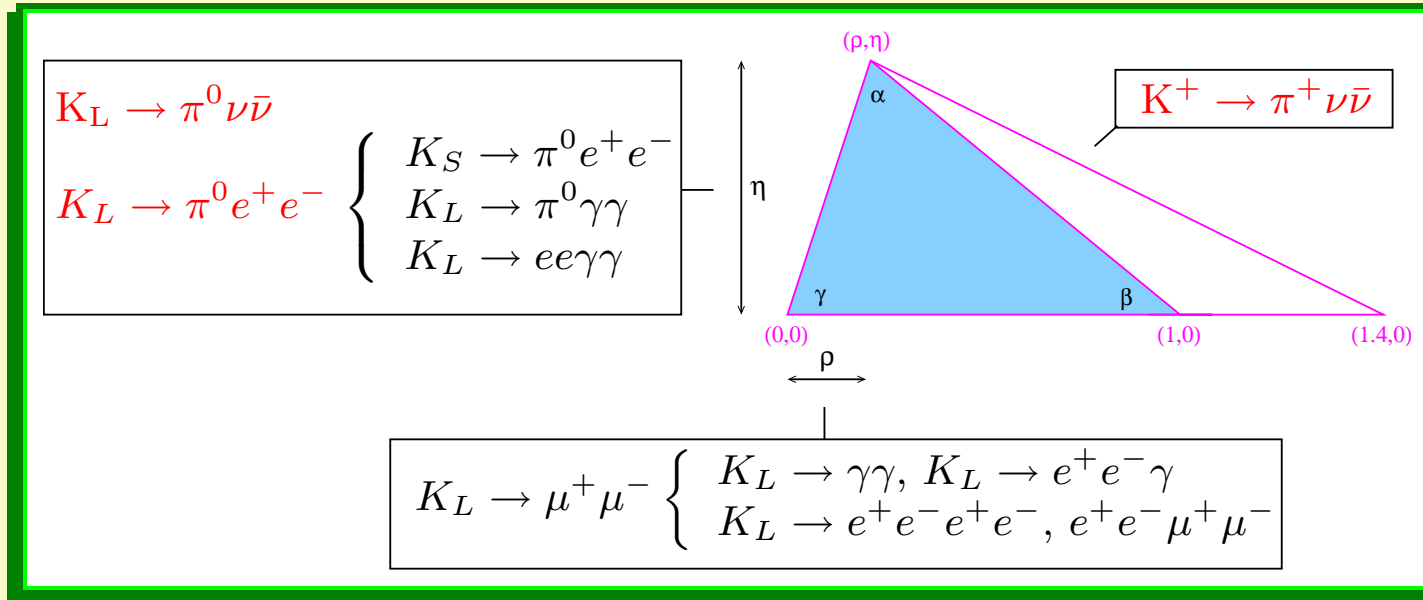


Latest Results from NA48 on K_L and K_S CP Violating Related Rare Decays

On behalf of NA48 Collaboration

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Northwestern University

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Fourth Tropical Workshop on
Particle Physics and Cosmology , Australia



Results on χ PT:

- $K_{L,S} \rightarrow \pi^0 \gamma \gamma$
- $K_{L,S} \rightarrow \gamma \gamma$



Results on indirect CP-violation:

- $K_L \rightarrow e^\pm \pi^\mp \nu_e$ not so rare...



Results that are input for direct CP-violation:

- $K_S \rightarrow \pi^0 e^+ e^-$
- $K_S \rightarrow \pi^0 \mu^+ \mu^-$

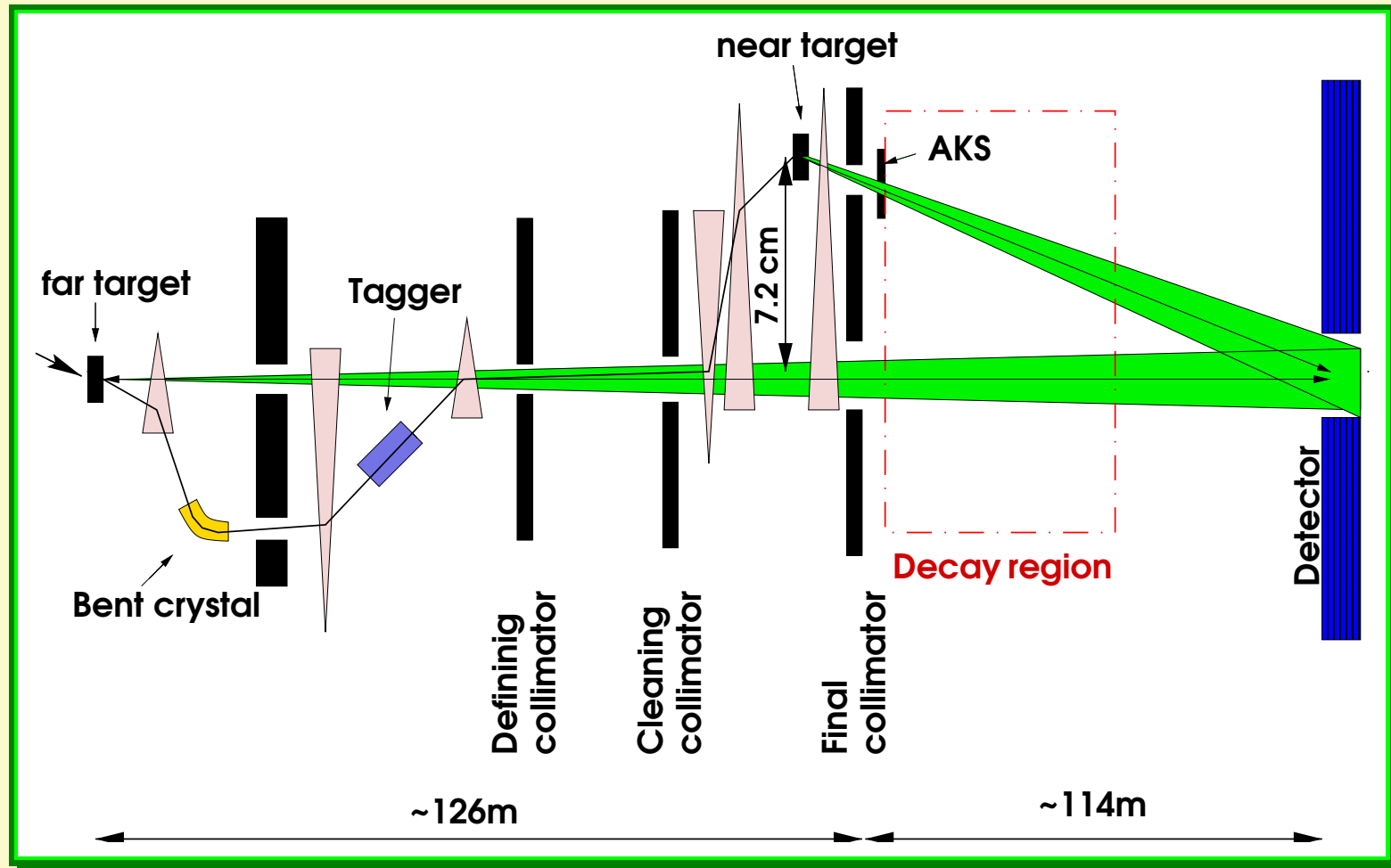


Future:

- V_{us} : Kaons & Hyperons
- Direct CP: K_\pm charged asymmetries

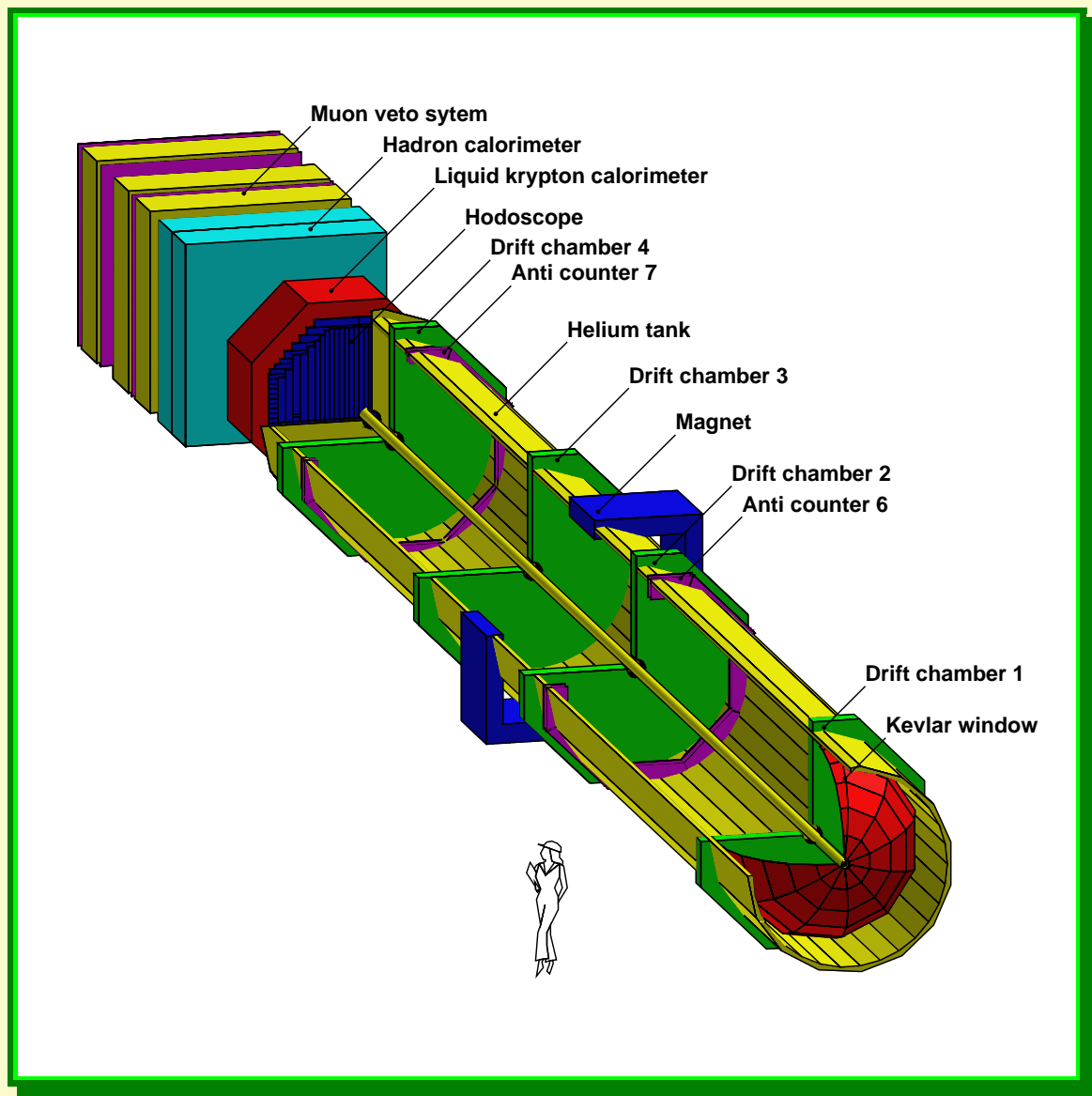
Simultaneous K_L and K_S Beam Line

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



➔ 2002 data-taking used only the K_S target

Detector



Overview of NA48 runs

1997

$K_L + K_S$
 ϵ'/ϵ

1998

$K_L + K_S$
 ϵ'/ϵ
(K_L decays)

1999

$K_L + K_S$ ϵ'/ϵ K_L decays	K_L K_{e3} $K_{\mu3}$	HI K_S K_S decays
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2000 (no spectrometer)

K_L ϵ'/ϵ checks K_L decays	η checks	HI K_S K_S decays
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2001

$K_L + K_S$
 ϵ'/ϵ
($K_{L,S}$ decays)

2002

HI K_S
 K_S , *Hyperon* decays

2003

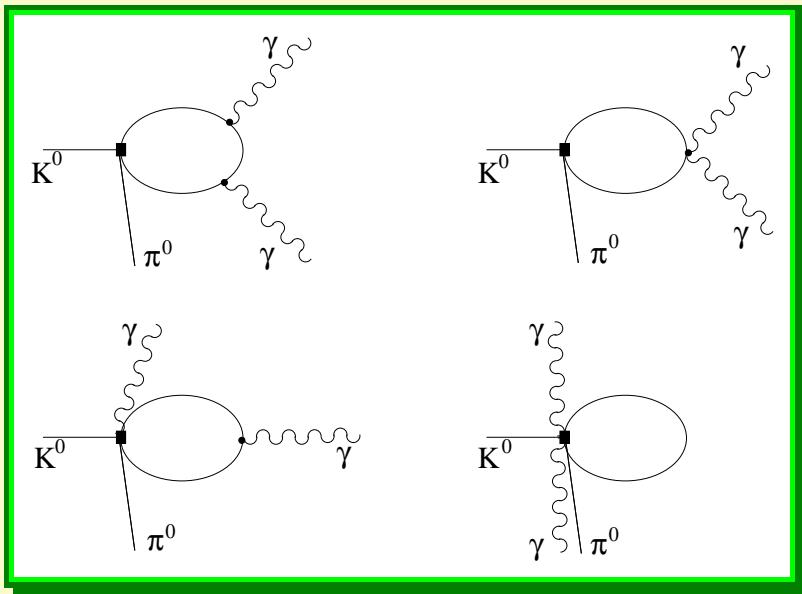
Dual K^\pm 3π assymetry	Dual K^+ K_{e3} , $K_{\mu3}$
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$K_L \rightarrow \pi^0 \gamma \gamma$: Physics

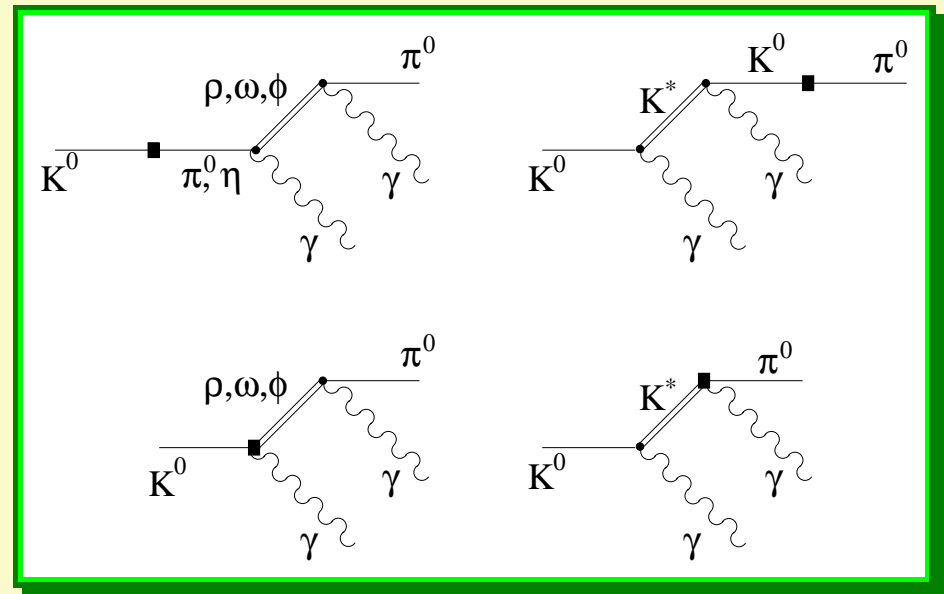
→ Decay amplitudes

- χ PT, $\mathcal{O}(p^4)$ 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 $K_L \rightarrow \pi^0 e^+ e^-$ to be predicted.

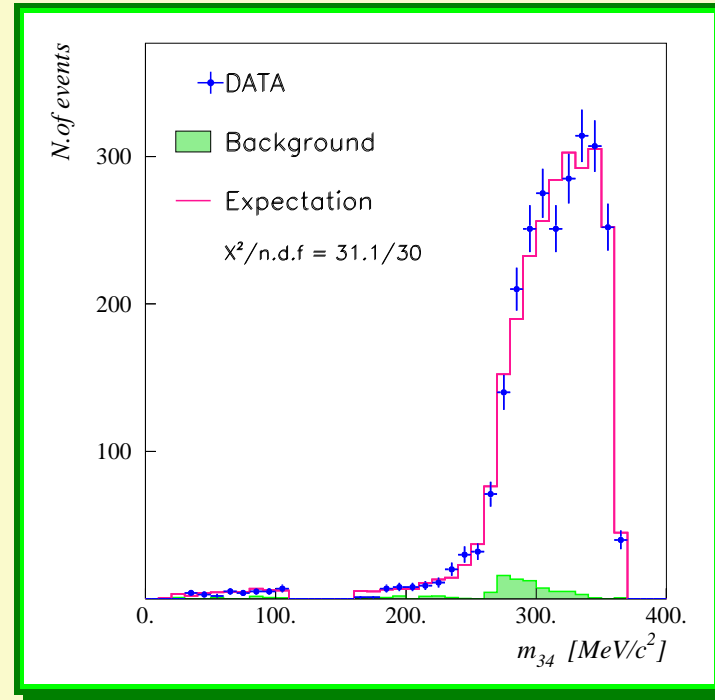
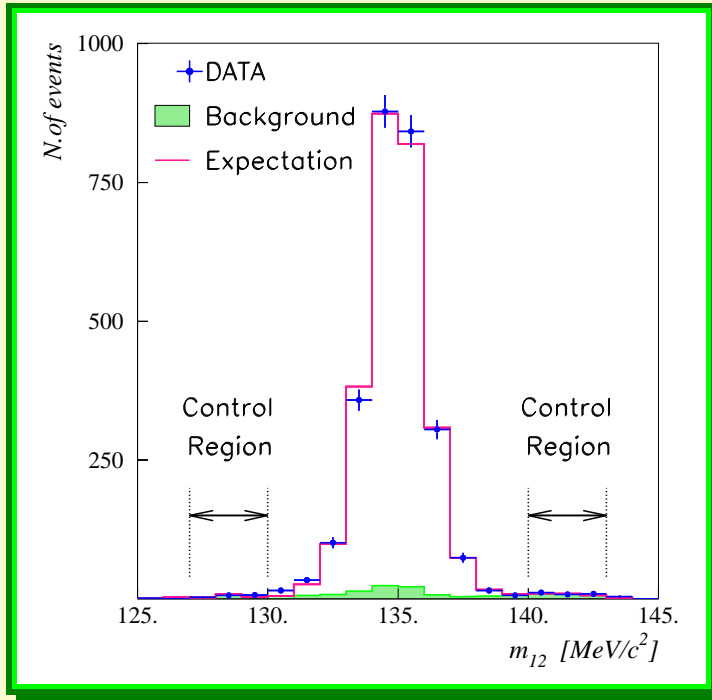
$\mathcal{O}(p^4)$



VMD



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



➔ 1998-1999 Data.

➔ **2558** $K_L \rightarrow \pi^0 \gamma \gamma$ selected events ($132 < m_{1,2} < 138$ MeV/c²).

➔ Background:

- $K_L \rightarrow 2\pi^0$: $(0.16 \pm 0.08)\%$
- $K_L \rightarrow 3\pi^0$: $(2.74 \pm 0.42)\%$
- **Pile-up**: $(0.32 \pm 0.21)\%$

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

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

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

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

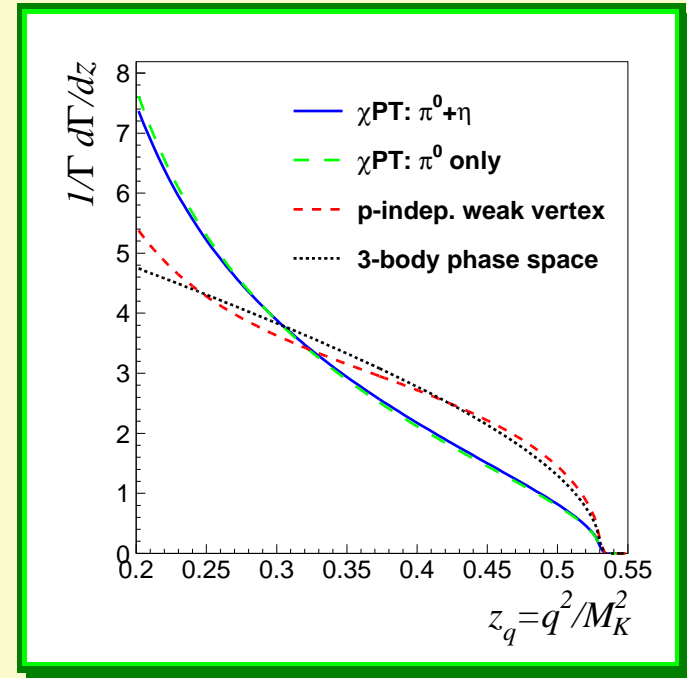
- Normalization channel: $K_L \rightarrow \pi^0 \pi^0$
- Main source of systematics:
 - Acceptance, a_ν .

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

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

→ χ PT prediction

- $BR(K_S \rightarrow \pi^0 \gamma \gamma)_{z_q > 0.2} = 3.8 \cdot 10^{-8}$
(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**
 - $K_S \rightarrow \pi^0 \pi^0$
 - $\Xi^0 \rightarrow \Lambda \pi^0 \rightarrow n \pi^0 \pi^0$
 - $K_L \rightarrow \pi^0 \gamma \gamma$

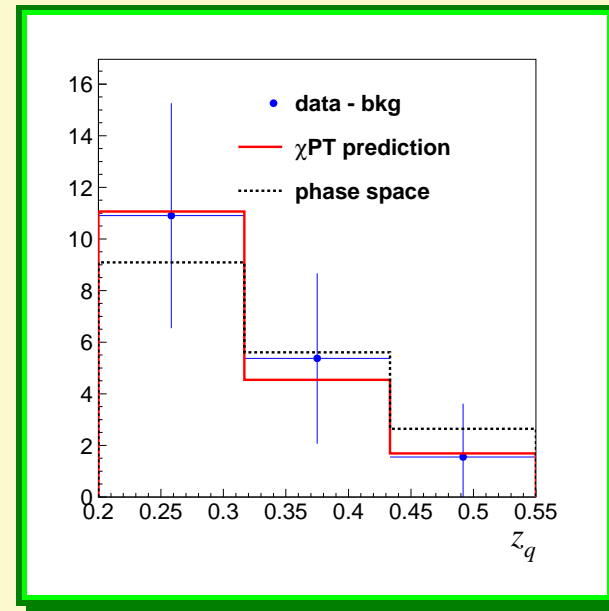
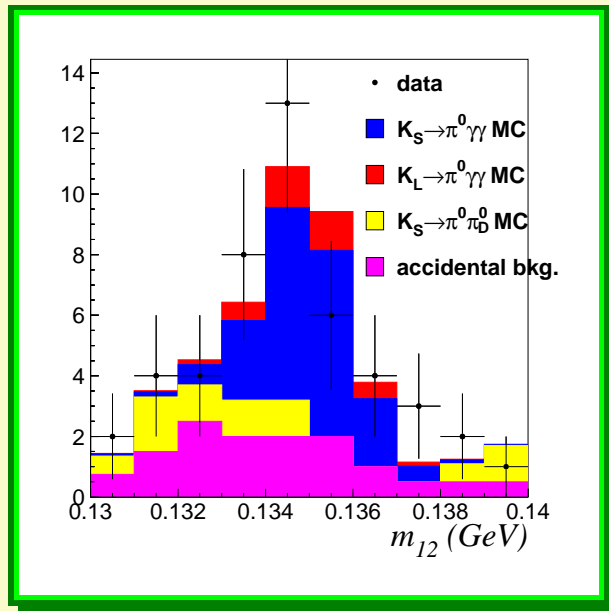
- Timing
- Kinematics
- Kinematics
- Irreducible

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

→ 31 signal candidates

→ Systematic Effects

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



→ Result

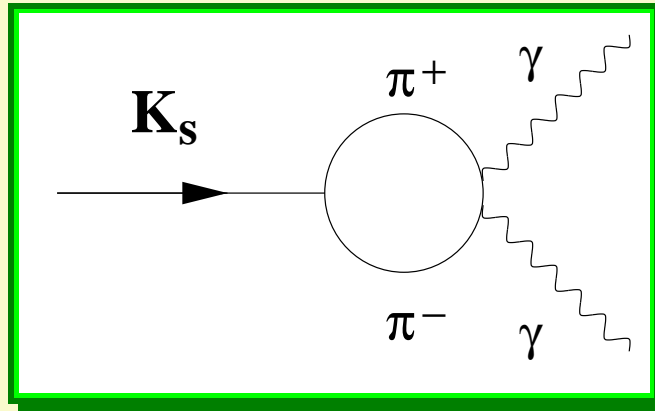
$$BR(K_S \rightarrow \pi^0 \gamma \gamma) = (4.9 \pm 1.6_{stat} \pm 0.8_{syst}) \cdot 10^{-8}$$



$K_S \rightarrow \gamma\gamma$: Physics

→ Decay Amplitude

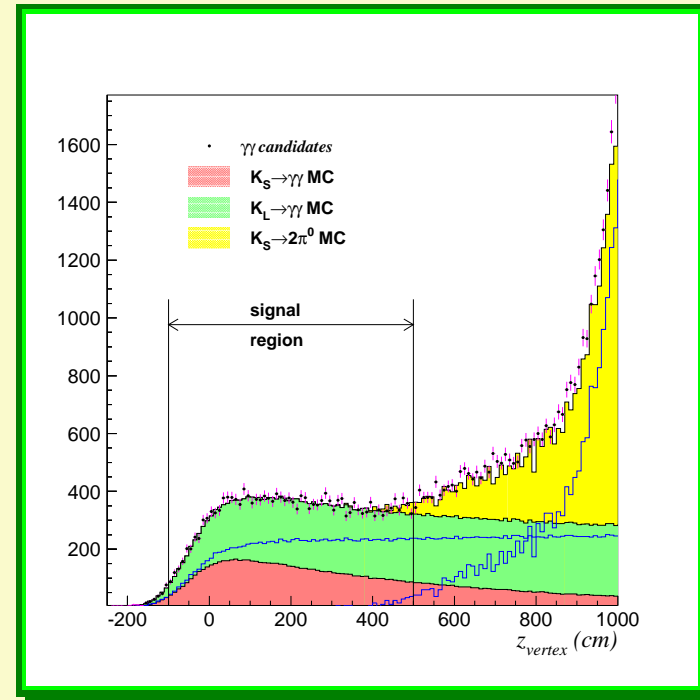
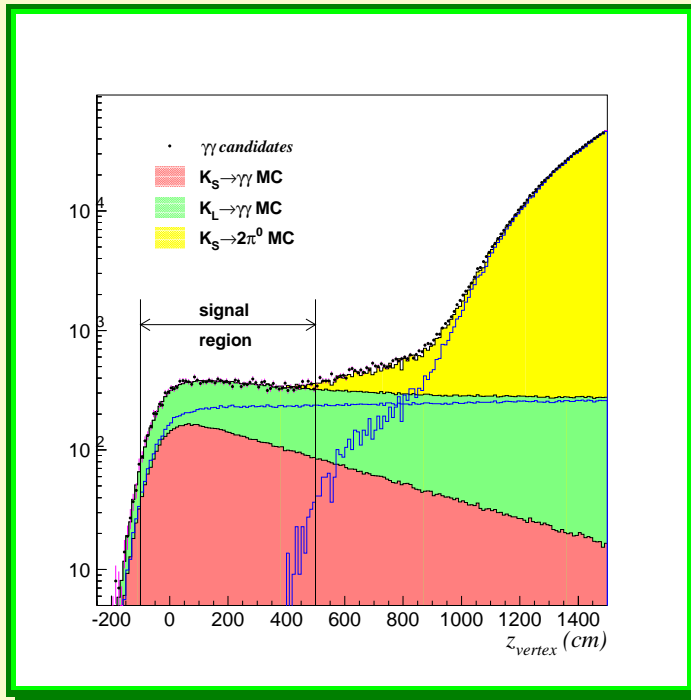
- χ PT $\mathcal{O}(p^4)$ prediction: $BR = 2.1 \cdot 10^{-6}$ (D'Ambrosio, Escriu, Goity)



→ Measurement

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

$K_S \rightarrow \gamma\gamma$: Analysis



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

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

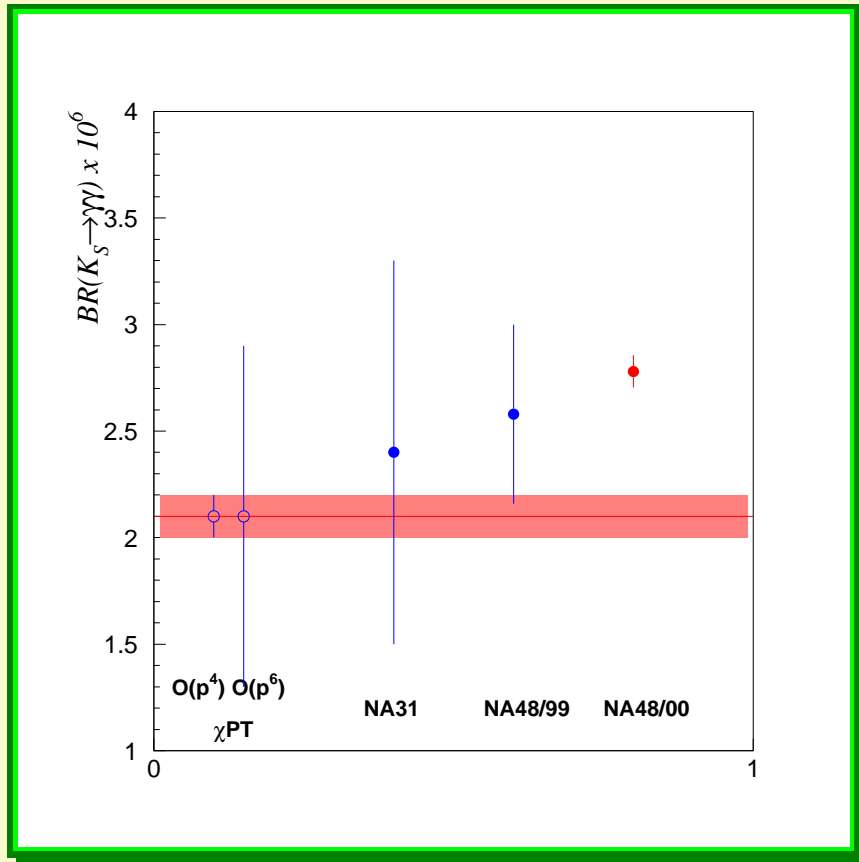
PDG: $(2.77 \pm 0.08) \cdot 10^{-3}$

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

$K_S \rightarrow \gamma\gamma$: Result

7461 ± 172 signal candidates

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



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

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

$$K_L \rightarrow e^\pm \pi^\mp \nu_e$$

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

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

Measurement:

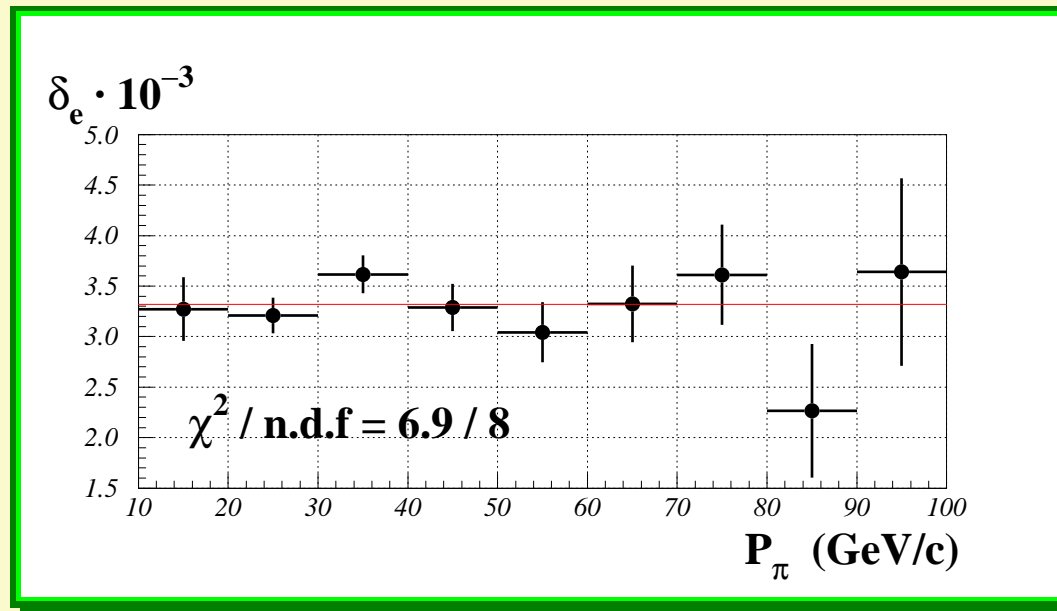
- 2001 Data.
- $\delta_e = \frac{N(K_{e3}^+) - N(K_{e3}^-)}{N(K_{e3}^+) + N(K_{e3}^-)}$.
- $e - \pi$ identification by $E(LKr)/p$.
- Selected Events $\sim 2.1 \cdot 10^8$ ($\sim 10^8$ per B orientation mode).
- Statistical Error $\sim 7 \cdot 10^{-5}$.

$K_L \rightarrow e^\pm \pi^\mp \nu_e$: Analysis (Preliminary)

→ Systematic Effects

- Fake asymmetry from particle interactions
- Data control samples:
 - $K_L \rightarrow \pi^+ \pi^- \pi^0$
 - $K_S \rightarrow \pi^+ \pi^-$
- 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



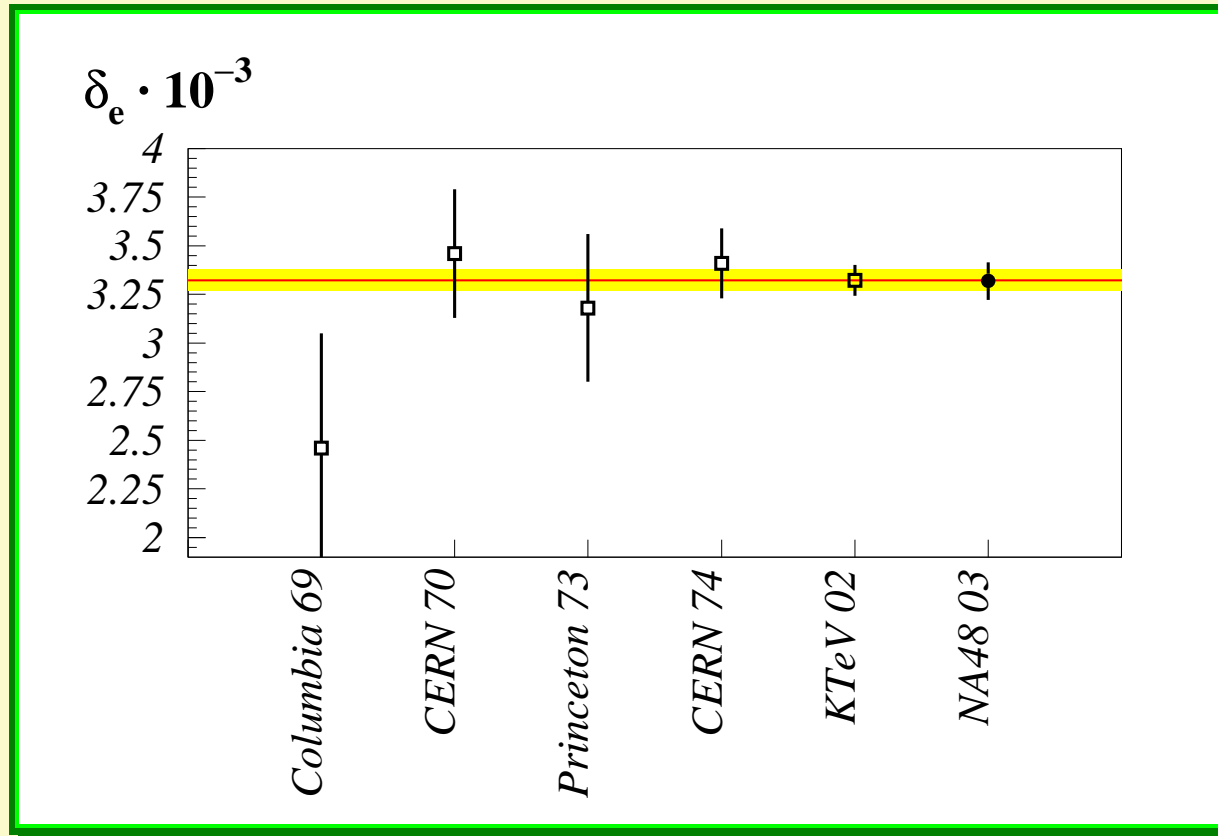
$K_L \rightarrow e^\pm \pi^\mp \nu_e$: Result (Preliminary)

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

PRELIMINARY

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

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



Conclusions on results from 1997-2001 data

- $K_L \rightarrow \pi^0 \gamma \gamma$ Phys.Lett. B 536 (2002) 229-240
- $a_\nu = -0.46$.
 - Negligible CPC contribution to $K_L \rightarrow \pi^0 e^+ e^-$.

- $K_S \rightarrow \pi^0 \gamma \gamma$ Preliminary
- First measurement of Branching Ratio.

- $K_{L,S} \rightarrow \gamma \gamma$ Phys.Lett. B 551 (2003) 7
- Precise measurement of the $\Gamma(K_L \rightarrow \gamma \gamma) / \Gamma(K_L \rightarrow 3\pi^0)$.
 - Large $\mathcal{O}(p^6)$ contribution to $BR(K_S \rightarrow \gamma \gamma)$.

- $K_L \rightarrow e^\pm \pi^\mp \nu$ Preliminary
- Competitive charge asymmetry measurement.

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

Current limit: $BR(K_L \rightarrow \pi^0 ee) < 5.1 \times 10^{-10}$ [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]

$BR(K_L \rightarrow \pi^0 ee)|_{CPD} \sim \text{few} \times 10^{-12}$



Indirect CP violation:

– $BR(K_L \rightarrow \pi^0 e^+ e^-)|_{CPI}$
 $= |\epsilon|^2 \left(\frac{\tau_L}{\tau_S}\right) BR(K_S \rightarrow \pi^0 e^+ e^-)$



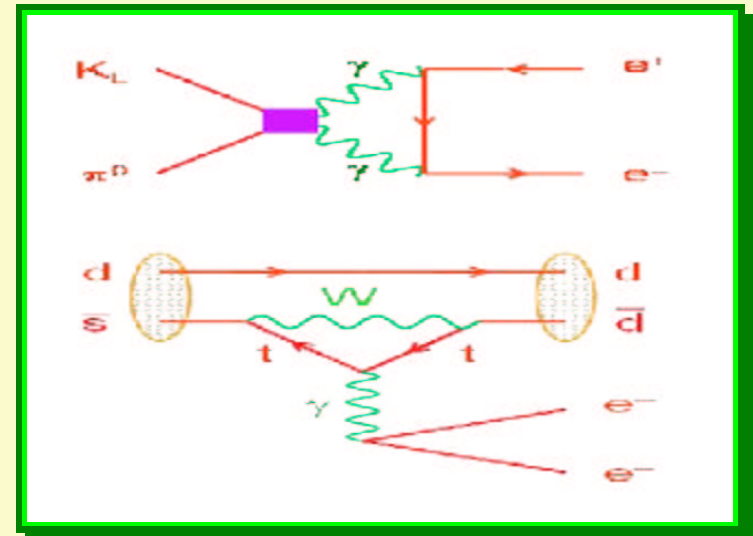
CP conserving: Given by $BR(K_L \rightarrow \pi^0 \gamma \gamma)$

– $BR(K_L \rightarrow \pi^0 e^+ e^-)|_{CPC}$
 $= \left(0.47_{-0.18}^{+0.22}\right) \cdot 10^{-12}$



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

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



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

⇒ 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
$K_S \rightarrow \pi_D^0 \pi_D^0$	0.03	0.007
$K_L \rightarrow ee\gamma\gamma$	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

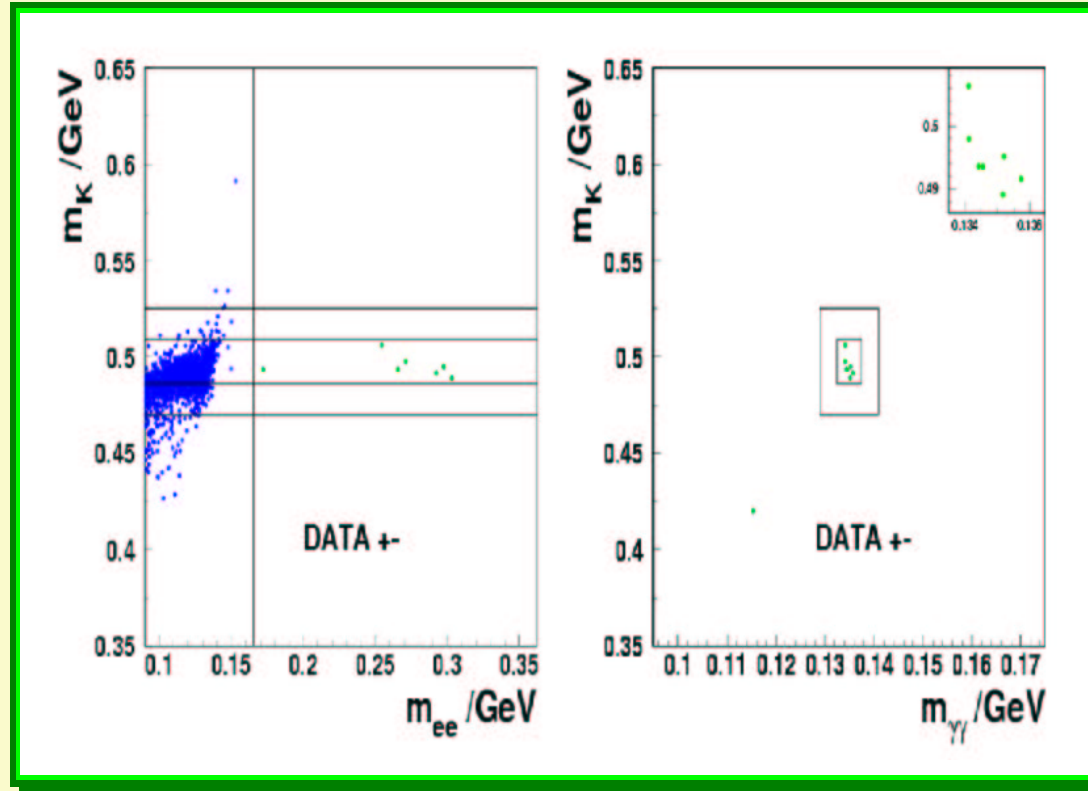
Total background in the signal region is $0.15^{+0.05}_{-0.04}$ event

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

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

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

PRELIMINARY



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

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

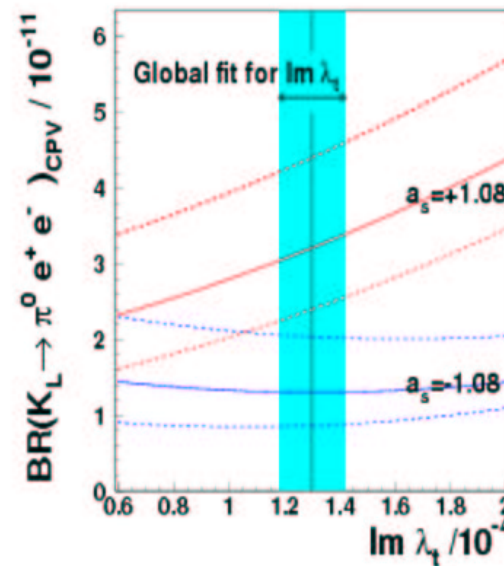
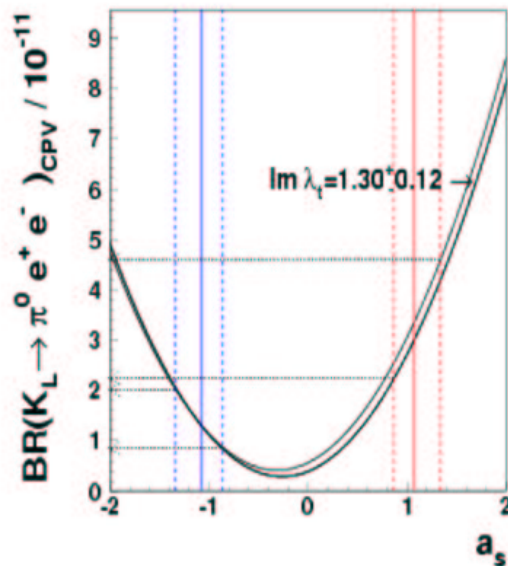
PRELIMINARY

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

Measurement of $|a_s|$ allows $BR(K_L \rightarrow \pi^0 e^+ e^-)$ to be predicted as a function of $Im(\lambda_t)$ to within a sign ambiguity :

$$BR(K_L \rightarrow \pi^0 e^+ e^-)_{CPV} = \left(\underset{\text{indirect}}{15.3 a_s^2} \pm \underset{\text{interference}}{6.8 \frac{Im(\lambda_t)}{10^{-4}} |a_s|} + \underset{\text{direct}}{2.8 \left(\frac{Im(\lambda_t)}{10^{-4}} \right)^2} \right) \times 10^{-12}$$

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

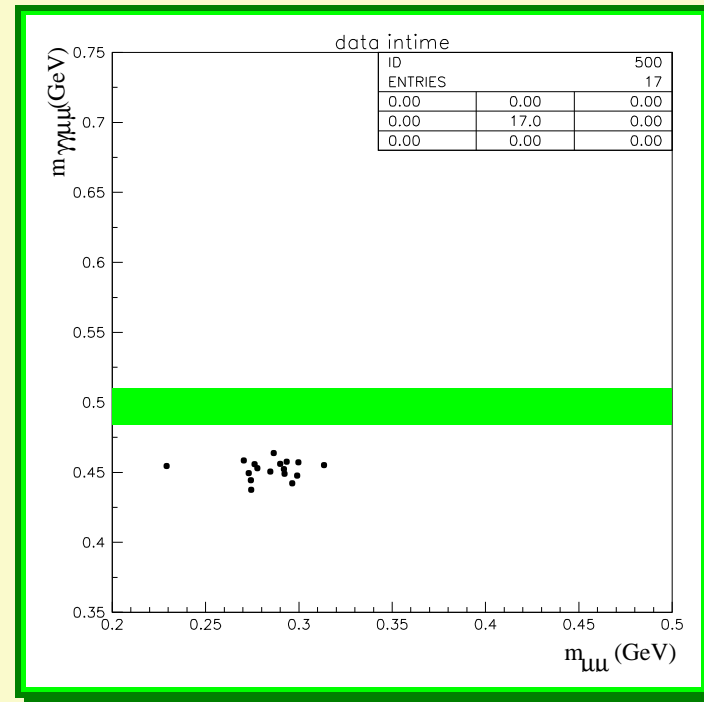
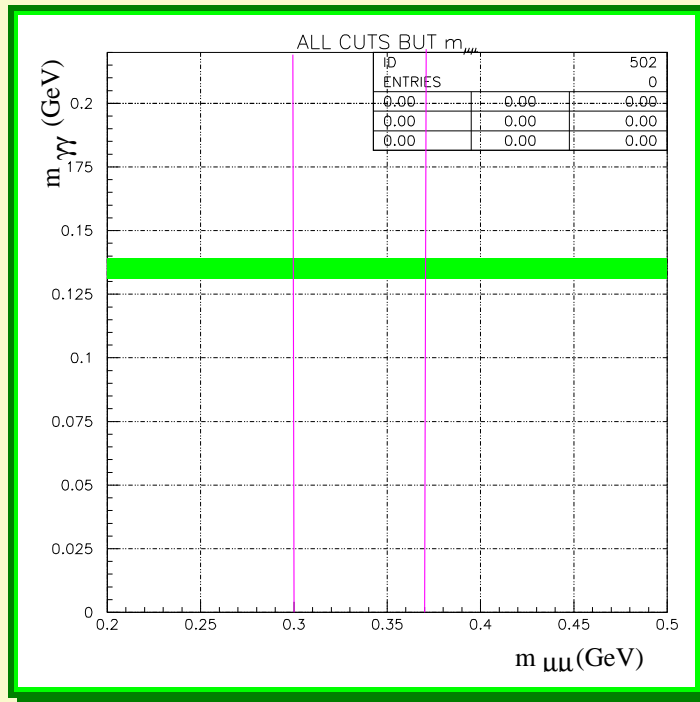


$$BR(K_L \rightarrow \pi^0 e^+ e^-) = (1 - 4) \times 10^{-11}$$



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

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



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

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

Test of unitarity... problem with $K \rightarrow \pi l \nu_l$ 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})

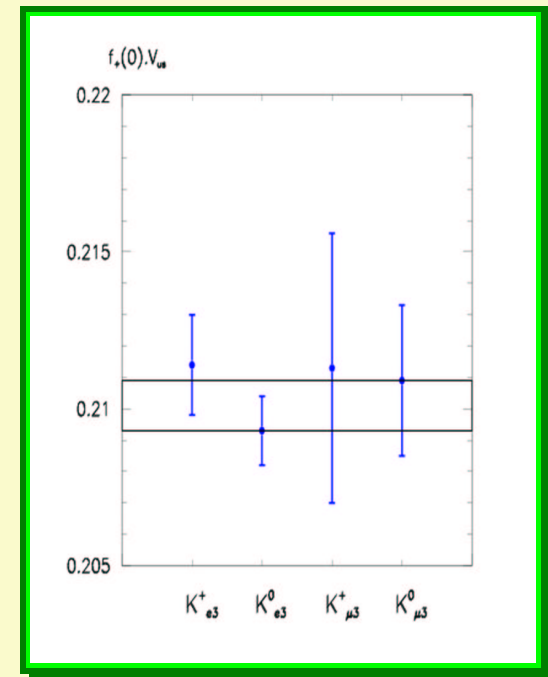
In the future, V_{ud} from $\pi^+ \rightarrow \pi^0 e^+ \nu$ (PSI-experiment).

- Recent result based on 70K events from BNL-865:

$$BR(K^+ \rightarrow \pi^0 e^+ \nu_e) = (5.17 \pm 0.02 \pm 0.09 \pm 0.04)\% \\ \Rightarrow \text{PDG } (4.87 \pm 0.06)\%$$

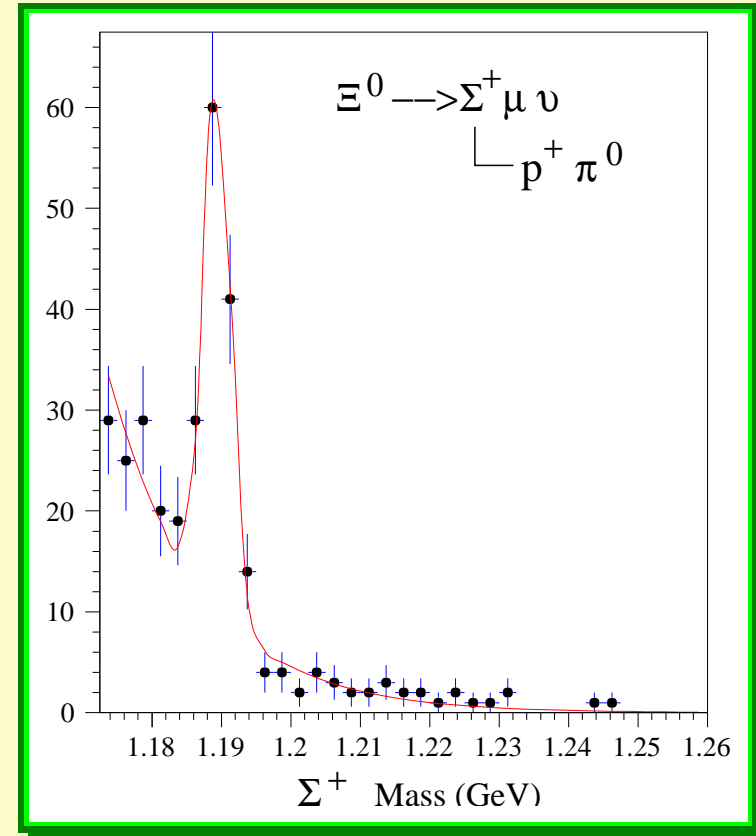
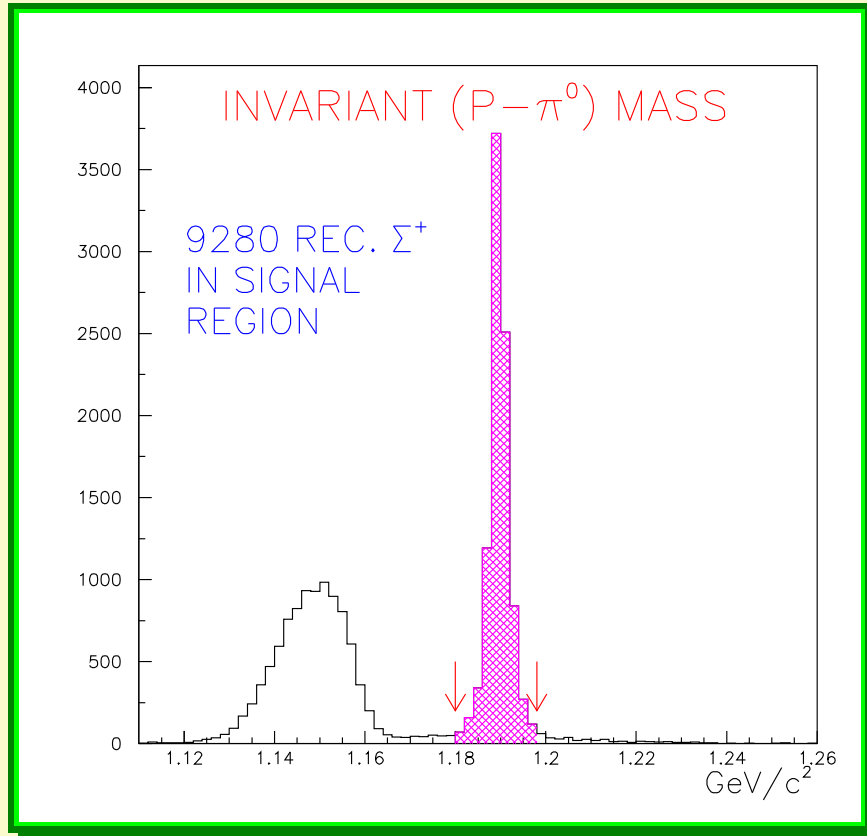
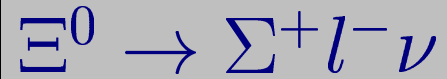
$$\Rightarrow V_{us} \rightarrow 0.2272 \dots$$

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



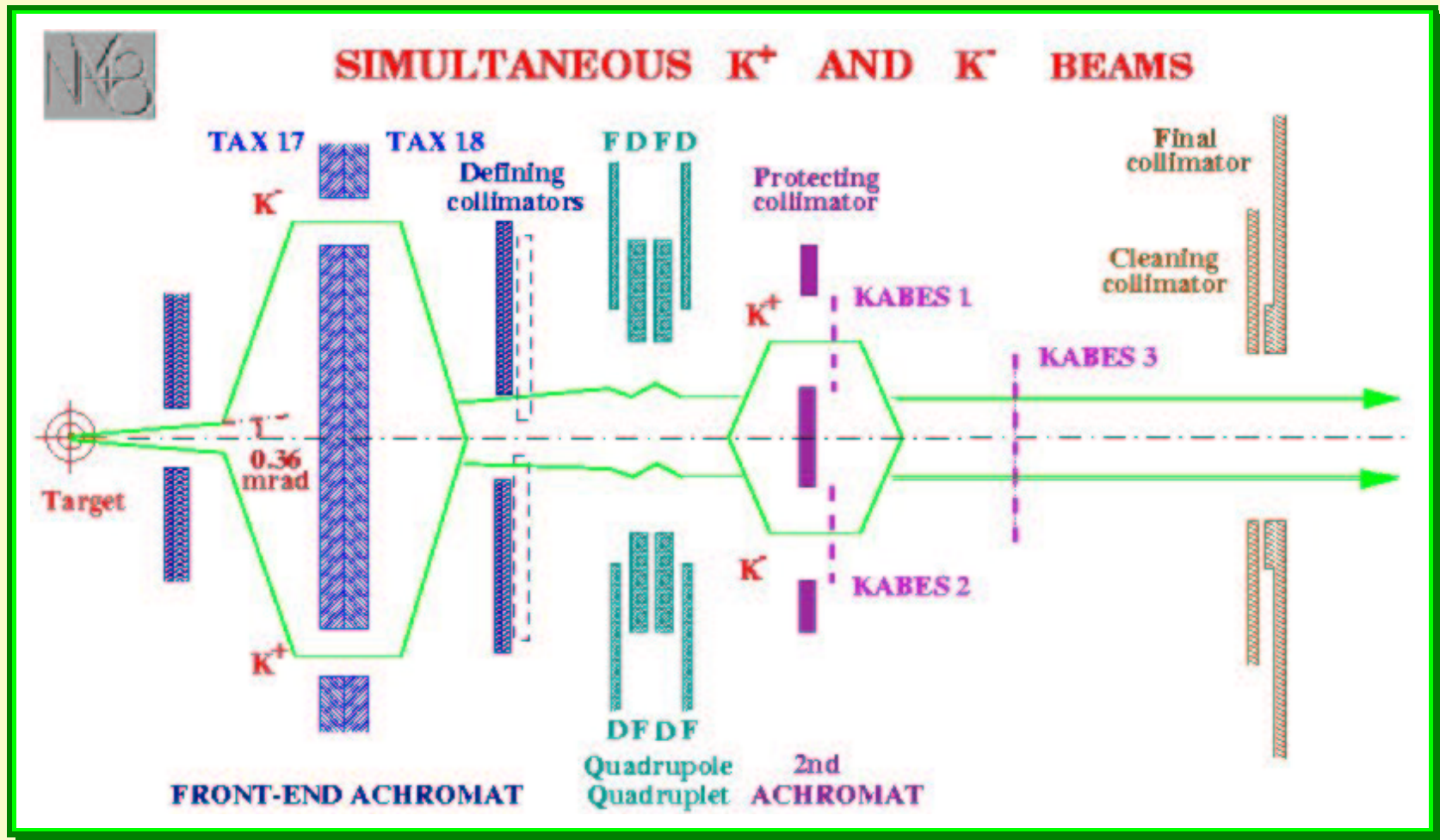
Calderon & Lopez-Castro

Hyperon Semi-leptonic Decays



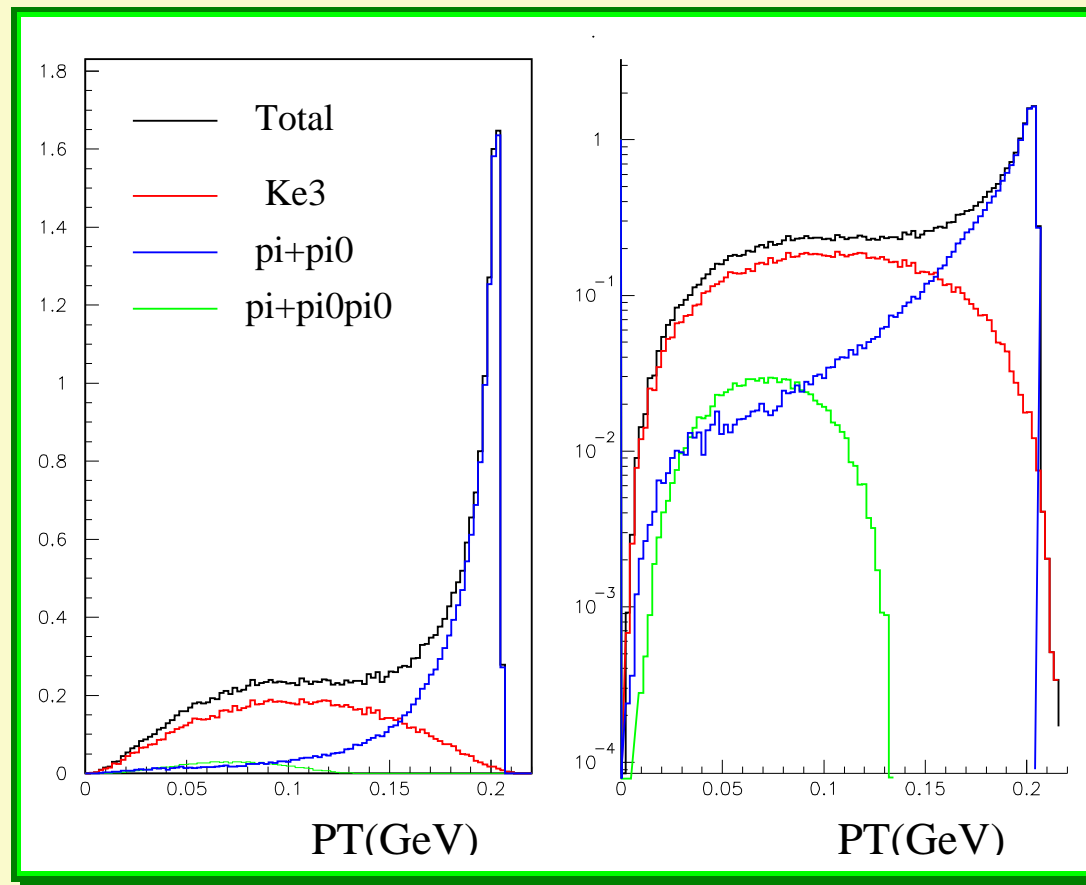
- Sample from KTeV 700 events, our sample is $>10K$ events. Sensitive to g_2 ?
- First Observation for muon channel.

K^+ and K^- Beam Line



Main program of K^+ and $K^- \longrightarrow$ Direct CP

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



We are aiming at recording 2×10^9 $\pi\pi\pi$ means (10^9 Ke3 and $K\mu 3$)/Downscaling.

Conclusions 2002 and 2003 data

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

→ $K_S \rightarrow \pi^0 e^+ e^-$

7 events found with 0.15 background events expected

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

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



⇒ well established signal!

→ $K_S \rightarrow \pi^0 \mu^+ \mu^-$

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.