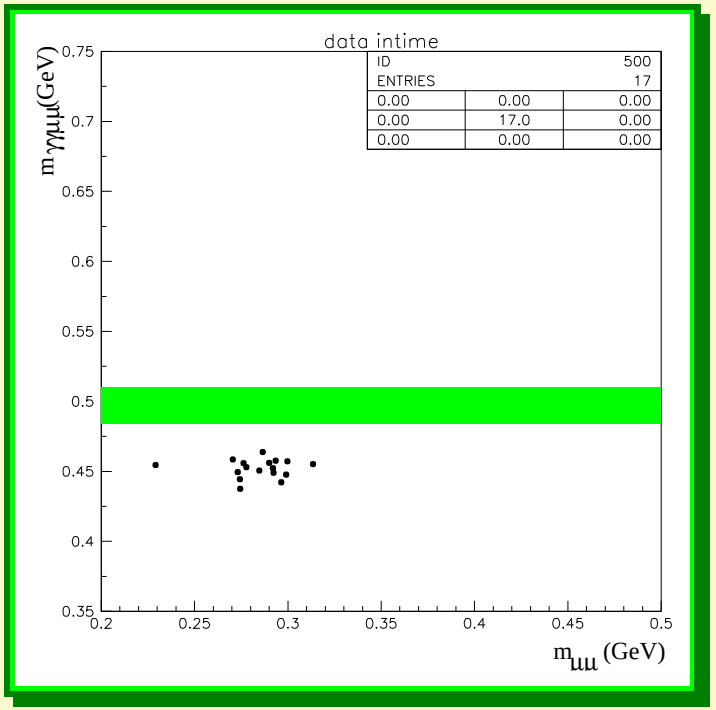
$$BR(K_L \to \pi^0 e^+ e^-) = (1 - 4) \times 10^{-11}$$

PRELIMINARY

Implications for $K_L \to \pi^0\mu^+\mu^-$

$$BR(K_S \to \pi^0 e^+ e^-)/BR(K_S \to \pi^0 \mu^+ \mu^-) \simeq 5$$





- Single event sensitivity 6.1×10^{-10}
- Background estimate in progress.....we are still blind!
- In the long term, this is a more prommising channel due to the reduce 'Greenlee-like' background.

Current limit from KTeV: $BR(K_L \to \pi^0\mu^+\mu^-) < XX \times 10^{-10}$

Test of unitarity... problem with $K \to \pi l \nu_l$ and V_{us}?

V_{us} contributes 30-50 % to the error in the unitarity test from $V_{us}^2 + V_{ud}^2 + V_{ub}^2 = 1$ depending on the error taken for V_{ud}:

$$V_{us}^2 + V_{ud}^2 + V_{ub}^2 = 1 - \delta$$

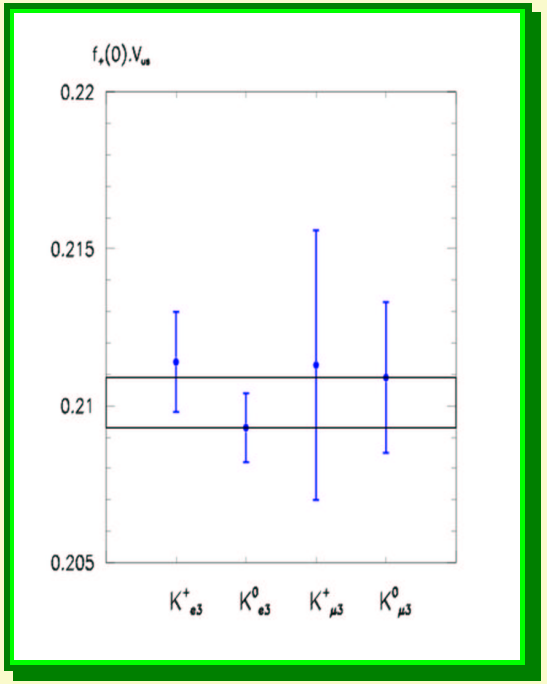
$\delta = (3.2 \pm 1.4) \times 10^{-3}$ (superallowed Fermi β decay V_{ud})

In the future, V_{ud} from $\pi^+ \to \pi^0 e^+ \nu$ (PSI-experiment).

- Recent result based on 70K events from BNL-865:
  $BR(K^+ \to \pi^0 e^+ \nu_e) =$
  $(5.17 \pm 0.02 \pm 0.09 \pm 0.04)\%$
  $\Rightarrow$ PDG $(4.87 \pm 0.06)\%$

  $\Rightarrow V_{us} \to 0.2272$ ...

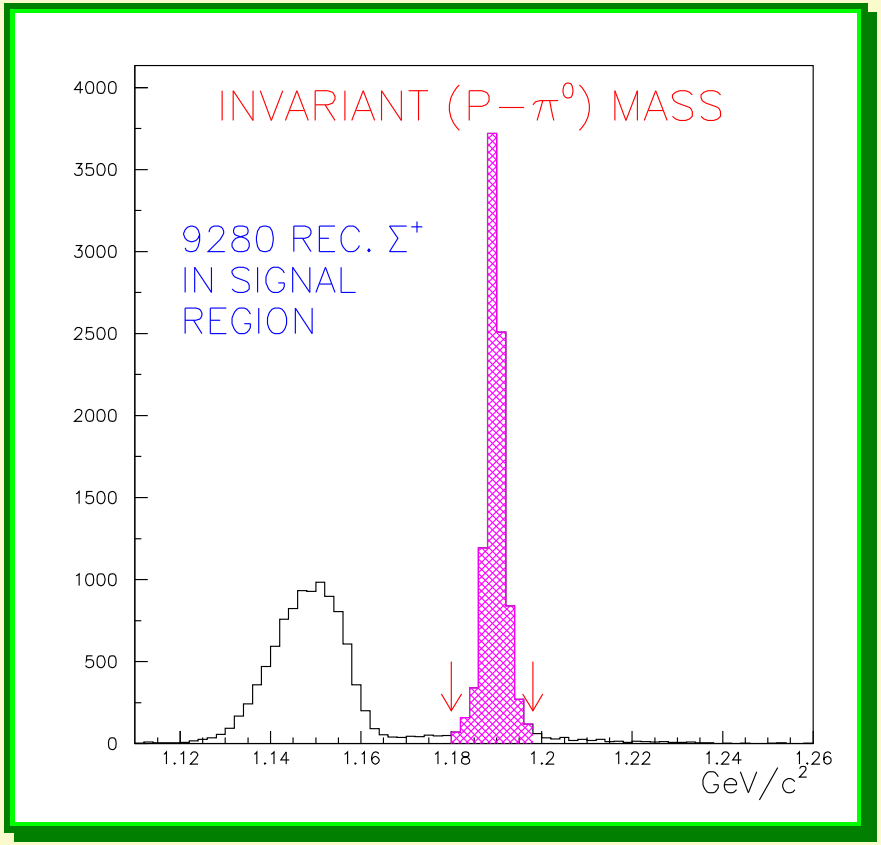
- NA48 to measure V_{us} from both Hyperons (2002, 10K) and K_{e3} (2003, millions)

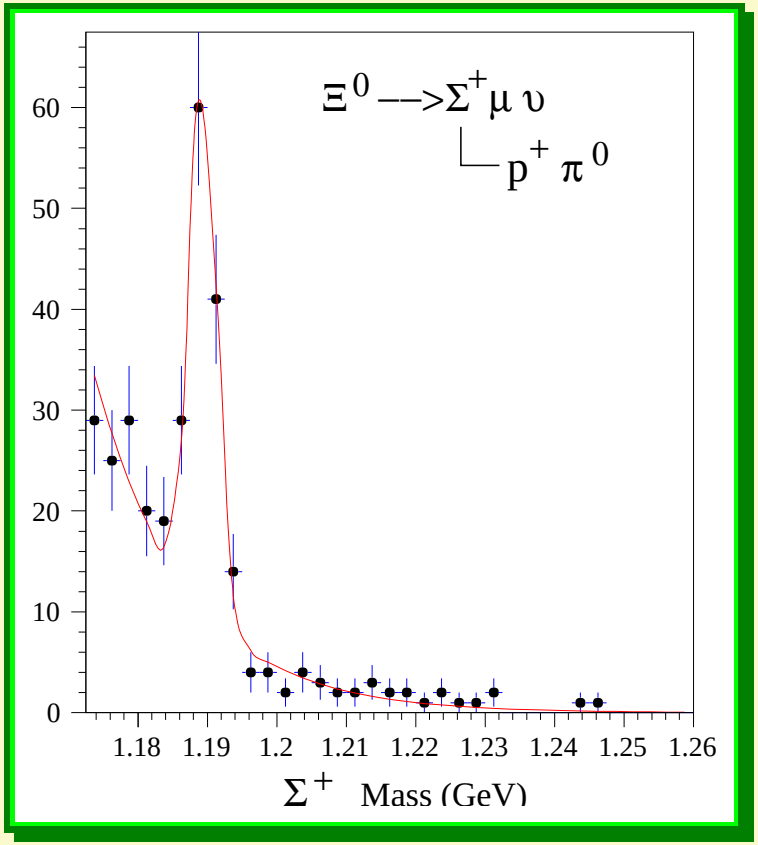


Calderon & Lopez-Castro

Hyperon Semi-leptonic Decays

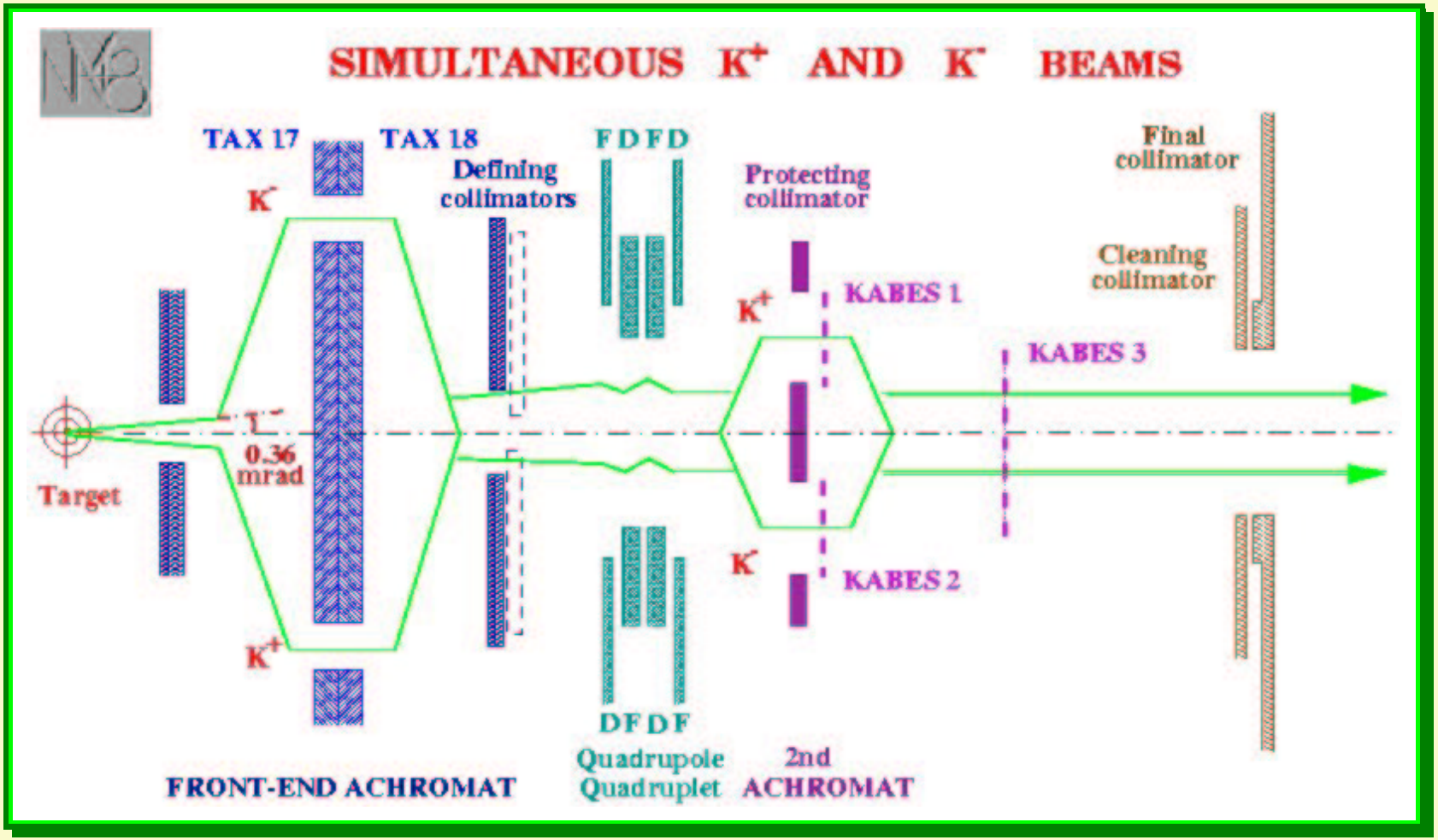
$\Xi^0 \to \Sigma^+ l^- \nu$





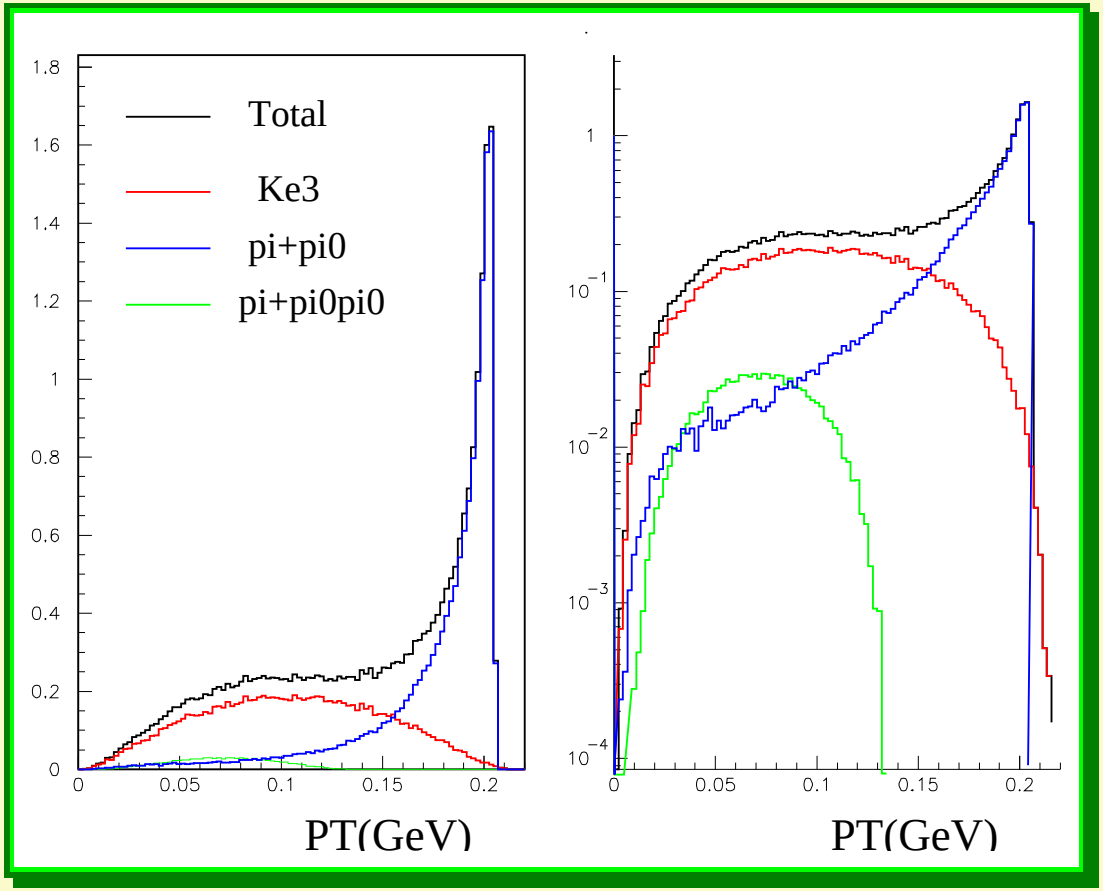
- Sample from KTeV 700 events, our sample is >10K events. Sensitive to g_2?
- First Observation for muon channel.

K^+ and K^- Beam Line



Main program of K^+ and K^- ⟹ Direct CP

Besides Direct CP-violation studies from the $k \to 3\pi$, we will study semileptonic and radiative decays.



We are aiming at recording 2×10^9 $\pi\pi\pi$ means (10^9 Ke3 and Kμ3)/Downscaling.

Conclusions 2002 and 2003data

4.2$\times 10^{10} K_S$ decays in the fiducial volume in 89 days.

- **$K_S \to \pi^0 e^+ e^-$**

  7 events found with 0.15 background events expected

  $$Br(K_S \to \pi^0 e^+ e^-) = \left(5.8^{+2.8}_{-2.3}\right) \cdot 10^{-9}$$

  $$|a_s|^2 = 1.08^{+0.26}_{-0.21}$$

  PRELIMINARY

  $\Rightarrow$ **well stablished signal!**

- **$K_S \to \pi^0 \mu^+ \mu^-$**

  Single events sensitivity is better than 10^{-10}

- ***Semileptonic decays***

  Analysis is now ongoing

- **2003 $K^\pm$**

  Program has already started...further information on CP-violation to be available in the near future from $\pi^\pm\pi^\pm\pi^\mp$, $\pi^0\pi^0\pi^0$, $\pi^\pm\gamma\gamma$, asymmetries.