THE KAON VARIATIONS

Exploring CP and flavour physics with kaons

Prepared for connoisseurs,
for the refreshment of their spirits by

M. S. Sozzi – University of Pisa

Trieste – July 2\textsuperscript{nd}, 2008
<table>
<thead>
<tr>
<th>Program</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conclusions</td>
<td>Introduction</td>
</tr>
<tr>
<td>Aria</td>
<td>$\varepsilon'/\varepsilon$</td>
</tr>
<tr>
<td>Canone alla seconda</td>
<td>$\varepsilon$, semi-leptonics and CKM</td>
</tr>
<tr>
<td>Canone alla terza</td>
<td>CPV in $3\pi$ decays</td>
</tr>
<tr>
<td>Canone all’unisono</td>
<td>$\pi\pi$ scattering lengths and QCD</td>
</tr>
<tr>
<td>Fughetta</td>
<td>Other decays and symmetries</td>
</tr>
<tr>
<td>Quodlibet</td>
<td>Future prospects</td>
</tr>
<tr>
<td>Alla marcia</td>
<td></td>
</tr>
<tr>
<td>Aria da capo</td>
<td>Conclusions</td>
</tr>
</tbody>
</table>

CPT@ICTP July 2008
M.Sozzi – The Kaon variations
Introduction

Kaons: lightest kind of flavoured matter
- The birth of the flavour physics puzzle
- The first failure of a discrete symmetry
- The matter-antimatter asymmetry

A large and significant part of particle physics…

Is there still something to be learned by using kaons?
Kaons remain a privileged observatory for flavour physics phenomena

- All the features of flavour physics are present (i.e. all kinds of CP violation – “same size” as in B)
- Very simple (minimal) system
- Very nicely accessible experimentally (rates, branching ratios, backgrounds, …)
- Pretty hard for theorists…
### Searches for CP/T violation with K

<table>
<thead>
<tr>
<th>Transitions among CP eigenstates with opposite eigenvalues [direct CPV]</th>
<th>$K_2 \rightarrow \pi\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search for physical states not being CP eigenstates (non-exp. decay of CP eigenstates) [indirect CPV]</td>
<td>$K_L \rightarrow \pi\pi$ and $K_s \rightarrow \pi\pi\pi$</td>
</tr>
<tr>
<td>Differences in the partial decay widths or decay properties of particles and antiparticles [direct CPV]</td>
<td>$\Delta g(K \rightarrow 3\pi)$</td>
</tr>
<tr>
<td>Direct test of time-reversibility</td>
<td>$P(K^0 \rightarrow K^0) \neq P(K^0 \rightarrow K^0)$</td>
</tr>
<tr>
<td>Measure of non-zero T-odd quantities</td>
<td>$P_T(K_{\mu3})$ Triple prod.</td>
</tr>
<tr>
<td>CPT tests</td>
<td>$M(K^0) - m(\bar{K}^0)$</td>
</tr>
</tbody>
</table>
“At present our experimental understanding of CP violation can be summarized by the statement of a single number”. (J. Cronin, 10.12.1980)

The search for (direct) CPV in the \( K \rightarrow 2\pi \) decay amplitude: a long series of precision counting experiments

\[
\left| \eta_{00} \right|^2 = \frac{\Gamma(K_L \rightarrow \pi^0 \pi^0)}{\Gamma(K_S \rightarrow \pi^0 \pi^0)} \frac{\Gamma(K_S \rightarrow \pi^+ \pi^-)}{\Gamma(K_L \rightarrow \pi^+ \pi^-)} = 1 - 6 \text{Re}(\epsilon'/\epsilon)
\]

The (inconclusive) legacy of the NA31 (CERN) and E731 (FNAL) experiments

The whole of K physics in the last decade stems from this central experimental program

CPT@ICTP July 2008

M. Sozzi – The Kaon variations
KTeV (1996-1999)

FNAL Main Injector (120 GeV) p
Double $K_L$ beam ($<p>=70$ GeV/$c$)
Regenerated $K_S$
Pure CsI calorimeter
Data taking in 1997 and 1999
100 physicists, 12 USA/Japan institutions
NA48 (1996-2001)

CERN SPS (450 GeV) p
$K_S$ and $K_L$ beams ($<p>=100$ GeV/$c$)
$K_S$ tagging by time-of-flight
Liquid Krypton calorimeter
130 physicists, 16 European institutions
**ε′/ε – New KTeV result**

**Preliminary result from 1999 data-taking**

Doubling the statistics to full data set:
- $6 \text{M } K_L \rightarrow \pi^0\pi^0$, $10 \text{M } K_S \rightarrow \pi^0\pi^0$, $25 \text{M } K_L \rightarrow \pi^+\pi^-$, $43 \text{M } K_S \rightarrow \pi^+\pi^-$

Reduction of systematics through improvements in MC simulation, mostly for neutral mode

\[ \text{Re}(\epsilon'/\epsilon) = (19.2 \pm 1.1 \pm 1.8) \cdot 10^{-4} \]

**KTeV (2003):**

\[ (20.7 \pm 1.5 \pm 2.4) \cdot 10^{-4} \]

M. Sozzi – The Kaon variations
New world average:

Including $\Delta I = 3/2$ correction
[EPJ C36 (2004) 37]

$\chi^2 = 5.3/3$, consistency 14%

(was 6.2/3, consistency 10%)

Direct CPV in K decays at $\approx 9$ standard deviations

$\text{Re}(\epsilon'/\epsilon) = (16.4 \pm 1.9) \cdot 10^{-4}$

[PDG scaled error]
\( \varepsilon'/\varepsilon \) – its meaning

1999: proof of direct CP violation (after 36 years!)

The first test of the CKM paradigm for CP violation

CPV is a universal property of weak interactions

\[
\frac{\Gamma(K^0 \rightarrow \pi^+ \pi^-) - \Gamma(\bar{K}^0 \rightarrow \pi^+ \pi^-)}{\Gamma(K^0 \rightarrow \pi^+ \pi^-) + \Gamma(\bar{K}^0 \rightarrow \pi^+ \pi^-)} = (5.18 \pm 0.61) \times 10^{-6}
\]

(\( \text{BR}=2.0 \cdot 10^{-3} \))

\( \mathcal{O}(10^7) \) events

2005 EPS Prize to the NA31 collaboration

2007 APS Panofsky Prize to Italo Mannelli (Pisa), Heinrich Wahl (CERN) and Bruce Winstein (Chicago)

Compare e.g.

\( A_{CP}(B^0 \rightarrow \eta K^*(892)) = 0.21 \pm 0.06 \)

(\( \text{BR}=1.6 \cdot 10^{-5} \)) \( \mathcal{O}(10^2) \) events
\( \varepsilon' \) confronts the SM

While the significance of \( \varepsilon' \neq 0 \) clearly *trascends* its precise value... and (dire) theoretical difficulties make precise computation of such quantity within the Standard Model.

\( \varepsilon'/\varepsilon \) theoretical pre/post-dictions (SM)

Experimental values are compatible with the SM

(accidentally quasi-superweak)

\( \varepsilon'/\varepsilon \) measured to 10%

(Impatiently) waiting for lattice QCD to become also a *quantitative* test of SM.
New KTeV byproducts

\[ \Delta m = (5269.9 \pm 12.3) \cdot 10^6 \, \text{fs}^{-1} \]
\[ \tau_s = (89.623 \pm 0.047) \cdot 10^{-12} \, \text{s} \]
\[ \phi(\varepsilon) = (43.86 \pm 0.63) ^\circ \]
\[ \phi(\varepsilon) - \phi_{SW} = (0.40 \pm 0.56) ^\circ \]
\[ \phi_{00} - \phi_{+-} = (0.30 \pm 0.35) ^\circ \]

[No CPT: \( \Delta m = (5279.7 \pm 19.5) \cdot 10^6 \, \text{fs}^{-1} \) ]
[No CPT: \( \tau_s = (89.589 \pm 0.070) \cdot 10^{-12} \, \text{s} \) ]

Using 30K double-Dalitz decays of \( \pi^0 (\pi^0 \rightarrow e^+e^-e^+e^-) \), the neutral pion is shown to be pseudoscalar to better than 89.2% (96.8% if CPT assumed) at 90% CL.

CPT@ICTP July 2008

M. Sozzi – The Kaon variations
CPV in charged $K_{\pi 3}$

- Any CPV in charged kaons is of the **direct** type.
- Most copious decay modes possibly supporting CPV:
  - $\text{BR}(K^\pm \rightarrow \pi^\pm \pi^+ \pi^-) = 5.57\%$ “charged”
  - $\text{BR}(K^\pm \rightarrow \pi^\pm \pi^0 \pi^0) = 1.73\%$ “neutral”

Large statistics, simple selection, low backgrounds

- Hadronic uncertainties
- Small rescattering phases
  $\rightarrow$ Small asymmetry in SM

 Width asymmetries suppressed: compare Dalitz plot *shapes* (no absolute K flux measurement)

CPT@ICTP July 2008

M. Sozzi – The Kaon variations
**NA48/2: search for CPV in $K_{\pi 3}$**

**Kinematics:**
\[
s_i = (P_{K^-} - P_{\pi})^2 \quad i=1,2,3 \quad (3=\text{odd } \pi)
\]
\[
s_0 = (s_1 + s_2 + s_3)/3
\]
\[
u = (s_3 - s_0)/m_{\pi}^2 = 2m_K (m_K/3 - E_{\text{odd}})/m_{\pi}^2
\]
\[
u = (s_2 - s_1)/m_{\pi}^2 = 2m_K (E_1 - E_2)/m_{\pi}^2
\]

**Matrix element:**
\[
|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2
\]

$A_g = (g_+ - g_-)/(g_+ + g_-) \neq 0$ ?

NA48/2 exploited maximal cancellations (robustness)
- **Simultaneous** $K^+$ and $K^-$ beams, **superimposed** in space, with narrow momentum spectra
- Detect asymmetry only from slopes of **ratios** of normalized $u$ distributions
- **Equalize** averaged $K^+$ and $K^-$ **acceptances** by frequently alternating polarities of relevant magnets

CPT@ICTP July 2008  
M.Sozzi – The Kaon variations
CPT@ICTP July 2008 M.Sozzi – The Kaon variations

NA48/2 beams

$P_K$ spectra, $60 \pm 3$ GeV/c

$2 \div 3 \times 10^{12}$ K/spill ($\pi/K \sim 12$)

$\pi$ decay products stay in pipe

Beams coincide within $\sim 1$mm all along 114m decay volume, always in vacuum

$10^{11}$ K decays per year collected
Data-taking 2003-04: $3.1 \times 10^9 + 9.1 \times 10^7$ events selected ($K^+/K^- \approx 1.8$)
No significant background, complementary analysis in the two modes
Exploit multiple cancellations of instrumental effects via inversion of magnetic fields and simultaneous beams
Final results on full statistics (2003+2004)

\[ \text{Ag(C)} = (-1.5 \pm 1.5_{\text{stat}} \pm 0.9_{\text{trig}} \pm 1.1_{\text{syst}}) \cdot 10^{-4} \]
\[ = (-1.5 \pm 2.1) \cdot 10^{-4} \]

(3.1 \cdot 10^9 \text{ decays})

\[ \text{Ag(N)} = (1.8 \pm 1.7_{\text{stat}} \pm 0.5_{\text{syst}}) \cdot 10^{-4} \]

(9.1 \cdot 10^7 \text{ decays})

\[ \text{Ag(C)} = (1.8 \pm 1.8) \cdot 10^{-4} \]

Statistics dominated. x10 improvement. No CPV found.


**K± asymmetries vs. the SM**

**THEORY:**

- **SM contribution:** many theoretical computations
- Large uncertainties (~1 order of magnitude)
- Enhancements possible beyond SM

- $A_g \sim 10^{-5}$ compatible with SM
- $A_g > 1 \cdot 10^{-4}$ SUSY / New Physics

NP window “closed”, part of SUSY model parameter space excluded

---


SM estimate (NLO ChPT):

- $A_g(C) = (-1.4 \pm 1.2 \pm ?) \cdot 10^{-5}$
- $A_g(N) = (1.1 \pm 0.7 \pm ?) \cdot 10^{-5}$
Precise measurements obtained by $K_L$ semi-leptonic charge asymmetry in KTeV and NA48 using a few 100M decays per experiment:

$$\delta_L(\ell) = \frac{\Gamma(K_L \rightarrow \pi^- \ell^+ \nu) - \Gamma(K_L \rightarrow \pi^+ \ell^- \bar{\nu})}{\Gamma(K_L \rightarrow \pi^- \ell^- \bar{\nu}) + \Gamma(K_L \rightarrow \pi^+ \ell^+ \nu)} = \frac{2 \text{Re}(\varepsilon)}{1 + |\varepsilon|^2}$$

(assuming CPT)

$$\delta_L(e) = (3.322 \pm 0.055) \cdot 10^{-3}$$

(world average)
At Frascati DAΦNE Φ-factory with separate e+e- rings and 12.5 mrad crossing angle working at $\sqrt{s} = m(\Phi) = 1019.4$ MeV

Integrated luminosity:
\[ \sim 2.5 \, \text{fb}^{-1} \, 1999-2006 \]
\[ (\sim 2.5 \cdot 10^9 K_S K_L \text{ events}) \]
KTeV, KLOE, NA48: $\varepsilon$

\[ \eta_{+-} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} \approx \varepsilon + \varepsilon' \approx \varepsilon \]

**KTeV**: direct measurement of \( BR(K_L \rightarrow \pi^+\pi^-)/BR(K_L \rightarrow \pi^+\pi^-) \)
84K events in 1997

**KLOE**: direct measurement of \( BR(K_L \rightarrow \pi^+\pi^-)/BR(K_L \rightarrow \pi^+\pi^-) \)
45K events from subsample of 2001-2002 data

**NA48**: direct measurement of \( BR(K_L \rightarrow \pi^+\pi^-)/BR(K_L \rightarrow \pi^+\pi^-) \)
47K events from 2-day run in 1999

"The BR revolution"
- Proper treatment of radiative corrections
- Several correlations

CPT@ICTP July 2008
$\epsilon$ confronts the SM

$\epsilon \neq 0$ constrains (poorly) the apex of the Unitarity Triangle due to the theoretical difficulty in handling the hadronic uncertainties.

$\epsilon$ measured to 0.5%
Waiting for lattice QCD for $K$ to become also a quantitative test of SM.

New accurate and precise $B_K$ required.

M. Sozzi – The Kaon variations
CPV in hadronic $K_S$ decays

3$\pi$ states are (predominantly) CP-odd

Estimate (indirect CPV): $\Gamma_S(3\pi) \approx \Gamma_L(3\pi)|\eta|^2$, or

$\text{BR}(K_S \rightarrow 3\pi^0) \approx \text{BR}(K_L \rightarrow 3\pi^0) |\varepsilon|^2 (\tau_S/\tau_L) \approx 1.9 \cdot 10^{-9}$

**Hadron machines:** look for $K_S$-$K_L$ interference.
NA48/1 (2005, assuming CPT): $\text{BR}(K_S \rightarrow 3\pi^0) < 2.3 \times 10^{-7}$ (90% CL) with 5+100 million K decays.

**Phi-factories:** search for tagged $K_S \rightarrow 3\pi^0$ decays.
KLOE (2005): $\text{BR}(K_S \rightarrow 3\pi^0) < 1.2 \times 10^{-7}$ (90% CL) with 2 signal events.
Improvements expected from here...

**No CPV in sight yet**
First measurement of $K_S$ semi-leptonic decays ($K_S \rightarrow \pi \mu \nu$ also seen):

$$\text{BR}(K_S \rightarrow \pi e \nu) = (7.028 \pm 0.092) \times 10^{-4}$$

2001-2002 data (410 pb$^{-1}$):
13K events

(Indirect) CP-violating charge asymmetry:

$$\delta_s(e) = \frac{\Gamma(K_S \rightarrow \pi^- e^+ \nu) - \Gamma(K_S \rightarrow \pi^+ e^- \bar{\nu})}{\Gamma(K_S \rightarrow \pi^- e^+ \nu) + \Gamma(K_S \rightarrow \pi^+ e^- \bar{\nu})}$$

$$= (1.5 \pm 9.6_{\text{stat}} \pm 2.9_{\text{syst}}) \times 10^{-3}$$

CPT test by comparison to $\delta_L(e)$ (still far from being significant)

M. Sozzi – The Kaon variations
Cabibbo angle 45 years later

In 2004 a slight violation of the unitarity appeared in the first (best) row of the CKM matrix:\n$|V_{ud}|$ from $\beta$ decays, $|V_{ub}| \approx 10^{-5}$ ignored

All experiments re-measured semi-leptonic decays of neutral and charged $K$ with sub-percent precision.

<table>
<thead>
<tr>
<th>mode</th>
<th>$f_+(0)V_{us}$</th>
<th>% err</th>
<th>BR</th>
<th>$\tau$</th>
<th>$\Delta$</th>
<th>Int</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \pi \nu\nu$</td>
<td>0.21625(60)</td>
<td>0.28</td>
<td>0.09</td>
<td>0.19</td>
<td>0.15</td>
<td>0.09</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi \mu\nu$</td>
<td>0.21675(66)</td>
<td>0.31</td>
<td>0.10</td>
<td>0.18</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi \nu\nu$</td>
<td>0.21542(134)</td>
<td>0.67</td>
<td>0.65</td>
<td>0.03</td>
<td>0.15</td>
<td>0.09</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi e\nu$</td>
<td>0.21728(84)</td>
<td>0.39</td>
<td>0.26</td>
<td>0.09</td>
<td>0.26</td>
<td>0.09</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi \mu\nu$</td>
<td>0.21758(111)</td>
<td>0.51</td>
<td>0.40</td>
<td>0.09</td>
<td>0.26</td>
<td>0.15</td>
</tr>
<tr>
<td>average</td>
<td>0.21661(47)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$?
$|V_{us}|$: Cabibbo angle

Using $f_+(0) = 0.9644(49)$ from RBC-UKQCD:

$|V_{us}| = 0.22461 \pm 0.00124$

$f_+(0)$ needed from theory (lattice QCD): now around 0.5% error (?)

Unitarity is safe
Speaking of lattice QCD...

“Once upon a time, it is told, lattice QCD theorists used to work in the quenched approximation... That was a long time ago...”

It seems accuracy reached the few % figure

Issues for K physics:
- Percent control of $|V_{cb}|$ and $m_c$ to exploit future $K^+\rightarrow\pi^+\nu\bar{\nu}$
- $B_K$ to exploit $\epsilon$ measurement (10% $\rightarrow$ 1%)
- $\epsilon'/\epsilon$ ($\Delta I=1/2$) (100% $\rightarrow$ anything)
- $f^+(0)$ to extract $|V_{us}|$ (0.8% $\rightarrow$ 0.1%)
- Control of $K_L\rightarrow\gamma\gamma$ to possibly extract SD physics from $K_L\rightarrow\pi^0\ell\bar{\ell}$

M. Sozzi – The Kaon variations
NA48 byproducts: $\pi\pi$ scattering

"A threshold cusp" (Wigner 1948)

Unperturbed matrix element:

$$M_0 = 1 + \frac{1}{2} g_0 u + \frac{1}{2} h'u^2$$

Final state pion scattering effect:

Stimulated much theoretical work:
Cabibbo et al., Gamiz et al., Colangelo et al.

M. Sozzi – The Kaon variations
As remarked by N. Cabibbo (2004) this effect is potentially the best measurement of a fundamental observable of QCD (pion scattering lengths), also measured by other means (with and without Kaons)

60 M events (full statistics). Using a2(a0) constraint from ChPT:

\((a_0-a_2)\)m_+ = 0.268 ± 0.003
\(\text{stat} ± 0.002\) _syst ± 0.001 _ext [Cabibbo et al.]
\((a_0-a_2)\)m_+ = 0.266 ± 0.003
\(\text{stat} ± 0.002\) _syst ± 0.001 _ext [Colangelo et al.]

Theoretical work needed to fully exploit the precision of the experimental data (rad. corr., theory error)

Evidence for \textit{pionium} bound state formation \(O(10^{-5})\) of \(K \rightarrow 3\pi\)
$\mathbf{K^\pm \rightarrow \pi^\pm \pi^+ \pi^-}$ Dalitz plot

**NA48/2** unprecedented statistics allows improvement in slope measurements. 

*Deliberately ignore* non-analytic (cusp) and radiative effects

Full MC tuning, agreement to $10^{-3}$ level

\[
\frac{d\Gamma}{du dv} \sim C(u,v) \times (1 + gu + hu^2 + kv^2)
\]

Naïve Coulomb correction

**Final results** from partial 2003 statistics

(0.47×10^9 events)

\[
g = (-21.134 \pm 0.014)\%
\]

\[
h = (1.848 \pm 0.039)\%
\]

\[
k = (-0.463 \pm 0.012)\%
\]

“Naïve” slopes (comparable with PDG)

X10 PDG precision

Systematics dominated by $\pi$ mom. resolution
Cusp in KL decays

Same effect is present in $KL \rightarrow 3\pi^0$, much smaller in size (iso-spin).

**NA48/2**: 100M events

68.3M $K_L \rightarrow \pi^0\pi^0\pi^0$

KTeV

+125M MC events

M. Sozzi – The Kaon variations
**K_L → \Pi^0\Pi^0\Pi^0** Dalitz plot

**KTeV**

\[ h_{000} = (0.59 \pm 0.20 \pm 0.48 \pm 1.06) \cdot 10^{-3} \]

fixing \( m_+(a_0-a_2) = 0.268 \)

\( (\chi^2/\text{dof} = 2805.3/2765) \)

Assuming circular symmetry of Dalitz plot (no rescattering)

However: fitting both the slope and the scattering length difference, the sensitivity is small and

\[ h_{000} = (-2.09 \pm 0.62 \pm 0.72 \pm 0.28) \cdot 10^{-3} \]

\( m_+(a_0-a_2) = 0.215 \pm 0.014 \pm 0.025 \pm 0.006 \)

\( (\chi^2/\text{dof} = 2790.6/2764) \)

CPT@ICTP July 2008

M. Sozzi – The Kaon variations
K^{±}e^4 (K^{±}→π^{+}π^{-}e^{±}ν) is the “classic” approach to low-energy ππ scattering.

- 5 kinematic variables
- 3 form factors
- Keep S- and P-waves
- Expand in powers of q^2 (dipion system)

Extract δ = δ_S − δ_P phase difference between S- and P-waves in F(q^2) axial form-factor

Isospin-breaking corrections

1.15 M events (2003+2004)
0.5% background
x24 MC statistics
Independent fits in bins of m(ππ)
Radiative corrections
With theoretical input $\delta$ can be related to $a_2$ and $a_0$:

Look also at CP...

M. Sozzi – The Kaon variations
KTeV (2006): 112K events (40% of total)  
\[ \text{DE/(IB+DE)} = 0.689 \pm 0.021 \]  
for \( E_{\gamma} > 20 \text{ MeV} \)

\[ K \rightarrow \pi \pi \gamma \]

KTeV (2006): 112K events (40% of total)  
\[ \text{DE/(IB+DE)} = 0.689 \pm 0.021 \]  
for \( E_{\gamma} > 20 \text{ MeV} \)

\[ K \rightarrow \pi \pi \gamma \]

\[ K_L \rightarrow \pi^+ \pi^- \gamma \]

\[ K^\pm \rightarrow \pi^+ \pi^0 \gamma \]

\[ \chi^2_{\text{obs}} = 85.8/85 \]

\[ \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]

\[ K \rightarrow \pi \pi \gamma \]
Rare decay (BR = 3 \cdot 10^{-7}) first seen by KTeV
Internal $\gamma$ conversion allows helicity analysis:
asymmetry in angle $\phi$ between $\pi\pi$ and ee planes,
in agreement with theory (indirect CPV)

Also $K_L \rightarrow e^+e^-e^+e^-$ (KTeV, NA48)
and related CPV parameters

All consistent with usual ($\varepsilon$) CPV
Reminder: the only direct measurement of TV
Direct comparison of T-conjugate (virtual) transitions:

\[ A_T = \frac{P(\bar{K}^0 \rightarrow K^0) - P(K^0 \rightarrow \bar{K}^0)}{P(\bar{K}^0 \rightarrow K^0) + P(K^0 \rightarrow \bar{K}^0)} \]

Using semi-leptonic decays and assuming CPT in decays

\[ A_T(t) = 4 \text{Re}(\epsilon) + 2 \frac{\text{Re}(x_-)[e^{-\Delta t/2} - \cos(\Delta m t)] + \text{Im}(x_+) \sin(\Delta m t)}{\cosh(\Delta \Gamma t/2) - \cos(\Delta m t)} \]

**CPLEAR (1998):**

\[ \langle A_T \rangle = (6.6 \pm 1.3) \cdot 10^{-3} \]

Fully consistent with indirect CPV in \( K^0 \) mixing
T-odd correlations

Looked for in 3-body decays (w. spin) or 4-body decays (momenta)
Beware of fake asymmetries by Final State Interactions

\( K_{e4} (K \to \pi\pi e\nu) \) BR \( \approx 4.1 \cdot 10^{-5} \) or \( K_{e3\gamma} (K \to \pi e\nu\gamma) \) BR \( \approx 2.7 \cdot 10^{-4} \) or
\( K_{\mu3\gamma} (K \to \pi\mu\nu\gamma) \) BR \( \approx 2.4 \cdot 10^{-5} \)

\[ \xi = \frac{(p_\pi \times p_\mu) \cdot p_\gamma}{|p_\pi \times p_\mu| |p_\gamma|} \quad A_\xi = \frac{N(\xi > 0) - N(\xi < 0)}{N(\xi > 0) + N(\xi < 0)} \]
**Ke3γ:** FSI: $A_\xi \approx (0.5-1) \cdot 10^{-4}$ in the SM - NP models: $A_\xi \approx \text{few } 10^{-4}$

**ISTRAta+ (2005):** $A_\xi = 0.015 \pm 0.021$ (1400 events)

**NA48/2:** few $10^5$ events and cancellation of FSI effects by $K^+/K^-$ comparison, *in progress*

---

**Km3γ:** FSI: $A_\xi \approx 1.1 \cdot 10^{-4}$ in the SM - NP models: $A_\xi \approx 2.5 \cdot 10^{-4}$

**ISTRAta+ (2006):** $\text{BR}(K^- \rightarrow \pi^0 \mu^- \nu \gamma) \approx 9 \cdot 10^{-5}$

$A_\xi = -0.03 \pm 0.13$ (400 events)
More T-odd: $PT(\mu)$

$PT(\mu)$ in $K\mu_3$ decays

$$PT(\mu) = \left| \frac{p_\pi \times p_\mu}{|p_\pi \times p_\mu|} \cdot S_\mu \right|$$

Experiments in the ’70s on $K_L \rightarrow \pi^- \mu^+\nu$ reached the FSI limit:

$$\text{Im } \xi = (-7 \pm 26) \times 10^{-3} \quad (\xi = \text{ratio of the two contributing FFs})$$

KEK E246:
660 MeV/c $K^+$ stopped in active target.
Final result (8.3M $\pi^0 \mu^+\nu$ decays, 1996-2000):

$$PT(\mu) = (-1.7 \pm 2.3 \pm 1.1) \times 10^{-3}$$
$$\text{Im } \xi = (-5.3 \pm 7.1 \pm 3.6) \times 10^{-3}$$

$\times 10$ improvement expected at J-PARC [see later talk]
Lepton-flavour violation

KTeV exploited its large $K_L$ sample and PID capability to search for LFV as a $s \rightarrow d \mu e$ transition:

\[ BR(K_L \rightarrow \pi^0 \mu^\pm e^\mp) < 7.56 \cdot 10^{-11} \] (90% CL)

\[ BR(K_L \rightarrow \pi^0 \pi^0 \mu^\pm e^\mp) < 1.64 \cdot 10^{-10} \] (90% CL)

\[ BR(\pi^0 \rightarrow \mu^\pm e^\mp) < 3.59 \cdot 10^{-10} \] (90% CL)

[PR 100 (2008) 131803]
**Leptonic decays**

\[
R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1 + \delta R_{QED}\right) = (2.477 \pm 0.001) \cdot 10^{-5} \quad [\text{SM}]
\]

Strong helicity suppression: high sensitivity to NP

Was known to \(\approx 5\%\)
2005: 1-3\% enhancements not unnatural in SUSY
[Masiero et al. PRD74 (2006) 011701]

**NA48:** 2 (non-dedicated) short runs in 2003,2004
8K evts., background \((K\mu2)\) and trigger limitations
\(R_K = (2.416 \pm 0.043 \pm 0.024) \cdot 10^{-5} \) [prel. 03]
\(R_K = (2.455 \pm 0.045 \pm 0.041) \cdot 10^{-5} \) [prel. 04]

**KLOE:** 8K evts.
\(R_K = (2.55 \pm 0.05 \pm 0.05) \cdot 10^{-5} \) [prel.]

**NA62:** Dedicated 4-month run (2007)
Goal: 0.5\% error

CPT@ICTP July 2008
NA62: Leptonic decays

2007 dedicated run:
- Higher beam momentum (60 → 75 GeV/c)
- Higher momentum kick
- K⁺ only
- Improved trigger
- Simultaneous sample of “pure” μ collected to check PID

112K candidates (<10% background)

Analysis in progress

M. Sozzi – The Kaon variations
**K → πℓℓ decays**

Switch to *quantitative* test of the SM

Flavour sector, probing extremely high energy scales: precision frontier *complementary* to LHC energy frontier

Some (tiny!) BRs can be computed to *very high* (few percent) precision

<table>
<thead>
<tr>
<th>Reaction</th>
<th>BR (CPV dir)</th>
<th>CPV dir (Precision)</th>
<th>CPC+CPV (Evts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \pi^0 e^+e^-$</td>
<td>$10^{-11}$ (3·$10^{-12}$)</td>
<td>$&lt; 2.8 \cdot 10^{-10}$ (FNAL KTeV)</td>
<td>CPC+CPV 3 ev. (2.05 bkg)</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^0 \mu^+\mu^-$</td>
<td>$10^{-11}$ (1·$10^{-12}$)</td>
<td>$&lt; 3.8 \cdot 10^{-10}$ (FNAL KTeV)</td>
<td>CPC+CPV 2 ev. (0.87 bkg)</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu\nu$</td>
<td>$8\cdot 10^{-11}$ (at 7%)</td>
<td>$1.47^{+1.30}_{-0.89} \cdot 10^{-10}$ (BNL E787+E949)</td>
<td>Dedicated expt. 3 evts. (bkg. 0.45)</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^0 \nu\nu$</td>
<td>$2.8\cdot 10^{-11}$ (at 2%)</td>
<td>$&lt; 6.7 \cdot 10^{-8}$ (KEK E391a)</td>
<td>CPV dir &quot;Nothing to nothing&quot;</td>
</tr>
</tbody>
</table>
The (new) “holy grail”

\[ BR_{SM} (K \rightarrow \pi \nu \nu) \propto r_{IB} BR(K^+ \rightarrow \pi^0 e^+ \nu) \frac{\alpha^2}{\sin^4 \theta_W} \]

\[ \sum_l \left[ \frac{\text{Im} V_{ts}^* V_{td}}{|V_{us}|} X (m_t, \alpha_s) + \frac{\text{Im} V_{cs}^* V_{cd}}{|V_{us}|} X_{NL} (m_c, m_t, \alpha_s) \right] \]

The best measurement of $|V_{td}|$?
Rather a highly-sensitive search for NP
Comparison of the two can discriminate by itself the flavour structure of NP

SM Leading diagrams to $K \rightarrow \pi \nu \nu$ decays
E787/E949: $1.47^{+1.30}_{-0.89} \times 10^{-10}$ (3 events)

Process with very small parametric uncertainty

$K^+ \rightarrow \pi^+\nu\bar{\nu}$
Learning about new physics

Astounding parametric precision, can be:
\[ \approx 5\% \text{ for } K^+ \text{ and } \approx 1\% \text{ for } K_L. \]
“Normal science is when the theoretical processes which can be easily handled by theorists are experimental nightmares (and vice versa)”. (Apologies to T. Kuhn)

“Just look for a decay of a short-lived particle with $10^9$ background, with a poor signature and no kinematic closure.”

“This is our plan for the next 1,000 years.”

High fluxes, high vacuum, high hermeticity, excellent vetoing, excellent resolutions... an interesting challenge

M. Sozzi – The Kaon variations
The long march

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]

\[ K_L \rightarrow \pi^0 \nu \bar{\nu} \]
The funding axe fell heavily on flavour physics in the US in recent times: KAMI \((K_L \rightarrow \pi^0 \ell\ell @ FNAL)\), E949 \((K^+ \rightarrow \pi^+ \nu\nu @ BNL)\), KOPIO \((K_L \rightarrow \pi^0 \nu\nu @ BNL)\), CKM \((K^+ \rightarrow \pi^+ \nu\nu @ FNAL)\).

The most recent proposals were for a \(K_L \rightarrow \pi^0 \nu\nu\) and a stopped \(K^+ \rightarrow \pi^+ \nu\nu\) experiment at the (improved) 8 GeV FNAL booster, in the perspective of a future MW proton driver (project-X):

- \(K_L \rightarrow \pi^0 \nu\nu\): 30 ev/year @ booster, 300-900 ev/year @ project-X
- \(K^+ \rightarrow \pi^+ \nu\nu\): 40 ev/year @ booster, 300-1500 ev/year @ project-X

May 2008 - P5: only possible in a “HEP fund doubling” scenario
Japan: E391a (KEK)

Pilot project for J-PARC experiment
“Pencil” beam: \( \langle p \rangle \approx 3 \text{ GeV/c}, n/K \approx 60 \)
Photon vetoes at 1 MeV level
Hadronic background MC
\( p_T \) and decay vertex cuts
Run I partial analysis (10% of data):

$$BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.1 \cdot 10^{-7} \quad (90\% \ CL)$$

Run II:
Solved problems with material on beam and DAQ inefficiency, reduced n flux

Control bkg: 1.9±0.2, obs. 3,
0.39±0.08, obs. 2
Background: exp. 0.44±0.11, obs. 0
Acceptance 0.67%

$$BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 6.7 \cdot 10^{-8} \quad (90\% \ CL)$$

Single-event sensitivity: 2.89·10^{-8}
Still below Grossman-Nir bound

Also:

$$BR(K_L \rightarrow \pi^0 \pi^0 \nu \bar{\nu}) < 4.7 \cdot 10^{-5} \quad (90\% \ CL)$$

CPT@ICTP July 2008
Japan: J-PARC

Beam to experiments in second half of 2008
Japan: J-PARC E14

Improved beamline (reduced halo, n/K ≈ 7, lower background, veto)
Re-use E391a barrel
Thicker and more fine-grained CsI calorimeter (KTeV)
Waveform digitization
Upgraded vetos (KOPIO-like beam hole γ veto)

Goal: 2.7 ev. (S/N ≈ 1.6) in 3 years
Construction 2009, first physics run 2011?
Step 2: 100 SM events (S/N ≈ 4.8)

CPT@ICTP July 2008

M.Sozzi – The Kaon variations
New approach: decay in flight
(75 GeV/c unseparated K+ beam)

Reuse some parts of NA48 apparatus
and existing SPS protons (1/20)

Background rejection:
- K+ tracking in 1 GHz
- PID(π/µ) by RICH
- γ vetoing (low-E π, low ineff.)
- Kinematics

CPT@ICTP July 2008
2 signal regions:
I (92% kinematically constrained bkg.)
II (8% not-constrained bkg.)

Expect $\approx 80$ SM events
with $S/N \approx 10$ in 2 years (2012+)

Waiting for final approval
Strengthening the collaboration

CPT@ICTP July 2008
M. Sozzi – The Kaon variations
Is there still something to be learned by using kaons?

I think so.

The program has been quite varied so far, much more than could be expected at the start.

As the focus of HEP moves and shifts in the era of the coming of LHC

there is reason to believe it will continue to be so.
Spare slides
Leptonic decays

Large (but acceptable) $\tan\beta$ region can dramatically enhance effect
The Bell-Steinberger legacy

Unitarity imposes a relation linking (indirect) CP- and CPT-violating parameters to all the physical decay amplitudes. Fruitful in the K system:

\[
\begin{pmatrix}
\Gamma_S + \Gamma_L + i \tan \phi_{sw} \\
\Gamma_S - \Gamma_L
\end{pmatrix}
\begin{pmatrix}
\text{Re} \varepsilon \\
1 + |\varepsilon|^2
\end{pmatrix}
= \frac{1}{\Gamma_S - \Gamma_L} \sum_f A(K_L \rightarrow f)A^*(K_S \rightarrow f)
\]

Experimental input: $K_S, K_L$ lifetimes and masses, decay amplitudes and CPV asymmetries. With KLOE (2006) input:

\[
\begin{align*}
\text{Re}(\varepsilon) &= (160.2 \pm 1.3) \cdot 10^{-5} \\
\text{Im}(\delta) &= (1.2 \pm 1.9) \cdot 10^{-5}
\end{align*}
\]
NA48/2: detector asymmetry cancellation

Detector left-right asymmetry cancels in 4 ratios of $K^+$ over $K^-$ u distributions:

\[
R_{\text{US}} = \frac{N(A + B + K^+)}{N(A + B - K^-)}
\]

\[
R_{\text{UJ}} = \frac{N(A + B - K^+)}{N(A + B + K^-)}
\]

\[
R_{\text{DS}} = \frac{N(A - B + K^+)}{N(A - B - K^-)}
\]

\[
R_{\text{DJ}} = \frac{N(A - B - K^+)}{N(A - B + K^-)}
\]

(same deviation by spectrometer in numerator and denominator)

Beam line: $K^+$ Up

Beam line: $K^-$ Down

Spectrometer field

Jura

Saleve

K+–DIR

Reverse each day

Reverse each week

Indices correspond to
- beamline polarity (U / D)
- direction of kaon deviation in spectrometer (S / J)

CPT@ICTP July 2008

M. Sozzi – The Kaon variations
(A) Experiment: \( K \to \mu \nu/\pi \to \mu \nu \) (0.5%)
Experiment: \( |V_{ud}| \) (0.03%)
Lattice: \( f_K/f_\pi \) (0.8% ?)
[W. Marciano (2004)]

(B) Experiment: \( K \to \pi \ell \nu \) BR & FF (0.2%)
Lattice: \( f^{K\pi}(0) \) (0.5% ?)

Consistency No trouble with unitarity

M. Sozzi – The Kaon variations
(1) $\mu \rightarrow e$ conversion
(2) Participation to super-B factory abroad

No $K$ physics in this scenario
### Roadmap for Funding Scenario B

#### Roadmap for the Scenario with Constant level of Effort at the FY2007 Level

<table>
<thead>
<tr>
<th>Category</th>
<th>FY07</th>
<th>FY08</th>
<th>FY09</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The Energy Frontier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 Tevatron collider</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.1 Initial LHC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2 SuperLHC-Phase 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.3 SuperLHC-Phase 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3 ILC / Lepton Collider</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. The Intensity Frontier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Neutrino Physics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.1 Mini and SciBOONE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.2 MINOS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.3 DoubleCHOOZ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.4 T2K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.5 Daya Bay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.6 MINERVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.7 NOvA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.8 Double Chooz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.9 First Section Liquid Argon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.10 Dbl Beta Dec-Current</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.11 Dbl Beta Dec-New Init.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2 Precision Measurements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2.1 Offshore B Factory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2.2 Mu-e Conv Exp</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2.3 Rare K Decays</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3 DUSEL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4 High Intens Proton Sce FermiLab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. The Cosmic Frontier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1 Dark Matter-Current Expts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2 Dark Matter-New Initiatives</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3 Dark Energy-DES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.4 Dark Energy-DEEM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5 Dark Energy-LSST</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.6 High Energy Particles from Space</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Accelerator and Detector R&amp;D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Key**
- **Green**: Operation
- **Red**: Construction
- **Yellow**: R&D

**Composed for connoisseurs, for the refreshment of their spirits**