Neutrino Factories and Muon Colliders

First results from MuScat

W. Murray
CCLRC
How well do we understand neutrinos?

- Neutrino flavour changing well-established
  - Atmospheric $\nu_\mu$ decrease: Super-K, Soudan, IMB, K2K etc.
  - Solar $\nu_e$ deficit: Homestake, Sage, Super-K, Kamland etc.
  - Solar $\Sigma\nu$ correct: SNO

- Oscillations per se *much* less well established

- But what else can it be? We know what we are seeing...we never got neutrinos wrong before...
Evolution and the age of the Earth?

The Physicists thought they knew what they were talking about:  

- W. Thomson: Sun age less than tens of millions of years
- And Earth too hot only 1 million years ago for life

Darwin: "Thomson's views on the recent age of the world have been for some time one of my sorest troubles."
Radioactivity

1914: Chadwick measures electron energy

The energy of the electron should be fixed

Violation of energy conservation??

Wrong

\[ n \to p + e^- \]

Helium–3 (1,2)

Tritium (2,1)
Neutrino Postulated by Pauli

1934: Bethe and Peierls calculate probability of neutrino interactions with nuclei: billions of times smaller than for an electron

50% probability requires 4 Light Years of lead!

Pauli: “I have done something very bad today in proposing a particle that cannot be detected. It is something no theorist should ever do.”

Wrong

Rudolf Peierls
1933: Fermi calls the particle the **neutrino**. Builds theory of beta-decay (weak interaction).

Mass was known to be small so set to zero
Neutrino Interactions:

- A neutrino can be made (destroyed) if a $e/\mu/\tau$ is destroyed (made) at the same time.
- Other processes pair create/destroy

Conservation of electron number
Solar rates

Total predicted rate greatly exceeds observed!
Atmospheric angle distribution

First claim to observe oscillations: Super-Kamiokande

Zenith Angle Distribution in 1998

\[ P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m^2_{23} L}{4E_\nu} \right) \]
SNO Results

SNO measures:

\[ \nu_e + d \rightarrow p + p + e^- \]
\[ \nu_x + d \rightarrow p + n + \nu_x \]
\[ \nu_x + e^- \rightarrow \nu_x + e^- \]

CC - \( \nu_e \) only
NC - \( \nu_e, \nu_\mu \) and \( \nu_\tau \) equally
ES - \( \nu_e + 0.154(\nu_\mu + \nu_\tau) \)

**Difference \( \Rightarrow \) more than just \( \nu_e \) in the neutrinos from the Sun.**

\[ \phi_{CC} = 1.72^{+0.05+0.11}_{-0.05-0.11} \]
\[ \phi_{NC} = 4.81^{+0.19+0.28}_{-0.19-0.27} \]
\[ \phi_{NC} = 4.81^{+0.19+0.28}_{-0.19-0.27} \]

Neutrinos must have changed on the way.
Summary of Neutrinos:

- Flavour changing of neutrinos well established
  - Requires neutrino mass (Majorana? Dirac?)
  - Proof of oscillations still thin
- Good description of all (bar LSND) with:

<table>
<thead>
<tr>
<th>parameter</th>
<th>best fit</th>
<th>$2\sigma$</th>
<th>$3\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2 [10^{-5} eV^2]$</td>
<td>8.1</td>
<td>7.3–8.7</td>
<td>7.2–9.1</td>
</tr>
<tr>
<td>$\Delta m_{31}^2 [10^{-3} eV^2]$</td>
<td>2.3</td>
<td>1.7–2.9</td>
<td>1.4–3.3</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.30</td>
<td>0.25–0.34</td>
<td>0.23–0.38</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.50</td>
<td>0.38–0.64</td>
<td>0.34–0.68</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.00</td>
<td>$\leq 0.028$</td>
<td>$\leq 0.047$</td>
</tr>
</tbody>
</table>

'Solar' "Atmospheric"
Further evidence for oscillations

Strong constraint on oscillation parameters, especially $\Delta m^2$
Selection criteria

Following events are not used:
- horizontally going events
- low energy events

Select events with high L/E resolution
\[ \Delta(L/E) < 70\% \]

Similar cut for: FC multi-ring μ-like, OD stopping PC, and OD through-going PC

2121 FC μ-like and 605 PC
Evidence for oscillatory signature

Decay and decoherence disfavored at 3.4 and 3.8σ level, respectively.
Kamland: $\nu_e$ disappearance
Kamland data: Energy spectrum

- Clear suppression
- Energy dependent
Kamland data: L/E

- Two-sigma evidence for oscillation peaks
Kamland data: LMA

- Happy face
  - $\Delta M^2 \nu \theta_{12}$
- 5.6 sigma exclusion of bi-maximal mixing
- limits on $\theta_{13}$
How do neutrino oscillations work?

- Neutrinos are produced via Weak interactions:
  \[ Wlv_1 \text{ vertex} \]

- Propogate as mass eigenstates
  - Each mass eigenstate admixture of all flavours
    - e/mu/tau conservation broken at each neutrino production
  - Coherent mixture of states
  - Summed amplitude of the 'wrong' states zero at W vertex
  - Oscillations de-phase the states – if velocities different
Why don't quarks oscillate?

- $B_s$ oscillates, but this is $b \bar{s} \rightarrow \bar{b} s$

- $b \bar{s} \rightarrow d \bar{s} \rightarrow b \bar{s}$ does not happen, $b \rightarrow s \gamma$ does

- One mass eigenstate, not several
  - Quarks interact (QED, QCD) allowing observation of which mass eigenstate produced
  - Mass differences observable from production kinematics
  - (Quarks normally MADE in mass eigenstates)
Neutrino Propagation

- Neutrinos *can* decay
  - $\nu_2 \rightarrow \nu_1 \gamma$
  - Lifetime is very long
  - If neutrino masses were larger decay would be visible

- Decoherence stop neutrino oscillation
  - If New Physics$^\text{TM}$ allows in-flight mass determination.
  - Kinematics does not ($\pi \rightarrow \mu \nu_\mu$) allow production tagging
Mass Spectrum

Matter particles

Neutrino mass range

Small mass crucial to phenomenology
Dark energy and Neutrinos

Dark energy – 73% of Universe, totally unknown

- **Idea**: Neutrinos make lousy CDM candidate because they don't clump
- Dark Energy doesn't clump
- Maybe neutrinos are the dark energy?
- Requires neutrino mass to depend upon density
  - Perhaps mixing with $\nu_R$ gives sensitivity to environment?
  - It is certainly a novel window on gut-scale physics...
- Dark energy scale very close to solar neutrino scale

*astro-ph/0309800
hep-ph/0401099
hep-ph/0405141*
Do Neutrinos oscillate in air?

- To date there is no proof that they do.
- Only weak upper bounds on $\Delta M^2$ in rock
  - Super-K might be seeing LSND scale oscillations!
- Can accommodate all data, and explain dark energy.
Lessons/predictions

- **Document and consider environment of neutrino in neutrino oscillation experiments**
  - $\theta_{13}$ measurements in reactor experiments
  - Consider environment in direct mass search and $0\nu\beta\beta$ measurements

Predictions:

- Tritium endpoint searches for absolute $\nu$ mass depends on density of source?
- A MiniBooNE signal for $\nu_\mu$ disappearance or $\nu_e$ appearance
The Neutrino Factory

- Use $\mu \rightarrow e\nu_\mu\bar{\nu}_e$ as source of known neutrino beams: $10^{21}$/yr
- 4MW protons at 2-20GeV on dense target
- Efficient collection of $\pi$, allow decay to $\mu$
- Cool muons for injection into accelerator: LH$_2$ absorber
- Fast acceleration to 20-50GeV: Linac? RCS?
- Storage ring with straight sections pointing at detectors 2000-8000km away
- Large detector, at least sensitive to muon charge, tau ID or electron charge useful bonus.
The Neutrino Factory

Proton Driver

0.18 GeV linac

3 GeV RCS

15 GeV RCS

Target and capture

Drift

Phase rotation and bunching

Cooling

Muon Cooling

TT2A

Muon Accelerators

2 GeV muon linac

2 - 8 GeV

8 - 50 GeV recirc. linac

Muon Storage Ring

Mice
Possible beamlines

- **Soudan, USA**
  - $\nu_e = 1.2\%$
  - $\nu_\mu = 70.7\%$
  - $\nu_\tau = 28.1\%$

- **Gran Sasso, Italy**
  - $\nu_e = 0.0\%$
  - $\nu_\mu = 97.7\%$
  - $\nu_\tau = 2.3\%$

- **Kamioka, Japan**
  - $\nu_e = 2.0\%$
  - $\nu_\mu = 48.7\%$
  - $\nu_\tau = 49.3\%$

---

**Neutrino Factory**

**Ultimate long baseline neutrino oscillation facility**
Neutrino Factory: I & II

• define benchmark neutrino factories:

<table>
<thead>
<tr>
<th></th>
<th>P(MW)</th>
<th>( \mu )‘s/year</th>
<th>( T_\nu + T_\nu ) (y)</th>
<th>M(kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino factory I:</td>
<td>0.75</td>
<td>( 10^{20} )</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Neutrino factory II:</td>
<td>4.00</td>
<td>( 5.3 \times 10^{20} )</td>
<td>8</td>
<td>50</td>
</tr>
</tbody>
</table>

• baseline 3000km

• magnetized iron detector \( \Rightarrow \) wrong sign \( \mu \)‘s

simulations of various options:
Barger, Geer, Raja, Whisnant, Marfatia, ...
Cervera, Donini, Gavela, Gomez-Cadenaz, Hernandez, Mena, Rigolin, ...
Bueno, Campanelli, Rubbia, ...
Minakata, Yasuda, ...
Freund, Huber, ML, Winter, ...

...
• different sensitivity reductions by systematics
• correlations & degeneracies lead to severe sensitivity reductions
• break C&D by combining different experiments of comparable potential

M. Lindner NuFact04
Sensitivity to the sign of $\Delta m_{31}^2$

- $\text{sign}(\Delta m_{31}^2)$ very hard to determine with superbeams
- Degeneracies with $\delta_{CP}$ are the main problem

$\Rightarrow$ combine experiments!

Huber, ML, Winter, hep-ph/0204352
Measurement of CP Violation

Sensitivity to CP–Violation at \( \delta_{CP} = +\pi/2 \)

- \( \Delta m^2_{21} \) [eV^2]
- \( \sin^2 2\theta_{13} \)

- \( 1.1 \times 10^{-5} \) JHF–HK
- \( 3.7 \times 10^{-5} \) JHF–HK, NuFact–II
- \( 4.7 \times 10^{-4} \) JHF–HK, JHF–SK, NuFact–I, NuFact–II

- CP violation with high luminosity superbeams feasible
- sensitivity is \( \delta_{CP} \) dependent

Huber, ML, Winter, hep-ph/0204352
Beta beams

- β beams: Nuclei which release neutrinos
  - If muons can be boosted before decay, why not ions?
  - longer lifetime, only 1 flavour of muon
  - SPL at CERN as source, SPS/LHC as accelerator, just need storage ring.
  - Need very high energy to get high neutrino energy

- Does beta beam augment a ν factory?
  - No.
  - Nor does it fully replace one
Beta-beam baseline design

**Ion production**
- Proton Driver
  - SPL
- Ion production
  - ISOL target & Ion source
- Beam preparation
  - ECR pulsed
- Ion acceleration
  - Linac
- Acceleration to medium energy
  - RCS

**Acceleration**
- Acceleration to final energy
  - PS & SPS

**Neutrino source**
- Decay ring
  - $B \rho = 1500 \text{ Tm B}$
  - $B = 5 \text{ T}$
  - $C = 7000 \text{ m}$
  - $L_{ss} = 2500 \text{ m}$
- $^6\text{He}: \gamma = 150$
- $^{18}\text{Ne}: \gamma = 60$

**Experiment**
- $\nu, \bar{\nu}$
Targetry

- Aim if for 4MW power on small target
- Roger Bennett: Solid targets
  - magic properties do not last when exposed to beams
  - Prospects not good right now: Wait for more results
- Harold Kirk, liquid metal jet
  - Designed 15T pulsed solenoid, delivery Nov. 2004
  - Experiment TT2A 2006??
Neutrino Factory Targetry Concept

Capture low $P_T$ pions in a high-field solenoid
Use Hg jet tilted with respect to solenoid axis
Use Hg pool as beam dump

TT2A experiment at CERN aims to test all important elements in 2006
Neutron Production using Hg

SNS Target Configuration

SNS Neutron Spallation Target

Beta Beams

Fission Converter
Mice
MICE apparatus: Beam & HALL

- MICE Muon Beam Line:
  - Shielding to be re-installed
  - Prepare beam line for installation in next long ISIS shutdown – early (?) 2006
Mice has now been approved
• Lord Sainsbury announced phase I a month ago.

• ~£10M investment in accelerator technology
Muon Colliders

- D. Cline pursuing Muon collider potential
  - precise, high energy collisions; no beamstrahlung
  - Collider beam time structure different from Neutrino Factory
  - A/H discovery at LHC would mandate muon collider
  - Progress on ring coolers makes them possible
A/H factory

- Heavy SUSY Higgses quasi-degenerate
- Only muon collider scans peaks
- Can test CP violation in Higgs sector
6D Cooling in Gas-filled Rings

Closed orbits scale such that the path length of each orbit is proportional to the particle momentum.

\[ 6D \text{ Merit} = \text{Transmission} \times \frac{(\varepsilon_x \varepsilon_y \varepsilon_z)_{\text{initial}}}{(\varepsilon_x \varepsilon_y \varepsilon_z)_{\text{final}}} \]

Key Issue: Gas filled RF Cavities
Reach required emittance?
Study 2a - Fernow

- Studys 1 & 2: Fermilab/BNL NuFact schemes
- Study 2a tries to reduce cost from study 2.
  - Adiabatic RF bunching – no induction Linac
  - Simplified cooling cooling, lower B fields
  - Similar performance, front end cost 53%: Overall 67%
  - $\mu^+ \mu^-$ beams: Good or bad?
    - Separation only metres
Communique from the 6th International Workshop on Neutrino Factories and Superbeams, 26th July – 1st August 2004, Osaka, Japan

About 160 particle and accelerator physicists from Europe, Japan and the US met in Osaka (Japan) from 26th July to 1st August 2004, to discuss progress in neutrino physics and options for producing intense beams of neutrinos to explore their properties in detail, to make new discoveries about neutrinos, and thereby to understand better their nature. One of the highlights of the meeting was the strong indication that the cost of the most powerful facility, the Neutrino Factory, could be reduced by at least one third, compared with previous estimates.

There are three new schemes for producing these intense beams of neutrinos – “superbeams”, “beta beams” and the “neutrino factory”. ....

There is a clear programme of R&D for the next five years to take the key technologies from design to prototype.

As chair of the final session, Dr Steve Geer (Fermilab, USA) said that “the scientific case for new experiments with intense beams of neutrinos over long baselines becomes stronger with each workshop”.
Comparison of MuScat Data with Geant 4

Motivation
Description
Data taking
Results

The History

- MuScat to check multiple scattering of Muons at ~100MeV/c
  - Low Z materials for Ionisation cooling
  - Key is liquid Hydrogen
- Engineering run, Triumf 2000
  - Solid targets
  - MWPC problems
- Decide to build new fibre tracker for Autumn 2001
- Missed slot, re-allocated Spring 2003
- Data *still* being analysed, preliminary results here
Why check Multiple Scattering?

Ionization cooling is an interaction between cooling and heating.

No published data on muon scattering at relevant energies.

Electron data from 1942 are the most relevant.
Why check Multiple Scattering?

Ionization cooling is an interaction between cooling and heating.

No published data on muon scattering at relevant energies.

Electron data from 1942 are the most relevant..
Why check Multiple Scattering?

Ionization cooling is an interaction between cooling and heating.

No published data on muon scattering at relevant energies.

Electron data from 1942 are the most relevant.
The Basic Muscat design

- This is a cartoon of the experiment in June 2000
- MWPCs replaced with the Sci-Fi tracker.
Geant Simulation:

- S2 scintillator
- SciFi tracker
- LH$_2$ target
- S1 scintillator
- Collimator
The Fibre Tracker

- 512 scintillating fibres in x and y
- Fibre diameter 1mm, spacing 0.6mm, covers $30\text{cm}^2$
- 3 planes, 3096 fibres
  - A lot of rubber bands!
- Fibres potted in dark resin
  - too much material for Mice
One Mounted Plane

- 3 double planes
- Each with 8 fibre bundles
- Mounted in dedicated vacuum vessel
- Black resin in case of cross-talk or light leaks.
**The Clear Fibre Bundles**

- 512 scintillating fibres grouped as 256x2
- Readout with clear fibre
  - One end match to detector edge
  - Other end potted into vacuum feedthrough/PMT interface
- 24 bundles, with 6000 fibres
The Clear Fibre Bundles II

- Each in $16\text{mm}^2$ grid
- Feeding 256 fibres to 16 anode HPK PMT
- Anodes 16mm by 1mm
- Hard to keep round fibres in square grid
  - ~50% success
- Readout at both SciFi ends gives fibre mapping.
Bundle – PMT mating

- Fibre 1mm diameter
- Anode spaced 1mm
- But..1.5mm of glass separating
- Cone angle 29° in glass
  - Up to 0.8mm transverse movement
  - 35% of light on neighbours
Digitization Electronics

- Sample and hold system, 24 ADCs
- Works well for all channels
- Electronic noise low
  - Easy to select single photon

- Very happy
Stability of pedestals

- Pedestal drift over 30 days of cosmic data taking
- Stable to about 30 counts
- This is about 1% of the signal from one photon
- No problem
PMT 31

- Hit distribution
  - This PMT has 1 dead anode

- Mean signal size
  - Fixed in simulation

- Mean signal on neighbours
  - not fixed
Efficiency of plane 1

- Efficiency generally good,
- but with dips
- This is simulated via the pulse heights

Efficiency

Run 280 – Thick Steel

88%
Reconstruct tracks

- Example cosmic ray
- 1-3 hits on each plane
- Ambiguity solved in track
  - *Much* easier with 4\textsuperscript{th} point (target)
- Using just one plane would give problems
Cross-talk between anodes in PMT

- Distribution in SciFi plane 1, with no target, just collimator
- Ghosts due to cross-talk understood and suppressed

Plane 1 only

Ghosts

Require 3-in-row

mm
Track chi2

- Fit with target plus 3 planes
  - Demonstrate alignment
  - Tails not perfect
Sci Fi Summary

- Detector was a lot of work to build
  - **Stable** for the run

- Number of P.E. marginal, but OK

- Some cross-talk between channels
  - Quite well understood

- It works
Collimator system

- Built in Birmingham
- Used angled surfaces to minimize direct bounces
Active collimator

- Muons can penetrate collimator
  - give tails on distribution
- Use Scintillator as active collimator
Active Collimator response

- Yellow is hits in plane 1
- red line have hit in one
- green hit in other
- Collimators have slipped ~100μm
Time of flight

- Special run with mixed particle beam
- Used to calibrate momentum
- \( P = 172 \pm 2 \text{MeV}/c \)

Timing problems, removed
Flight time v arrival time

- pions
- muons
- electrons
- proton overlaps
Timing problems, removed

- Normal run
- Pion shoulder on muon beam
Contamination from Tina

- Below 1% pion contamination
- Allowed for in analysis
### Targets

Millions of events were collected with each of the following targets.

<table>
<thead>
<tr>
<th>No.</th>
<th>Target</th>
<th>Thickness, mm</th>
<th>X0, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/12</td>
<td>Lithium 2</td>
<td>12.72</td>
<td>0.81</td>
</tr>
<tr>
<td>1</td>
<td>Lithium 1</td>
<td>6.43</td>
<td>0.41</td>
</tr>
<tr>
<td>2</td>
<td>Lithium 2</td>
<td>12.72</td>
<td>0.81</td>
</tr>
<tr>
<td>3</td>
<td>Beryllium</td>
<td>3.73</td>
<td>0.53</td>
</tr>
<tr>
<td>4</td>
<td>Carbon</td>
<td>2.5</td>
<td>1.53</td>
</tr>
<tr>
<td>5</td>
<td>Aluminium</td>
<td>1.5</td>
<td>1.69</td>
</tr>
<tr>
<td>6</td>
<td>None</td>
<td>0.24</td>
<td>1.36</td>
</tr>
<tr>
<td>7</td>
<td>Iron</td>
<td>5.05</td>
<td>28.68</td>
</tr>
<tr>
<td>8</td>
<td>Long, full</td>
<td>150</td>
<td>1.53</td>
</tr>
</tbody>
</table>

Pink targets are shown now.
No target: check collimator

Tails in data exceed simulation.

This is not understood:

- neutrons?
- noise?
- tracks
No target: check collimator

Require planes 1 and 3 gives consistent answers

Tails smaller, Discrepancy smaller

Problem is $4 \times 10^{-5} @ 30\text{mm}$
Thick steel target, 28% X0

Geant 4.6.1

description good

Used to study detector response:

Efficiency modeled reasonably well
Thick steel target

Extra Efficiency correction applied

Residual error below 10%
Thin Steel

Good in core

Difference from 25mm

Problem is $4 \times 10^{-4}$ @30mm

Geant underestimates tails [MC sample small here]
Aluminium

Good in core

Difference at 30mm

Problem is $4 \times 10^{-4} \ @ 30\text{mm}$
Carbon

Good in core

Some hint of difference at 30mm

[MC sample small here]
Thick Beryllium

Very satisfactory agreement

20% effects are not significant at this stage
Thick Lithium

**Tails lower in data?**

Very similar to the Beryllium Andrievsky's factor 2 at 1% not seen
15cm liquid hydrogen

Tails possibly lower in data

Excellent agreement
15cm liquid hydrogen: tail 50%

Adjust G4's MSC tail parameter

Distribution shows peaks around 30cm

Same place problems seen in high-Z materials

► Tuning might help those?
15cm liquid hydrogen: G4.6.0p1

Tails overstated by a factor 2 or more

Geant 4.6.0p1: Known buggy
80 Million events recorded; data being analysed

- Detailed efficiency calculation
- Deconvolution of detector from data

Geant 4.6.1 is a GOOD description of multiple scattering in this region

- For High Z materials may be some tuning to do?
- Andrievsky discrepancy for Lithium not confirmed
Conclusions

- The neutrino has proved physicists wrong
  - Not once, but many times
  - It may do it again.
- Neutrino mass may be responsible for our existence
- Neutrino factory
  - Required whatever the truth is.
  - Could be a UK hosted project
  - Cost much less than a linear collider