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ESS
NEUTRINO
SUPER BEAM

Neutrino Beam Optimization for the ESSνSB Experiment

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IRN Neutrino

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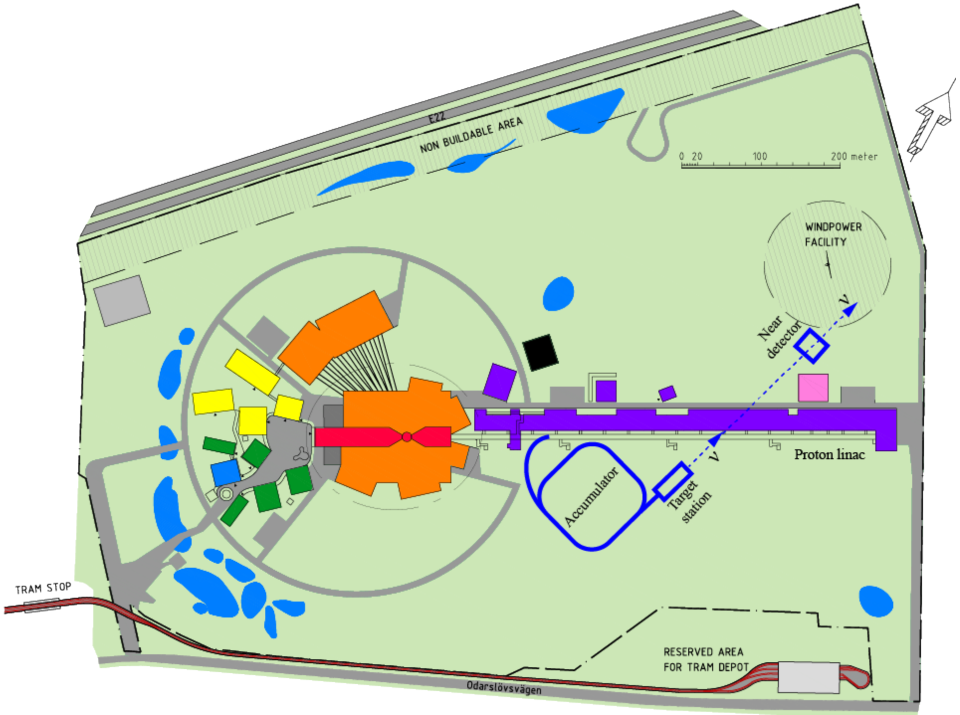
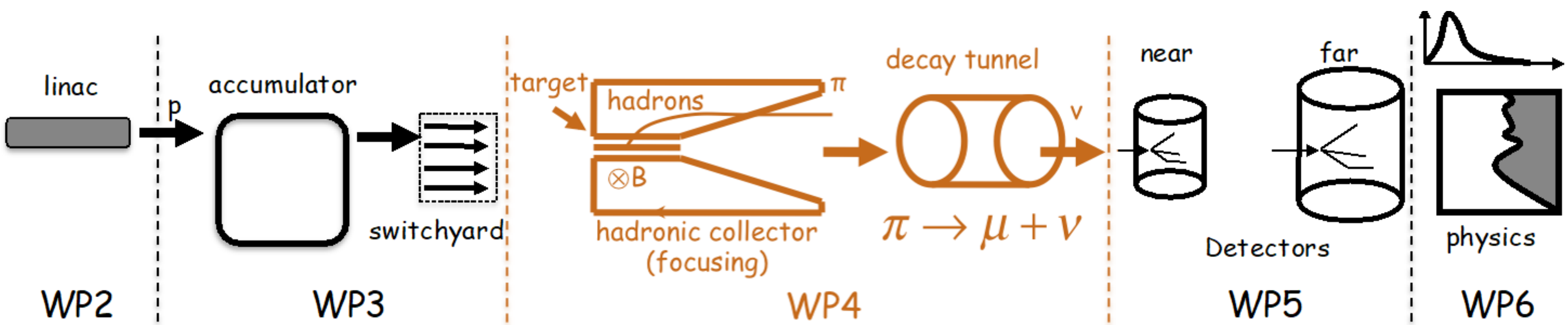
The ESSνSB Project



- ESSνSB is a project, currently in a Design Study phase funded by EU-H2020, which aims at the production of an intense neutrino beam by using the ESS linac, under construction in Lund (Sweden).
  - Upgrading of the linac for an additional 5 MW, 14 Hz rep rate, 2.5 GeV proton beam, with ~1.5 μs pulse duration at the level of the target station.
  - High precision measurement of CP violating neutrino oscillation phase δ_{CP}.



References:
[1] E. Baussan et al., Nucl. Phys. B, 885:127–149 (2014)
[2] M. Dracos et al., PoS, NuFact2019:024 (2020)

The ESSνSB Project

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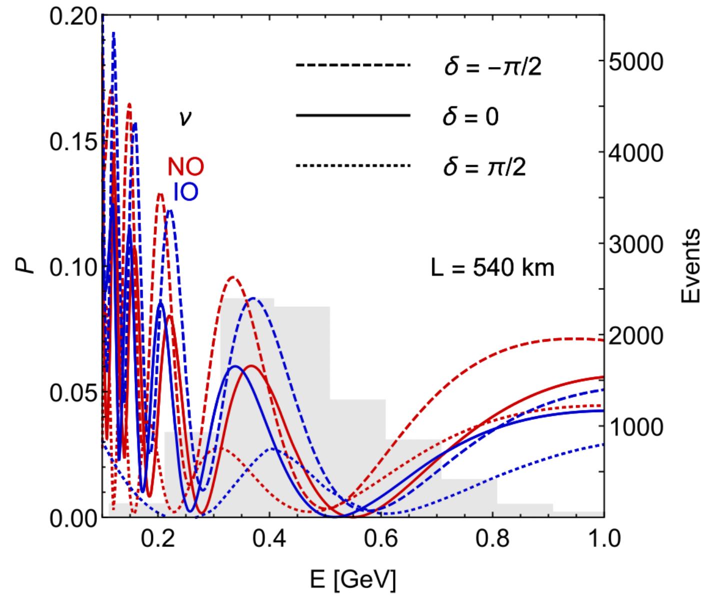


Oscillation Probability and Number of Events for the case of maximal probability oscillation at Far Detector (540 km) [1]

$$A = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

1st Osc Max: $A = 0.3 \sin \delta_{CP}$

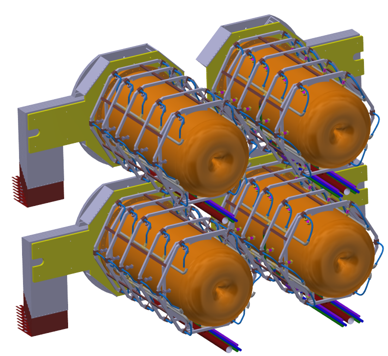
2nd Osc Max: $A = 0.75 \sin \delta_{CP}$

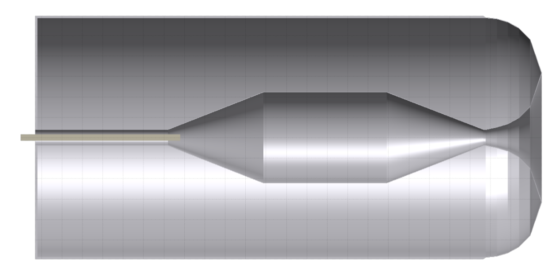
- Neutrino detection at the 2nd Oscillation Maximum
  - Less statistics than 1st oscillation maximum, but less contribution from systematics.
  - 2 locations under consideration: Garpenberg (current baseline) and Zinkgruvan.
- Statistics achievable from the neutrino beam is therefore a key ingredient of the experiment.

References:
[1] M. Blennow *et al.*, Eur. Phys. J. C80:190 (2020)

The ESSνSB Target Station

- Main components of the Target Station:
  - 4 target/horn system for hadron production/collection.
    - Each target consists of a packed bed of titanium spheres. The total radius and length of the proposed target is 1.5 cm and 78 cm, respectively.
    - Each horn has a MiniBooNE-like shape of about 60 cm radius and 2.5 m length each, in the current baseline.
    - The magnetic field is generated by a 350 kA half sinusoidal current pulse in the horn.
  - Pions produced and collected are let to decay in flight in a decay tunnel (4 m x 4 m x 25 m).
  - The hadrons and muons are then absorbed by a beam dump at the end of the decay tunnel.





The Genetic Algorithm as Optimization Technique for the ESSνSB Neutrino Beam

- A Genetic Algorithm driven optimization has been developed for the design of the ESSνSB target station [1].
- The software used for the Genetic Algorithm calculations is the Python toolkit DEAP [2].
- The Genetic Algorithm (GA) optimization method has been already used for the design of other neutrino beam experiments, such as LBNO [3] and DUNE [4].
- In this work, different realizations of the 4 target/horn system and decay tunnel are produced and let to evolve by using the Genetic Algorithm to find the optimal configuration.
  - The neutrino flux is obtained with a FLUKA [5] code with a simplified geometry of the target station consisting of the 4 target/horn system and the decay tunnel.
  - The neutrino fluxes are used to calculate with GloBES [6] the fraction of range of δ_{CP} values which can be reached at 5σ C.L.. This represents the FoM of our system.
  - At a given generation, after which no significant improvements in the optimization procedure are observed, the configuration with the maximum of fraction of δ_{CP} values covered is considered as the optimal configuration.

References:

[1] L. D'Alessi *et al.* [ESSvSB], "Optimization of the Target Station for the ESSνSB Project Using the Genetic Algorithm", NeuTel Conference 2021.
[2] F. Fortin, F.-M. De Rainville, M.-A. Gardner, M. Parizeau, C. Gagné, Journal of Machine Learning Research, 13:2171-2175 (2012).
[3] M. Calviani, S. Di Luise, V. Galymov, and P. Velten, Nucl. Part. Phys. Proc., 273-275:2681–2683 (2016).
[4] R. Acciarri et al., FERMILAB-DESIGN-2016-02, arXiv: 1512.06148 [physics.ins-det] (2016).
[5] A. Ferrari, P. R. Sala, A. Fasso, and J. Ranflt, FLUKA: a multi-particle transport code, CERN-2005-10 (2005), INFN-TC-05-11, SLAC-R-773, V. Vlachoudis, FLAIR: A Powerful But User Friendly Graphical Interface For FLUKA, in Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, 2009.
[6] P. Huber et al, Comput. Phys.Commun. 167 195 (2005) [arXiv:hep-ph/0407333], P. Huber et al, Comput. Phys. Commun. 177432–438 (2007) [arXiv:hep-ph/0701187].

The Genetic Algorithm: Overview

- The Genetic Algorithm (GA) is a method for optimization studies based on evolutionary algorithms and it is inspired by the processes of natural selection.
  - The goal of the GA is to find a set of parameters of a system for which the value of a given Figure of Merit (FoM) is optimal.

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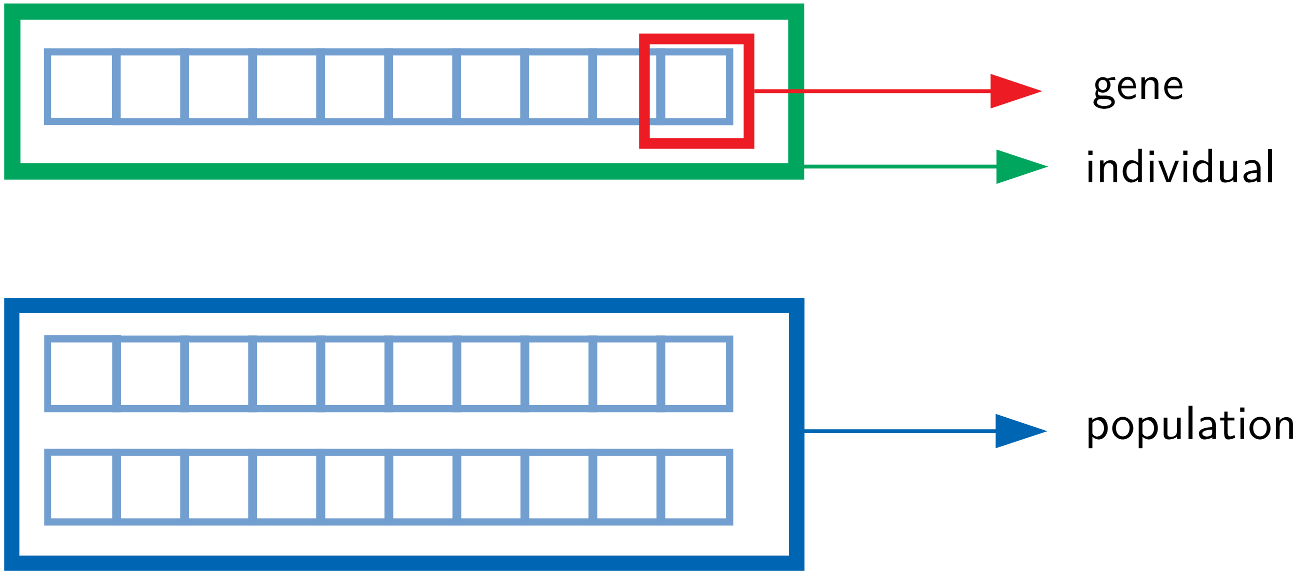
  - The **individual**, which is represented by a set of parameters (**genes**) which span the parametric space on which the optimization study is performed.
  - The **population**, which is a set of individuals.



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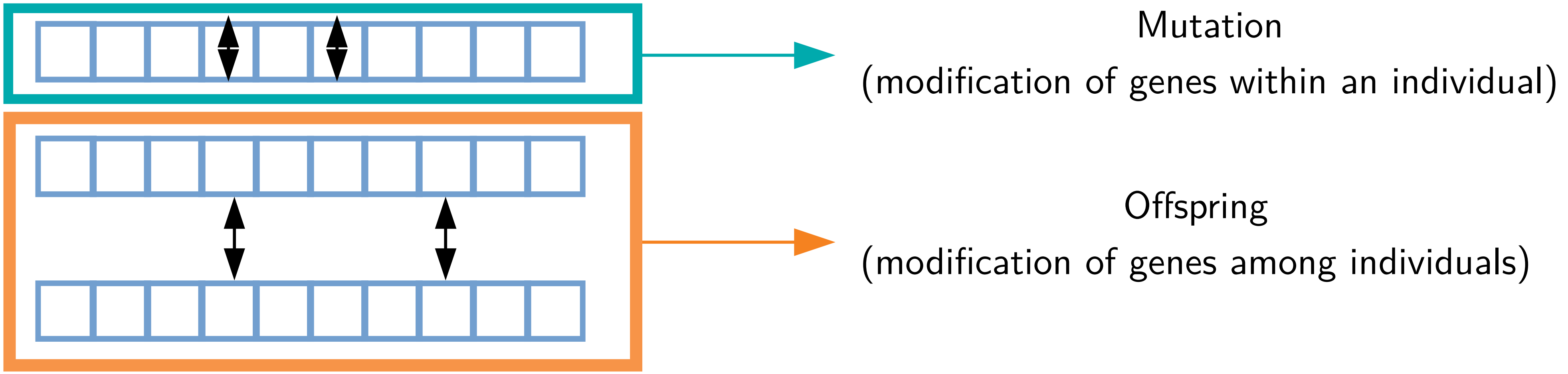

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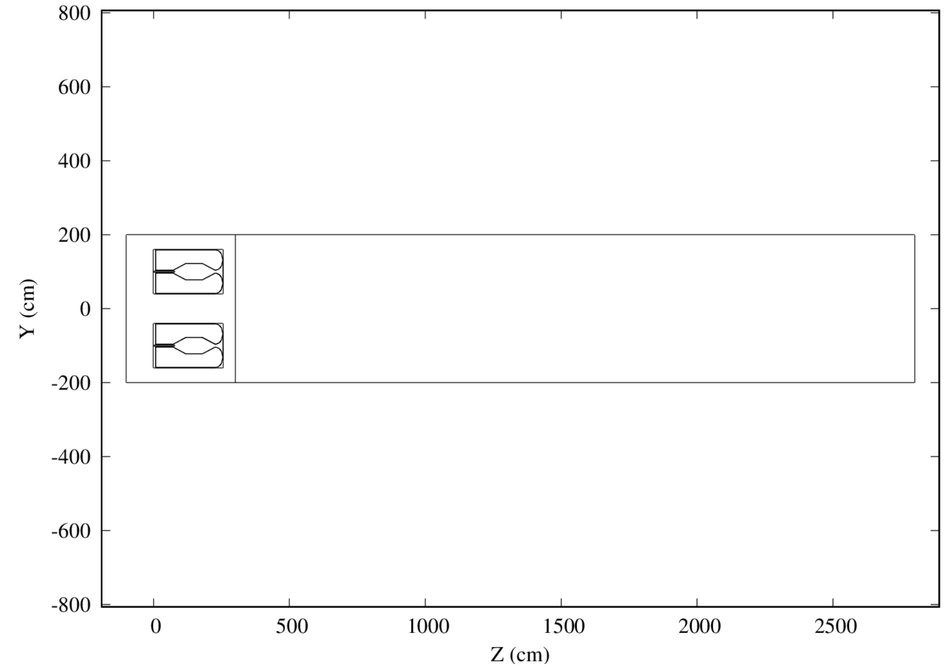
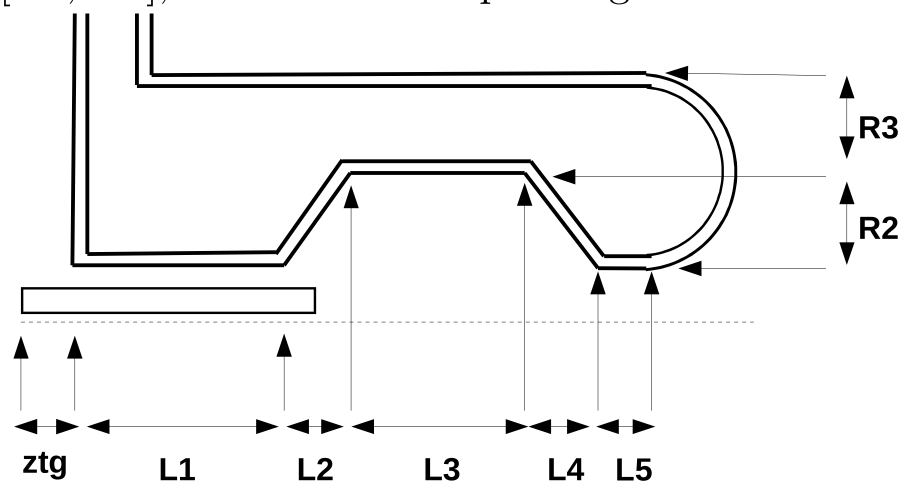
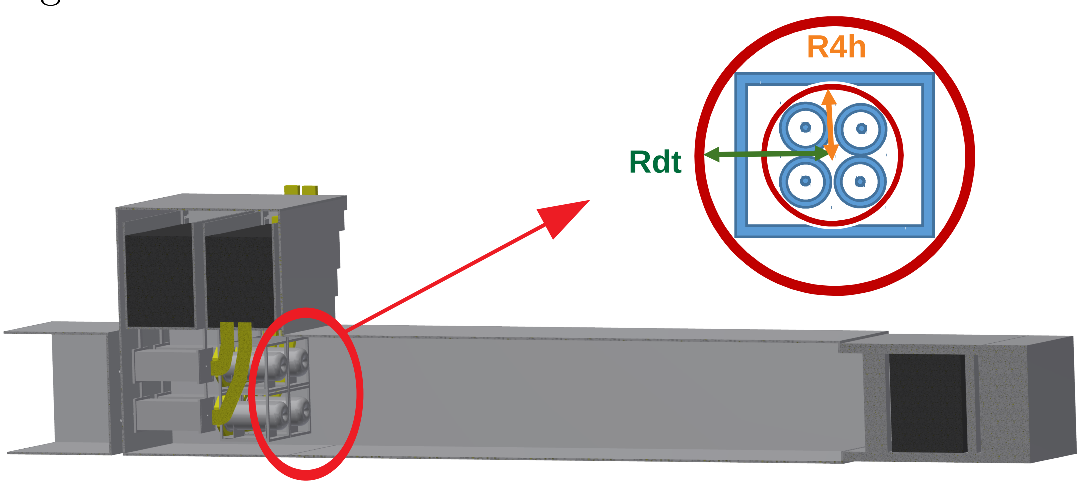
- The GA operates on the configuration of the genes of the individuals through modification of the genes on the individual (**mutations**) or on genes between two or more individuals (**offspring**) and proceeds with the evaluation of the FoM on the modified individuals.
- The set of the modified individuals and unmodified ones represents the population of the next **generation**.
  - Only individuals with best fit values are kept for the population of the next generation.

The Genetic Algorithm Applied to the Design of the Target Station Components

- The starting point of the Genetic Algorithm (GA) applied to the ESSνSB experiment is the current baseline of the Magnetic Horn (MH) and Decay Tunnel (DT) geometry.
- For our work, the following parameters of the horn and decay tunnel have been considered:
  - L1, L2, L3, L4, R2, R3, ztg, Ldt (Length of Decay Tunnel).
  - The radius of the Decay tunnel is calculated so that the ratio Rdt/R4h is constant.
- The value of the i-th parameter has been rescaled by a scale factor, which value is included in the range [0.5, 1.5], w.r.t. the corresponding baseline value.







Convergence and Resulting Shape of the Horn

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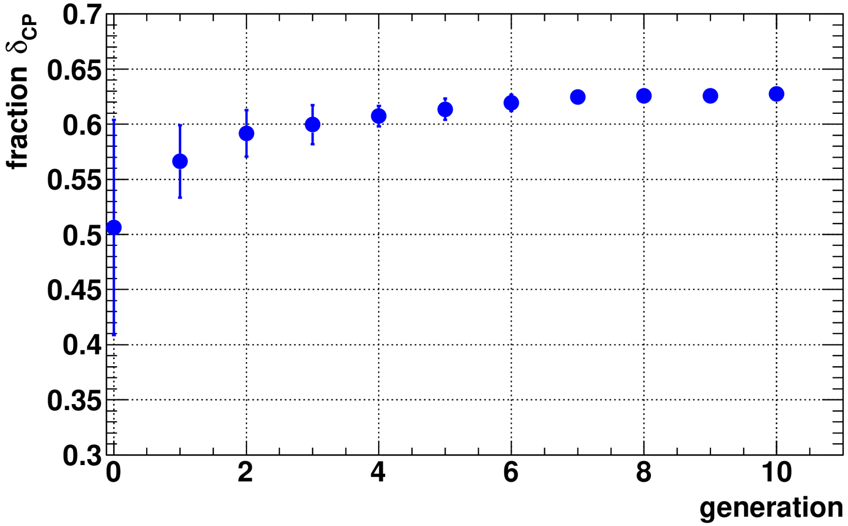
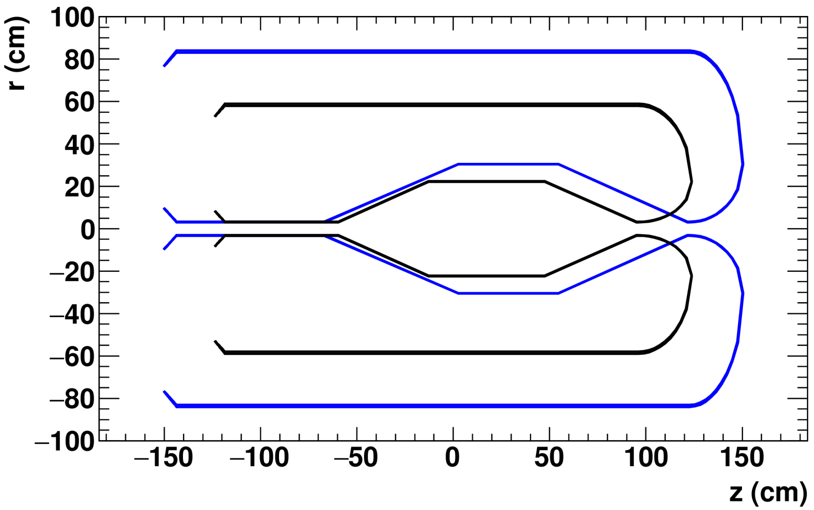
- The code converges already after few generations.
  - For the optimization of this system, the convergence refers more on the evolution to a populations in which many individuals tends to have same performance (the std calculated on the population is smaller).



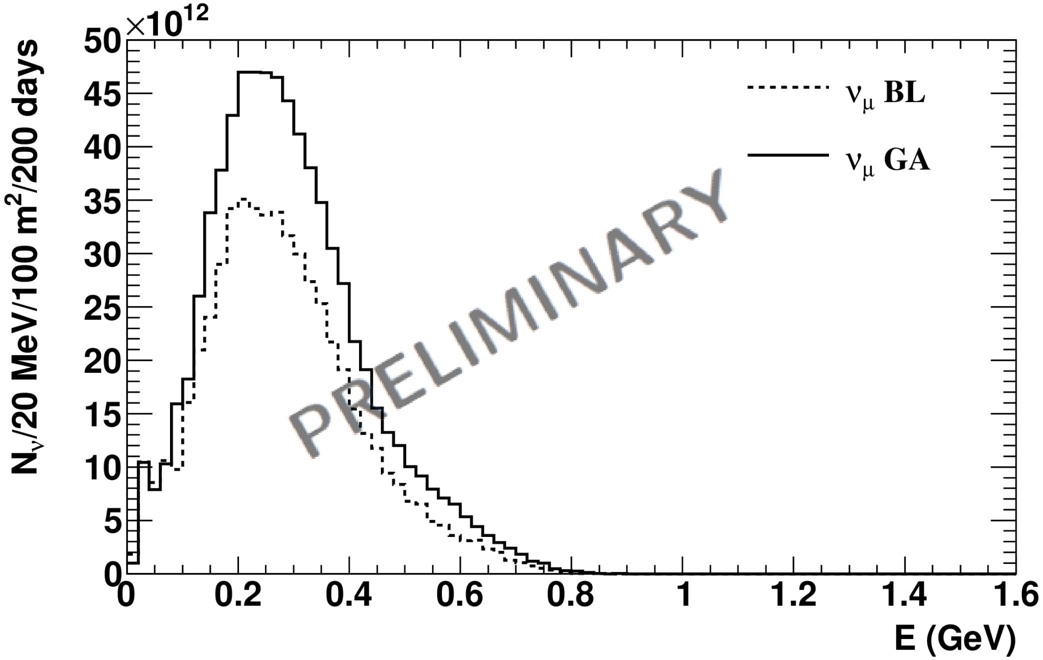
- According to our results, a larger shape of the horn (with fine tuning of the parameters of the inner region of the horn) is preferred.

- The results showed also that the GA tends to prefer longer decay tunnel lengths.

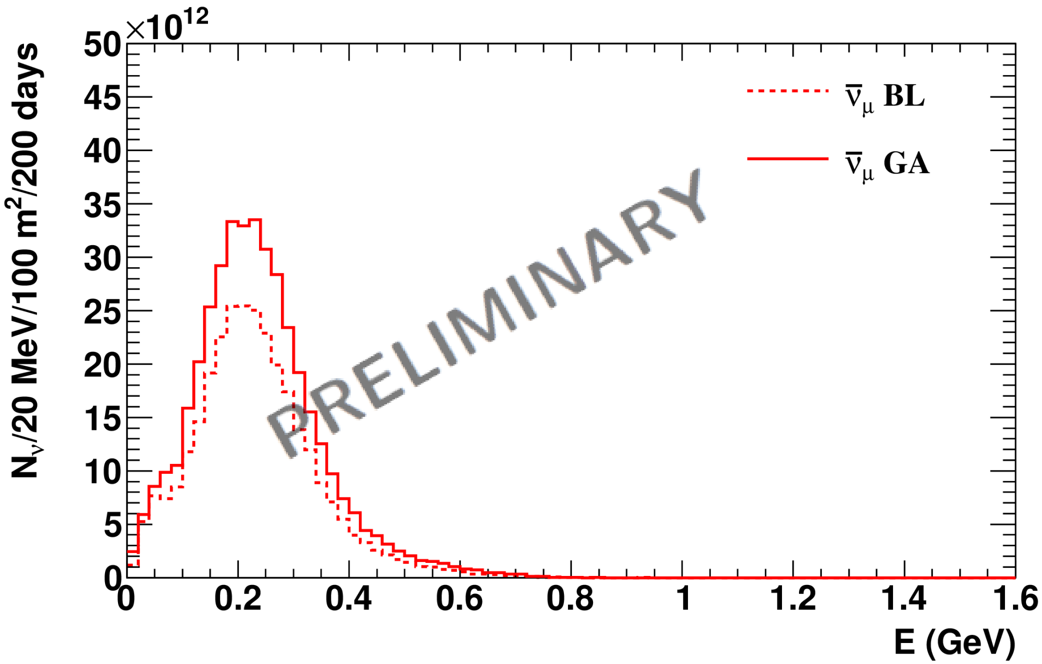


Results with the Optimized Horn and Decay Tunnel Profile

- As a first consequence of the performance of the new 4horn/decay tunnel system, the statistics in the right sign neutrinos is improved.



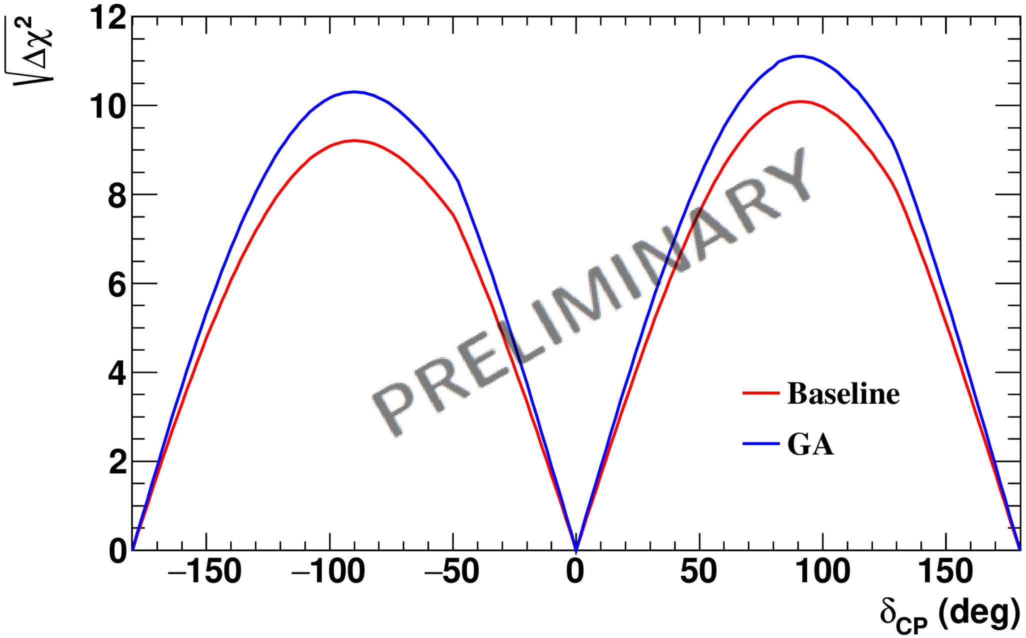
Neutrino Mode

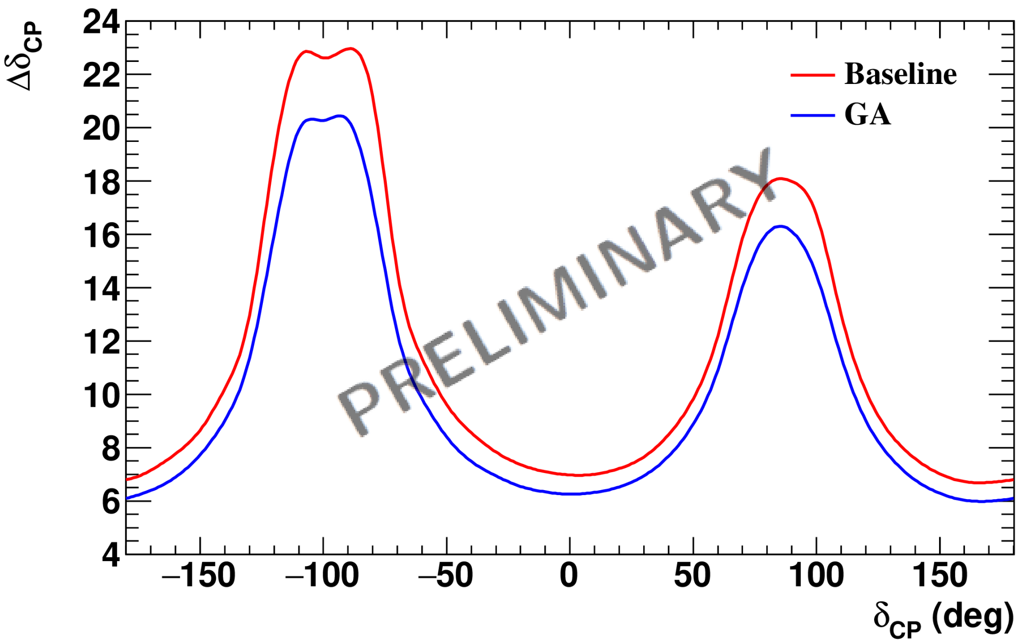


Antineutrino Mode

Results with the Optimized Horn and Decay Tunnel Profile

- Furthermore, the sensitivity results improved as well.
- Results here shown refers to the neutrinos detected at 540 km (Garpenberg)
  - NH, SO
  - Systematic errors on signal/background: **5/10%** .
- Further details in future publications.





Conclusions

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- The Genetic Algorithm provides a powerful tool to scan the parameter space for the optimized design of the target station components.
- The code shows fast convergence and the optimized geometry of the hadron collector and decay tunnel provides enhanced Physics performance of the experiment.
- Studies are currently on going to determine the feasibility of the horn geometry suggested by the optimization study, from the mechanical point of view.
- Soon results will be published on the improved sensitivity of the ESSνSB experiment.

Acknowledgement

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Thank You for Your Attention!