Neutrino CP Violation with the European Spallation Source neutrino Super Beam

Marcos Dracos
IPHC-Strasbourg
European Spallation Source

Neutron facility equivalent to SNS)

under construction phase (~1.85 B€ facility)
The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, $10^{15}$ protons).
- Duty cycle 4%.
- 2.0 GeV protons
  - up to 3.5 GeV with linac upgrades
- $>2.7 \times 10^{23}$ p.o.t/year.

Linac ready by 2023 (full power)
What does it mean 5 MW?

• **One beam pulse:**
  ○ has the same energy as a 16 lb (7.2kg) shot traveling at
    • 1100 km/hour
    • Mach 0.93
  ○ Has the same energy as a 1000 kg car traveling at 96 km/hour
  ○ You boil 1000 kg of ice in 83 seconds

• And this for 14 pulses/sec...
European Spallation Source

Proton linac

RFQ delivered last week

Target station

cryoplants

klystrons

Proton linac
ESS schedule

- **2003**: First European design effort of ESS completed
- **2009**: Decision: ESS will be built in Lund
- **2012**: ESS Design Update phase complete
- **2014**: Construction work starts on the site
- **2019**: First neutrons on instruments
- **2023**: ESS starts user program
- **2025**: ESS construction complete
European Spallation Source as Neutrino Facility for CP violation observation (2\textsuperscript{nd} Oscillation maximum)

\[ \nu_\mu \rightarrow \nu_e \]
Oscillation probability
(neutrino beams)

\[
P_{\nu_\mu \rightarrow \nu_e (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \approx 4 s_{23}^2 s_{13}^2 \frac{1}{(1 - r_A)^2} \sin^2 \left( \frac{1 - r_A}{2} \Delta L \right)
\]

"atmospheric"

\[
+8 J_r \frac{r_\Delta}{r_A (1 - r_A)} \cos \left( \delta_{CP} \frac{\Delta L}{2} \right) \sin \frac{r_A \Delta L}{2} \sin \left( \frac{1 - r_A}{2} \Delta L \right)
\]

"interference"

\[
+4 c_{23}^2 c_{12}^2 s_{12} \left( \frac{r_\Delta}{r_A} \right)^2 \sin^2 \frac{r_A \Delta L}{2}
\]

"solar"

\[
J_r \equiv c_{12} s_{12} c_{23} s_{23} s_{13}, \quad \Delta \equiv \frac{\Delta m_{31}^2}{2 E_\nu}, \quad r_A \equiv \frac{a}{\Delta m_{21}^2}, \quad r_\Delta \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, \quad a = 2 \sqrt{2} G_F N_e E_\nu
\]

matter effect

• for antimatter: \( \delta_{CP} \rightarrow -\delta_{CP} \) and \( a \rightarrow -a \)
• fake matter/antimatter asymmetry due to matter effect

\[
\mathcal{A} = \frac{P_{\nu_\mu \rightarrow \nu_e} - P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}}{P_{\nu_\mu \rightarrow \nu_e} + P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}} \text{Matter-antimatter asymmetry}
\]

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$\delta_{CP}$ and matter-antimatter asymmetry magnitude

$$A^C_P = P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = J^{PMNS}_{CP} \cdot \sin\delta_{CP}$$

with: $J^{PMNS}_{CP} \sim 3 \times 10^{-3}$ (Jarlskog invariant)

(for hadrons: $J^{CKM}_{CP} \sim 3 \times 10^{-5}$, not enough even if $\delta_{CP} \sim 70^\circ$)

Theoretical models predict that if $|\sin\delta_{CP}| \geq 0.7$

$(45^\circ < \delta_{CP} < 135^\circ$ or $225^\circ < \delta_{CP} < 315^\circ$), this could be enough to explain the observed asymmetry.
Use all this ESS linac power to go to the second oscillation maximum

but why?
Neutrino Oscillations with "large" \( \theta_{13} \)

for small \( \theta_{13} \)

1\textsuperscript{st} oscillation maximum is better

\( \theta_{13} = 1^\circ \)

("small" \( \theta_{13} \))

\( \theta_{13} = 8.8^\circ \)

("large" \( \theta_{13} \))

\( \delta_{\text{CP}} = -90 \)

\( \delta_{\text{CP}} = 0 \)

\( \delta_{\text{CP}} = +90 \)

• 1\textsuperscript{st} oscillation max.: \( A = 0.3 \sin \delta_{\text{CP}} \)

• 2\textsuperscript{nd} oscillation max.: \( A = 0.75 \sin \delta_{\text{CP}} \)

more sensitivity at 2\textsuperscript{nd} oscillation max.

Having access to a powerful proton beam...

What can we do with:

- 5 MW power
- 2 GeV energy
- 14 Hz repetition rate
- $10^{15}$ protons/pulse
- $>2.7 \times 10^{23}$ protons/year

conventional neutrino (super) beam
ESSνSB ν energy distribution

- almost pure $\nu_\mu$ beam
- small $\nu_e$ contamination which could be used to measure $\nu_e$ cross-sections in a near detector

at 100 km from the target, per year (in absence of oscillations)

<table>
<thead>
<tr>
<th></th>
<th>positive $N_\nu \times 10^{10}$/m$^2$</th>
<th>%</th>
<th>negative $N_\bar{\nu} \times 10^{10}$/m$^2$</th>
<th>%</th>
</tr>
</thead>
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<tr>
<td>$\nu_\mu$</td>
<td>396</td>
<td>97.9</td>
<td>11</td>
<td>1.6</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>6.6</td>
<td>1.6</td>
<td>206</td>
<td>94.5</td>
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<tr>
<td>$\nu_e$</td>
<td>1.9</td>
<td>0.5</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>0.02</td>
<td>0.005</td>
<td>1.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Can we go to the 2\textsuperscript{nd} oscillation maximum using our proton beam?

Yes, if we place our far detector at around 500 km from the neutrino source.

MEMPHYS like Cherenkov detector
(MEGaton Mass PHYSics studied by LAGUNA)

- Neutrino Oscillations
- Proton decay
- Astroparticles
- Understand the gravitational collapsing: galactic SN
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos

- 500 kt fiducial volume (\textasciitilde20\times\text{SuperK})
- Readout: \textasciitilde240k 8” PMTs
- 30\% optical coverage

New 20" PMTs with higher QE and cheaper (see JUNO), the detection efficiency will improve the detector performance keeping the price constant, not yet taken into account.
Neutrinos in the far detector

540 km (2 GeV), 10 years

\[ \delta_{CP} = 0 \]

Below ντ production, almost only QE events, not suffering too much by π^0 background.
2nd Oscillation max. coverage

E = 2 GeV  L = 540 km

N

NH

IH

\[ \delta = -\frac{\pi}{2} \]
\[ \delta = 0 \]
\[ \delta = \frac{\pi}{2} \]

2nd oscillation max. well covered by the ESS neutrino spectrum

1st oscillation max.

full coverage of the 2nd oscillation max.

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M. Dracos, IPHC-IN2P3/CNRS/UNISTRA
ESS Linac modifications to produce a neutrino Super Beam

European Spallation Source Linac
How to add a neutrino facility?

• The neutron program must not be affected and if possible synergetic modifications.
• Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
• Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
  • H⁻ source (instead of protons),
  • space charge problems to be solved.
• ~300 MeV neutrinos.
• Target station (studied in FP7 EUROν).
• Underground detector (studied in FP7 LAGUNA).
• Short pulses (~μs) will also allow DAR experiments (as those proposed for SNS) using the neutron target.
Possible locations for far detector

<table>
<thead>
<tr>
<th>Location</th>
<th>Baseline from CERN (km)</th>
<th>Baseline from Protvino (km)</th>
<th>Baseline from ESS (km)</th>
</tr>
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<td>Pyhäsalmi, FI</td>
<td>2300</td>
<td>1160</td>
<td>1140</td>
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<tr>
<td>Zinkgruvan, SE</td>
<td>1530</td>
<td>1420</td>
<td>360</td>
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<tr>
<td>Garpenberg, SE</td>
<td>1730</td>
<td>1300</td>
<td>540</td>
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<td>Kristineberg, SE</td>
<td>2230</td>
<td>1530</td>
<td>1080</td>
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<td>Björkdal, SE</td>
<td>2270</td>
<td>1450</td>
<td>1100</td>
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<tr>
<td>Munksa, SE</td>
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<td>1620</td>
<td>1160</td>
</tr>
<tr>
<td>Kallak, SE</td>
<td>2400</td>
<td>1700</td>
<td>1260</td>
</tr>
<tr>
<td>Malmsberg, SE</td>
<td>2480</td>
<td>1620</td>
<td>1320</td>
</tr>
<tr>
<td>Kiirunavaara, SE</td>
<td>2530</td>
<td>1700</td>
<td>1380</td>
</tr>
<tr>
<td>Kaunisvaara, SE</td>
<td>2552</td>
<td>1580</td>
<td>1390</td>
</tr>
<tr>
<td>Løkken, NO</td>
<td>1900</td>
<td>1800</td>
<td>840</td>
</tr>
</tbody>
</table>

LAGUNA sites
Candidate active mines

- **Garpenberg mine**
  - Distance from ESS Lund 540 km
  - Depth 1200 m
  - Truck access tunnel

- **Zinkgruvan mine**
  - Distance from ESS Lund 360 km
  - Depth 1500 m
  - Truck access tunnel

Possible location of MEMPHYS in Zinkgruvan mine
Which baseline?


- ~60% $\delta_{cp}$ coverage at 5 $\sigma$ C.L.
- >75% $\delta_{cp}$ coverage at 3 $\sigma$ C.L.
- systematic errors: 5%/10% (signal/backg.)
Physics Performance
(CPV discovery)

- little dependence on mass hierarchy,
- $\delta_{\text{CP}}$ coverage at 5 $\sigma$ C.L. up to 60%,
- $\delta_{\text{CP}}$ accuracy down to 6° at 0° and 180° (absence of CPV for these two values),
- not yet optimized facility,
- 5/10% systematic errors on signal/background.
• $\delta_{\text{CP}}$ accuracy down to $6^\circ$ at $0^\circ$ and $180^\circ$
• $12^\circ$ accuracy at $\delta_{\text{CP}} = -90^\circ$ and $10^\circ$ at $\delta_{\text{CP}} = 90^\circ$
• 5/10\% systematic errors on...
Required modifications of the ESS accelerator for ESSνSB

F. Gerigk and E. Montesinos
CERN, Geneva, Switzerland

CERN-ACC-NOTE-2016-0050 8 July 2016

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4. Detailed upgrade measures
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4.3 RF sources, RF distribution & modulators
4.4 Cryogenics (plant + distribution)
4.5 Water cooling
4.6 Superconducting cavities, couplers & cryomodules
4.7 Beam physics
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6. Appendix 2: Indicative costing of the upgrade

Quotation from “Executive Summary: “No show stoppers have been identified for a possible future addition of the capability of a 5 MW H- beam to the 5 MW H+ beam of the ESS linac built as presently foreseen. Its additional cost is roughly estimated at 250 MEuros.”

Better to go to 2.5 GeV
The Linac modifications and operation

H⁻ source options

Into linac

Into ring

Into horn

time operation option

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The Accumulator

- **L = 384 m**
- **Q_x = 8.24**
- **Q_y = 8.38**

**RF**

**injection**

**FODO cells**

**4 superperiods**

**extraction**

**Dispersion-free straight sections**

**H^- stripping**

**Switchyard**

- Dipole magnets
- Stripping Foil
- Secondary Foil
- Stored protons in the ring
General Layout of the target station
**Target**

- Packed-bed target studied at RAL within the EuroNu project (arXiv:1212.0732)
- Titanium alloy canister containing packed bed of titanium spheres (Gas Helium as cooling medium)
- Single sphere diameter: 3 mm
- Canister radius/length: 12 mm / 780 mm

**Helium Flow**
Muons at the level of the beam dump

2.7x10^{23} p.o.t/year

**muons** at the level of the beam dump (per proton)

4.2x10^{20} μ/year (16.3x10^{20} for 4 m²)

4.1x10^{20} μ/year

more than 4x10^{20} μ/year from ESS compared to 10^{14} μ used by all experiments up to now (10^{18} μ for COMET in the future).

- input beam for future 6D μ cooling experiments (for muon collider),
- low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider**.
ESS neutrino and muon facility

2.7x10^{23} p.o.t/year

Protons dump

Neutrons to ESS

ESS proton driver

μ⁺ or μ⁻

μ decaying → π decay

Front end

Cooling

μ Test Facility

μ Decay channel or ring

ν_μ or ν_μ

ESSnuSB

nuSTORM

Neutrino Factory

Muon Collider

Accumulator

ESS

Protons dump

Long Baseline Detector

ν_μ + ν_ν
e + ν_μ

RS (5 GeV)

= 0.35 km

Target-Horn System

 Decay Tunnel

 Beam Dump

Collimating-Absorbing System

Bending System
Muons at ESS (ESSμSB)

The European Spallation Source, now in construction in Lund, with 5 MWatt of protons accelerated to a kinetic energy of 2.0 GeV at 14 Hz and $1.1 \times 10^{15}$ p/p and it may provide adequate intensity and repetition rate for the $O(10^{12} \mu$/pulse) collider program.

- **CERN** had considered the HP-HPL, a proton beam of 5 GeV kinetic energy with 50 Hz, 4 MWatt and $1.0 \times 10^{14}$ p/ pulse.

- In 2010 HP-HPL project has been cancelled: Therefore ESS may remain the main option.

Carlo Rubbia

SM Higgs rate $\approx 10^5$ ev/year ($10^7$ s) per crossing point
EuroNuNet

- COST application for networking: CA15139 (2016-2020)

  - EuroNuNet: Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery (http://www.cost.eu/COST_Actions/ca/CA15139)

- Major goals of EuroNuNet:
  - to aggregate the community of neutrino physics in Europe to study a neutrino long baseline concept in a spirit of inclusiveness,
  - to impact the priority list of High Energy Physics policy makers and of funding agencies to this new approach to the experimental discovery of leptonic CP violation.

- 13 participating countries

http://euronunet.in2p3.fr/
ESSνSB at the European level

- **A H2020 EU Design Study (Call INFRADEV-01-2017)**

- **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator

- **Duration**: 4 years

- **Total cost**: 4.7 M€

- **Requested budget**: 3 M€

- **15 participating institutes from 11 European countries including CERN and ESS**

- **6 Work Packages**

  - **Approved end of August 2017**
Design Study ESSvSB
(2018-2021)

Call: H2020-INFRADEV-2017-1
Funding scheme: RIA
Proposal number: 777419
Proposal acronym: ESSnuSB
Duration (months): 48
Proposal title: Feasibility Study for employing the uniquely powerful ESS linear accelerator to generate an intense neutrino beam for leptonic CP violation discovery and measurement.
Activity: INFRADEV-01-2017

More information on: http://essnusb.eu/

CDR end of 2021

partners: IHEP, BNL, SCK•CEN, SNS, PSI, RAL
Possible ESSνSB schedule
(2nd generation neutrino Super Beam)

2012: inception of the project

2016-2019: beginning of COST Action EuroNuNet

2018: beginning of ESSνSB Design Study, CDR and preliminary costing

2021: End of ESSνSB Design Study, CDR and preliminary costing

2022-2024: Preparatory Phase, TDR

2025-2026: Construction of the facility and detectors, including commissioning

2027-2034: Data taking


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Conclusion

• The ESS proton linac will be soon the most powerful linac in the world.

• ESS can also become a neutrino facility with enough protons to go to the 2\textsuperscript{nd} oscillation maximum and increase the CPV sensitivity.

• CPV: $5 \sigma$ could be reached over 60\% of $\delta_{\text{CP}}$ range by ESS\textsubscript{νSB} with large physics potential.

• Large associated detectors have a rich astroparticle physics program.

• The European Spallation Source will be ready by 2025, upgrade decisions by this moment.

• Rich muon program for future ESS upgrades.

• COST network project CA15139 and a EU-H2020 Design Study supports this project.
Backup
How the CPV coverage and resolution curves have been produced

- **T2HK:**
  - Same curves that Hyper-K has showed at the Neutrino Town Meeting at CERN and the one that was showed at Neutrino 2018.
  - Systematics are said by T2HK to be between 3% to 4%.
  - $\sin^2 2\theta_{13} = 0.1$ and $\theta_{23} = \pi/2$.

- **DUNE:**
  - Public globes file released by the DUNE collaboration with the CDR, the only change is to increase the number of years from 7 to 10.
  - $\sin^2 2\theta_{13} = 0.1$ and $\theta_{23} = \pi/2$, to be compatible with the T2HK line.

- **ESSnuSB:**
  - Instead of considering as usual "Opt. Snowmass errors" it is only assumed an overall 3% systematic error in the different
Beyond DUNE, JUNO, HyperK: ESSνSB, P2O and Neutrino factory

European Neutrino "Town" meeting and ESPP 2019 discussion, CERN, 24.10.2018

Roumen Tsenov
Department of Atomic Physics, University of Sofia
CPV performance comparison between ESSnuSB, DUNE and Hyper-K assuming 3% systematic errors for ESSnuSB in line with the other two.

ESSνSB 500 kt tank at 540 km.

ESSνSB 500 kt tank at 360 km.

ESSνSB 250 kt tank at 540 km and 250 kt tank at 360 km.
Fraction of $\delta_{CP}$

- Garpenberg (540 km)
- Zinkgruvan (360 km)
- Lund

My personal opinion: these scenarios are too optimistic for all facilities

Corfu, 04/09/2019
# Systematic errors

<table>
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<tr>
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<td>Fiducial volume ND</td>
<td>0.2%</td>
<td>0.5%</td>
<td>1%</td>
<td>0.2%</td>
<td>0.5%</td>
<td>1%</td>
<td>0.2%</td>
<td>0.5%</td>
<td>1%</td>
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<tr>
<td>Fiducial volume FD</td>
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<td>2.5%</td>
<td>5%</td>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
</tr>
<tr>
<td>(incl. near-far extrap.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Flux error signal $\nu$</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>1%</td>
<td>2%</td>
<td>2.5%</td>
<td>0.1%</td>
<td>0.5%</td>
<td>1%</td>
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<tr>
<td>Flux error background $\nu$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>correlated</td>
<td></td>
<td></td>
<td>correlated</td>
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<tr>
<td>Flux error signal $\bar{\nu}$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>1%</td>
<td>2%</td>
<td>2.5%</td>
<td>0.1%</td>
<td>0.5%</td>
<td>1%</td>
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<td>Flux error background $\bar{\nu}$</td>
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<td>40%</td>
<td>correlated</td>
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<td>Background uncertainty</td>
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<td>7.5%</td>
<td>10%</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
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<tr>
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<td>15%</td>
<td>20%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>10%</td>
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<td>20%</td>
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<tr>
<td>Cross secs × eff. RES$^\dagger$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
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<td>15%</td>
<td>20%</td>
<td>10%</td>
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<td>Cross secs × eff. DIS$^\dagger$</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
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<td>10%</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
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<tr>
<td>Effec. ratio $\nu_e/\nu_\mu$ QE$^*$</td>
<td>3.5%</td>
<td>11%</td>
<td>–</td>
<td>3.5%</td>
<td>11%</td>
<td>–</td>
<td>–</td>
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<td>Effec. ratio $\nu_e/\nu_\mu$ RES$^*$</td>
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<td>–</td>
<td>2.7%</td>
<td>5.4%</td>
<td>–</td>
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<tr>
<td>Effec. ratio $\nu_e/\nu_\mu$ DIS$^*$</td>
<td>2.5%</td>
<td>5.1%</td>
<td>–</td>
<td>2.5%</td>
<td>5.1%</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Matter density</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
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Comparison using the same systematic errors

The ESS neutron facility