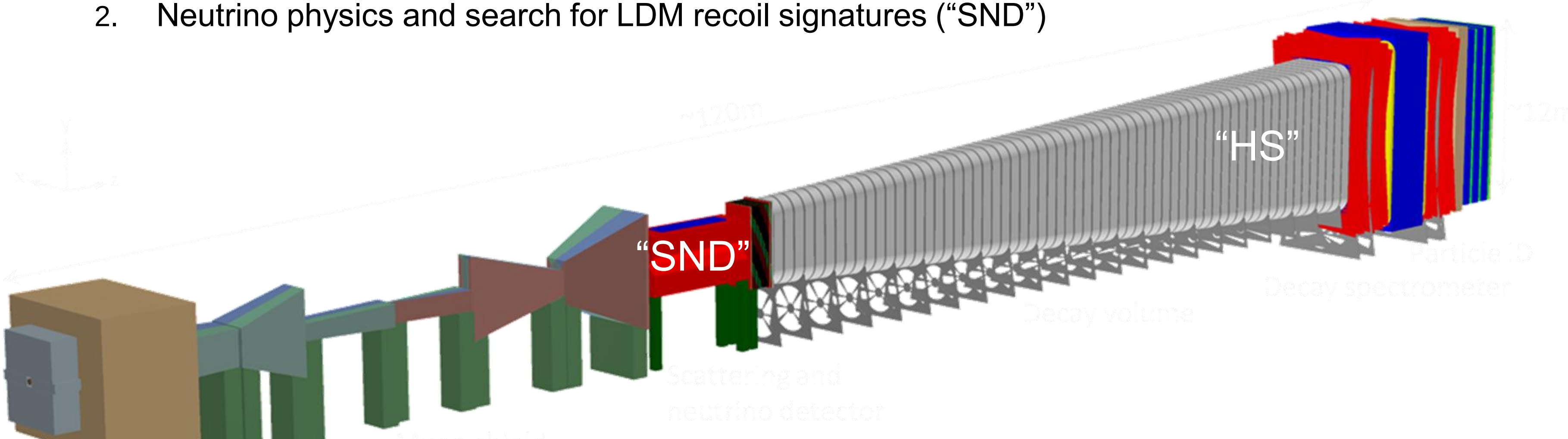
Example: BDF/SHiP magnetic muon shield optimization with ML

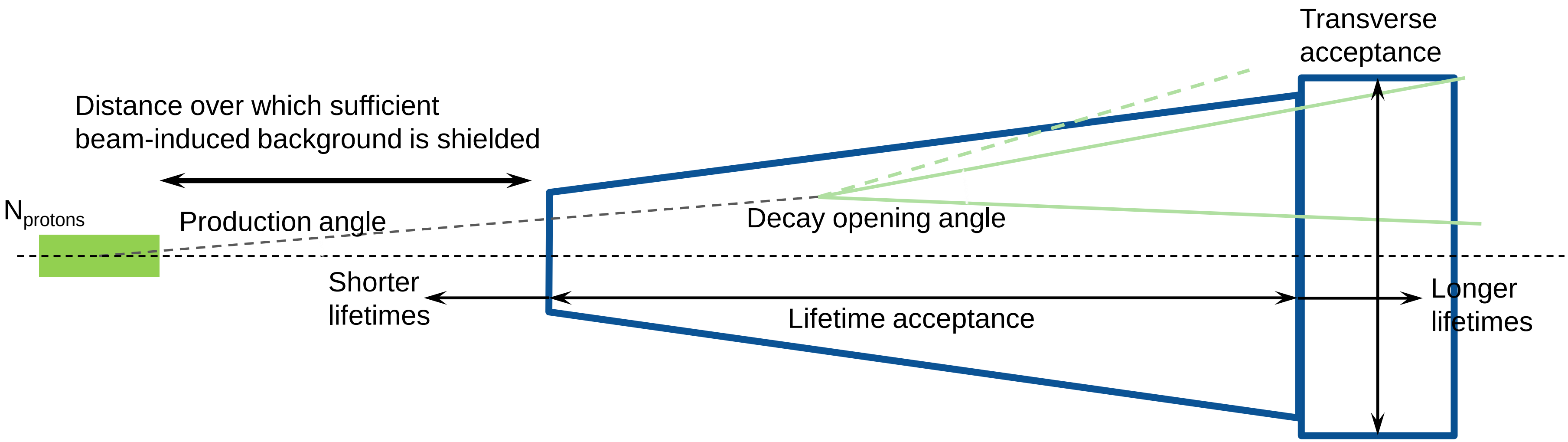
SHiP experimental setup

- Physics cased based on $2x10^{20}$ protons on target (5 years of nominal operation)
  - ➔ Signal yields from $>10^{18}$ D mesons, $>10^{16}$ τ, $>10^{21}$ photons (>100 MeV)
- Dual detector system
  1. Search for HS decays (“HS detector”)
  2. Neutrino physics and search for LDM recoil signatures (“SND”)



Challenge is background suppression

Detector optimisation



Signal(mass, coupling) $\propto N_p \times \iiint_{min}^{max} f(\text{Production angle, Decay opening angle, Lifetime})\, d\phi\, d\alpha\, d\tau$

➔ Distribution for production angle, decay opening angle, lifetime depend on physics model and mass

Background suppression is combined effect of upstream shielding ⊗ detector

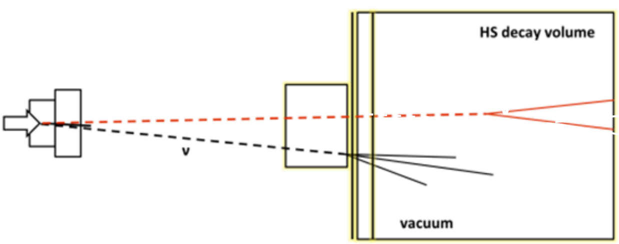
➔ Optimisation of geometry in terms of signal vs background is matter of choice of working point

➔ Re-optimisation involves shortening the muon shield at the cost of somewhat higher muon rates

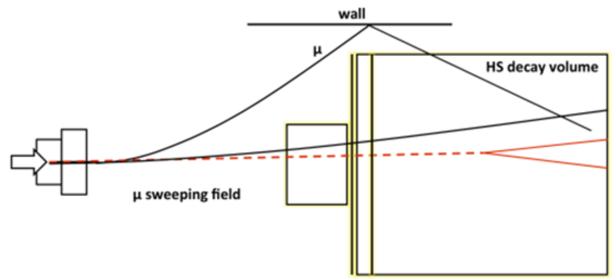
➔ CDS detector rate limitation came from the use of emulsion film in SND

Muon background

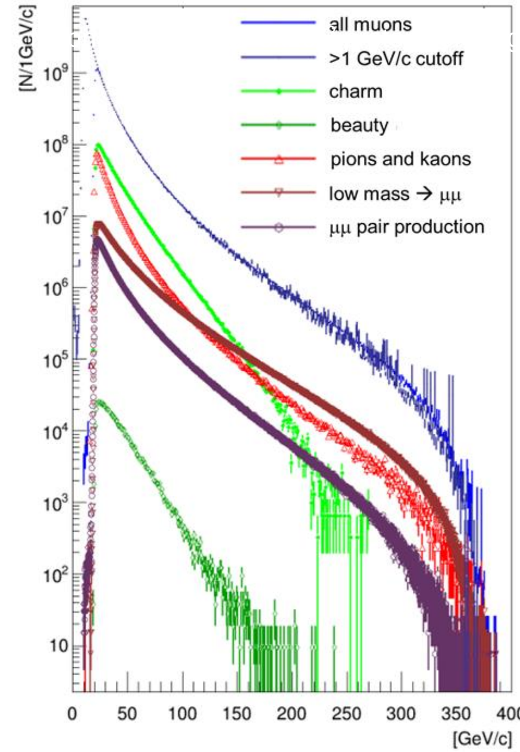
- Beam-induced background flux
  - $\mathcal{O}(10^{11})$ muons (>1 GeV/c) per spill of $4\text{x}10^{13}$ protons
  - 4.5×10^{18} neutrinos and $3\text{x}10^{18}$ anti-neutrinos in acceptance in 2×10^{20} proton on target

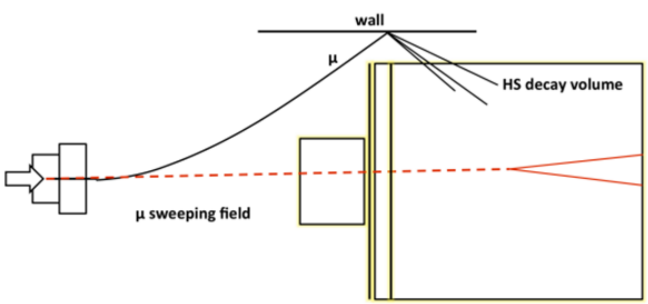


Neutrino interactions

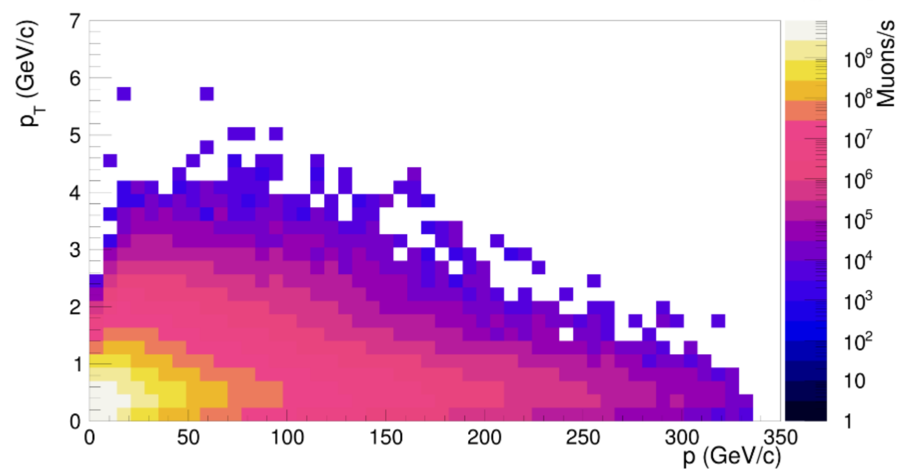


Muon combinatorial

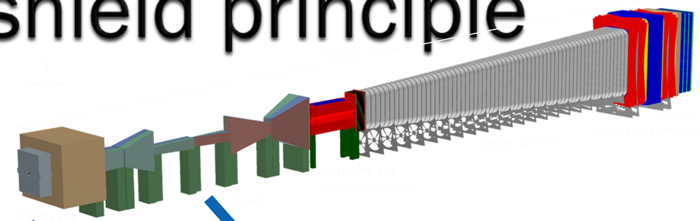


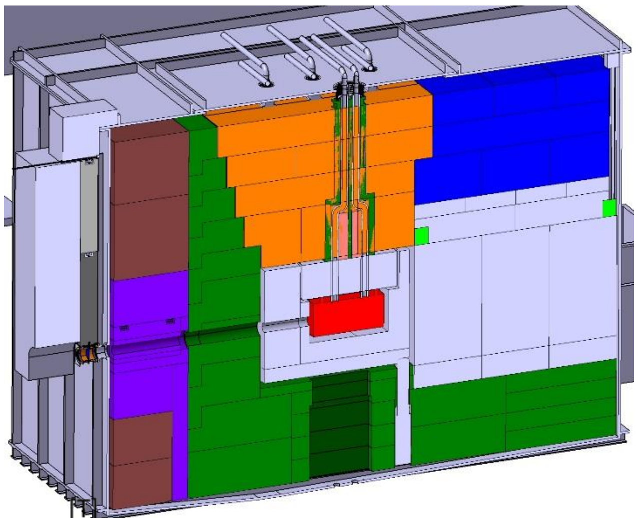


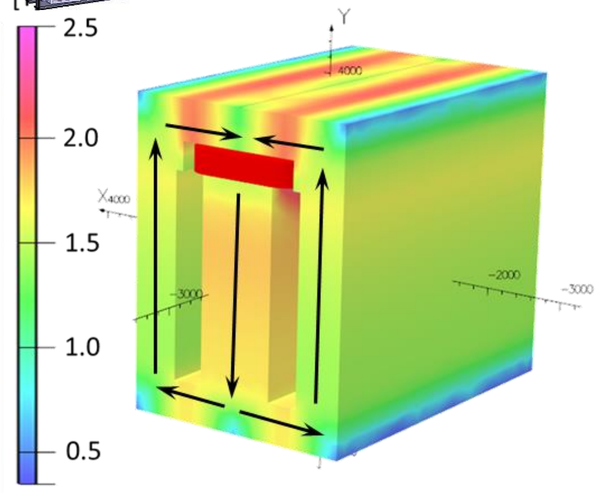
Deep inelastic

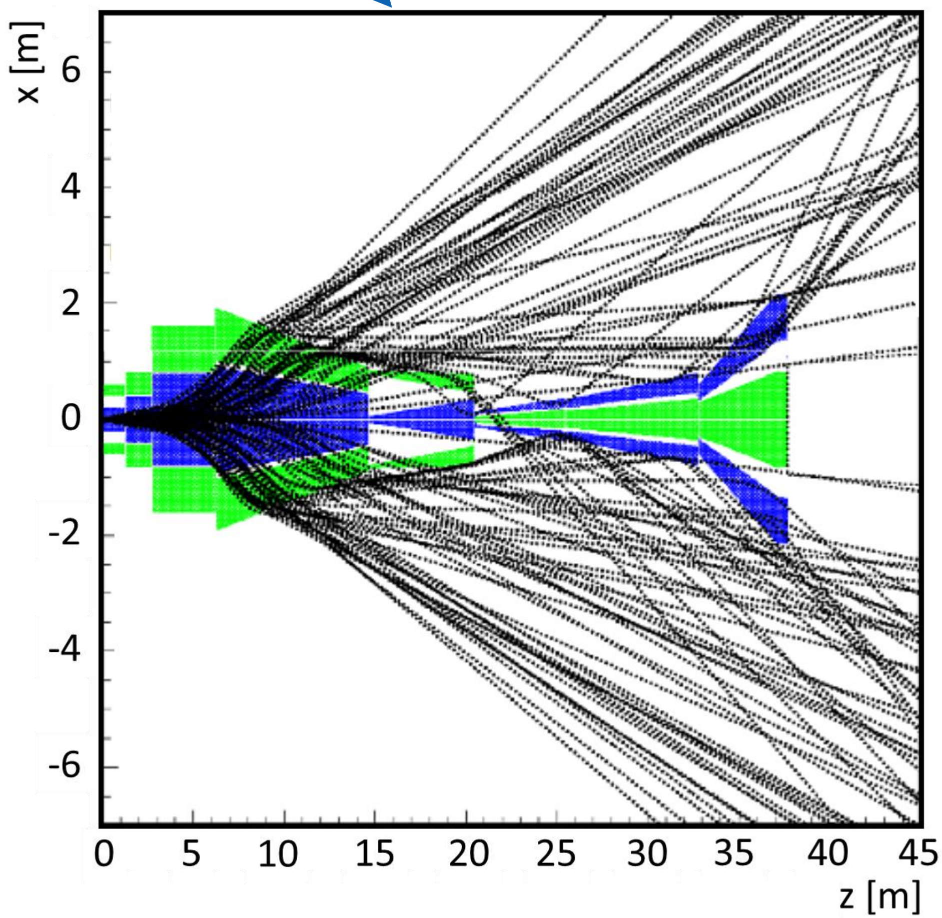


Magnetic shield principle



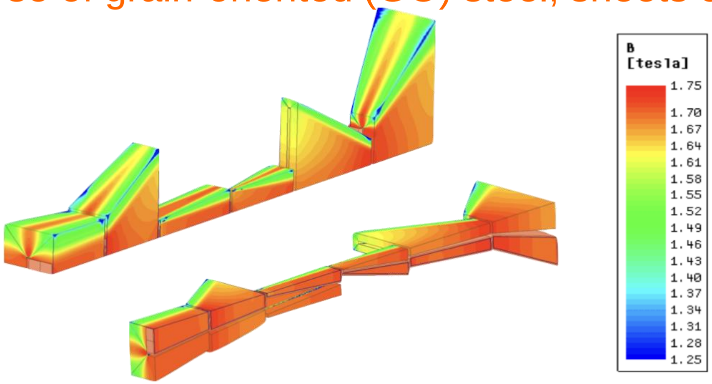


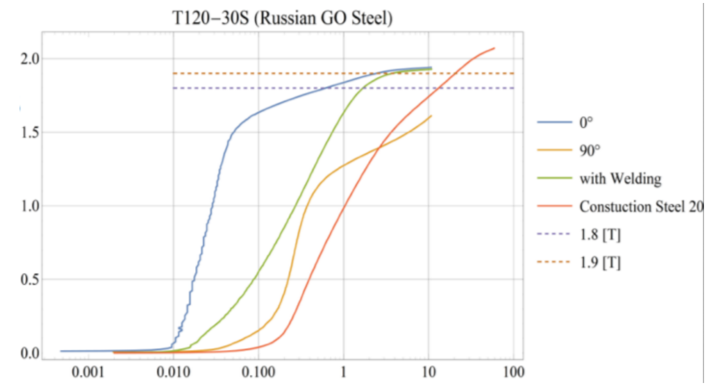




Muon shield (free-standing)

- Narrow spaces for coil ➔ limit coil current-turn and power dissipation (air cooling)
  - ➔ Use of grain-oriented (GO) steel, sheets of 0.3-0.5 mm

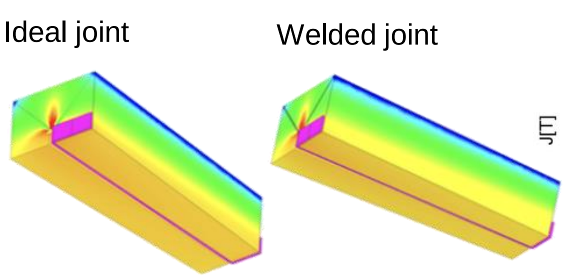


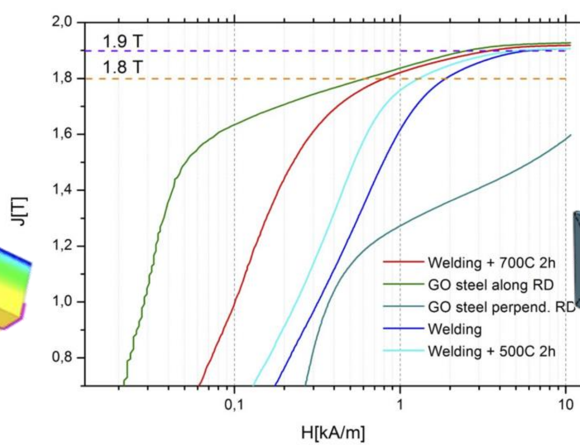


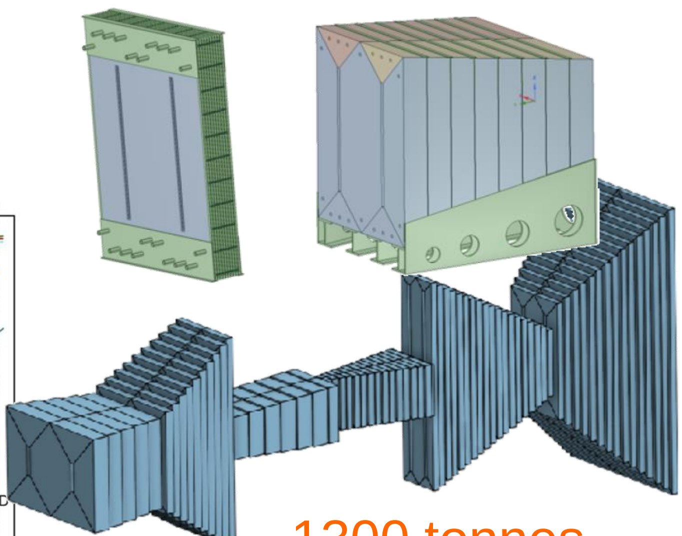
- Technology studies produce realistic field maps for simulation

➔ Assembly of GO steel

- Investigation of welding followed by annealing
- Welding of 5cm (150 sheets) blocks looks feasible
- Requires large vacuum chamber

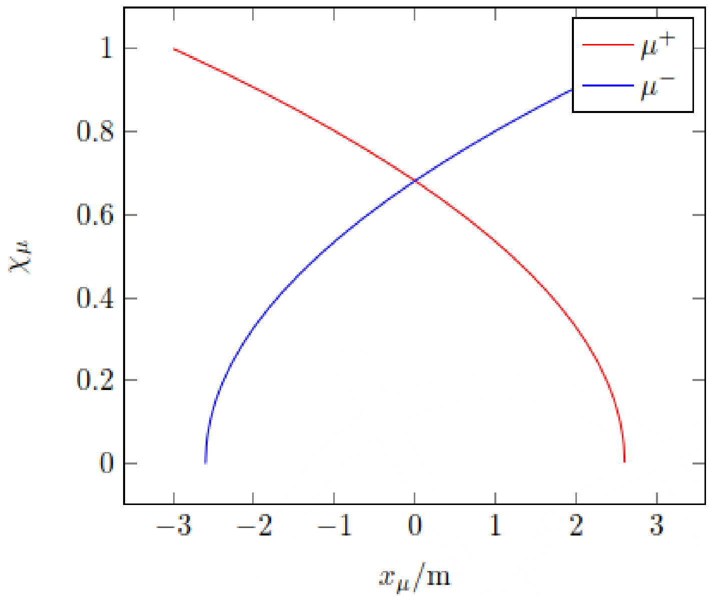






Muon shield (free-standing part)

- Optimization of field configuration by Machine Learning with a sample of muons simulated with PYTHIA/GEANT
  - Assumptions: 1.7 T average field in core
    6 magnets of 5m length
    10cm space between magnetic regions
  - Whole setup described by 56 parameters
  - Bayesian optimization procedure



gb = gradient boosted decision trees
rf = random forests

- Current loss function

$$f(W,\chi_\mu) = \begin{cases} 10^8 \ if \ W > 3kt \\ 1 + e^{10\times(W-W_0)/W_0} \times \left[1 + \sum_\mu \chi_\mu(x_\mu)\right] \end{cases}$$

W weight of the muon shield
W_0 weight of the baseline
χ_μ weighted position of muon μ passing sensitive plane at position x_μ

- Penalise muons entering the acceptance
- Length optimised implicitly via the weight
- Weight cut-off as regularisatio

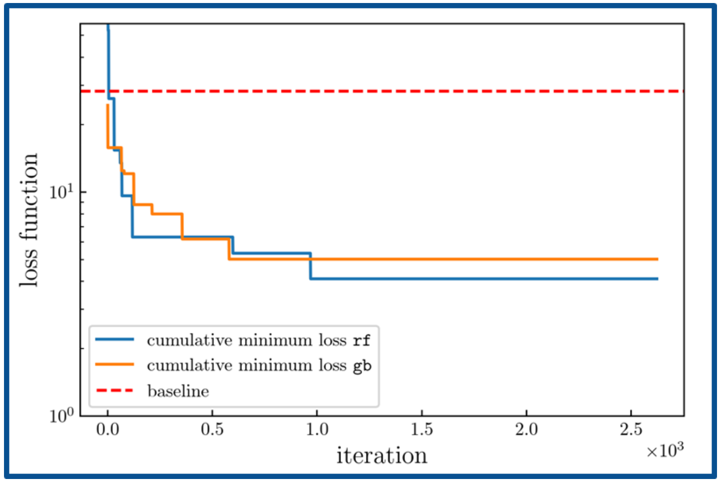
➔ Optimization produces an idealistic field map

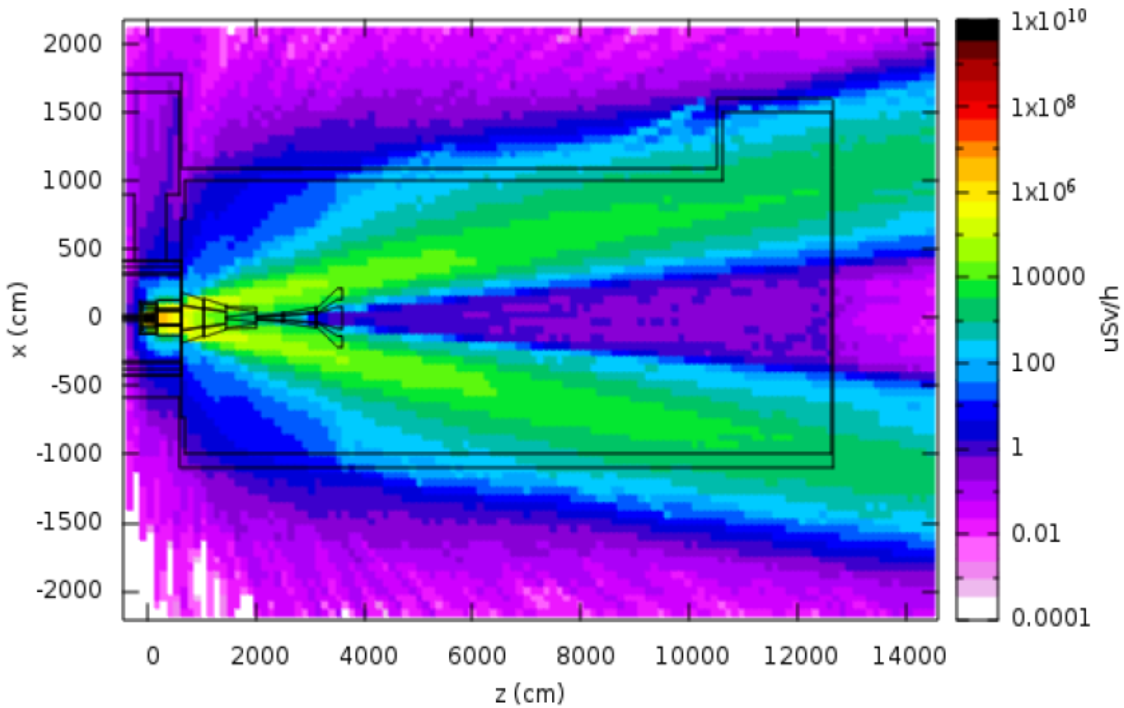
Sounds easy

- Simulating one spill of 4E13 protons = month of CPU with 1600 cores

- Bayesian optimisation does not scale well for high-dimensional problems.
  - Computing model imposes additional constraints.
  - Make up to 100 guesses at once (with 16 nodes parallelising every function evaluation)
  - Use scikit-optimize implementation of Bayesian optimisation (DOI 10.5281/zenodo.1170575)
  - Use Gaussian processes and random forests as surrogate models.
  - Reduce muon sample by factor ~40 to speed up evaluation and even out coverage of phase space: 18 million beam-induced muons

Example of the result



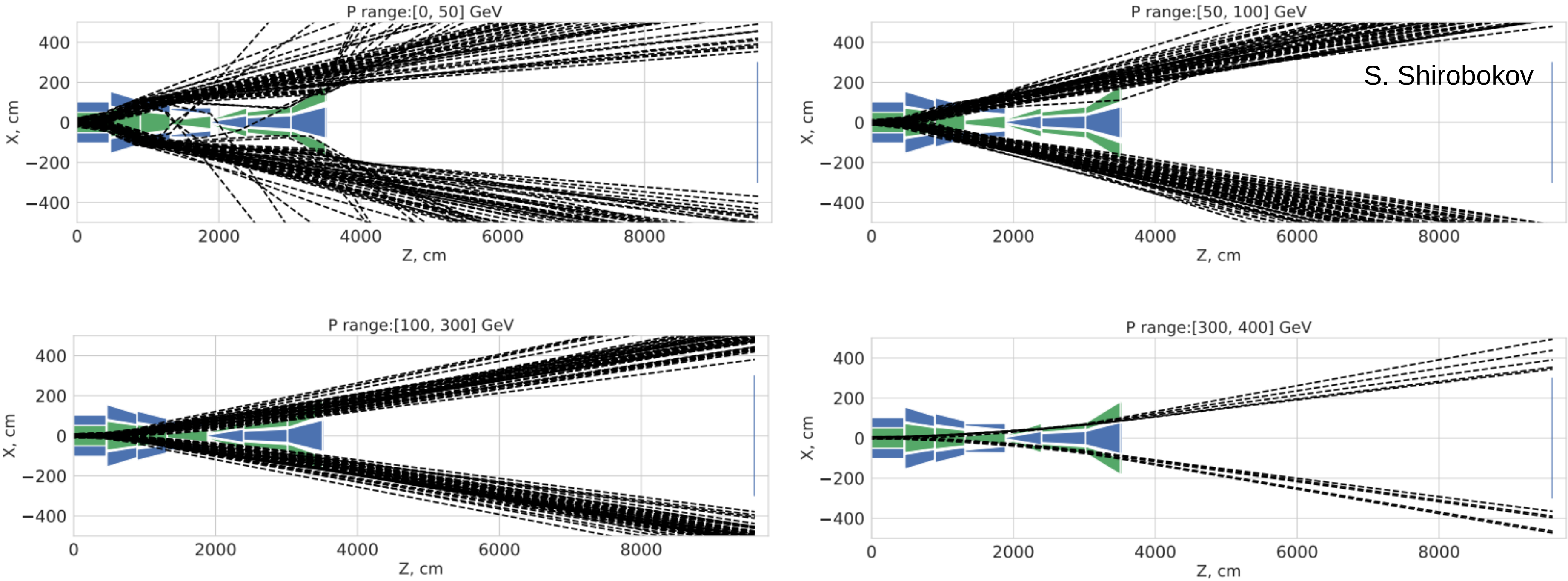


FLUKA, C. Ahdida

- Muon flux “bow wave” determines ultimate envelope for the fiducial volume

Example of results

- Typical muon paths in current shield for different energy ranges



- Muons impinging on decay volume: 5.8×10^4 / spill
- Reconstructed muons in spectrometer 3×10^4 / spill
- 2.1×10^8 muon DIS interactions in decay volume wall in 2×10^{20} protons on target

➔ Rate of muons in spectrometer come from wrong muon charge/magnet polarity, large angle scattering and magnet inefficient regions (coils, structural etc)

Radiation protection...

- C. Ahdida