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Presented on behalf of the NA48
Collaboration at CERN,
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# DIRECT CP VIOLATION IN NEUTRAL KAON DECAYS

Final result of the NA48 Experiment[1] at CERN, obtained from data taken in 1997-2001.

Determination of Re$(\varepsilon'/\varepsilon)$ from $K_{L,S} \to \pi\pi$ decays.

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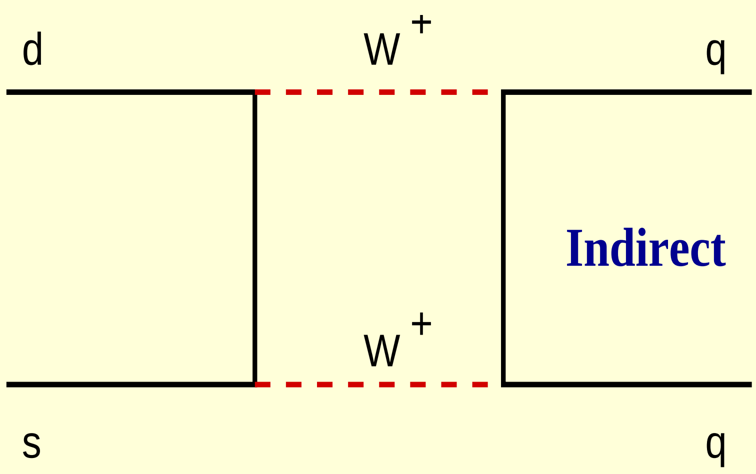
[1] Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Warszawa, Wien

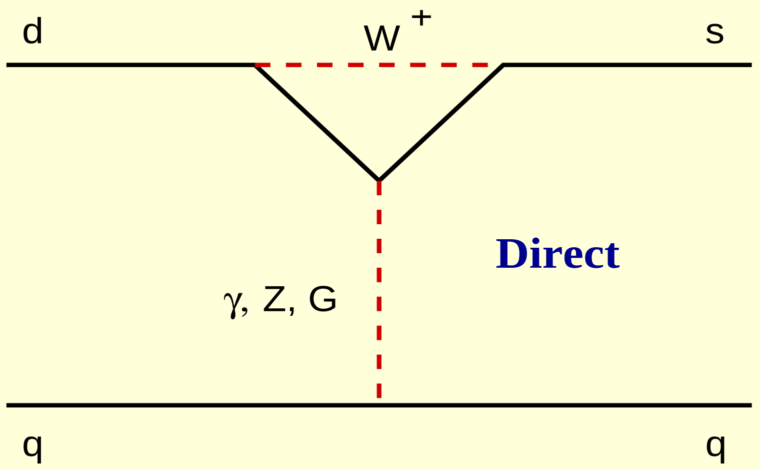
## DIRECT CP VIOLATION AND THE IDEA OF MEASUREMENT




- Indirect: transitions $\Delta S = 2$, e.g.
  $|K_L\rangle$(undefined CP) $\rightarrow |2\pi\rangle$(CP=+1)
  $|K_L\rangle \sim \varepsilon|K_1\rangle + |K_2\rangle$

$$\varepsilon = \frac{\langle 2\pi(I=0)|K_L\rangle}{\langle 2\pi(I=0)|K_S\rangle} = (2.28 \pm 0.01) \times 10^{-3} e^{i\delta_\varepsilon}$$

# DIRECT CP VIOLATION AND THE IDEA OF MEASUREMENT, cont.



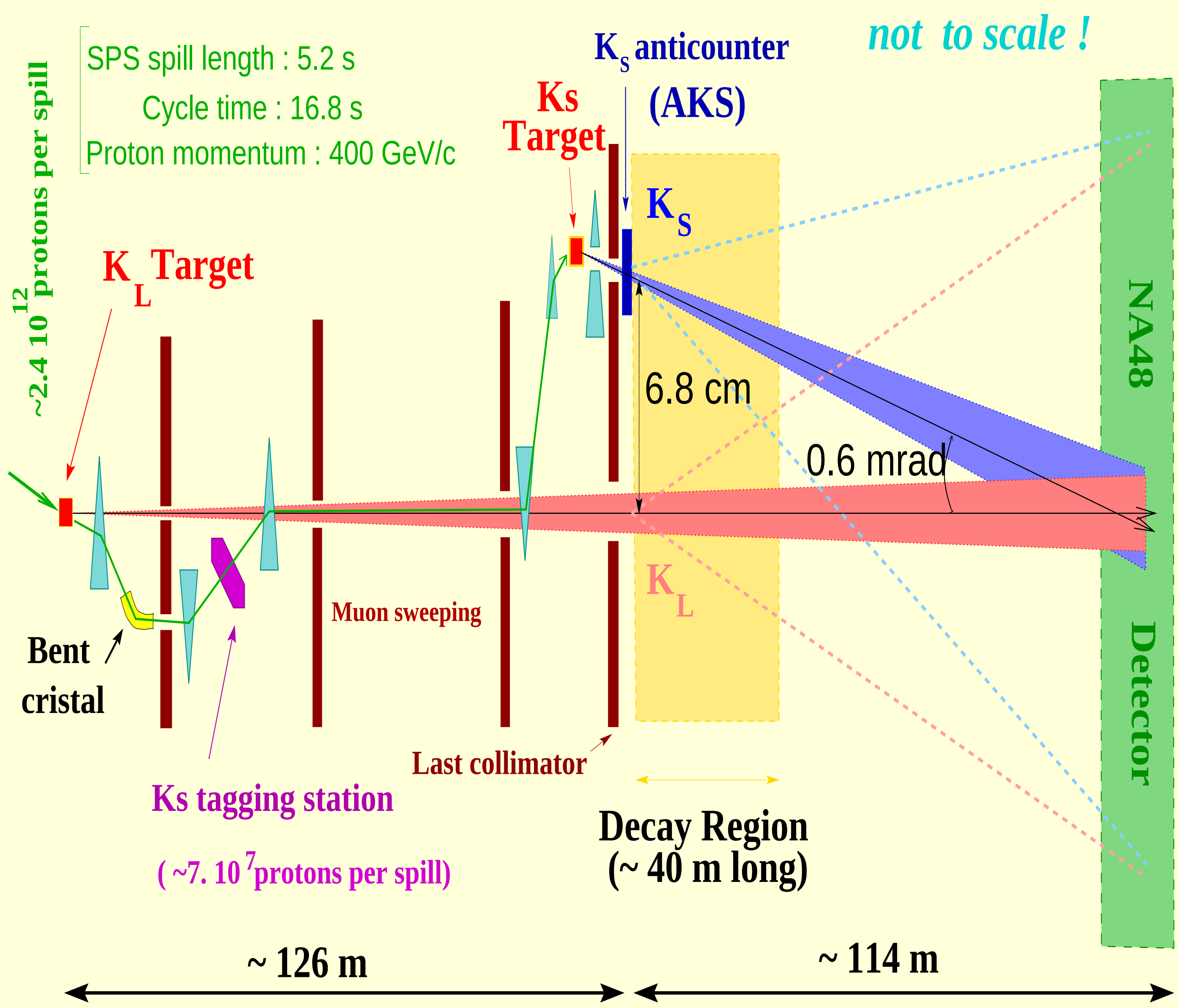

- Direct: transitions $\Delta S = 1$, e.g. $|K_2\rangle(CP = -1) \to |2\pi\rangle(CP = +1)$ requires $I = 0, 2$ interference

$$\frac{\varepsilon'}{\varepsilon} \sim \frac{\langle 2\pi(I=2)|K_L\rangle}{\langle 2\pi(I=0)|K_L\rangle} - \frac{\langle 2\pi(I=2)|K_S\rangle}{\langle 2\pi(I=0)|K_S\rangle}$$

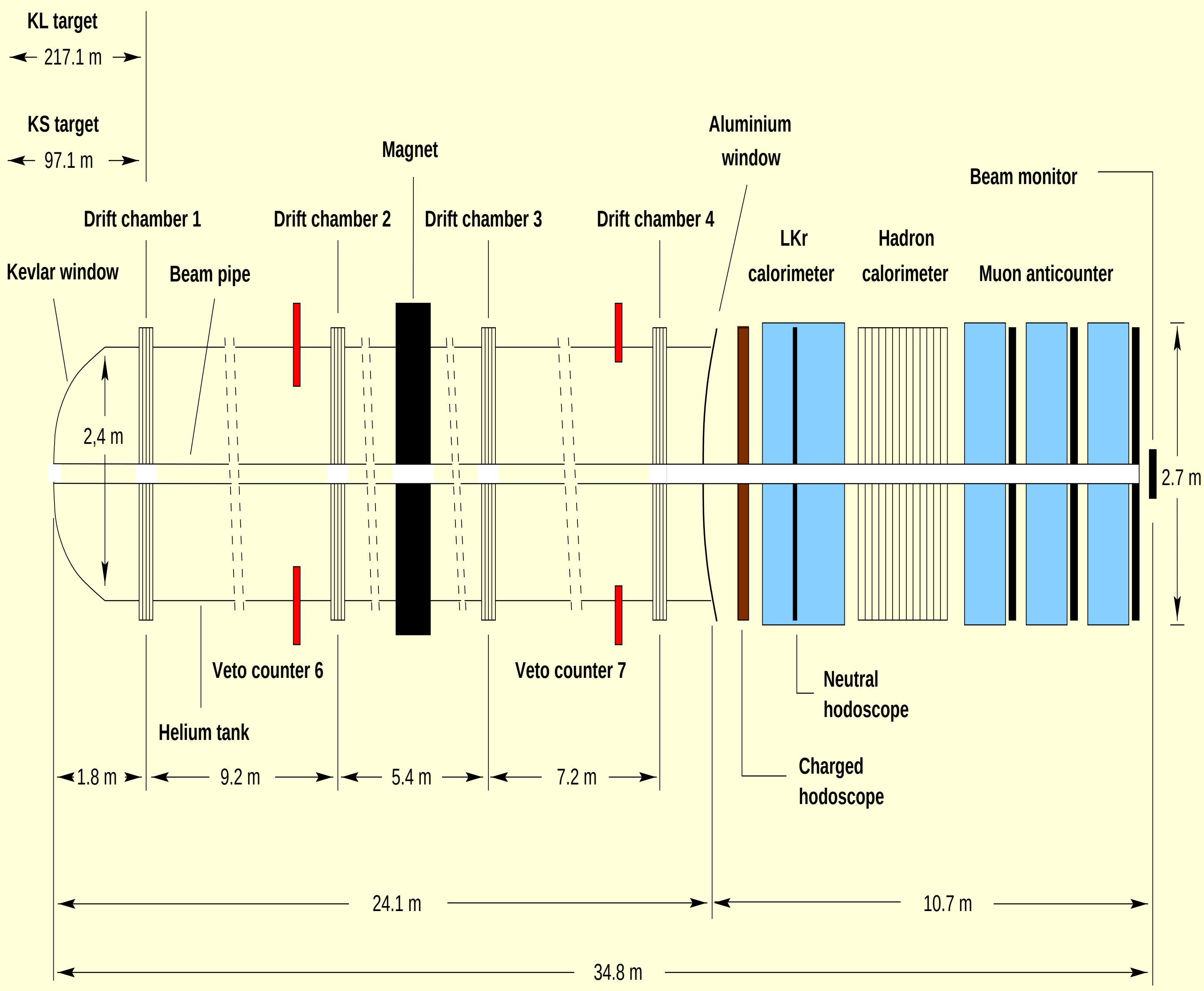
Hence, the double ratio method

$$\frac{|\langle \pi^0\pi^0|K_L\rangle / \langle \pi^0\pi^0|K_S\rangle|^2}{|\langle \pi^+\pi^-|K_L\rangle / \langle \pi^+\pi^-|K_S\rangle|^2} = 1 - 6\,\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

# NA48 KAON BEAMS

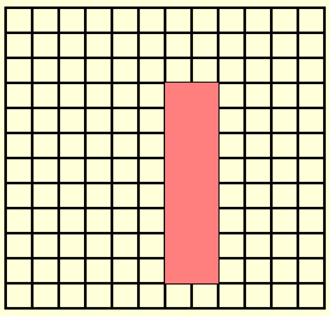


# NA48 SPECTROMETER



# TRIGGERS

## Trigger for $K \to \pi^0\pi^0$



Analogue sums in 2 x 8 supercells
summed into 64 raws and column

- $E_{TOT} > 50$ GeV,
- center of energy < 25 cm,
- $z_{vertex} < 5\ \tau_{K_S}$,
- $N_{peaks\ \ x,y} < 6$

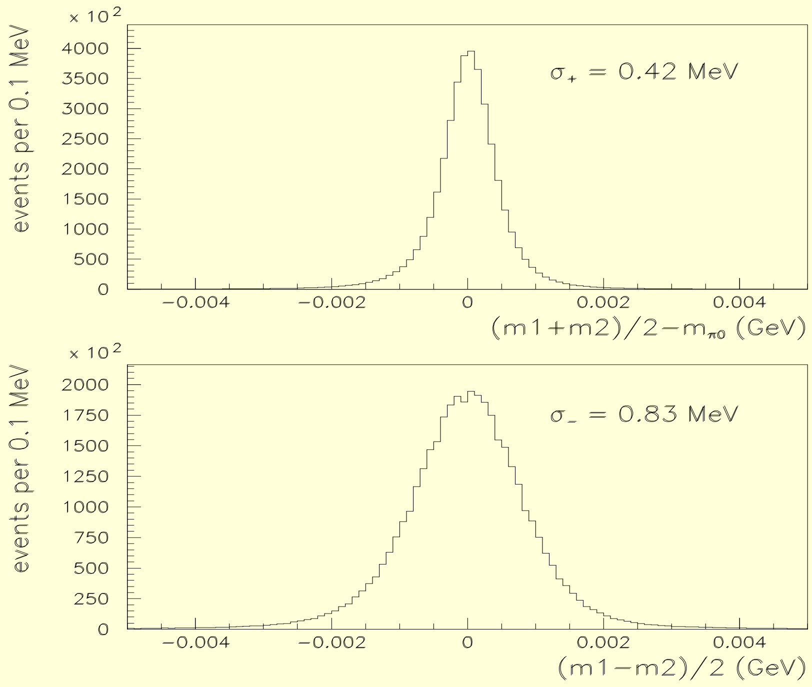
## TRIGGERS, cont.

Trigger for $K \to \pi^+\pi^-$ (2-step)

- 1st level:
  - opposite quadrant hodoscope signals,
  - chambers $N_{hit}$,
  - $E_{TOT} > 35$ GeV
- 2nd level: fast event-building asynchronous processors array reconstruct tracks; requirements for vertex, tracks and mass quality

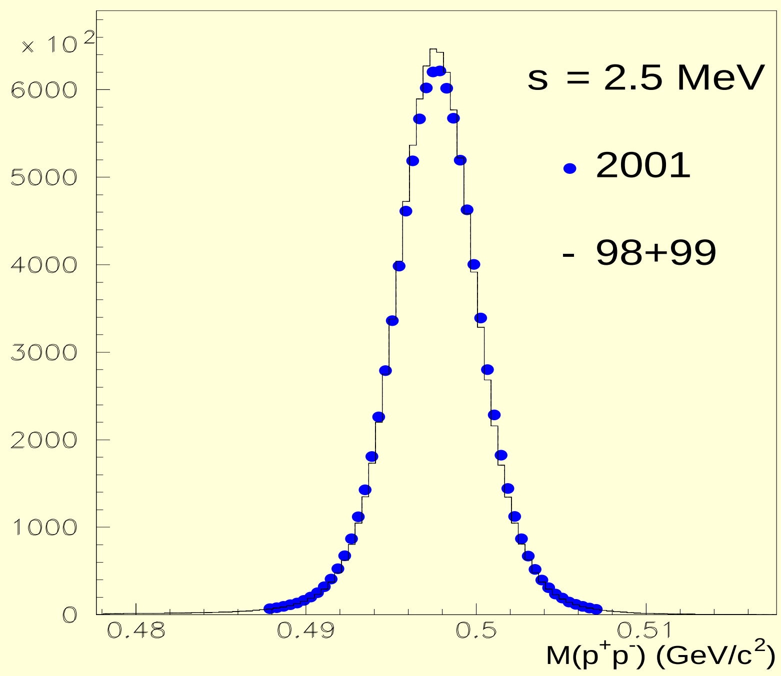
## EVENT RECONSTRUCTION AND SELECTIONS

- Neutral mode:
  - $E_{\gamma_{1,2,3,4}}$ + impacts $\longrightarrow z_{vertex}$
  - $z_{vertex} \longrightarrow m_{\gamma\gamma}s$
  - Good combinations of $\gamma$s by $\chi^2_{min}$



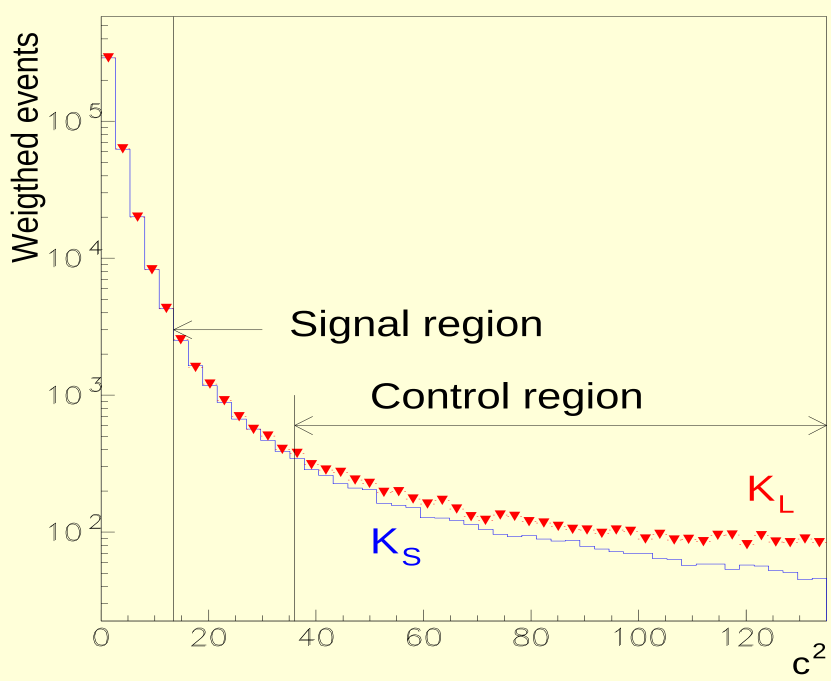
# EVENT RECONSTRUCTION AND SELECTIONS, cont.

- Charged mode:
  - $\pi^{+-}$ tracks and momenta
  - K mass and energy



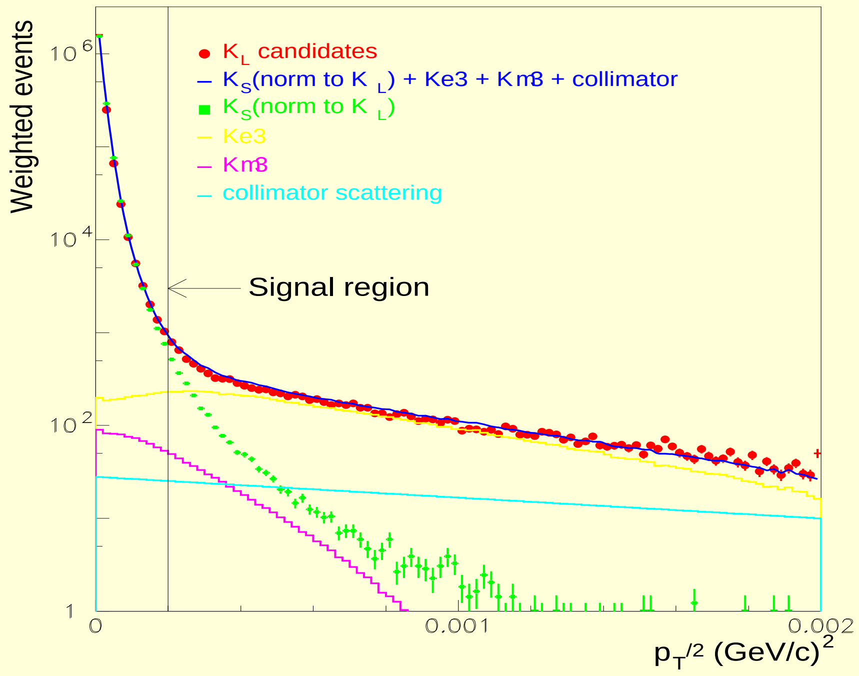
## BACKGROUND REJECTION

- Neutral mode: (uniquely $K_L \to 3\pi^0$)
  - No additional showers in LKr within $\pm 3$ ns around event time
  - $\chi^2 < 3.7\sigma(m_{\gamma\gamma})$



## BACKGROUND REJECTION, cont.

- Charged mode:
  - For $K_S$, $\Lambda \to p\pi^-$ suppressed using close $p_+$ and $p_-$
  - For $K_L$, $K_{e3}$ and $K_{\mu 3}$ by $E/p < 0.8$ or no veto hits, $m_{+-}$, small $p_T$



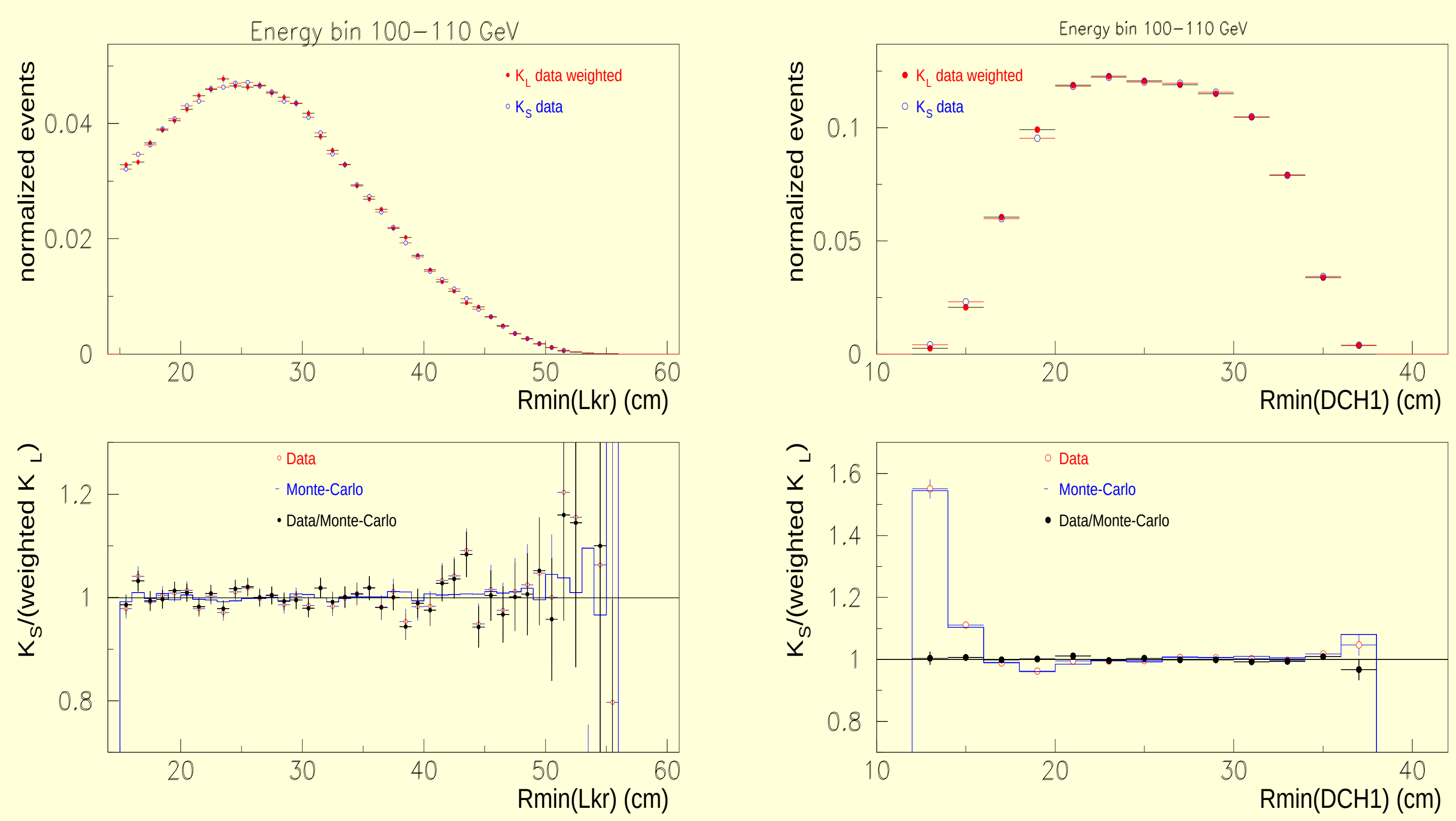
## ACCEPTANCE CORRECTIONS

Need for corrections for $\tau_{K_L} \neq \tau_{K_S}$

$K_L$ distributions weighted

$$W(\tau) = \frac{I(\tau \text{ from } K_S \text{ target})}{I(\tau \text{ from } K_L \text{ target})}$$

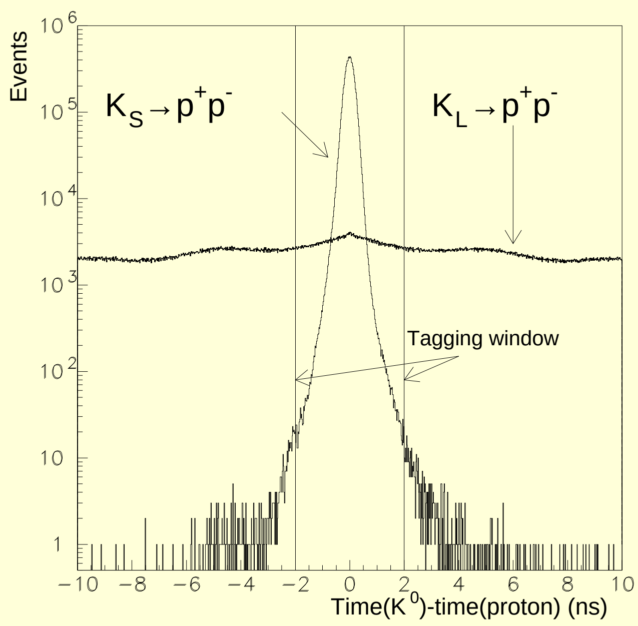
$I$ – complete $K \to 2\pi$ intensity.

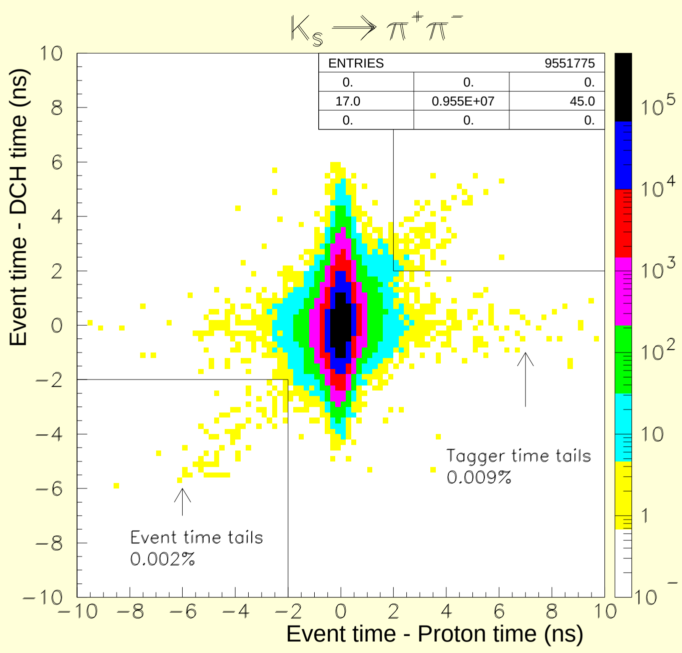


# PROBLEM OF $K_S$ TAGGING

For $\pi^+\pi^-$ mode $K_L$ and $K_S$ distinguishable by vertex $x, y$, but not for $\pi^0\pi^0$.

Require $t_{tagger}$ and $t_{event}$ to coincide within time window ($\pm 2$ ns).



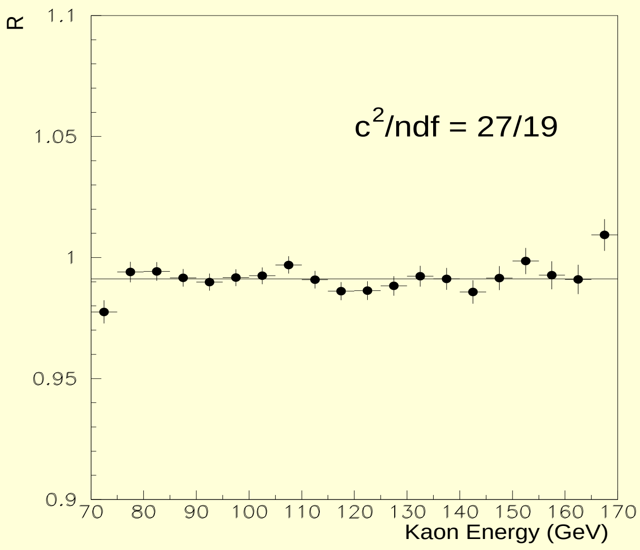



## TWO SOURCES OF SYSTEMATIC UNCERTAINTIES RELATED TO TAGGING

- $K_S$ tagging inefficiency: small probability not to register time coincidence, same for $\pi^+\pi^-$ and $\pi^0\pi^0$ modes; estimated from $\pi^+\pi^-$ mode using vertex positions.
  Effect on $R$ is $(1.9 \pm 0.4) \times 10^{-4}$
- Mistagging: accidental coincidence between event and proton times; estimated from $\pi^+\pi^-$ mode from the fraction of $K_L$ (identified from vertex) having proton in $\pm 2$ ns.
  Slight difference between modes due to intensity conditions.
  Effect on $R$ is $(4.3 \pm 1.8) \times 10^{-4}$

# STATISTICS AND RESULTS

| | M-events |
|---|---|
| $K_L \to \pi^0\pi^0$ | 4.7 |
| $K_S \to \pi^0\pi^0$ | 7.4 |
| $K_L \to \pi^+\pi^-$ | 21.6 |
| $K_S \to \pi^+\pi^-$ | 31.8 |

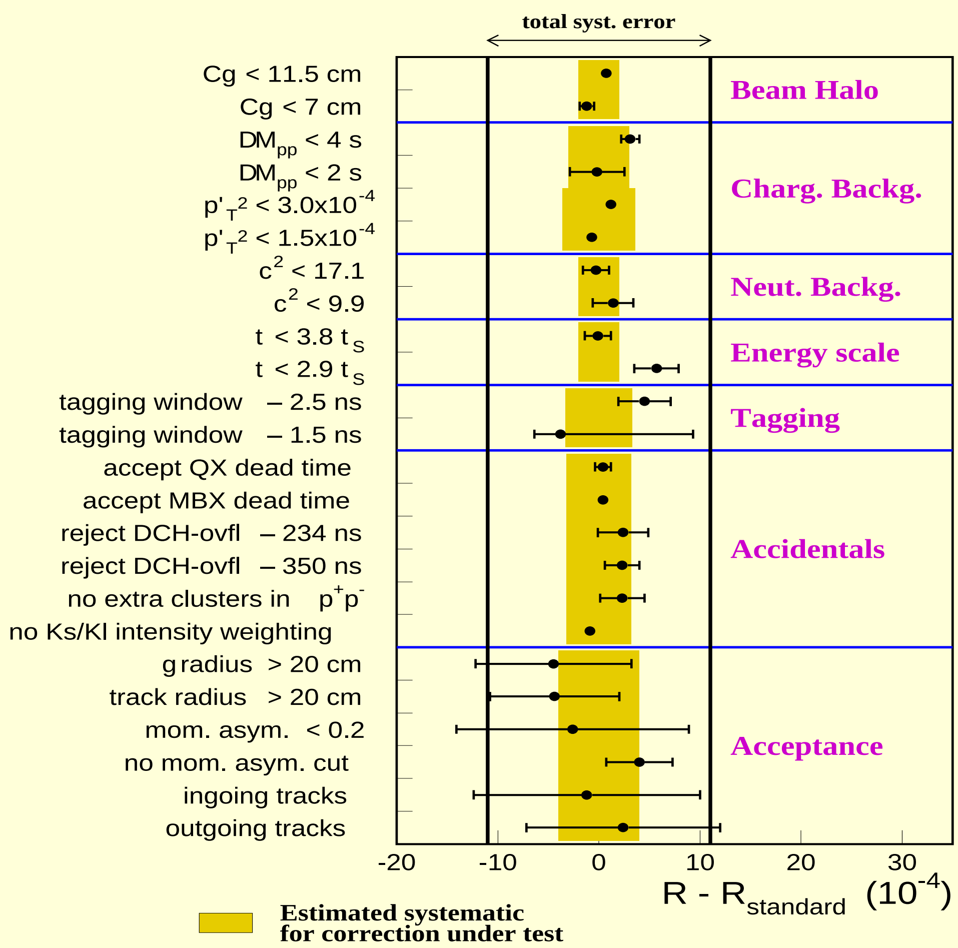



$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (14.7 \pm 1.4 \pm 0.9 \pm 1.5) \times 10^{-4}$$

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (14.7 \pm 2.2) \times 10^{-4}$$

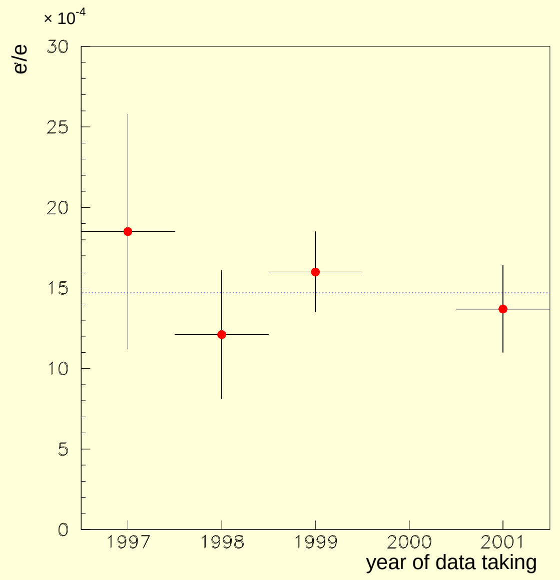
# SYSTEMATICS AND CORRECTIONS

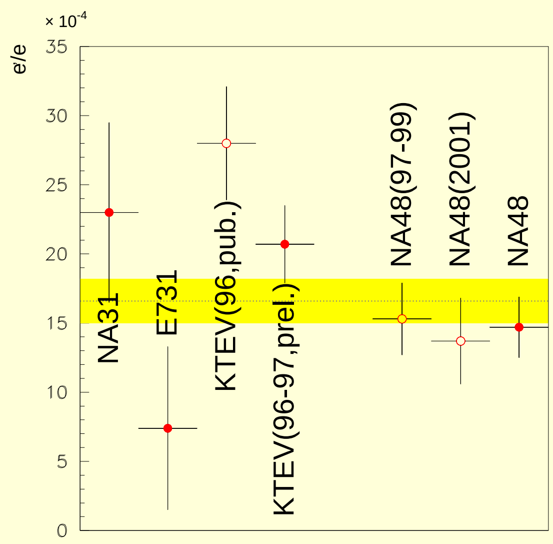
R stability against cut variations




Acceptance and charged background are major systematic culprits.

## NA48 vs. WORLD DATA




- NA48 result stable over 5 years of data taking
- Fair consistency between experiments:
  - previous generation: NA31, E731
  - present generation: NA48, KTeV. (KTeV result is not yet final.)

Direct CP violation $\varepsilon' > 0$ is experimentally proved in $K^0$ decays.

## WHAT DOES THIS RESULT MEAN

- Grand average a.d. 2002 (early 03) from[2] NA31, E731, NA48 and KTeV

  $$\text{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (16.7 \pm 1.6) \times 10^{-4}$$

- Standard model calculations of Re $\left(\frac{\varepsilon'}{\varepsilon}\right)$; theory not in shape yet.

- Exclusion of superweak interactions (should be $\varepsilon' = 0$); still some claims for marginal likelihood to save it.

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[2]Not accounting for results of much lower accuracy from before 1991

## STANDARD MODEL CALCULATIONS OF Re $\left(\frac{\varepsilon'}{\varepsilon}\right)$

In Munich notation (A. Buras et al.)

$$\frac{\varepsilon'}{\varepsilon} = \text{Im}\ \lambda_t \left( P^{(1/2)} - \frac{1}{\omega} P^{(3/2)} \right)$$

where $\lambda_t = V_{ts}^* V_{td}$,

$$P^{(1/2)} = r \sum_n y_n \langle 2\pi(I=0)|Q_n|K^0\rangle$$

$$P^{(3/2)} = r \sum_n y'_n (\langle 2\pi(I=2)|Q_n|K^0\rangle + \omega\langle 2\pi(I=0)|Q_n|K^0\rangle)$$

Matrix elementsi (m.e.):

$$\langle 2\pi(I=0)|Q_n|K^0\rangle = B_n^{(1/2)} \langle I=0|Q_n|K^0\rangle$$

$$\langle 2\pi(I=2)|Q_n|K^0\rangle = B_n^{(3/2)} \langle I=2|Q_n|K^0\rangle$$

Im $\lambda_t = (1.2 \pm 0.2) \times 10^{-4}$ from unitarity triangle analysis.

Electroweak m.e. under control,

but QCD m.e. $B_n^{(1/2)}$, $B_n^{(3/2)}$ are not.

## STANDARD MODEL CALCULATIONS OF Re $\left(\frac{\varepsilon'}{\varepsilon}\right)$, cont.

- $P^{(1/2)}$ dominated by $\Delta I = 1/2$ G-penguin.
- $P^{(3/2)}$ dominated by $\Delta I = 3/2$ $Z^0$-penguin, prop. to $m_t^2$, thus competitive to G.
- Destructive interference between two $\rightarrow$ possible cancellation, sensitive to QCD m.e. and $m_t$.
- Using CKM parameters

  $$\frac{\varepsilon'}{\varepsilon} = A^2\lambda^5\eta \cdot \text{(function of } B_n\text{s and } m_t\text{)}$$

  Assuming present CKMs and $B_n$s with no errors, current $\varepsilon'/\varepsilon)_{exp}$ would favour low $m_t < 150$ GeV.

## STANDARD MODEL CALCULATIONS OF Re $\left(\frac{\varepsilon'}{\varepsilon}\right)$, cont.

Since $m_t = 174.3 \pm 5.1$ GeV, $\eta$ would have to be lower than previously supposed;
$A$ and $\lambda$ known pretty precisely;
$\eta$ contributes to $V^*_{cd}V_{cs}$ and $V^*_{td}V_{ts}$ terms.

But uncertainties on $B_n$s obscure the picture.

- Contribution of final state interactions to $\varepsilon'/\varepsilon$ is not estimated (may not be negligible, relative momenta of $\pi$s are not small !)

## CONCLUDING REMARKS

- Elusive direct CP violation in K decays is no longer illusion.

  Experimentally, $\frac{\varepsilon'}{\varepsilon} > 0$ is firm, both from NA48 alone and from world data pooled.

- Calculation of $\frac{\varepsilon'}{\varepsilon}$ is still a challenge for theory, mainly due to long-range QCD contributions.

  Hence the meaning of the result for physics is not yet fully understood.