Working Group 5 Summary
“Beyond PMNS”

WG Conveners
Richard Efrain Ruiz (Université catholique de Louvain, Belgium)
Danny Marfatia (University of Hawaii, USA)
Carsten Rott (Sungkyunkwan University, Korea)

THE 21ST INTERNATIONAL WORKSHOP ON NEUTRINOS FROM ACCELERATORS
August 26 - August 31, 2019
The Grand Hotel, Daegu, KOREA
• In total had 24 talks in the parallel sessions including 4 talks in the joined session with WG1

• In this summary

  • Main focus on talks and topics not already covered as part of plenary talks
  • Order does not reflect order of talks in the parallel session, but grouping of topics and synergy
## Schedule

### Tuesday (WG5 Session 1)

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00-14:25</td>
<td>Federico Scutti</td>
<td>Search for heavy neutrinos with the ATLAS detector</td>
</tr>
<tr>
<td>14:25-14:50</td>
<td>Si Hyun Jeon</td>
<td>Tests of neutrino mass models at CMS</td>
</tr>
<tr>
<td>14:50-15:15</td>
<td>Yu Seon Jeong</td>
<td>Prompt tau neutrinos at the LHC</td>
</tr>
<tr>
<td>15:15-15:40</td>
<td>Osamu Sato</td>
<td>Study of tau-neutrino production at the CERN SPS</td>
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</tbody>
</table>

### Tuesday (WG5 Session 2)

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:00-16:25</td>
<td>Paschal Coyle</td>
<td>Neutrino Oscillation measurements and BSM physics searches with Neutrino Telescopes in the Mediterranean</td>
</tr>
<tr>
<td>16:25-16:50</td>
<td>Tom Stuttard</td>
<td>Neutrino oscillations and PMNS unitarity with IceCube/DeepCore and the IceCube Upgrade</td>
</tr>
<tr>
<td>16:50-17:15</td>
<td>Phillip Litchfield</td>
<td>Prospects for BSM physics searches and NSI at Hyper-K and T2HKK</td>
</tr>
<tr>
<td>17:15-17:40</td>
<td>Alan Bross</td>
<td>Neutral Current events and new physics at nuSTORM</td>
</tr>
</tbody>
</table>
### Thursday 29/08

#### Thursday (WG5 Session 3)

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
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<tbody>
<tr>
<td>11:00-11:30</td>
<td>Mathieu Perrin-Terrin</td>
<td>Search for exotic decays with NA62</td>
</tr>
<tr>
<td>11:30-12:00</td>
<td>Chunsil Yoon</td>
<td>Neutrino physics with the SHiP experiment at CERN</td>
</tr>
<tr>
<td>12:00-12:30</td>
<td>Kihyeon Cho</td>
<td>BSM at DUNE</td>
</tr>
</tbody>
</table>

#### Thursday (WG5 Session 4)

<table>
<thead>
<tr>
<th>Time</th>
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<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00-14:30</td>
<td>Raymond Volkas</td>
<td>Radiative neutrino mass models and the flavour anomalies</td>
</tr>
<tr>
<td>14:30-15:00</td>
<td>Giovanni Gallucci</td>
<td>Status of the HOLMES experiment to directly measure the electron neutrino mass with a calorimetric approach.</td>
</tr>
<tr>
<td>15:00-15:30</td>
<td>Kang Young Lee</td>
<td>New physics searches with SHIP</td>
</tr>
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#### Thursday (WG5 Session 5)

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<thead>
<tr>
<th>Time</th>
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<th>Title</th>
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<tbody>
<tr>
<td>16:00-16:30</td>
<td>Shao-Feng Ge</td>
<td>New Physics and the Leptonic CP Phase Measument</td>
</tr>
<tr>
<td>16:30-17:00</td>
<td>Dukjae Jang</td>
<td>Sterile Neutrinos in Astrophysical Environments : Big Bang Nucleosynthesis and Supernova Neutrino Process</td>
</tr>
<tr>
<td>17:00-17:30</td>
<td>Juan Antonio Aguilar Sánchez</td>
<td>Search for Dark Matter and BSM Physics with the IceCube Neutrino Observatory</td>
</tr>
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</table>
### Friday (WG5 Session 6)

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00-14:30</td>
<td>Yoomin Oh</td>
<td>Reactor short baseline neutrino experiments including NEOS</td>
</tr>
<tr>
<td>14:30-15:00</td>
<td>Jaehoon Yu</td>
<td>Sterile neutrino searches with the ICARUS detector</td>
</tr>
<tr>
<td>15:00-15:30</td>
<td>Mark Ross-Lonergan</td>
<td>Status of the MicroBooNE Low-energy Excess Search</td>
</tr>
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</table>

### Friday (WG1+WG5 Session 7)

<table>
<thead>
<tr>
<th>Time</th>
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<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:00-16:25</td>
<td>Stephen Robert Dennis</td>
<td>Status of SBND</td>
</tr>
<tr>
<td>16:25-16:50</td>
<td>Fumihiko Suekane</td>
<td>Status of JSNS2 experiment</td>
</tr>
<tr>
<td>16:50-17:15</td>
<td>Adam Jude Aurisano</td>
<td>Sterile Neutrinos search via NC disappearance at NOvA</td>
</tr>
<tr>
<td>17:15-17:40</td>
<td>Joshua Hignight</td>
<td>Sterile Neutrino Searches with IceCube</td>
</tr>
</tbody>
</table>

*Example: Notation used in top right corner of slides (Speaker name, #Session, #Talk in session)*
Neutrino Masses
• Seesaw Model: natural way to generate neutrino masses
• Within the SM expand dim-5 operator at tree level:
  fermion singlet, scalar triplet, fermion triplet

Collider experiments have access to different incarnations of Type-I/II/III.

**Typical signatures:**

**Type-I**
- Signatures including muons and electrons

**Type-III**
- Two leptons in final state with same or opposite charge.
Test of Neutrino Mass Models at CMS

CMS:
- 2.8σ excess at m(eejj)~2 TeV
- 2.5σ excess also seen from Leptoquark analysis but only in e channel (eejj, evjj)

ATLAS:
- SS analysis: no excess

In 13 TeV data:
- No excess in signal region
- Exclude m_{WR} up to 4.4 TeV
CMS Results summary

- **Composite Model**: excluded up to $m(N)=4.6$ TeV for $m(N)=\Lambda$

- **Type-I Seesaw Model**
  - 2 leptons: limits on $|V_{\ell N}|^2$ set up to $m(N)=1200$ GeV
  - 3 leptons: limits on $|V_{\ell N}|^2$ set down to $m(N)=1$ GeV

- **Type-III Seesaw Model**: excluded up to 880 GeV for flavour democratic case

- **Left-Right Symmetric Model**
  - $\tau\tau$: excluded up to $m(N)=1.45$ TeV for $m(N)=m(W_R)/2$
  - $ee/\mu\mu$: excluded up to $m(N)=2.2$ TeV for $m(N)=m(W_R)/2$

More searches forthcoming using full 13 TeV run data

- Used full 13 TeV run data
- ✓ No excess above SM prediction
- ✓ Excluded up to $m(\Sigma)=880$ GeV
• ATLAS Run-II searches will be updated with the final dataset.

• Many updates in program: new channels/techniques

Analyses covered:

- Minimal Type-I multi-leptonic:
  • (Lint = 36.1 / 32.9 fb⁻¹): 1905.09787.

- Minimal Type-III semi-leptonic:
  • (Lint = 79.8 fb⁻¹): ATLAS-CONF-2018-020.

- Left-Right symmetric Type-I semi-leptonic with resolved topology:
  • (Lint = 36.1 fb⁻¹): JHEP 01 (2019) 016.

- Left-Right symmetric Type-I semi-leptonic with boosted topology:
  • (Lint = 80 fb⁻¹): 1904.12679.
Review flavour anomalies

- Hints for $\mu$ vs $e$ universality violation in $b\to s$ transitions
- Hint of non-standard angular observable in $B\to K^*\mu^+\mu^-$
- Hints for $\tau$ vs $\mu/e$ universality violation in $b\to c$ transitions

$$R_{D(*)} = \frac{\Gamma(\bar{B} \to D(*)\tau\nu)}{\Gamma(\bar{B} \to D(*)\ell\nu)}$$

Radiative neutrino mass models to explain neutrino masses and observed anomalies

Important future tests:
- $\mu\to e$ conversion most important constraint. COMET and Mu2e experiments will probe much of the allowed parameter space!
- Belle-II

Bigaran, Gargalionis, Volkas: 1906.01870
Direct measurement (1)

- Kinematics of weak decay with \( \nu \) emission:
  - low Q nuclear \( \beta \) decays (\(^{99m}\)Re, \(^{168}\)Ho...)
  - model independent: only E, p conservation
  - \( \nu \) mass appears as a distortion in the Kurie plot

\[
N(E_\beta) \propto p \beta E_\beta (Q - E_\beta) \sqrt{(Q - E_\beta - m_\nu) F(z,E_\beta) S(E_\beta)}
\]

2 different approaches:
- **spectrometry**: source placed outside the detector (KATRIN approach)
- **calorimetry**: source embedded inside the detector (ECHO, MARE, HOLMES approach)
  \( \Rightarrow \) low T \( \mu \)-calorimeters

**Electron capture (EC)** in Holmium 163

\[ ^{163}\text{Ho} + e^- \rightarrow ^{163}\text{Dy}^* + \nu \]

**HOLMES Sensitivity**
- 32pixels + 1 month \( \sim 10 \text{eV} \)
- Expected to reach \( \sim 1 \text{eV} \) in comparison

- current best calorimetric measurements \( \sim 20 \text{eV} \)
- KATRIN \( \sim 0.2 \text{eV} \)

**Summary**

- **Direct measurement**: \( \lesssim 2 \text{eV} \)
  (Mainz & Troitsk experiments)
- **Double beta decay**: \( \lesssim 0.5 \text{ eV} \)
  (only Majorana neutrino)
- **Cosmological** and astrophysical data: \( \lesssim 0.2 - 1.3 \text{eV} \) (model dependent)

**HOLMES** is a calorimetric experiment with \(^{163}\)Ho that aims to reach the statistical sensitivity around 1 eV.

Three batches of \(^{163}\)Ho are purified and ready to be moved in Genova.
The procedure to distillate holmium is tested. Some refinements are needed.
The procedure to fabricate sputter target is tested.
The installation of the implanter for isotopic separation is mainly finished.
Every part has been individually tested. Integration and first tests in progress.
HOLMES detector production procedure is defined and the firsts (not implanted) detectors
are being characterized.
Readout is on test and is almost ready.

With 32 pixels for 1 month \( \rightarrow m \) sensitivity \( \lesssim 10 \text{ eV} \)

**Advantage**: HOLMES technology scalable
Detector design and test (1)

Transition Edge Sensors Superconductive Detectors (TES)
- Molybdenum/copper ($T_c \sim 100$ mK)
- Very steep $R$ vs $T$ dependency in transition region;
- Gold absorber with $^{163}$Ho inside coupled to TES thermometer;
- Ho sandwiched between two 1 mm thick gold layers for a total electron containment
- Fast detectors to reduce pile-up
  - tunable rise time $\sim L/R$
  - decay time dependent on detector characteristics $C/G$

TES design, production and preliminary test is done @NIST

- TES
- $\text{Si}_2\text{N}_3$ membrane
- Cu structure for thermalization (High G)
- Absorber
Beam Dump Experiments and Tau Neutrinos
Future tau neutrino measurements

- Opportunities to measure $\nu_\tau$ cross section
  - SHiP: high statistics $\nu_\tau$ measurement at the SPS beam dump facility
  - reduction of $\nu_\tau$ beam uncertainty with DsTau to $\sim$10%
  - FASER: high energy $\nu_\tau$ measurements at the LHC.3

- $\nu_\tau$ cross section has influence to
  - Long baseline neutrino oscillation experiments
    - DUNE, Hyper-K (+KNO), T2K
    - $\nu_\tau$ is background to $\nu_e$, due to $\tau \rightarrow e$
  - Astrophysical $\nu_\tau$ measurement
    - IceCube, KM3NeT, GVD, …
Detector Location: 480 m from ATLAS IP
Planned with two stages
FASER 1 (during Run 3): 
  \( R_d = 10 \text{ cm}, L_d = 1.5 \text{ m}, \)
  Luminosity = 150 fb\(^{-1} \),
  Rapidity: \( \eta \gtrsim 9.2 \)
FASER 2 (during HL-LHC): 
  \( R_d = 1.0 \text{ m}, L_d = 5.0 \text{ m}, \)
  Luminosity = 3000 fb\(^{-1} \)
  Rapidity: \( \eta \gtrsim 6.9 \)

FASER (ForwArd Search ExpeRiment)

- Neutrinos in large rapidity region will provide a good opportunity for measurement of neutrino cross section at TeV energies.
- With sizeable number of tau neutrino (\( \nu_\tau \)), it will be possible to test lepton universality in neutrino interaction.
- Abundant \( \nu_\tau \) will help investigate oscillation in/beyond the SM.
  - better understanding of \( \nu_\tau \) CC interaction will be able to reduce the uncertainty due to the tau (\( \tau \)) decay in the oscillation experiments.
  - possible to probe oscillation between \( \nu_\tau \) and sterile neutrino (\( \nu_s \)) using the event spectrum.
• Sterile neutrinos at FASER
• Abundant tau neutrinos and broad energy spectrum ($\nu_\tau \rightarrow \nu_s$) - 7000-8000 $\nu_\tau$ events expected with energies ranging from 100GeV - 1TeV

FASER can test “larger” mass sterile neutrinos ($\Delta m^2 > 100$eV$^2$)

Oscillation probability in two flavour approximation:

$$P(\nu_\alpha \rightarrow \nu_\beta) \approx \sin^2 2\theta_{\alpha\beta} \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$

Condition for noticeable signal:

$$\frac{\Delta m^2 L}{4E} \sim \frac{\pi}{2}$$

For the baseline 480 m and neutrinos with

- $E \sim 170$ GeV $\Rightarrow \Delta m^2_s \sim 440$ eV$^2$ ($m_s \sim 20$ eV)
- $E \sim 350$ GeV $\Rightarrow \Delta m^2_s \sim 900$ eV$^2$ ($m_s \sim 30$ eV)
DsTau studies tau neutrino production in 400 GeV proton beam dump, for future tau neutrino measurements.

Collecting 1000 $D_s \rightarrow \tau \rightarrow X$ double kink events from $2.3 \times 10^8$ proton tungsten interactions.

June 2019 - DsTau approved by CERN Research Board as CERN NA65

Plan for physics runs in 2021, 2022 (NA65)

- 2 weeks each
- The exposure speed achieved in the pilot run is quick enough
The SHiP detector

- Active muon shield: deflect $\mu$ from $2\gamma$ meson decay, $\sim 35m$ long, 1.7 T magnet
- Hadron absorber: eliminate $2\gamma$ mesons ($\pi, K$) $\sim 5m Fe$
- Target and hadron absorber
- Muon shield
- Scattering and neutrino detector
- LDM & Tau neutrino
- ECC+CES (Nuclear emulsion)
- TT, RPC
- Decay volume
- Vacuum vessel: $\sim 50m$ long evacuated decay vessel surrounded by liquid scintillator veto system
- HS decay spectrometer
- ECAL,Muon detector
- PID, Energy & Time

Project Schedule

- Using High-intensity 400 GeV SPS proton beam
- Data expected
  - $2 \times 10^{20}$ pot, 5 years run

NuFACT2019 WG5 Summary
August 26 - August 31, 2019
About **10,000 Tau neutrino & Anti-tau Neutrino CC events** are expected with target mass of ~10 tons. - Expect first observation of the **Anti-tau neutrino**

**Tau neutrino physics** - Cross section, Magnetic moment - First evaluation of the F4 and F5 - Study of Strange quark content of nucleon

**Light Dark Matter search in SND**

LDM ($\chi$) can produce via dark photon ($A'$) decay

$$pp \rightarrow \pi^0 \chi$$

$$\pi^0 \rightarrow A' \gamma$$

$$A' \rightarrow \chi \bar{\chi}$$

$\chi$: LDM

Scatter on e

$$\chi e \rightarrow \chi e$$

Neutral Current DM-electron scattering is highly peaked in the forward direction. Cutting on very forward scattering can remove most other projected background.
Heavy Neutral Leptons (HNL)

Beam: 400 GeV/c protons
4x10^{39} pot/spill
2x10^{24} pot/5 years

illustration of SHiP target, W-Mo based

h → h'pℓN
h → h'pℓN

At SPS energies:
\[ \sigma(\overline{p}p \rightarrow \tau^- \pi^+) / \sigma(\overline{p}p \rightarrow X) \approx 0.15 \]
\[ \sigma(\overline{p}p \rightarrow e^+ \nu \pi^+) / \sigma(\overline{p}p \rightarrow X) \approx 2 \times 10^{-6} \]
\[ \sigma(\overline{p}p \rightarrow b \overline{b} \pi X) / \sigma(\overline{p}p \rightarrow X) \approx 1.6 \times 10^{-7} \]

Dark Photons A'

photons
A'
\[ \mu^+ \]

If mA' < 2mχ, the Dark Photon decays to SM particles
If mA' > 2mχ the Dark Photon can decay also to DM with a coupling

Graph showing SHiP sensitivities with muon coupling dominance: U_{2e}^2 U_{4e}^2 U_{4l}^2 = 0.1:0

Graph showing SHiP 2x10^{39} pot
- solid: without B, ∆
- dotted: with B, ∆
Dark Scalar sensitivity

Axion Like Particles (ALP)
The NA62 Experiment
The NA62 Experiment

Time Line

- 2015 - 2016 Commissioning, 1% nominal intensity, no GTK
- 2016 - 2018 Physics 35% → 65% nom. intensity
  - $3 \times 10^{16}$ POT

2021-2022: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- Two year to complete the measurement of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

2023: Beam Dump

- One year in beam dump to accumulate $\mathcal{O}(10^{18})$ POT

Science Program

- Neutrino oscillations (fully reconstructed $K^+ \rightarrow \mu^+ \nu$)
- Heavy Neutral Leptons
- Dark Photons
- Axion Like Particles (ALPs)
• **Scientific objectives:**
  1. %\text{-}level (v_e N) cross sections
     • Double differential
  2. Sterile neutrino search
     • Beyond Fermilab SBN

• **nuSTORM_v3**
  • based on existing technology
  • but reoptimization of the storage ring to cover muon energies from 1-6GeV
    • Cover both experiments (Hyper-K and DUNE)
  • Mayor cost - muon storage ring (decay ring)
Neutrino Telescopes
ANTARES

- 42km offshore Toulon, depth 2475m
- Main Electro-Optic Cable/Junction Box 2001-2002
- Completed 2008
- 12 lines, ~70m spacing
- 25 storeys per line, 15m spacing
- 3x10-inch PMTs per storey
- Decommissioning 2017
Construction on going

ORCA/ARCA

Oscillation Research with Cosmics In the Abyss

Astroparticle Research with Cosmics In the Abyss

Construction on going

<table>
<thead>
<tr>
<th></th>
<th>ORCA</th>
<th>ARCA</th>
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<tbody>
<tr>
<td>String spacing</td>
<td>20 m</td>
<td>90 m</td>
</tr>
<tr>
<td>OM spacing</td>
<td>9 m</td>
<td>36 m</td>
</tr>
<tr>
<td>Instrumented mass</td>
<td>8 Mton</td>
<td>500*2 Mton</td>
</tr>
</tbody>
</table>

Depth=2450 m

115 strings
18 DOMs / string

~ 225 m

~ 200 m

9 m

~ 23 m
PMNS unitarity

- PMNS mixing matrix is unitary in standard oscillation picture
  - e.g. mixing between the 3 known neutrino flavours

- Additional (sterile?) states $\rightarrow$ 3x3 matrix is subset of full unitary matrix

- Test unitarity by measuring 3x3 matrix elements
  - $\nu_\tau$ elements least well measured

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{\tau 1} \\ U_{\tau 2} \\ U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\nu_\tau$ CC cross section suppression

- $\nu_\tau$ CC inaccessible at most LBL energies
- $\sigma_{CC}(\nu_\tau N)/\sigma_{CC}(\nu_\mu N)$
- $\sigma_{CC}(\bar{\nu}_\tau N)/\sigma_{CC}(\bar{\nu}_\mu N)$
- $\sigma_{CC}(\nu_\tau N)/\sigma_{CC}(\nu_\mu N)$

DeepCore Sensitivity to O(10 GeV)

IceCube - PMNS Unitarity
The IceCube Upgrade

- NSF has funded a $30M extension to IceCube
  - Deployment in 2022/2023
  - 700 multi-PMT sensors
  - Improved ice calibration

ν_μ disappearance sensitivity (3 yr)

10% precision after 1 year
(6% after 3 years)

Competitive with long baseline experiments in disappearance channel
**KM3NeT/ORCA: Tau neutrino appearance**

- $\nu_\tau$ appearance tests PMNS unitarity and BSM theories
- 30% deviations allowed by world data
- $\approx 3k \nu_\tau$ CC events/year with full ORCA
- Rate constrained within $\approx 5 (25\%)$ for 115 (7) DUs in 1 year
Further science goals of ORCA (115 lines):

- Precision measurements of Atmospheric Neutrino Oscillation Parameters
- Determination of the neutrino mass ordering
Velocity Independent PICO and IceCube

Deviations from the SHM will affect spin-dependent limits.

Construction of independent limits assuming as the superposition of streams with fixed velocity.

Conservative limits: only the velocity stream with the highest allowed scattering cross-section is selected
IceCube is a multipurpose experiment with a rich program on BSM and Dark Matter searches.

Indirect detection of Dark Matter with neutrino telescopes provides complementarity to other techniques due to different backgrounds and systematics.

IceCube has world-best limits on spin-dependent scattering cross-section.

The detection of the astrophysical neutrino flux has open the opportunity.
Sterile Neutrinos in Astrophysical Environments
Sterile Neutrinos in Astrophysical Environments

Sterile neutrinos

Cosmic expansion rate

$H^2 \propto \rho_{\nu_s}$

Neutrino induced reaction rate

$\nu_s \leftrightarrow \nu_a$

I. Big Bang Nucleosynthesis

200 MeV to 1-0.01 MeV

Quark Hadron Transition

Big Bang Nucleosynthesis

II. Supernova Neutrino process

Supernova 1987A: $16.2 M_\odot$

Neutrino propagation

10 km, 2400 km, 46000 km, 250000 km
The viability of 3+1 neutrino model on the supernova neutrino process
BSM with long baseline
Non-standard Oscillation

Non-Standard Interactions (NSI)

Shown here the allowed regions (68, 90 and 95% CL) for an exposure of 300 kton-MW-year.

DUNE may potentially improve present constraints on $|\epsilon_{e\mu}|$ and $|\epsilon_{e\tau}|$ by at least a factor of 2.

Diverse program including
- Non-Unitary Mixing
- CPT Violation
- Dark Matter
- Nucleon decay
- …
Boosted Dark Matter

- **Galactic halo** can produced dark matter which could interact inelastically in DUNE. ⇒ Dark photon

Visible in the detector fiducial volume

- Dark matter from the **center of the Sun** could interact elastically with the DUNE. ⇒ Lepto-phobic $Z'$

1. Cold dark matter captured by dark matter concentrated region, such as the Sun or Galaxy Center

2. Produce lighter, boosted dark matter via annihilation or decay

3. Boosted dark matter interact with electrons or nucleons in detectors

4. Look for scattered electrons or recoil protons

JCAP02(2015)005

Expected 5σ discovery reach with 1-year DUNE lifetime

Angle between Sun and particles produced
Intermediate Water Cherenkov Detector
- 2km from target
- Adjust OA angle between 1~4°

The Hyper-K Experiment
Sterile analyses with Hyper-K

Can simply extend/improve on T2K analyses, with more statistics and improved systematic controls.

- Possibly do $P(\nu_\mu \rightarrow \nu_\mu)$ as well
- Also update SK search for $\nu_s$ with atmospheric neutrinos
  - Uses active-sterile matter effect in the core.

More interesting is prospects from IWCD at 2km

- Via $\nu_\mu \rightarrow \nu_e$ channel
- Still have ND280 constraint
- Use OA variation to constrain BGs

LE perfectly for testing LSND/MB regime
Also analysed in JHEP 01 (2017) 071:

NSI can resemble the CP-violation signal that we are looking for!

Some NSI parameter combinations are near-degenerate with normal mixing. We couldn’t discover NSI, but we would still get $\delta_{CP}$ wrong.

2nd detector in Korea in combination Hyper-K can resolve degeneracies.
Shao-Feng Ge 5-1

Leptonic CP Measurement & New Physics Alternatives

Evlslin, Ge & Hagiwara [1506.05023]

SFG [arXiv:1704.08518]
SFG, Hitoshi Murayama [arXiv:1904.02518]

Scalar NSI @ Accelerator Neutrino Oscillation

Cyclotron Complex \( \mu^+ \) DAR

Super-Kamiokande @Mozumi Mine

Hyper-Kamiokande @Tochibora Mine

ν from Tokai

\[
\begin{align*}
\text{NH} & \\
\text{T2Kv+μDAR (5%)} & \\
\text{IH} & \\
\end{align*}
\]

\[
\begin{align*}
\text{Average } \Delta m^2 & \\
\text{Baseline Length [km]} & \\
\end{align*}
\]
Sterile Neutrinos
Reactor Short Baseline

NEOS in 2017

Carsten Rott
Phase-I and Phase-II

NEOS Phase II

Phase-I and Phase-II

NEOS phase-II

![Graph showing counts/day vs. Prompt Energy [MeV] and Δm² vs. sin²2θ₁₄]
Neutral current interaction rate is the same for 3 active neutrinos

- NC rate is insensitive to 3 flavor oscillations

Sterile neutrino do not interact in the detector

- $\nu_\mu \rightarrow \nu_s$ reduce the NC rate at the FD

One oscillation term for $\nu_\mu \rightarrow \nu_s$ oscillations at atmospheric frequency

Narrow-band beam was optimized to produce events with energies very close to atmospheric maximum

Wavelength shifting fibers carry light out of the cells to APDs.

NuMI Antineutrino Beam

NuMI is the world's most powerful neutrino beam running at 700 kW power since January 2017

Recorded $12.5 \times 10^{20}$ protons on target (POT) in antineutrino mode
Carsten Rott
NuFACT2019 WG5 Summary
August 26 - August 31, 2019

Recent Searches for Sterile Neutrinos with NOvA

Far Detector Spectra

- Neutrino data:
  - Predicted $191.2 \pm 13.8$ (stat) $\pm 22.0$ (syst) events
  - Observed 214 events

- Antineutrino data:
  - Predicted $122 \pm 11$ (stat) $\pm 18$ (syst) events
  - Observed 121 events

No significant suppression of neutral current

Observe no evidence for sterile-neutrino-driven oscillations in the neutral current channel in either neutrino or antineutrino beam modes

Next steps
- Analysis improvements to allow for fitting a wider range of $\Delta m^2_{41}$ are in progress
- Test beam program is in progress to significantly reduce uncertainties on detector response to hadrons, currently the dominant uncertainty
Recent Searches for Sterile Neutrinos with NOvA

- At high $\Delta m^2_{41}$, extrapolation method breaks down due to disappearance in Near Detector.
- Perform joint fit in both detectors, treating ND and FD on equal footing
- Use covariance matrix to account for correlated systematics between two detectors, maintaining the cancellation of uncertainties
  - Technique recently used by MINOS/MINOS+ (Phys. Rev. Lett. 122, 091803 (2019)), but this will be the first use in NOvA

**Status:**

- Analysis improvements to allow for fitting a wider range of $\Delta m^2_{41}$ are in progress
- Test beam program is in progress to significantly reduce uncertainties on detector response to hadrons, currently the dominant uncertainty
- Start data taking after the summer shutdown
Hg target (neutron & neutrino source)

- World-class high intensity neutron source driven by high power proton beam
  - beam energy: 3GeV
  - design beam power: 1MW
Start data taking from early 2020!
MicroBooNE

Unfolding results for an electron hypothesis

Assuming the LEE is due to an increase in the rate of NC resonant $\Delta$ with subsequent radiative decays

Assuming the LEE is due to an energy dependent increase in the rate of CC $\nu_e$ events

For further details and the work itself and latest publications, see

Mark Ross-Lonergan
Conclusions

MicroBooNE's LEE search involves using multiple reconstruction frameworks on multiple complementary analysis topologies for a variety of signal hypotheses.

All analysis's have now moved to our latest state-of-the-art Monte Carlo simulation involving the Genie v3 event generator overlayed with real cosmic data recorded in-situ at MicroBooNE, use of the Cosmic Ray Tagger (CRT) as well as latest improvements in signal processing and reconstruction.

Both electron and photon specific LEE analysis are tailoring further refinements to the sideband selections to provide the strongest constraints to the systematic uncertainties of any irreducible backgrounds.

Primary focus now is on fully incorporating and understanding all possible detector systematics of our LArTPC to ensure as robust a measurement as possible.

All LEE analyses at MicroBooNE are blind, with only 5e19 POT of data currently open for testing and comparison (~4% out of a total 13.2e20 POT in full data set)
ICARUS @ FNAL Plans

- TPC/TRG electronics and PMT electronics installation to be completed and tested by summer 2019
- After cryogenics commissioning, cool down and filling
- ICARUS T600 should be full and operational in Q4 of 2019
- Commissioning of CRT, DAQ, trigger and slow controls will follow.
- Commissioning with cosmics and neutrino beam to begin by the end of this year.

Light Collection System Upgrade
After an extensive overhaul, ICARUS at final stage of installation as the SBN FD at FNAL

SBN data taking expected in early 2020 followed by ND in 2021.

• ICARUS will see the first neutrinos early 2020!
Short Baseline Near Detector

- The largest, and closest detector.
- 112t LArTPC placed at 110m from the beam pipe.
- Capable of excellent precision cross-section measurements.
  - On argon
  - Which of course can feed into DUNE.
- Under construction.
  - All TPC components have arrived at Fermilab!
  - Expect to start taking physics data in early 2021.

SBND is a new Liquid Argon TPC being built for the SBN program at FNAL.
- Powerful capability to investigate potential light steriles and other new physics.
- Unprecedented precision cross-section measurements on Argon.

Rapid progress being made.
- Most components now at FNAL.
  - Cryostat to be assembled in October 2019.
  - TPC to be completed and moved to final building early 2020.
  - Commissioning and filling in 2020.
  - Collect 3 years of neutrino beam data from early 2021.

An exciting time to be on SBND!
Sterile Neutrinos L/E complementarity

modified from Diaz et al. PLB 700, 25 (2011)
In the Earth, for sterile neutrinos of $\Delta m^2 = O(1\text{eV}^2)$ there is a matter-induced (parametric) resonant effect when:

$$E_{\nu} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(\text{TeV})$$

- $\sin^2 \theta_{24} = 0.02$
- $\cos \theta_x = -1$
- Standard oscillations: $0.3 \text{ eV}^2$, $1 \text{ eV}^2$, $3 \text{ eV}^2$

Effects of sterile neutrinos below 100 GeV
- Modifies standard neutrino oscillations
- Effect is proportional to amount of matter along neutrino path
Future prospects

- Next generation sterile neutrino analysis
  - Improved event selection criteria
  - Reduced systematic uncertainties
  - Data sample (1 year $\Rightarrow$ 7 years)

Test both $\theta_{24}$ and $\theta_{34}$
Expected to test current global fit regions
Due to longer & multiple baselines improve on MINOS/MINOS+ limits by 2 orders of magnitude
Conclusions
• Rich science program to search for BSM physics at neutrino detectors

• Essential to understand the observed anomalies and what they are telling us about nature

• Tremendous potential for future search and expand scientific programs

• Thanks to all the speakers and their contributions to the WG5 session

• Thanks for chairing sessions!
  • Ana Teixeira, Juanan Aguliar, Jose Valle, Josh Spitz, Jaehoon Yu