ESSvSB – and $\delta_{cp}$

J. Cederkall with the ESSvSB collaboration

Special credit to: Marcos Dracos, IPHC, Tord Ekelöf, Uppsala university and many colleagues in ESSvSB.
OVERVIEW

• What is ESS and why ESSvSB?
• The proton accelerator
• The conceptual design— and its parts
• The physics reach
• Summary
ESS basic facts:

- Proton accelerator with superconducting cavities
- 2 GeV energy and 5 MW on target
- 4000 kg, ~2.5 m diameter, tungsten target wheel
- 6,000 000 kg steel shielding
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Main use is for applied physics, but fundamental physics can be done. Linac completion by ~2023
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(but fundamental physics can be done)
Linac completion by ~2023
Why and how to make it?

Why?
- Physics reach

Practicalities:
- LINAC upgrade
- Accumulator
- Target station
- Near detector
- Far detector
Matter – antimatter asymmetry

- The Sakharov conditions: needs to be fulfilled to explain the baryon asymmetry in the universe,
  - At least one B-number violating process
  - C and CP violation
  - Interactions outside thermal equilibrium

- Currently the observed baryon to photon ratio is much too large (factor $\sim 10^9$) to be explained by CP violation of the quarks (the CKM matrix).

- Lepton sector CP-violation an option to create asymmetry via leptogenesis scenarios with sphalerons

- Otherwise, new physics…?
Oscillation Probabilities — time evolution

\[
P^\pm (\nu_\mu \rightarrow \nu_e) = s_{23}^2 \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \quad \text{(atmospheric)}
\]
\[
+ c_{23}^2 \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \quad \text{(solar)}
\]
\[
+ J' \cos(\mp \delta_{CP} - \Delta_{31}) \quad \text{(CP interference)}
\]

Where

\[
J' = c_{13} \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})
\times \sin(\Delta_{31}) \sin(\Delta_{21})
\]

\[
\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}
\]

\[
\Delta m_{ij}^2 = m_i^2 - m_j^2
\]

\[
s_{ij} = \sin \theta_{ij}
\]

\[
c_{ij} = \cos \theta_{ij}
\]

\[
A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}
\]

\[
\approx \frac{\cos \theta_{23} \sin(2\theta_{12}) \sin \delta}{\sin \theta_{23} \sin \theta_{13}} \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects}
\]
\[ \theta_{13} = (8.9 \pm 0.4)^\circ \]
Why second ν oscillation maximum?

- 1\textsuperscript{st} oscillation max.: \( A = 0.3\sin\delta_{CP} \)
  
  \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \) is between \( \frac{1}{2} \) and 2 times \( P(\nu_\mu \rightarrow \nu_e) \).

- 2\textsuperscript{nd} oscillation max.: \( A = 0.75\sin\delta_{CP} \)
  
  \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \) is between \( \frac{1}{7} \) and 7 times \( P(\nu_\mu \rightarrow \nu_e) \).

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

\( \delta_{CP} = -90 \)
\( \delta_{CP} = 0 \)
\( \delta_{CP} = +90 \)

Why second $\nu$ oscillation maximum?

1. The ultimate precision in the determination of the leptonic CP violating angle $\delta_{CP}$ from neutrino oscillation measurements will be set by systematic errors.

2. The motivation for the effort to generate a world-uniquely intense neutrino beam using the ESS 5 MW linac is to have enough statistics to reach the second maximum where the CP signal is 3 times higher than at the first maximum, thus reducing the uncertainty in $\delta_{CP}$ due to systematic errors by a factor 3.
Measure $\delta_{\text{CP}}$ precisely, why?

See e.g. Silva Pascoli (Durham) contribution to Neutrino Telescopes 2019…

**Tests of flavour models**

Typically, the models considered have a reduced number of parameters, leading to relations between the masses and/or mixing angles.

Examples are the so-called sumrules, e.g.:

$$\sin \theta_{23} - \frac{1}{\sqrt{2}} = \sin \theta_{13} \cos \delta$$

$$\cos \delta = \frac{t_{23}s_{12}^2 + s_{13}^2 c_{12} t_{23} - s_{12}^2 t_{23} + s_{13}^2 / t_{23}}{\sin 2 \theta_{12} s_{13}}$$

**Does observing low energy CPV imply baryon asymmetry?**

In see-saw type I, let’s consider the case of low energy CPV, for instance delta (R real). An approximate formula:

$$|y_B| \cong 2.4 \times 10^{-11} |\sin \delta| \left( \frac{s_{13}}{0.15} \right) \left( \frac{M_1}{10^{11} \text{GeV}} \right)$$

Intermediate flavour regime:

$10^9 \text{GeV} < M_1 < 10^{12} \text{GeV}$

$$\epsilon_{77}^{(1)} = (0.515 - 3.94 \alpha_{13}) s_{13} \times 10^{-8} \sin \delta$$

$$\epsilon_{77}^{(1)} = 3.14 \times 10^{-7} \cos \frac{\alpha_{21}}{2}$$

A full study shows that delta can give an important (even dominant) contribution to the baryon asymmetry. For Majorana CPV, effects enhanced by a factor of \( \sim 10 \).
How to make it?
ESS LINAC

- 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
ESS LINAC - upgrade

- Min. effect on neutron program
- Double pulse rate 14 Hz -> 28 Hz
- Accumulator to compress the 2.86 ms pulse to a few μs.
- Use H⁻ instead of protons
How?

- Installation of 8 new cryo modules with RF stations to accelerate to 2.5 GeV
- Installation of H⁻ source, RFQ and MEBT
- Change/upgrade of klystrons
- New electrical station, substations and cabling
- ~€250 million construction cost to be compared to the ~€1.8 billion (2013) construction costs for ESS itself

No showstoppers identified
ESSνSB – Principal Layout

\[ \text{pp}/\text{pn} \rightarrow \pi^+ \rightarrow \mu^+ + \nu_{\mu^-} \rightarrow e^+ + \nu_e + \nu_{\mu} + \nu_{\mu} \]

\[ \pi^- \rightarrow \ldots + \nu_{\mu} \ldots \]

\[ \pi: \sim 10^{-8} \text{ s}, \mu \sim 10^{-6} \text{ s} \]
ESSvSB – accumulator

- **Baseline:** single-ring accumulator
  - Current studies give a 376 m circumference accumulator ring.
  - Space charge issues

- **Option:** 4 superposed rings located in the same tunnel,
  - Each ring receives 1/4 of the bunches during the multi-turn injection,
  - There has to be enough space between the bunches in the bunch train from the linac to permit the beam distribution system to inject from one ring to the next one,
  - Experience already exists from the CERN PS Booster of using 4 superimposed rings with the aim to avoid high space charge effects.
  - Estimated cost ~€200 million

Example: CERN PS Booster (1972)
ESSvSB – production

Design made in the EUROv SB project.

Four targets and horns for focusing to distribute current to run the horns and the power on the targets on several units.

Helium cooled targets with titanium alloy spheres situated inside the horns.

Estimated cost ~€200 million.
$\nu_\mu$ and $\bar{\nu}_\mu$ beam production

<table>
<thead>
<tr>
<th></th>
<th>positive</th>
<th></th>
<th>negative</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_\nu$ ($\times 10^{10}$/m²)</td>
<td>%</td>
<td>$N_\nu$ ($\times 10^{10}$/m²)</td>
<td>%</td>
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<tr>
<td>$\nu_\mu$</td>
<td>396</td>
<td>97.9</td>
<td>11</td>
<td>1.6</td>
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<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>
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<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>
ESSνSB spectrum and oscillation probability – fixed $L$ and $E_{\text{beam}}$

2$^{\text{nd}}$ oscillation max. well covered by the ESSνSB spectrum

$E_p = 2$ GeV

$L = 540$ km

1$^{\text{st}}$ oscillation max.

Neutrino energy
The physics reach

- 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),
- 5/10% systematic errors on signal/background,
- Not yet optimized facility

$L=540 \text{ km}$
Which baseline?

Baseline: active mine candidates

<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>
</thead>
<tbody>
<tr>
<td>Pyhäsalmi, FI</td>
<td>2300</td>
<td>1160</td>
<td>1140</td>
</tr>
<tr>
<td>Zinkgruvan, SE</td>
<td>1530</td>
<td>1420</td>
<td>360</td>
</tr>
<tr>
<td>Garpenberg, SE</td>
<td>1730</td>
<td>1300</td>
<td>540</td>
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<tr>
<td>Kristineberg, SE</td>
<td>2230</td>
<td>1530</td>
<td>1080</td>
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<tr>
<td>Björkdal, SE</td>
<td>2270</td>
<td>1450</td>
<td>1100</td>
</tr>
<tr>
<td>Munka, SE</td>
<td>2310</td>
<td>1620</td>
<td>1160</td>
</tr>
<tr>
<td>Kallak, SE</td>
<td>2400</td>
<td>1700</td>
<td>1260</td>
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<tr>
<td>Malmbergsberg, 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>1536</td>
<td>1740</td>
<td>500</td>
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<tr>
<td>Kongsberg, NO</td>
<td>1900</td>
<td>1800</td>
<td>840</td>
</tr>
</tbody>
</table>
Which baseline?

Far Detector — Conceptual Design

MEMPHYS like Cherenkov detector
(studied by LAGUNA)

- Neutrino Oscillations
- Proton decay
- Astroparticles
- SN-ν
- Solar Neutrinos
- Atmospheric Neutrinos

500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8” PMTs
- 30% optical coverage
- Estimated cost ~€700 million

Project for Neutrinos (GRIPnu)

A Socio-economic and Industrial Study of the Consequences of constructing a World-leading Neutrino Detector in Garpenberg in Region Dalarna commissioned by Garpenberg Council
Design Study ESSvSB 2018 - 2021

- **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**
Work packages:
- Management
- Linac Upgrade
- Accumulator
- Target station – alt. to horns?
- Detector performance (ND – FD)
- Physics reach
Funding – EuroNuNet Cost Action

• Major goals of EuroNuNet:
  • to aggregate the community of neutrino physics in Europe to study the ESSνSB 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 (network still growing).

- WG meeting, February 25th, 2017, Geneva (CERN)
- “Upgrading Existing High Power Proton Linacs Workshop”, November 8-9th, 2016, Lund (ESS)
ESSvSB – production

More than $4 \times 10^{20}$ μ/year from ESS compared to $10^{14}$ μ used by all experiments up to now.

4.2$x10^{20}$ μ/year

Muons at the level of the beam dump (per proton)
ESS neutrino and muon facility

Developments for μ physics

- μ test facility
- μ decay channel or ring
- μ storage ring
- μ collider

Next generation collider physics

- nuSTORM
- Neutrino Factory
Timeline

2012: Inception of the project

2016-2019: Beginning of COST Action EuroNuNet

2018: Beginning of ESSvSB Design Study (EU-H2020)

2021: ESSvSB design study finished. CDR and preliminary costing

2022-2024: Preparatory Phase, TDR

2025-2026: Preconstruction Phase, International Agreement

2027-2035: Construction of the facility and detectors, with commissioning

2036-: Data taking
Summary

Infrastructure

• The European Spallation Source Linac should be ready (5 MW, 2 GeV proton beam) by ~2023.

ESSvSB science reach

• Significantly better CPV sensitivity at the 2nd oscillation maximum.
• ESS will have enough protons to go to the 2nd oscillation maximum and increase its CPV sensitivity.
• CPV: $5 \sigma$ could be reached over 60% of $\delta_{CP}$ range at ESSvSB.
  • Large associated detectors can be used for astroparticle physics program.
  • Potential future muon program.

Existing funding/collaboration

• COST network project CA15139 supports the project.
• The EU-H2020 Design Study ESSvSB is approved and running
Systematic errors

- $\nu_e$ contamination from $\mu$, K
- $\pi^0$ going into two $\gamma$
- $\nu_\mu$ misidentified as $\nu_e$
- $\nu$-nucleus cross section (QE, RES, DIS)
- Energy reconstruction error due to multi-nucleon effects
# Errors summary

<table>
<thead>
<tr>
<th>Systematics</th>
<th>SB</th>
<th>BB</th>
<th>NF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial volume ND</td>
<td>0.2%</td>
<td>0.5%</td>
<td>1%</td>
</tr>
<tr>
<td>Fiducial volume FD (incl. near-far extrap.)</td>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
</tr>
<tr>
<td>Flux error signal $\nu$</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
</tr>
<tr>
<td>Flux error background $\nu$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
</tr>
<tr>
<td>Flux error signal $\bar{\nu}$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
</tr>
<tr>
<td>Flux error background $\bar{\nu}$</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
</tr>
<tr>
<td>Background uncertainty</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
</tr>
<tr>
<td>Cross secs $\times$ eff. QE $^\dagger$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
</tr>
<tr>
<td>Cross secs $\times$ eff. RES $^\dagger$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
</tr>
<tr>
<td>Cross secs $\times$ eff. DIS $^\dagger$</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
</tr>
<tr>
<td>Effec. ratio $\nu_e/\nu_\mu$ QE $^*$</td>
<td>3.5%</td>
<td>11%</td>
<td>–</td>
</tr>
<tr>
<td>Effec. ratio $\nu_e/\nu_\mu$ RES $^*$</td>
<td>2.7%</td>
<td>5.4%</td>
<td>–</td>
</tr>
<tr>
<td>Effec. ratio $\nu_e/\nu_\mu$ DIS $^*$</td>
<td>2.5%</td>
<td>5.1%</td>
<td>–</td>
</tr>
<tr>
<td>Matter density</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
</tr>
</tbody>
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