Outline

- **Kaon Physics at the SPS (NA48, NA62)**
  - CP-Violation & Quark Mixing
  - Lepton Universality
  - Strong Interaction at Low Energy
  - Rare Decays

- **Neutrino Physics at the SPS**
  - Long baseline neutrino experiments
    - CNGS1 OPERA
    - CNGS2 ICARUS
CP-VIOLATION AND QUARK MIXING
Baryon Asymmetry of the Universe (BAU)

\[ \frac{n_{\text{quark}} - n_{\text{antiquark}}}{n_{\text{quark}}} \text{ (Proto Universe)} \sim \frac{n_{\text{baryon}}}{n_{\text{photon}}} \text{ (Today)} \sim 5 \times 10^{-10} \]
Sakharov Conditions for BAU

Andrei Sakharov (1967)

To allow the development of an asymmetry between matter and anti-matter

1. Violation of Baryonic Number
2. Thermodynamic Non-equilibrium
3. Violation of C & CP

Origin of BAU: Baryogenesis or Leptogenesis?
CP-Violation

When the top-left and the bottom-right Pictures are not exactly the same, we have CP-Violation.

Da Gino Isidori:
http://scienzapertutti.infn.infn.it/P1/schedaCP.html
Types of CP-Violation

1. CP Violation in mixing \(| q/p | \neq 1\) (indirect)
2. CP Violation in decays \(| \frac{\bar{A}_f}{A_f} | \neq 1\) (direct)
3. CP Violation in the interference

\[ \Delta F = 2 \]

\[ \Delta F = 1 \]

The study of direct CP-violation in the two pion decays of the neutral kaons (\(\varepsilon'/\varepsilon\)) was the main motivation to study kaon decays at the SPS.
NA48/NA62 at CERN

1997: $\varepsilon'/\varepsilon$: $K_L+K_S$
1998: $K_L+K_S$
1999: $K_L+K_S$ Ks HI
2000: $K_L$ only Ks HI
2001: $K_L+K_S$ Ks HI
2002: $K_S$/hyperons
2003: $K^+$/K$^-$
2004: $K^+$/K$^-$
2007: $K^+e_2/K^-\mu_2$ tests
2008: $K^+e_2/K^-\mu_2$ tests
2012 Technical Run
2014- $K^+\rightarrow\pi^+\nu\nu$ Data Taking

Old Detector New Collaboration

New Detector NA62

(more on this later…)

Magnetic spectrometer (4 DCHs):
- 4 views/DCH
- $\Delta p/p = 0.48\% + 0.009\%p [GeV/c]

Liquid Krypton EM calorimeter (LKr)
- High granularity, quasi-homogeneous;
- $\sigma_E/E = 3.2%/E^{1/2} + 9%/E + 0.42% [GeV]$
- $\sigma_x=\sigma_y=0.42/E^{1/2} + 0.6mm (1.5mm@10GeV)$
Re $\varepsilon'/\varepsilon$ measurements versus time

$$R = \frac{\Gamma(K_L \rightarrow \pi^0 \pi^0)}{\Gamma(K_S \rightarrow \pi^0 \pi^0)} / \frac{\Gamma(K_L \rightarrow \pi^+ \pi^-)}{\Gamma(K_S \rightarrow \pi^+ \pi^-)} \approx 1 - 6 \text{ Re}(\varepsilon'/\varepsilon)$$

Direct CP Violation

$$\Gamma(K^0 \rightarrow \pi^+ \pi^-) \neq \Gamma(\bar{K}^0 \rightarrow \pi^+ \pi^-)$$

Crucial CERN Experiments: NA31 & NA48
Cabibbo-Kobayashi-Maskawa (CKM) Quark Mixing Matrix

With 3 generations CP violation is naturally introduced by an irreducible complex phase in the quark mixing matrix (Kobayashi & Maskawa, 1973)

\[
V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

(PDG 2012)

|V_{ud}| = 0.97425 ± 0.00022
|V_{us}| = 0.2252 ± 0.0009
|V_{cd}| = 0.230 ± 0.011
|V_{cs}| = 1.006 ± 0.023
|V_{cb}| = (40.9 ± 1.1) × 10^{-3}
|V_{ub}| = (4.15 ± 0.49) × 10^{-3}
|V_{tb}| = 0.89 ± 0.07

0^+ \rightarrow 0^+ super-allowed nuclear β decays
Kaon semi-leptonic and leptonic decays
2\mu/1\mu ratio in neutrino/antineutrino interactions
Average of semi-leptonic D and leptonic D_s decays
Combination of exclusive and inclusive B decays
Comb. of exclusive and inclusive charmless B decays
Single top-quark production cross-section

V_{td} & V_{ts} accessible from FCNC processes (loops)
CP-Violation in Kaons and CKM

- Neutral Kaon Mixing (\(\pi\pi\), semi-leptonic)

\[
|\varepsilon| = \frac{G_F f_K m_K m_W^2}{12 \sqrt{2} \pi^2 \Delta m_K} \hat{B}_K \left\{ \eta_1 S(x_c) \text{Im} \left( V_{cs} V_{cd}^* \right)^2 + \eta_2 S(x_t) \text{Im} \left( V_{ts} V_{td}^* \right)^2 \right\} + 2\eta_3 S(x_c, x_t) \text{Im} \left( V_{cs} V_{cd}^* V_{ts} V_{td}^* \right)
\]

\[
|\varepsilon| = (2.233 \pm 0.015) \times 10^{-3}
\]

- Neutral Kaon Decays into \(\pi\pi\)

\[
\text{Re} \left( \varepsilon' \right) \propto \text{Im} \left( V_{td} V_{ts}^* \right)
\]

PDG Average

\[
\text{Re} \left( \varepsilon' \right) = (1.67 \pm 0.23) \times 10^{-3}
\]

Direct CP-Violation
$V_{us}$ and universality

$$\frac{g}{\sqrt{2}} W^+_\alpha \left( \overline{U}_L V_{\text{CKM}} \gamma^\alpha D_L + \overline{e}_L \gamma^\alpha \nu_e L + \overline{\mu}_L \gamma^\alpha \nu_\mu L + \overline{\tau}_L \gamma^\alpha \nu_\tau L \right) + \text{h.c.}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

**Universality:** Is $G_F$ from $\mu$ decay equal to $G_F$ from $\pi$, $K$, nuclear $\beta$ decay?

$$G^2_{\mu} = \frac{(g_\mu g_e)^2}{M^4_W} \quad ? \quad G^2_{\text{CKM}} = \frac{(g_q g_\ell)^2}{|V_{ud}|^2 + |V_{us}|^2} \frac{1}{M^4_W}$$

**Physics beyond the Standard Model** can break gauge universality:
$V_{us}$ from semileptonic decays

\[
\Gamma(K_{\ell 3}(\gamma)) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 \\
\times I_{K\ell}(\lambda_{K\ell}) \left( 1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{EM} \right)
\]

with $K \in \{K^+, K^0\}$; $\ell \in \{e, \mu\}$, and:
- $C_K^2$ 1/2 for $K^+$, 1 for $K^0$
- $S_{EW}$ Universal SD EW correction (1.0232)

**Inputs from experiment:**
- $\Gamma(K_{\ell 3}(\gamma))$: Rates with well-determined treatment of radiative decays:
  - Branching ratios
  - Kaon lifetimes
- $I_{K\ell}(\{\lambda\}_{K\ell})$: Integral of form factor over phase space: $\lambda$s parameterize evolution in $t$
  - $K_{\ell 3}$: Only $\lambda_4$ (or $\lambda^\prime_4, \lambda^\prime\prime_4$)
  - $K_{\ell 3}$: Need $\lambda_4$ and $\lambda_0$

**Inputs from theory:**
- $f_+^{K^0\pi^-}(0)$: Hadronic matrix element (form factor) at zero momentum transfer ($t = 0$)
- $\Delta_K^{SU(2)}$: Form-factor correction for $SU(2)$ breaking
- $\Delta_{K\ell}^{EM}$: Form-factor correction for long-distance EM effects
### "Modern" $V_{us}$ experimental input

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Measurement</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL865</td>
<td>$\text{BR}(K^+ \rightarrow \pi^0 D \ell^+ \nu)/\text{BR}(K^- \rightarrow \pi^0 D \ell^- \nu)$</td>
<td>2003</td>
</tr>
<tr>
<td>KTeV</td>
<td>$\tau(K_J)$, $\text{BR}(K_{Le3}), \text{BR}(K_{L\mu3}), \lambda_+(K_{L\mu3}), \lambda_{+0}(K_{L\mu3})$</td>
<td>2003</td>
</tr>
<tr>
<td>ISTRA+</td>
<td>$\lambda_+(K_{e3}^0), \lambda_{+0}(K_{e3}^-)$</td>
<td>2004</td>
</tr>
<tr>
<td>KLOE</td>
<td>$\tau(K_J)$, $\text{BR}(K_{L\mu3}), \text{BR}(K_{Se3}), \lambda_+(K_{Se3})$</td>
<td>2005</td>
</tr>
<tr>
<td></td>
<td>$\lambda_{+0}(K_{L\mu3})$, $\tau(K^\pm)$, $\text{BR}(K_{Le3}), \text{BR}(K_{L\mu3})$</td>
<td>2006</td>
</tr>
<tr>
<td></td>
<td>$\text{BR}(K_{Le3}/2 \text{ tracks}), \lambda_+(K_{Le3})$</td>
<td>2007</td>
</tr>
<tr>
<td>NA48</td>
<td>$\tau(K_J)$, $\text{BR}(K_{Se3}/K_{Le3}), \lambda_{+0}(K_{L\mu3})$</td>
<td>2002</td>
</tr>
<tr>
<td>NA48/2</td>
<td>$\text{BR}(K^- e^+ \pi^0), \text{BR}(K^+\mu^+ \pi^- \pi^0)$</td>
<td>2004</td>
</tr>
</tbody>
</table>

The experiments determine the product of $V_{us} f_+(0)$ and $V_{us} f_K$.

Precise theoretical calculations (lattice QCD and chiral perturbation theory) allow one to perform stringent tests. The theory works very well for kaons.
“$V_{us}$ Revolution” with experimental input changing ~ 5% in some cases.....
The Cabibbo angle can be precisely determined (~0.4%)!

Unitarity test of CKM the first row (PDG 2012):

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999 \pm 0.0006$$
LEPTON UNIVERSALITY
**$R_K = K_{e2}/K_{\mu2}$**

\[
R_K = \frac{\Gamma(K^\pm \rightarrow e^\pm \nu)}{\Gamma(K^\pm \rightarrow \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\text{rad.corr.}})
\]

$R_K^{\text{SM}} = (2.477 \pm 0.001) \times 10^{-5}$

Cirigliano & Rosell PRL 99 (2007) 231801

- e.g. Masiero, Paradisi Petronzio
  PRD 74 (2006) 011701,
  JHEP 0811 (2008) 042

**BSM, LFV**

Leptonic decays of the pseudoscalar mesons are helicity suppressed in the standard model

**Example:**

$(\Delta_{13} = 5 \times 10^{-4}, \tan \beta = 40, M_H = 500 \text{ GeV/c}^2)$

$R_K^{\text{MSSM}} = R_K^{\text{SM}} (1 + 0.013)$. 
**NA62: $R_K = K_{e2}/K_{\mu2}$**

Full data set

145,958 $K^{\pm} \rightarrow e^{\pm} \nu$ candidates.
Electron ID efficiency: $(99.28\pm0.05)\%$. 
NA62: $R_K$ full data set

$$R_K = (2.488 \pm 0.007_{\text{stat}} \pm 0.007_{\text{syst}}) \times 10^{-5}$$

$$R_K = (2.487 \pm 0.010) \times 10^{-5}$$

Published (40% sample)
CERN-PH-EP-2011-004,
arXiv:1101.4805,
PLB B698 (2011) 105

<table>
<thead>
<tr>
<th>Background source</th>
<th>$B/(S+B)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu 2}$</td>
<td>(5.64(\pm)0.20)%</td>
</tr>
<tr>
<td>$K_{\mu 2}$ ($\mu \rightarrow e$)</td>
<td>(0.26(\pm)0.03)%</td>
</tr>
<tr>
<td>$K_{e2\gamma}$ ($SD^+$)</td>
<td>(2.60(\pm)0.11)%</td>
</tr>
<tr>
<td>$K_{e3(D)}$</td>
<td>(0.18(\pm)0.09)%</td>
</tr>
<tr>
<td>$K_{2\mu(D)}$</td>
<td>(0.12(\pm)0.06)%</td>
</tr>
<tr>
<td>Wrong sign K</td>
<td>(0.04(\pm)0.02)%</td>
</tr>
<tr>
<td>Muon halo</td>
<td>(2.11(\pm)0.09)%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>(10.95(\pm)0.27)%</td>
</tr>
</tbody>
</table>

Errors in momentum bins are partially correlated.
### $R_K$ world average

**Table: World average**

<table>
<thead>
<tr>
<th></th>
<th>$\delta R_K \times 10^5$</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG 2008</td>
<td>2.447 ± 0.109</td>
<td>4.5%</td>
</tr>
<tr>
<td>Today</td>
<td>2.488 ± 0.009</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

**Graph:**
- PDG 2008
- July 2011 average
- Clark et al. (1972)
- Heard et al. (1975)
- Heintze et al. (1976)
- KLOE (2009) = PDG 2010
- NA62 (2011) full dataset

**Other limits on 2HDM-II:**
- PRD 82 (2010) 073012
STRONG INTERACTION AT LOW ENERGY
Strong Interaction at low energy

- At high energy the strong interactions are described by Quantum Chromo Dynamics (QCD)
- Below ~ 1 GeV, the strong coupling becomes large and the perturbative description is not possible
- An effective theory, Chiral Perturbation Theory (ChPT) allows to study the strong interaction at low energy in terms of momenta and light meson masses
- Kaons are a good laboratory to study the strong interactions at low energy (ππ scattering, radiative decays, …)
NA48/2: $K^\pm \rightarrow \pi^+ \pi^- e^\pm \nu$ & cusp in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ cusp

$K^\pm \rightarrow \pi^+ \pi^- e^\pm \nu$ (Ke4)

Cusp in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays

Cusp-like structure at the $\pi^+ \pi^-$ invariant mass threshold
Consistent results on the scattering lengths obtained with completely independent techniques.
RARE DECAYS
Looking for physics beyond the SM

- **Direct searches:** LHC energy frontier
- **Indirect searches:**
  1. Improve measurement precision of CKM elements
     - Compare measurements of the same quantities which may or may not be sensitive to new physics
     - Extract all CKM angles and sides in many different ways → inconsistencies would signal new physics
  2. Study Flavour Changing Neutral Currents (FCNC) processes where the SM contributions are suppressed and precisely predictable → Rare Decays
A. Buras list of Flavour Superstars

Superstars of 2011 – 2015
(Flavour Physics)

- $S_{\psi\phi}$
- $\mathcal{CP}$ in $B_s^0 - \bar{B}_s^0$
- $B_s \rightarrow \mu^+\mu^-$
- $B_d \rightarrow \mu^+\mu^-$
- $K^+ \rightarrow \pi^+\nu\bar{\nu}$
- $K_L \rightarrow \pi^0\nu\bar{\nu}$
- $B_d \rightarrow K^*\mu^+\mu^-$
- $\gamma$ from Tree Level Decays
- $\mu \rightarrow e\gamma$
- $\tau \rightarrow \mu\gamma$
- $\tau \rightarrow e\gamma$
- $\mu \rightarrow 3e$
- $\tau \rightarrow 3$ leptons

$\varepsilon'/\varepsilon$

(Lattice)

EDM's

$(g-2)_\mu$

*) $\mathcal{CP}$ in $K_L \rightarrow \pi\pi$
Kaon Rare Decays & CKM

$\begin{align*}
K_L \rightarrow \pi^0 \nu \bar{\nu} \\
K_L \rightarrow \pi^0 e^+ e^- \\
K_L \rightarrow \pi^0 \gamma \gamma \\
K_L \rightarrow e e \gamma \gamma \\
K_L \rightarrow \gamma \gamma, K_L \rightarrow e^+ e^- \gamma \\
K_L \rightarrow e^+ e^- e^+ e^- , e^+ e^- \mu^+ \mu^- \\
\end{align*}$

$$V_{td} V_{tb}^* + V_{cd} V_{cb}^* + V_{ud} V_{ub}^* = 0$$

PDG 2012
NA48/1: $K^0_S \rightarrow \pi^0 e^+e^-$ and $K^0_S \rightarrow \pi^0 \mu^+\mu^-$

\[ \text{BR}(K_S \rightarrow \pi^0 ee) \times 10^{-9} = 5.8^{+2.8}_{-2.3} \text{(stat)} \pm 0.8 \text{(syst)} \]
PLB 576 (2003)

\[ \text{BR}(K_S \rightarrow \pi^0 \mu\mu) \times 10^{-9} = 2.9^{+1.4}_{-1.2} \text{(stat)} \pm 0.2 \text{(syst)} \]
PLB 599 (2004)

Blind analyses
Rare $K$ Decays: Next Frontier

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching Ratio ($\times 10^{10}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ($\gamma$)</td>
<td>Theory (SM)</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$</td>
<td>$0.85 \pm 0.07^{[1]}$</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$</td>
<td>$0.27 \pm 0.04^{[3]}$</td>
</tr>
</tbody>
</table>


• Must bridge the existing gap between theory and experiment
• A measurement of $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$ to 10 % determines $V_{td}$ without input from Lattice QCD
• The strong suppression of the SM component ($<10^{-10}$) offers good sensitivity to NP

Remarkable stopped kaon experiment
$K^+ \rightarrow \pi^+ \nu \nu$ in SM

$\text{BR} \equiv \text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$

$\text{BR(SM)} = (8.5 \pm 0.7) \times 10^{-11}$

J. Brod, M. Gorbahn

$\delta |V_{td}| / |V_{td}| \approx 0.4 \delta P_{c}/P_{c} \oplus 0.7 \delta \text{BR} / \text{BR} \oplus \delta |V_{cb}| / |V_{cb}|$

$\sim 2\%$ (mostly $\delta m_c$) 62\% BNL

7\% aim of NA62 (2y) 3\%
Kaon Rare Decays and NP

C. The Z penguin (and its associated W box)

- $SU(2)_L$ breaking: $SM: v^2_u Y^* Y_{u1} \sim m_t^2 V_{ts}^* V_{td}$

  $MSSM: v^2_u A_{u1}^* A_{u1} \sim m_t^2 \times O(1)?$  

  $MFV: v^2_u A_{u1}^* A_{u1} \sim m_t^2 V_{ts}^* V_{td} |A_0 a_2^* - \cot \beta |^2$.

- Relatively slow decoupling (w.r.t. boxes or tree).

(courtesy by Christopher Smith)

Buras, Ewerth, Jager, Rosiek '04

Isidori, Mescia, Paradisi, Trine, C.S. '06
NA62: $K^+ \to \pi^+ \nu \bar{\nu}$ in-flight @ CERN–SPS

SPS primary p: 400 GeV/c
Unseparated beam:
• 75 GeV/c ($\Delta p/p \sim 1\%$)
• 750 MHz
• $\pi/K/p$ (~6% $K^+$)

Target

CEDAR

Gigatracker (GTK)

Measure Kaon:
• Time
• Angles
• Momentum

Decay Region 65m

Total Length 270m

Beam Line + Infra.

CHOD

Charged Hodoscope

LKr

RICH

MUV

SAV

Small Angle Veto

LAV:

Large Angle Photon Veto

INFN

IHEP

INR

CERN

UK

Bulgaria

INFN

INFN

INFN

INFN

INFN

Belgium

Mainz

Mexico

US

JINR

CHANTI

JINR

CERN

Unseparated beam:
• 75 GeV/c ($\Delta p/p \sim 1\%$)
• 750 MHz
• $\pi/K/p$ (~6% $K^+$)
NA62 Technique: Decay in Flight

~92% of Kaon decays

Kinematically Constraint Decays

Unconstraint Decays

\[ m_{\text{miss}}^2 = (\vec{p}_K - \vec{p}_\pi)^2 \]
Gigatracker (GTK)

- **Requirements:**
  - Total rate: \( \sim 1 \text{ GHz /station} \) (hence the name!)
  - Time resolution: \( 200 \text{ ps / station} \)
  - Position resolution: pixel size 300 \( \mu \text{m} \times 300 \mu \text{m} \)
  - Thickness: 0.5 \( \% X_0 \) / station
  - Expected fluence: \( 2 \times 10^{14} \text{ 1 MeV n}_{\text{eq}} / \text{year / cm}^2 \)

- **Technology:**
  - Hybrid Si pixel
  - Flip-chip bonding
  - ASIC R/O chip 130 nm IBM CMOS with ToT front-end, DLL TDC

- **Choice of sensor:**
  - Planar Si 200 \( \mu \text{m} \) thick
  - Reverse Bias Voltage as high as possible (but at least 300 Volts)
GTK: Layout & Rate

MHz / mm$^2$
NA62 Vetoes

- Photon vetoes to reject $K^+ \rightarrow \pi^+ \pi^0$
  - $P(K^+) = 75$ GeV/c
  - Requiring $P(\pi^+) < 35$ GeV/c
  - $P(\pi^0) > 40$ GeV/c
  - It can hardly be missed in the calorimeters

  - **Signature:**
    - Incoming *high momentum* $K^+$
    - Outgoing *low momentum* $\pi^+$

  - 8 orders of magnitude $\pi^0$ suppression required

- Muon Veto to reject $K^+ \rightarrow \mu^+ \nu$
The NA62 A1-A8 LAV Stations all installed in ECN3
NA62 photon vetoes: expected \( \pi^0 \) rejection \( \sim 5 \times 10^{-8} \)

Expected background from \( K^+ \rightarrow \pi^+ \pi^0 \) as fraction of the \( K^+ \rightarrow \pi^+ \nu \nu \) (SM) signal as a function of the kaon decay vertex.
Straw Tracker in NA62

- There are two main performance requirements for secondary particles:
  
  \[ \frac{\Delta P}{P} \leq 1\% \]
  
  \[ \Delta \theta_{K\pi} \leq 60 \, \mu\text{rad} \]

  1. Spatial resolution ≤ 130 μm per coordinate and ≤ 80 μm per space/point
  2. ≤ 0.5% of a radiation length (X₀) for each chamber
  3. Installation inside the vacuum tank (P < 10⁻⁵ mbar) with minimum gas load for the vacuum system (~10⁻¹ mbar* l/s)
  4. For straws near the beam, operation in a high rate environment (up to 500kHz/Straw)
  5. Possible multiplicity veto for triggering

From this follow the main requirements on the straw detector:
Straw production

Straws are handled and transported under pressure

- PET 36 micron thick
- 9.9 mm diameter
- 50 nm copper
- 20 nm gold
- Ultrasound weld
Module assembly – straw insertion
Spacers
Straw Module

996 straws
NA62 Spectrometer Reconstruction

Giuseppe Ruggiero

Missing Mass Resolution

 phánh

Kinematic Rejection

The simulation includes:
- Multiple and Single large angle Coulomb scattering
- δ-rays
- Elastic and inelastic nuclear interactions
- Errors in the straw spectrometer pattern recognition
**NA62 RICH**

- $K_{\mu 2}$: largest BR: 63.4%
- Need $\sim 10^{-12}$ rejection factor
- Kinematics (GTK + STRAW): $\sim 10^{-5}$
- Muon Veto: $\sim 10^{-5}$
- Particle ID (RICH): $\sim 10^{-2}$

- Essential to match the pion track seen by the straw with track (kaon) seen by the beam spectrometer (rate: 800 MHz)
- To avoid a wrong match which spoils the kinematic suppression, the RICH must measure the pion time to 100 ps or better to connect to the kaon measured in the GTK
- Radiator: 17 m neon atmospheric pressure; spherical glass mirrors (17 m focal length; ~ 2000 Hamamatsu PMT R7400U-03)

Rings in NA62 RICH prototype

20 GeV/c

positrons

pion
RICH400: performance

Muon suppression (15-35 GeV/c): 0.7%

B. Angelucci et al., NIM A621 (2010) 205-211
The ORKA proposal at FNAL plans to extend significantly the sensitivity of the BNL stopped kaon technique (4\textsuperscript{th} generation experiment), while the KOTO experiment at J-PARC addresses $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ with a pencil beam.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal: $K^+ \rightarrow \pi^+ \nu \nu$ $[\text{flux} = 4.8 \times 10^{12} \text{ decay/year}]$</td>
<td>$55 \text{ evt/year}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0$ $[\eta_{\pi^0} = 2 \times 10^{-8} (3.5 \times 10^{-8}) ]$</td>
<td>$4.3% (7.5%)$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu$</td>
<td>$2.2%$</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^+ \pi^+ \pi^- \nu$</td>
<td>$\leq 3%$</td>
</tr>
<tr>
<td>Other 3-track decays</td>
<td>$\leq 1.5%$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0 \gamma$</td>
<td>$\sim 2%$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu \gamma$</td>
<td>$\sim 0.7%$</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^+ (\mu^+) \pi^0 \nu$, others</td>
<td>negligible</td>
</tr>
<tr>
<td>Expected background</td>
<td>$\leq 13.5% (\leq 17%)$</td>
</tr>
</tbody>
</table>
NEUTRINOS: CNGS1
OPERA
**OPERA Experiment**

- **Oscillation Project with Emulsion-tRacking Apparatus**
- Designed to make the first detection of neutrino oscillation in direct *appearance mode* through the study of $\nu_\mu \rightarrow \nu_\tau$.
- OPERA is a hybrid detector consisting of emulsion/lead target complemented by electronic detectors.
- It is placed in the high energy long-baseline CERN to LNGS beam (CNGS) 730 km away from the neutrino source.
- The CNGS beam has enough energy to be above the $\tau$ threshold.
OPERA Detector

SM1

VETO  Target area  Magnet and RPCs  PT  PT+XPC  BMS  SM2
OPERA Muon Spectrometer

PT: Precision Tracker: drift tubes 8 x 8 m²

Magnetised iron and RPC chambers
Neutrino interactions in OPERA

**CHARGED CURRENT**

\[ \nu_{\ell} \rightarrow \ell^{-} \quad W \rightarrow \nu_{\ell} e^{+} \]

**NEUTRAL CURRENT**

\[ \nu_{\ell} \rightarrow \nu_{\ell} \quad Z \rightarrow \nu_{\ell} e^{-} \]


**Charged Current (CC) neutrino interaction**

**Neutral Current (NC) neutrino interaction**
OPERA Emulsion Detector

- Target: 2x625 tons of lead/emulsion
- Target Part: 31 walls (62 in total)
- 1 wall: brick wall + target tracker (TT)
- Automatic brick manipulation
- TT consists of horizontal and vertical strips with 2.6 x 2.6 cm$^2$ effective granularity
- TT provides a trigger for $\nu$ interactions

Emulsion cloud chamber (ECC)
56 1mm thick lead plates
57 emulsion layers + changeable sheet

Brick piling station
Opera first $\tau$ Candidate

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cut-off</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missing $P_T$ at primary vertex (GeV/c)</td>
<td>&lt;1.0</td>
<td>0.57$^{+0.02}_{-0.17}$</td>
</tr>
<tr>
<td>Angle between parent track and primary hadronic shower in the transverse plane (rad)</td>
<td>$&gt;\pi/2$</td>
<td>3.01$^{+0.03}_{-0.03}$</td>
</tr>
<tr>
<td>Kink angle (mrad)</td>
<td>$&gt;20$</td>
<td>41$^{+2}_{-2}$</td>
</tr>
<tr>
<td>Daughter momentum (GeV/c)</td>
<td>$&gt;2$</td>
<td>12$^{+5}_{-4}$</td>
</tr>
<tr>
<td>Daughter $P_T$ when $\gamma$-ray at the decay vertex (GeV/c)</td>
<td>$&gt;0.3$</td>
<td>0.47$^{+0.24}_{-0.12}$</td>
</tr>
<tr>
<td>Decay length ($\mu$m)</td>
<td>$&lt;2$ lead plates</td>
<td>1335$^{+35}_{-35}$</td>
</tr>
</tbody>
</table>

Opera second $\tau$ Candidate

![Image of charged current neutrino events]

<table>
<thead>
<tr>
<th>Years</th>
<th>Status</th>
<th># of events for Decay search</th>
<th>Expected $\nu_\tau$ (Preliminary)</th>
<th>Observed $\nu_\tau$ Candidate Events</th>
<th>Expected BG for $\nu_\tau$ (Preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008-2009</td>
<td>Finished</td>
<td>2783</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010-2011</td>
<td>In analysis</td>
<td>1343</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Started</td>
<td></td>
<td></td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4126</td>
<td>2.1</td>
<td>2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Presented by M. Nakamura @ Neutrino-2012, Kyoto

Charm Data/MC comparison
NEUTRINOS: CNGS2
ICARUS
ICARUS Concept


- Innovative liquid argon time projection chamber, suitable for large volumes applications

- Spatial resolution comparable to that of bubble chambers but fully electronic
ICARUS T600 Detector

Taking data in LNGS hall B

Two identical modules
• 3.6 x 3.9 x 19.6 ~ 275 m³ each
• Liquid Ar active mass: ~ 476 t
• Drift length = 1.5 m (1 ms)
• HV = -75 kV E = 0.5 kV/cm
• v-drift = 1.55 mm/μs

• 4 wire chambers:
  • 2 chambers per module
  • 3 readout wire planes per chamber, wires at 0,±60°
  • ~ 54000 wires, 3 mm pitch, 3! mm plane spacing
  • 20+54 PMTs, 8” Ø, for scintillation light detection:
    • VUV sensitive (128nm) with wave shifter (TPB)
ICARUS T600 physics potential

- For $10^{20}$ pot:
  - ~2800 CC events
  - ~900 NC events
  - $\nu_\mu \rightarrow \nu_\tau$
  - $\nu_\mu \rightarrow \nu_e$
  - Sterile neutrinos
  - ...

- Self-triggered events
  - atmospheric $\nu$ CC interactions
  - Proton decay $3 \times 10^{32}$ nucleons
  - ...

T600 is a milestone towards the realization of multikton Lar detectors
ICARUS Energy Reconstruction


Deposited energy spectrum
For Charged Current (CC) neutrino Interactions

\( \langle E_{\text{Data}} \rangle = 10.1 \pm 0.5 \text{ GeV} \)
\( \text{rms} = 9.6 \text{ GeV} \)

\( \langle E_{\text{MC}} \rangle = 10.1 \pm 0.2 \text{ GeV} \)
\( \text{rms} = 11.6 \text{ GeV} \)

\( \langle E_{\text{MC} 5 \times 5} \rangle = 5.2 \pm 0.05 \text{ GeV} \)

Deposited energy spectrum
For Neutral Current (NC) neutrino Interactions

\( \langle E_{\text{Data}} \rangle = 7.5 \pm 0.9 \text{ GeV} \)
\( \text{rms} = 9.0 \text{ GeV} \)

\( \langle E_{\text{MC}} \rangle = 8.4 \pm 0.4 \text{ GeV} \)
\( \text{rms} = 10.4 \text{ GeV} \)
ICARUS: Electronic Bubble Chamber

Shown at NEUTRINO-2012
In Kyoto by F. Pietropaolo

<table>
<thead>
<tr>
<th>Track</th>
<th>$E_{\text{dep}}$ [MeV]</th>
<th>range [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(p)</td>
<td>185±16</td>
<td>15</td>
</tr>
<tr>
<td>5(p)</td>
<td>192±16</td>
<td>20</td>
</tr>
<tr>
<td>7(p)</td>
<td>142±12</td>
<td>17</td>
</tr>
<tr>
<td>8(\pi)</td>
<td>94±8</td>
<td>12</td>
</tr>
<tr>
<td>9(p)</td>
<td>26±2</td>
<td>4</td>
</tr>
<tr>
<td>10(p)</td>
<td>141±12</td>
<td>23</td>
</tr>
<tr>
<td>11(p)</td>
<td>123±10</td>
<td>6</td>
</tr>
</tbody>
</table>
Flavour & Neutrinos at SPS: Summary

Possible longer term evolution of this of the CERN programme:

- **Flavour:** test the SM relation by studying very rare decays of both charged and neutral kaons

\[
\frac{S}{(\sin^2 \beta)(\sin^2 \beta)}_{K \rightarrow \pi \nu \bar{\nu}} = \frac{(\sin^2 2\beta)}{B \rightarrow J/\psi K_s}
\]

- **Neutrinos:**
  - Long baseline experiments to address the neutrino mass hierarchy and CP violation in the leptonic sector
  - Short baseline experiments (e.g. P347) to clarify the situation of sterile neutrinos
Acknowledgements

- I have adapted material taken from the presentations of many of my colleagues in NA48/NA62 and public presentations made by the OPERA and ICARUS Collaborations
- These Collaborations deserve the credit
- I hope I succeeded to entice interest for the research programme that can be performed at the SPS
- The SPS is not just an injector: it has a unique physics programme with kaons, neutrinos, muons, ions and hadron beams
- I think that the overall CERN scientific programme is worth more than the sum of its single parts
- Thank you