Optimisation of the hadronic collector for the ESSνSB+ neutrino superbeam

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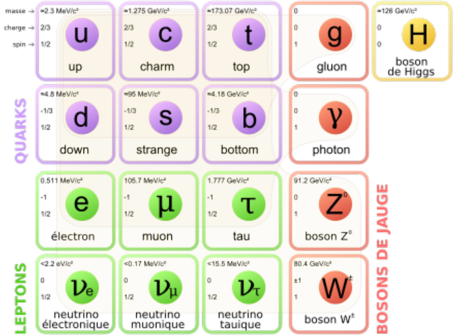
Standard Model

Best explanation for particle interactions.

Neutrinos:

- Three flavors
- Neutral massless lepton
- Only interact via weak interaction

Does not explain their mass and oscillations



Neutrino oscillations

- Oscillate when they propagate
- Each flavour is a combination of three mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The PMNS (Pontecorvo Maki Nakata Sakata) matrix U:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

With $c_{ij} = cos(\theta_{ij})$, $s_{ij} = sin(\theta_{ij})$ and δ_{CP}= CP phase

Neutrino oscillations

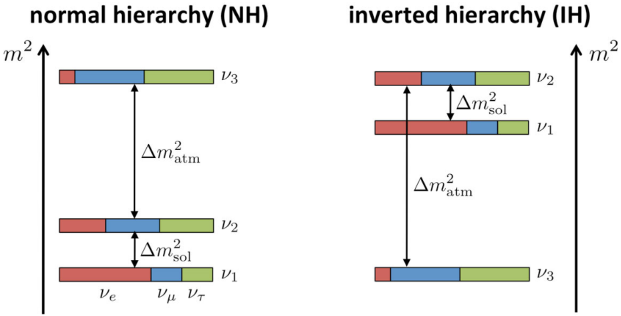
The oscillation probability between two flavors α and β is given by:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \sum_{i,j} U^*_{\beta i} U_{\alpha i} U_{\beta j} U^*_{\alpha j} e^{-i \frac{\Delta m^2_{ij} L}{2E}}$$

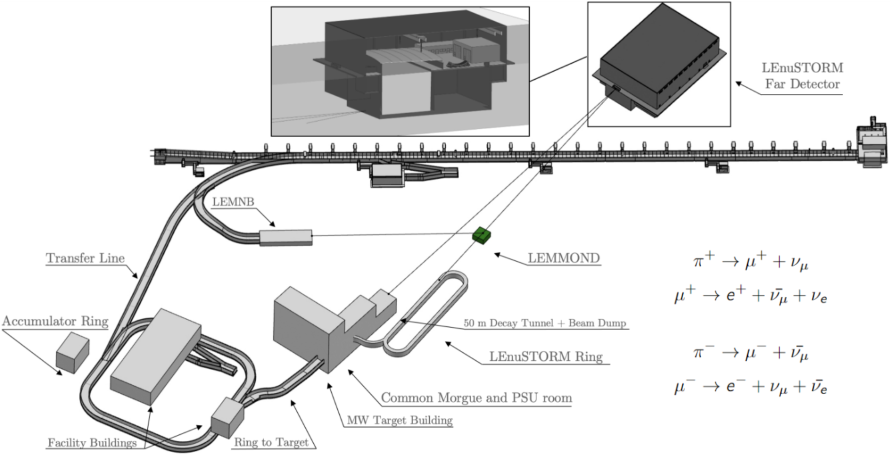
With $\Delta m^2_{ij} = m^2_i - m^2_j$

The oscillation depend 7 parameters :
θ_{12}, θ_{13}, θ_{23}, Δm^2_{12}, Δm^2_{13}, Δm^2_{23}, δ_{cp}

Unknown parameters:
δ_{CP} and Δm^2_{23} (sign only)



ESSνSB+



$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \bar{\nu_\mu} + \nu_e$$
$$\pi^- \to \mu^- + \bar{\nu_\mu}$$
$$\mu^- \to e^- + \nu_\mu + \bar{\nu_e}$$

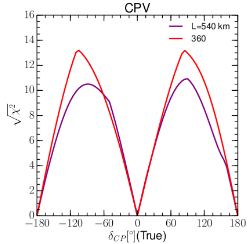
Located at Lund, Sweden.

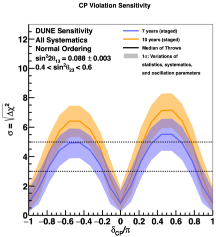
ESSνSB+

ESS : European Spallation source, generate neutron beam thanks to a 5 MW proton beam at 2 GeV to be upgraded to 2.5 GeV for neutrino projects.

ESSνSB: Measure of the δ_{cp} phase with precision below 8°.

ESSνSB+ : Measure cross section and study steril neutrinos.





Neutrinos production :

- **ESS Proton beam** : 2.5 GeV at 5 MW beam power
- **Target** : Cylinder with a base of 3 cm diameter and a length of 78 cm filled with Titanium sphere 3mm radius and helium for cooling (1.25 MW received).
- **Hadronic collector** : A toroidal magnetic field is created by applying a current of 352kA through a horn : $B(r, \theta, z) = \frac{B_0}{r}$
- **Extraction system and decay ring** : Magnetic dipoles, vertical and horizontal focusing quadrupole.

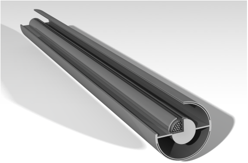
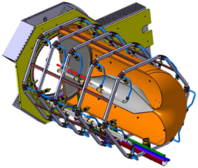
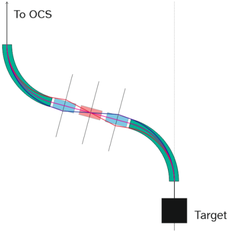
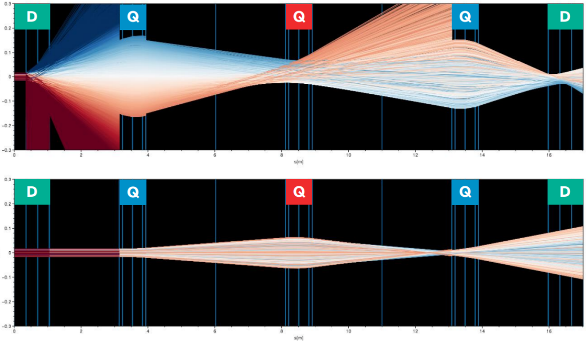
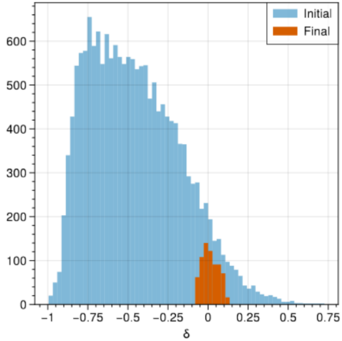




Figure: Target (left) Magnetic horn (center) Pion Extraction System (right)

Pions Extraction system:

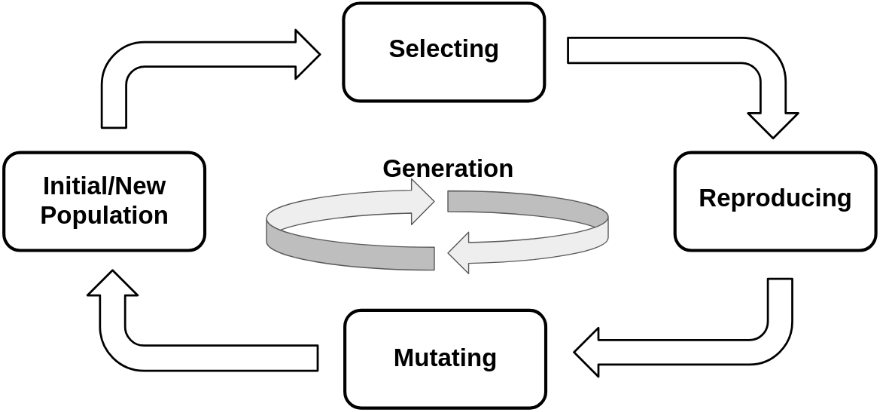




with $\delta = \frac{p - p_0}{p_0}$ and $p_0 = 600$ MeV. Only 6.6% of incoming pions can survive.

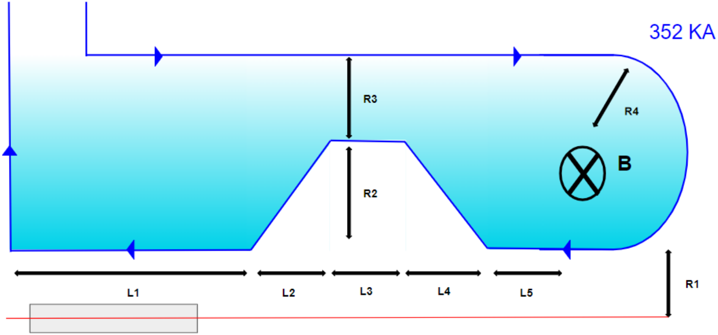
Genetic Algorithm

Goal : Maximize or minimize a multiparameter fonction using natural selection principle.



Horn simulation

Monte Carlo simulation based on Geant 4 in which the horn parameterized into 9 parameters:

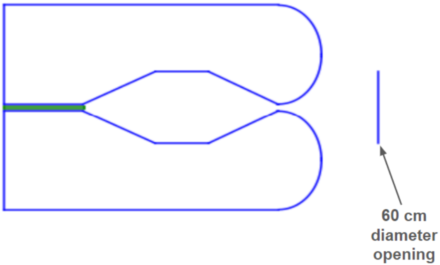


$$horn\ parameter = [L_1, L_2, L_3, L_4, L_5, R_1, R_2, R_3, R_4]$$

Reference Horn

The reference that we use is the horn optimized for ESSνSB :

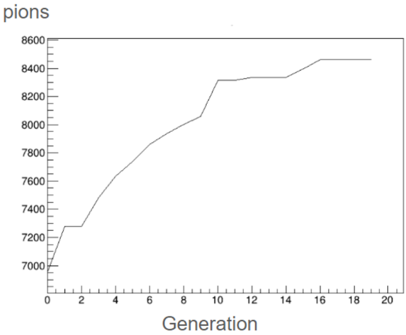
L1	L2	L3	L4	L5	R1	R2	R3	R4
766	697	519	670	10.8	30	273	558	412.5

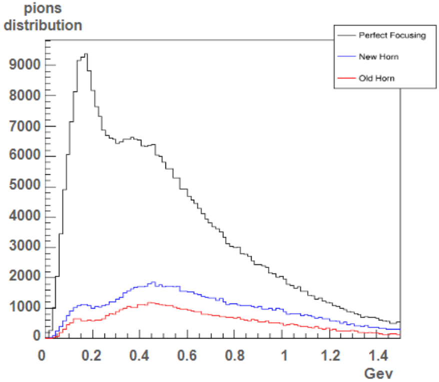


Result

First result of genetic algorithm with the amount of pions in the opening as a fitness parameter:

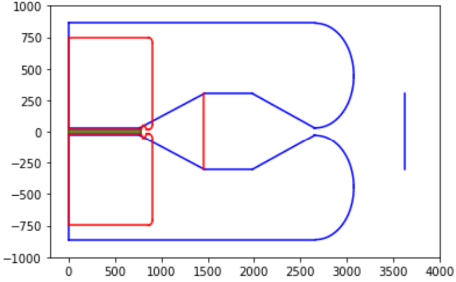
L1	L2	L3	L4	L5	R1	R2	R3	R4
780	20	20	20	20	30	20	631	20

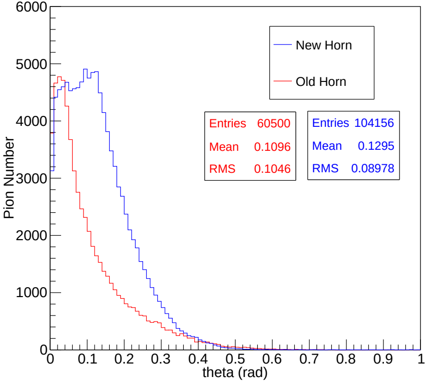




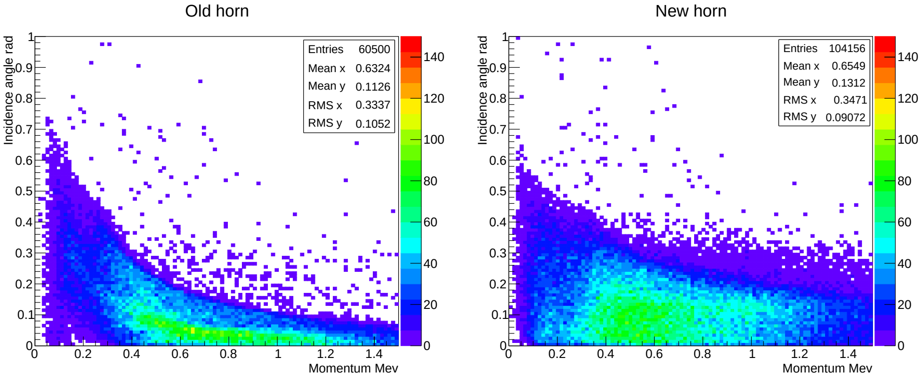
Result

- No more horn shape but a toroidal shape.
- More pions but a bigger dispersion in theta





Result



The mean of the distribution in theta:

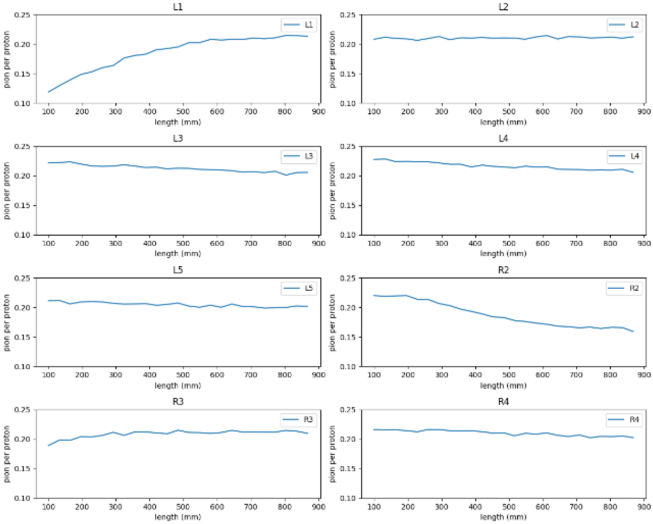
Old horn : 0.11 rad ; 632 MeV

New horn : 0.13 rad ; 654 MeV

Result

Influence of each parameter:

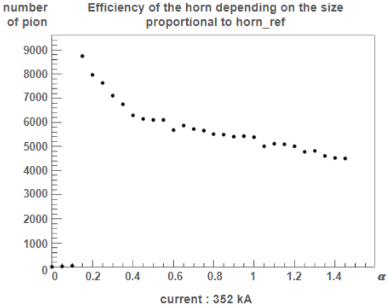
Parameters are scanned in the range [100,900] mm by fixing the other.

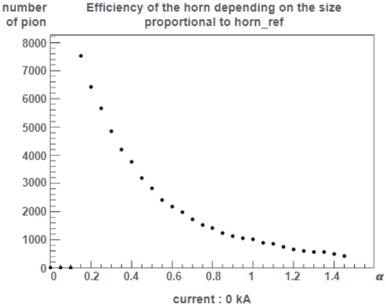


Result

Shape factor:

L2	L3	L4	L5	R2	R3	R4
$\alpha * L_{2_{ref}}$	$\alpha * L_{3_{ref}}$	$\alpha * L_{4_{ref}}$	$\alpha * L_{5_{ref}}$	$\alpha * R_{2_{ref}}$	$\alpha * R_{3_{ref}}$	$\alpha * R_{4_{ref}}$



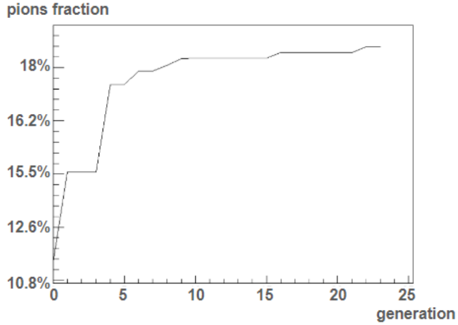


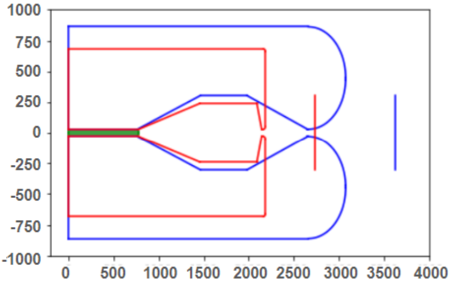
$$\Omega \simeq \frac{S}{\mathbf{L}^2}$$

Result

We rerun the genetic algorithm but the amount of pions in the opening with a momentum between 630 MeV et 770 Mev as a fitness parameter and we have this result:

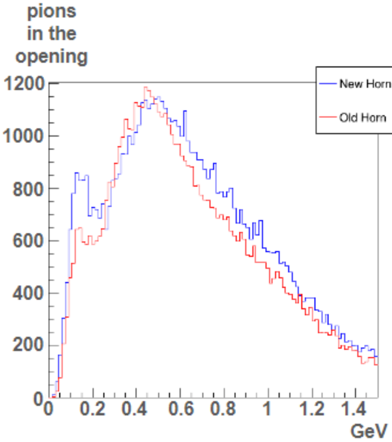
L2	L3	L4	L5	R2	R3	R4
678.92	631.15	52.79	20	209.96	442.33	21.73

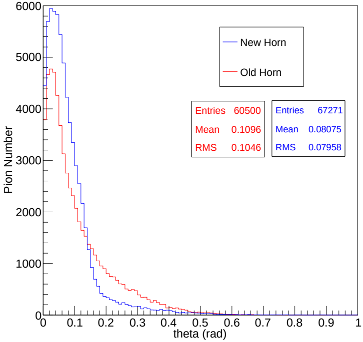




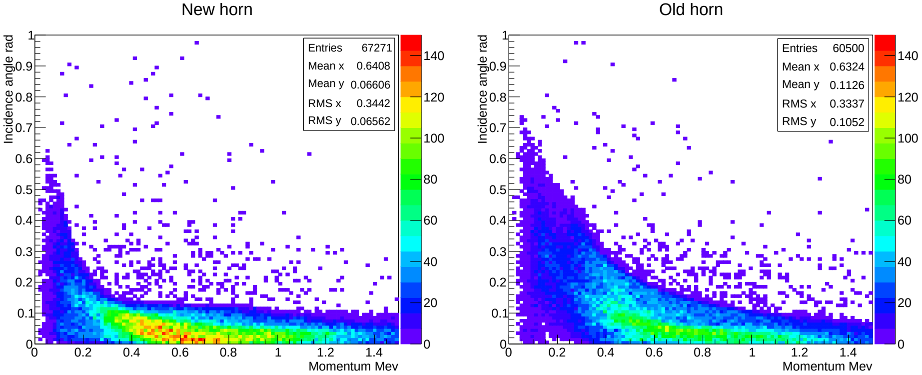
Result

With the old horn we have **16.1%** of the total number of pions with momentum between 630 MeV and 770 MeV. With the new horn we have **18.5%**.





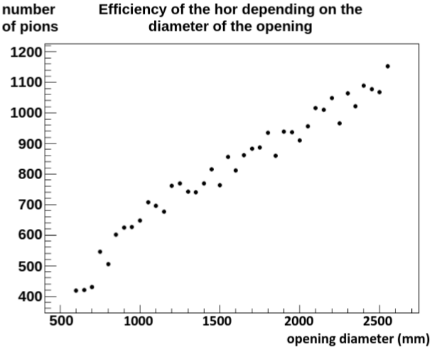
Result

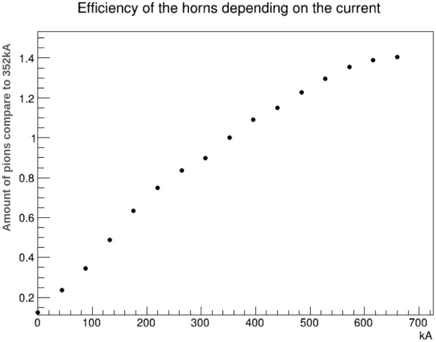


The theta distribution for pions momentum between [630,770] MeV has a RMS of **0.06 rad** compare to **0.1 rad** for the old one. The mean is **0.06 rad** compare to **0.1 rad**.

Result

Because the experiment is still in developpement, we need to know how the horn will work with some variation.





Summary

A genetic algorithm has been implemented which gave an improvement in terms of efficiency and angular dispersion for the horn.
The new horn is close to the ref. horn.

Improvement:

- Study the pions prodution in the target to increase the number of interesting pions.
- Determine electrical parameter
- apply genetic algorithm with 2 fitness parameter, number of pions and theta using pareto front or pareto strength.
- Simulate the extraction system (part or full system).

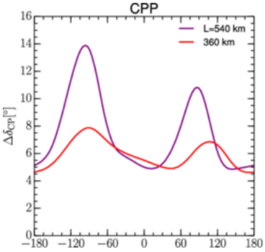
Backup

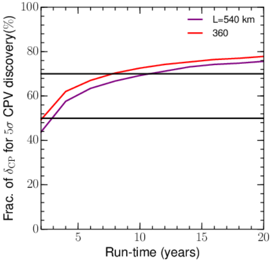
Backup

Backup

- steril neutrino : lsnd ; miniboone
- Δm^2_{23} : Juno
- δ_{cp} : Dune

ESSνSB cp :





Backup

$$\begin{pmatrix} ind_1 \\ ind_1 \\ \dots \\ ind_{n_p} \end{pmatrix} \xrightarrow{tournament} \begin{pmatrix} ind_i \\ ind_j \\ ind_k \\ ind_l \end{pmatrix} \xrightarrow{selection} ind_{max}$$

$$\begin{pmatrix} ind_1 = (a_1, a_2, a_3, a_4, a_5, a_6) \\ ind_2 = (b_1, b_2, b_3, b_4, b_5, b_6) \end{pmatrix} \xrightarrow{reproduction} \begin{pmatrix} newind_1 = (a_1, b_2, a_3, a_4, a_5, b_6) \\ newind_2 = (b_1, a_2, b_3, a_4, b_5, b_6) \end{pmatrix}$$

$$ind_1 = (a_1, a_2, a_3, a_4, a_5, a_6) \xrightarrow{mutation} (a_1, a_2, a_3 + \delta, a_4, a_5, a_6)$$