CHIPP Winter School of Particle Physics 2022

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Search for HNLs in events with taus at CMS and study of SM neutrinos with SND@LHC

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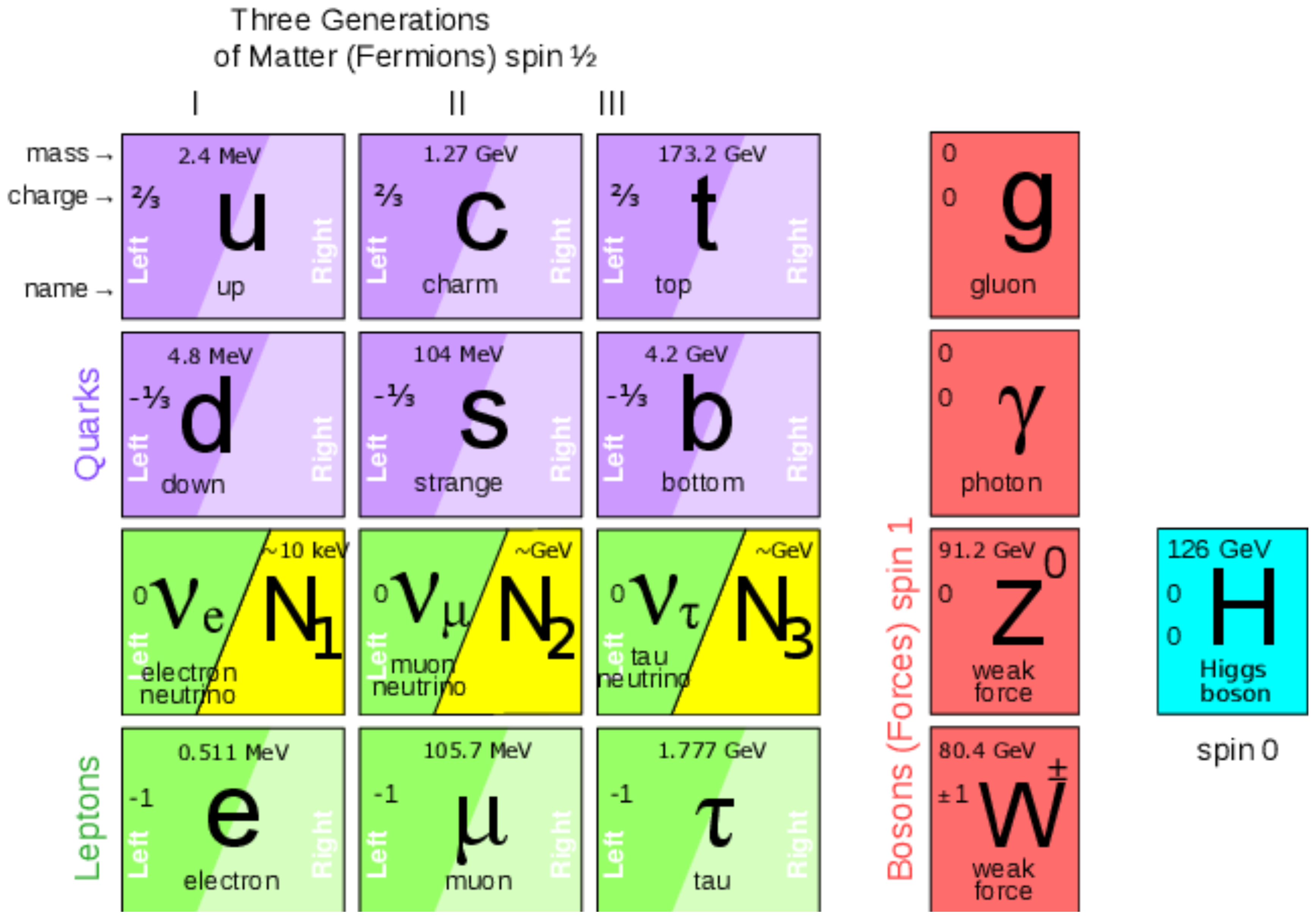
Part 1: Search for long lived heavy neutral leptons (HNLs) in events with displaced τ signature at CMS

νMSM theory and HNLs

Evidences for Physics beyond the Standard Model (SM) *Neutrino masses/oscillation (1998)*, Dark matter (1960s), *Baryon asymetry of the universe (BAU)*

Neutrino Minimal Standard Model theory (νMSM) *Mikhail Shaposhnikov*

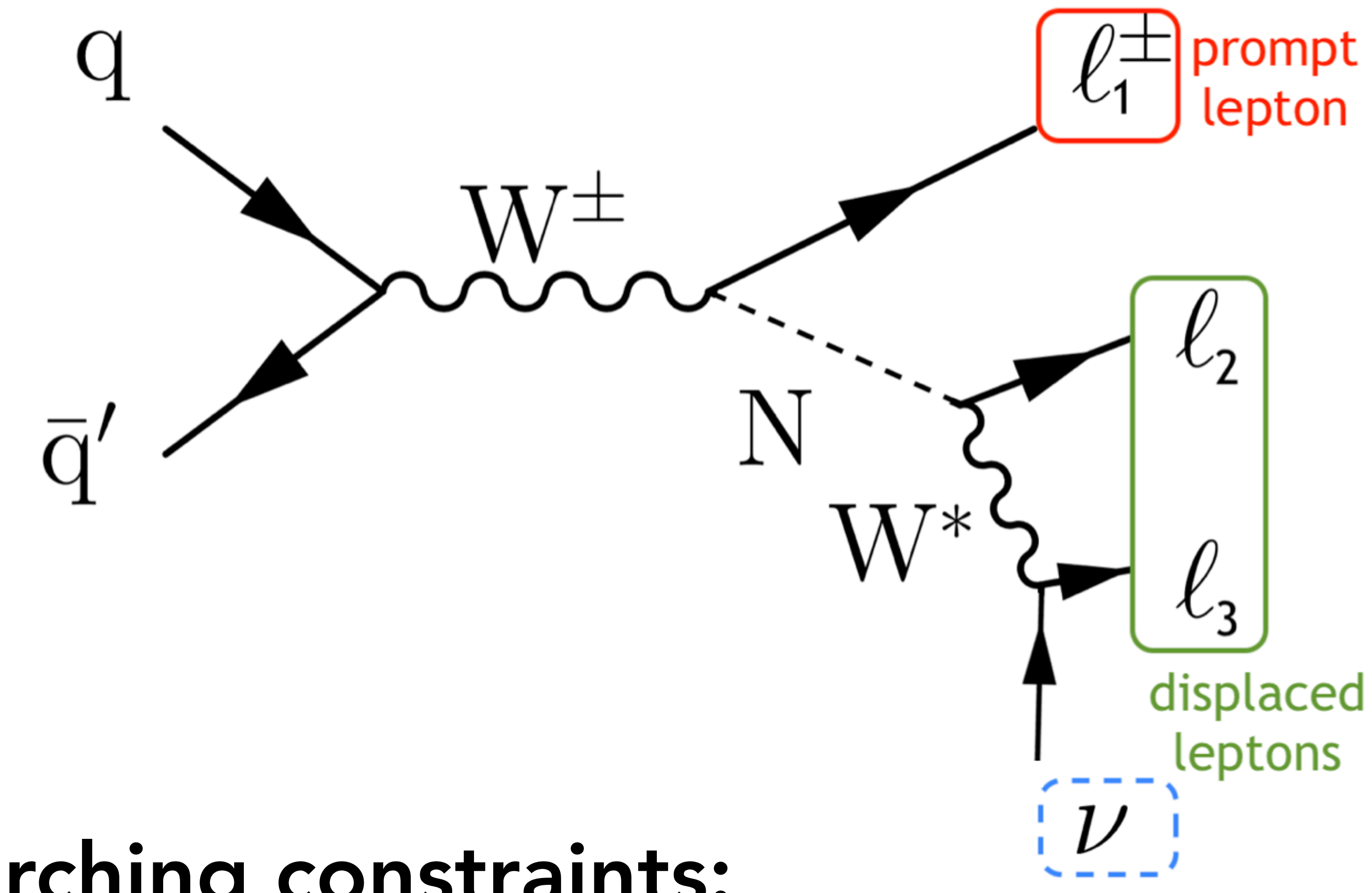
DM candidate
Explain BAU
Explain neutrino masses



- Addition of three Majorana massive right-handed neutrinos N_1, N_2 and N_3
- Sterile (i.e only sensitive to gravity force)
- Interact only with SM neutrinos through mixing
- Small mixing parameter $|V_{lN_i}|^2$ between ν_l and N_i (free parameters)
- Lepton-number-violation (LNV) is allowed
- From cosmological constraints: $m_{N_1} \lesssim$ keV & $m_{N_2} \sim m_{N_3} \sim$ 0.1GeV→TeV

$$\begin{bmatrix} |V_{eN_1}| & |V_{eN_2}| & |V_{eN_3}| \\ |V_{\mu N_1}| & |V_{\mu N_2}| & |V_{\mu N_3}| \\ |V_{\tau N_1}| & |V_{\tau N_2}| & |V_{\tau N_3}| \end{bmatrix} \quad ? \quad (m_{N_1}, m_{N_2}, m_{N_3})$$

Probed HNL signature

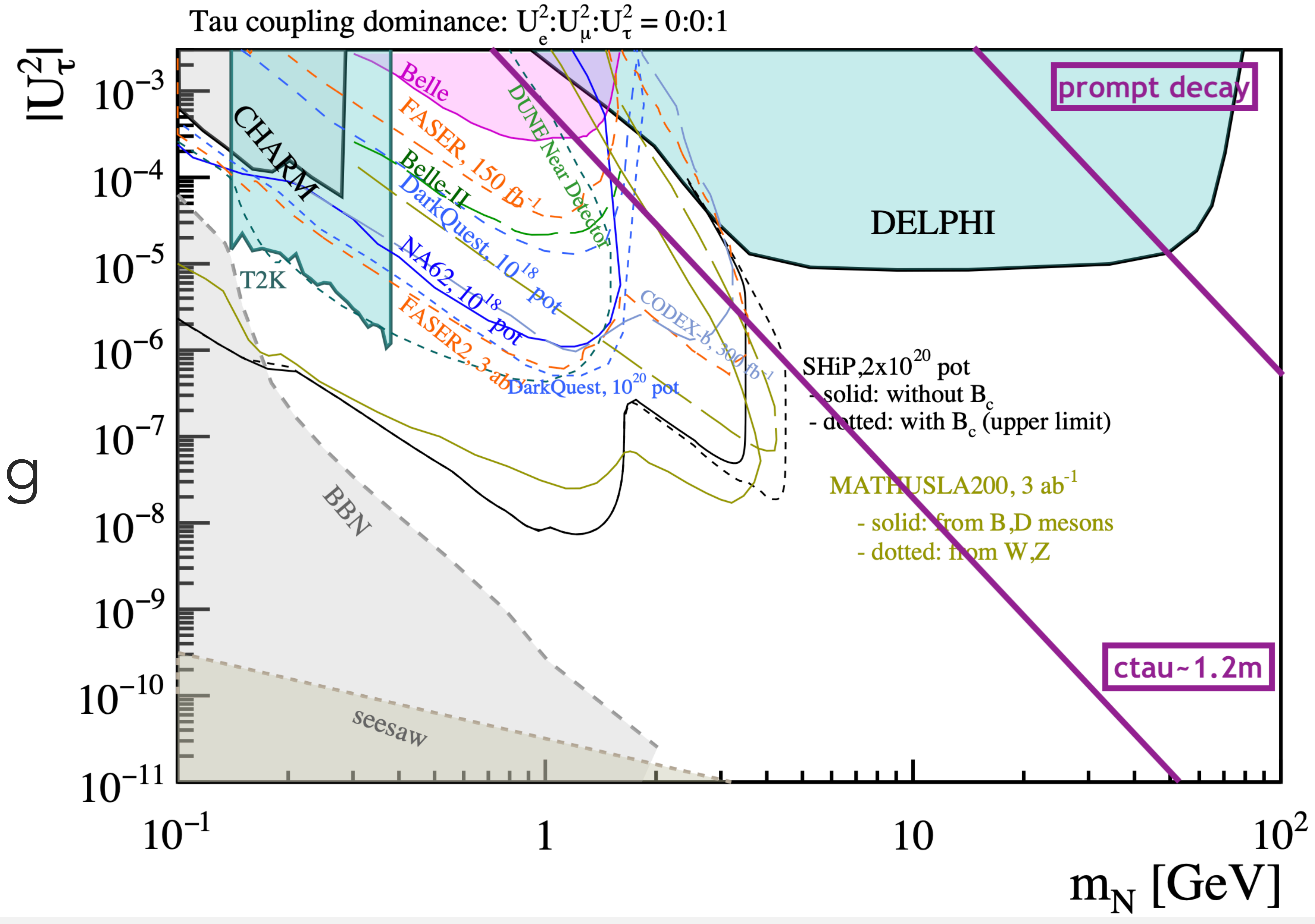


Description:

- N from the decays of W bosons produced in 13 TeV pp collisions
- N decaying into two leptons and a neutrino
- Prompt lepton (l_1) from the W boson decay
- Two leptons (l_2 and l_3) from N decay that can be displaced
- <u>Requirement:</u> at least one of the lepton to be a τ

Searching constraints:

- N can potentially mixed with all three lepton flavours
- In general, searches are benchmarked into scenarios in which a N couples to a single SM generation at the time.
- In our case, the one of interest is the HNL state with predominant mixing to tau neutrinos ($|V_{\tau N_1}| = 1$)
- N can possibly decay at macroscopic distances from production vertex if m_{N_i} or $|V_{\tau N_i}|^2$ are small enough as $\tau_{N_i} \propto |V_{lN_i}|^{-2} m_{N_i}^{-5}$
- Helps for background suppression

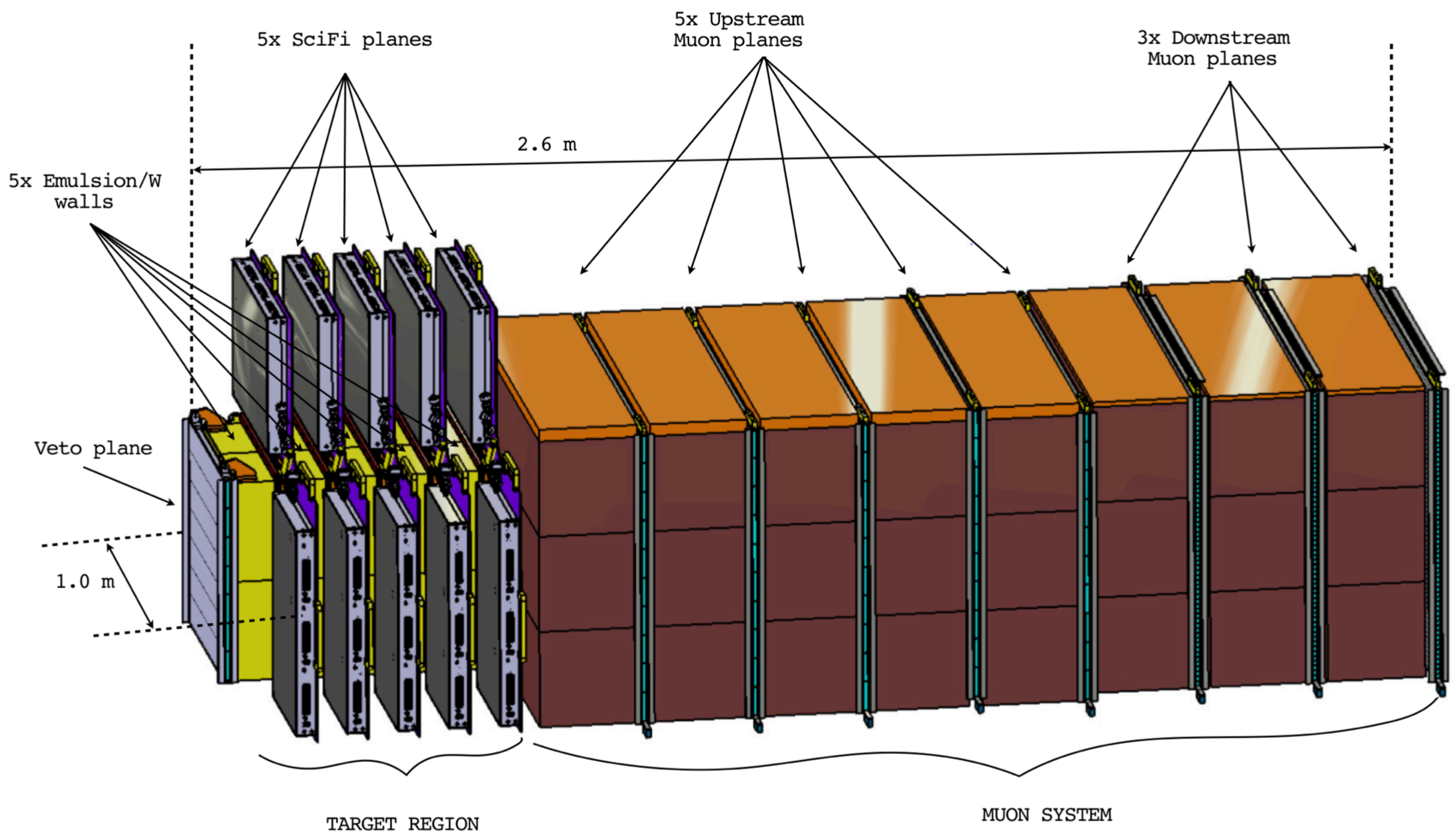


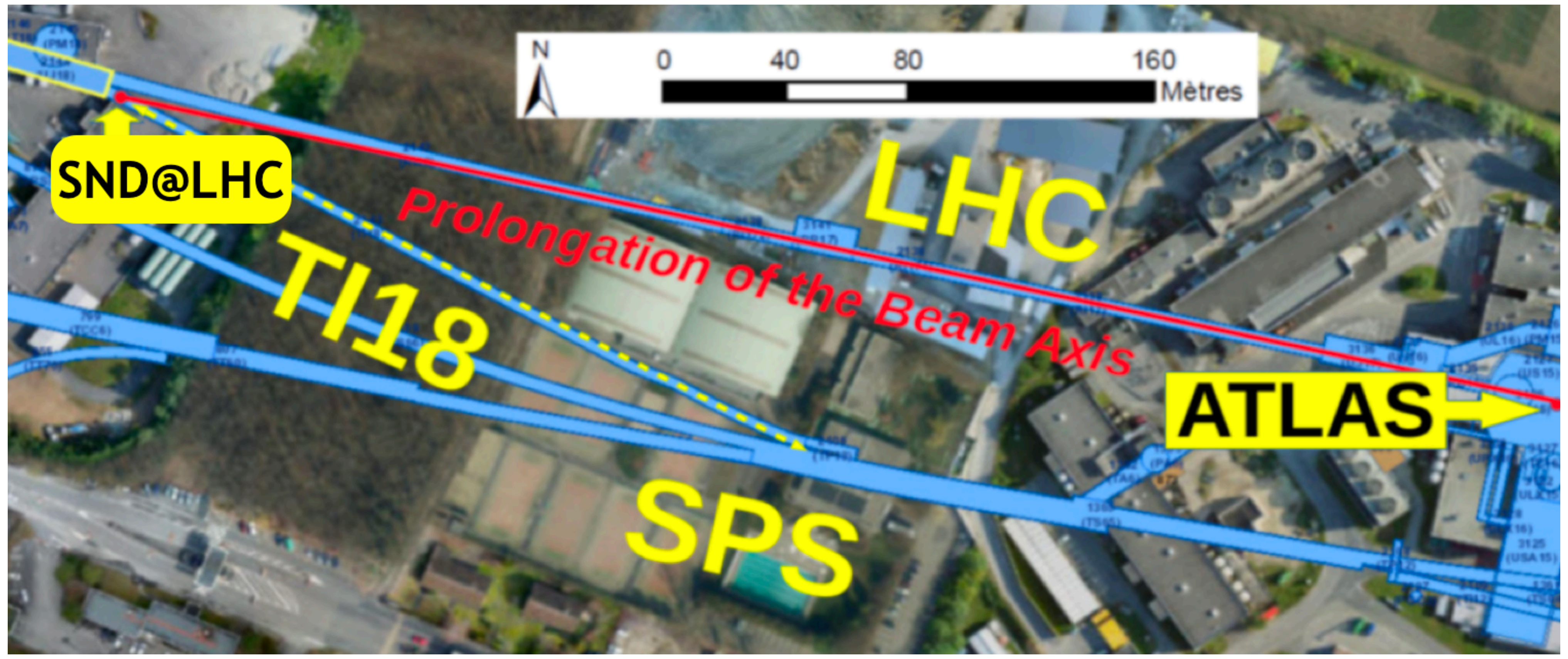
Part 2: Study of SM neutrinos with SND@LHC using a machine learning algorithm

SND@LHC experiment

Experiment description and goals:

- Compact experiment proposed to make measurements with neutrinos from the LHC
- Will collect 150 fb^{-1} of data in 2022–24 during Run 3
- Located 480 m downstream of IP1 in the TI18 tunnel (ATLAS as neutrino factory)
- Allows to search for Feebly Interacting Particles (FIPs)





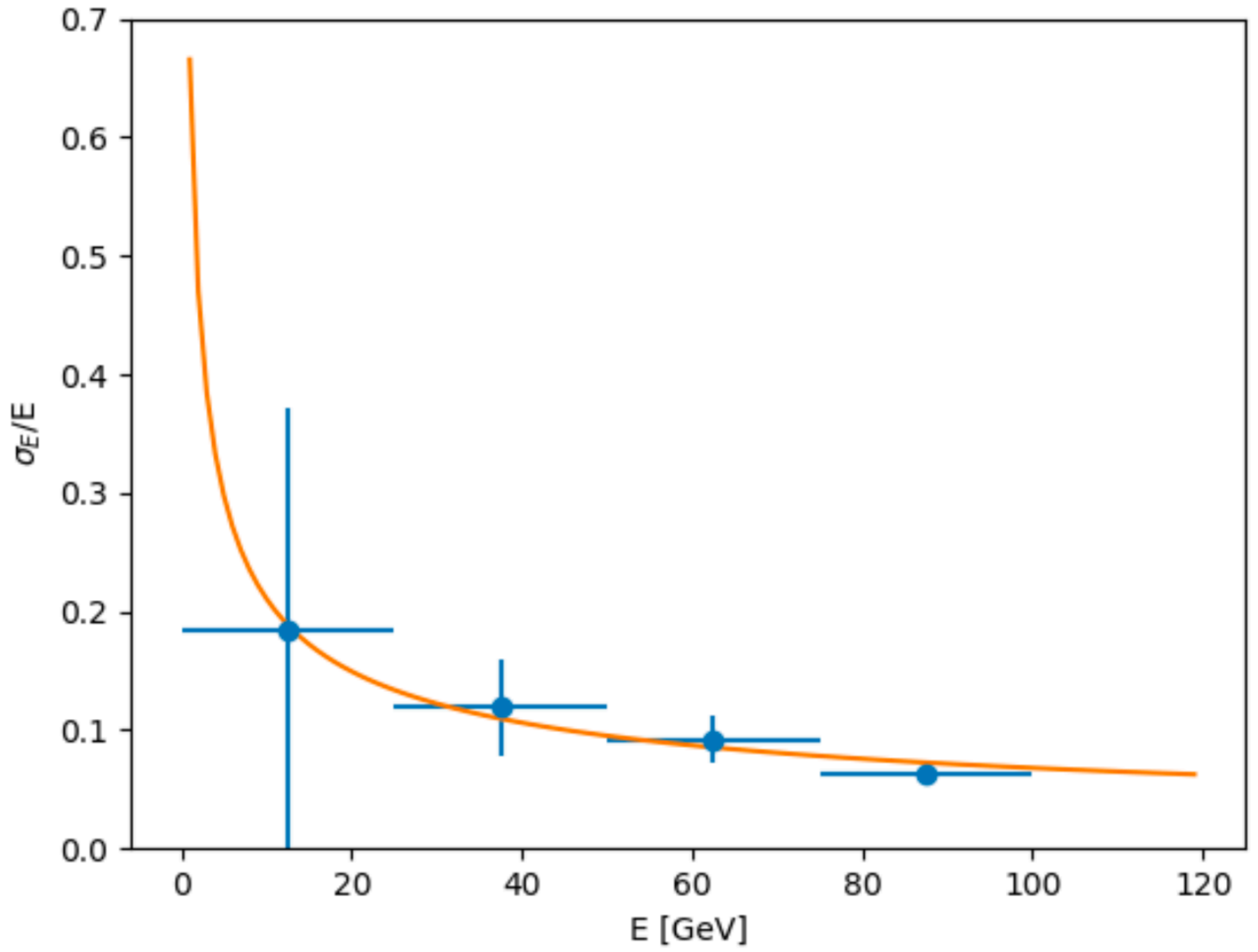
Detector concept:

- Hybrid system based on an 800kg target mass of tungsten plates, interleaved with emulsion and electronic trackers (SciFi), followed downstream by a muon system.

Study presentation

Motivation:

- To get "on-the-fly" informations on the events
- Impossible with emulsions: needs to be taken out from the detector and developed in order to extract the track information
- Use informations from electronic detectors (SciFi and muon planes) to perform prompt analysis (energy reconstruction, particle identification/ classification)
- SciFi will provide time and spatial information (resolution of ≥ 50 μm)



Naive approach:

- The detector can be considered as a non-homogeneous calorimeter, the energy of a particle producing a shower in the detector can be reconstructed by counting hits in the planes (gradient descent minimisation algorithm)
- But we believe better results can be achieved using ML techniques

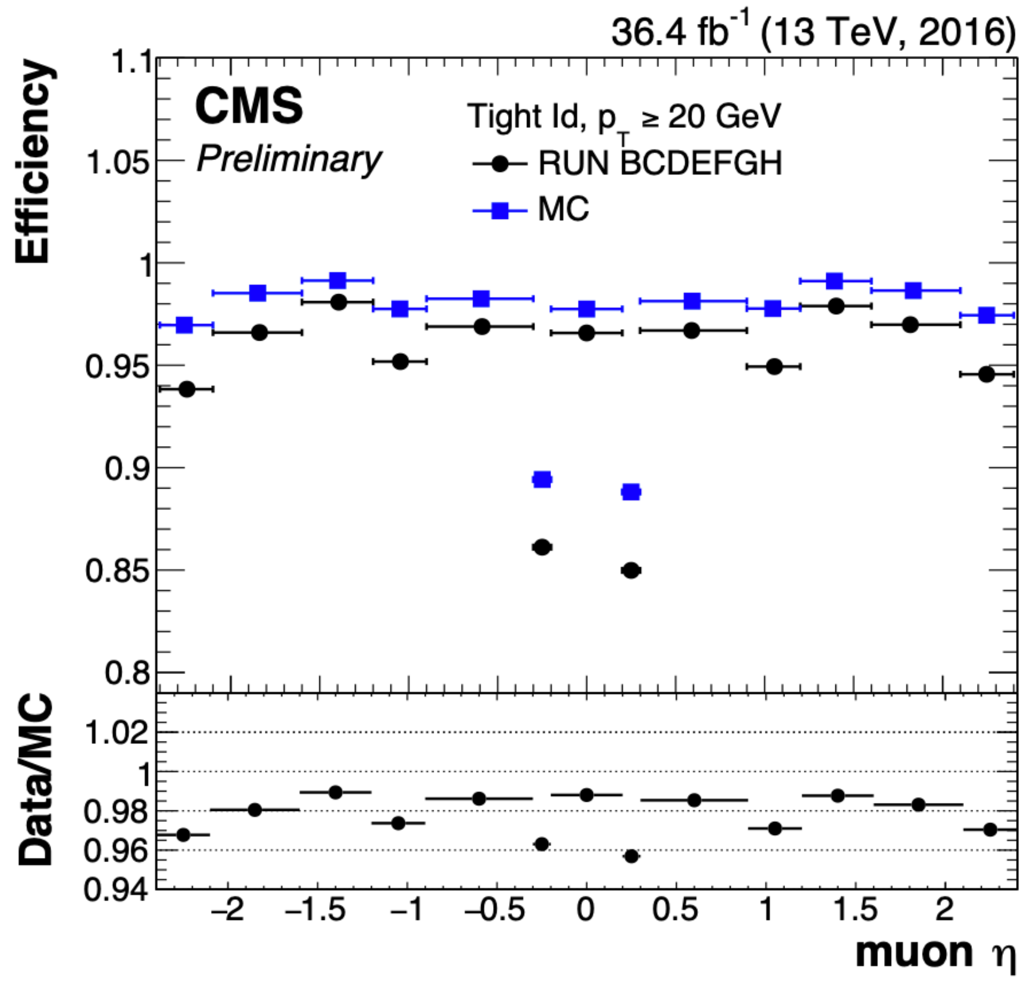
$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2}$$

Thank you!

Features of the probe signature

Advantages:

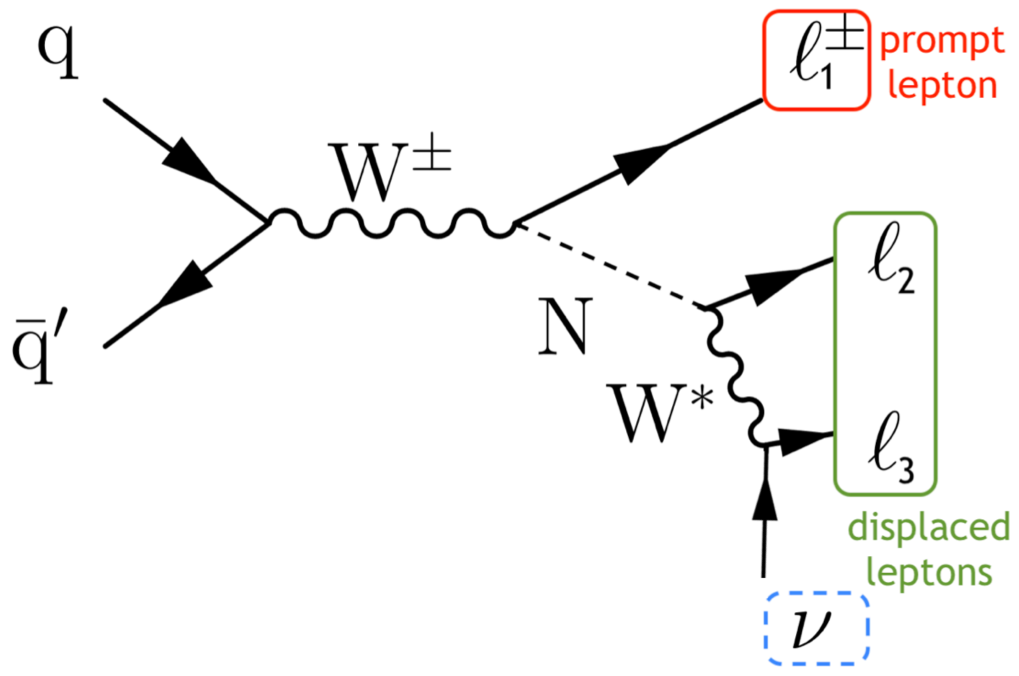
- prompt lepton l_1 can be μ or e and are well reconstructed, even at low energy, which makes it a highly efficient trigger
  -clean signal selection
  -significantly suppress background
- displaced signatures allows SM background suppression
- Allows LFV and LFC search

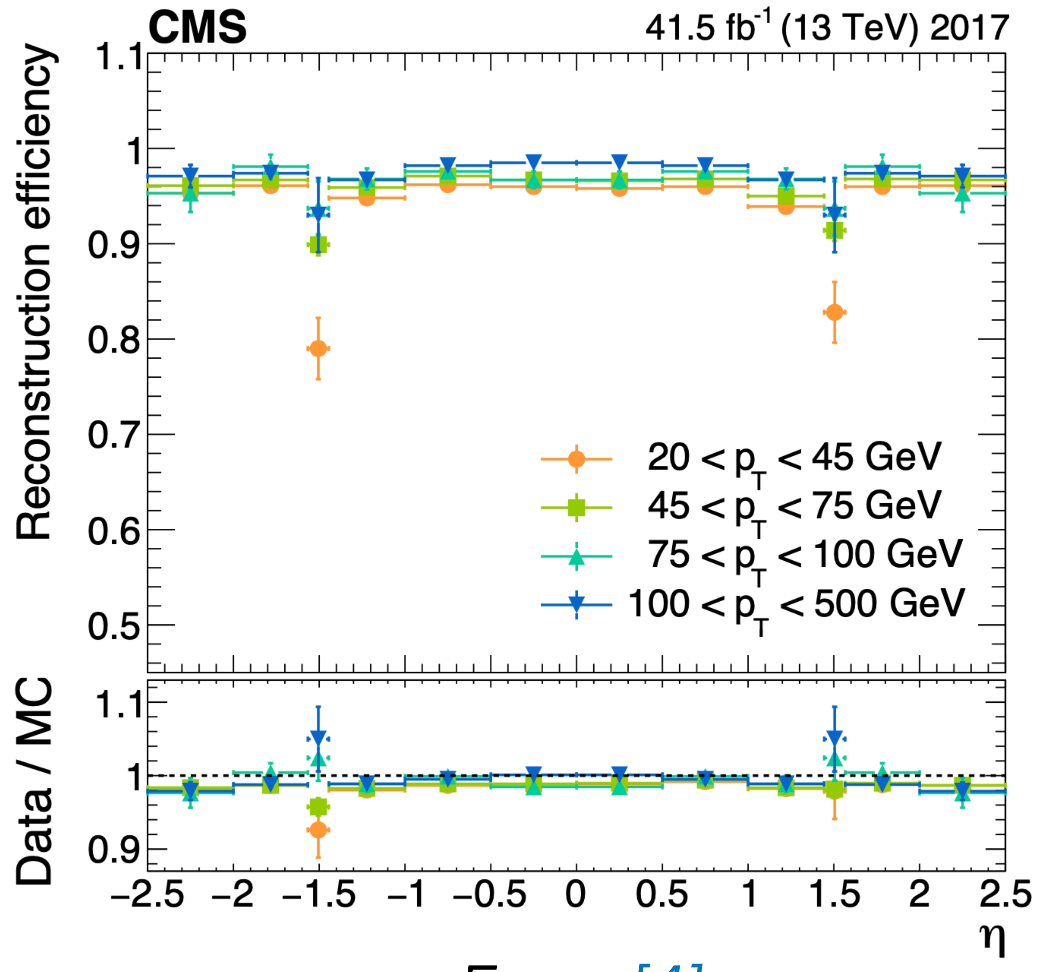


From [3]

Limits:

- Cannot provide N mass peak (missing energy with the ν)
- l_1 cannot be hadronic τ: too high SM background



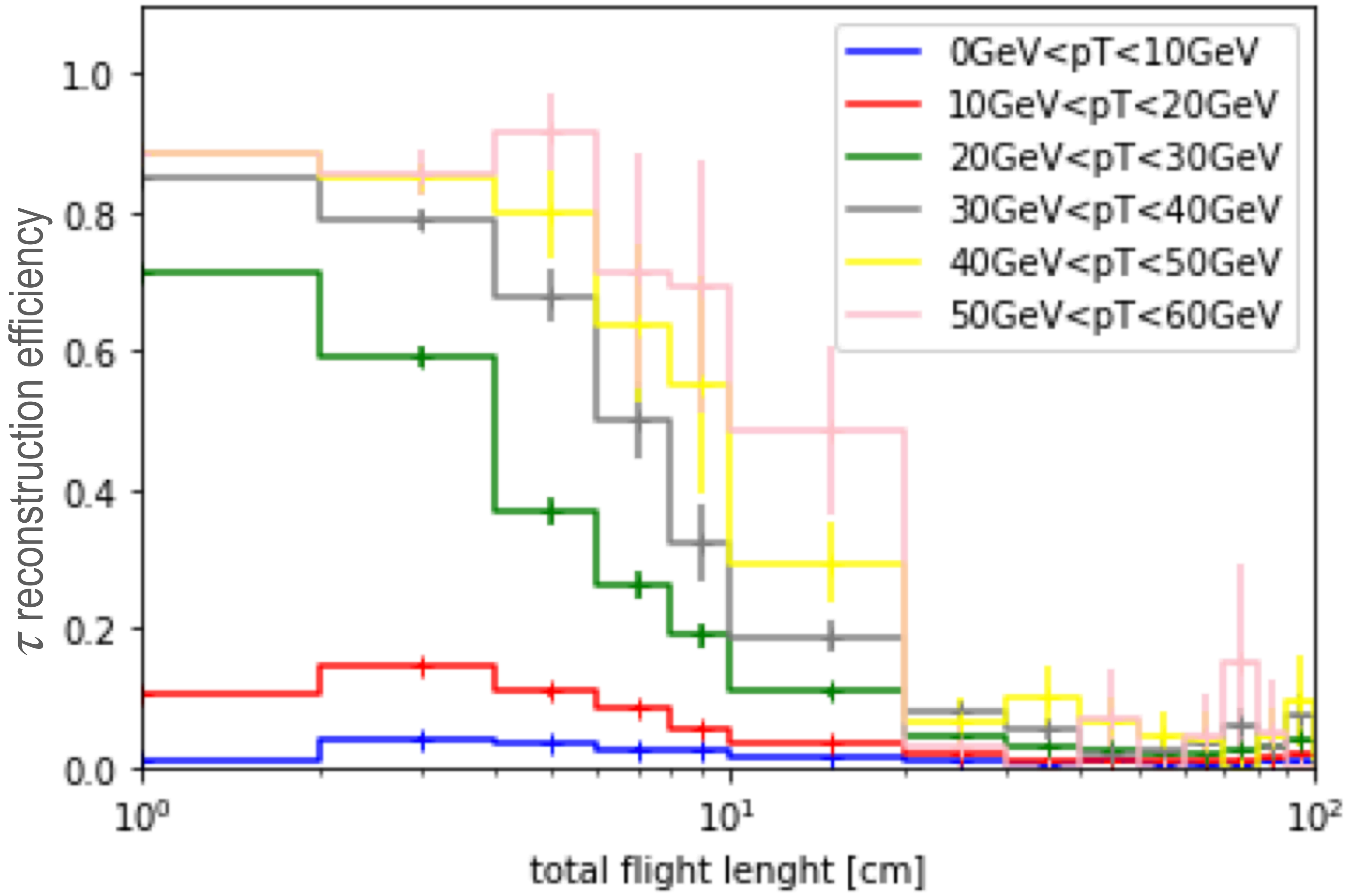


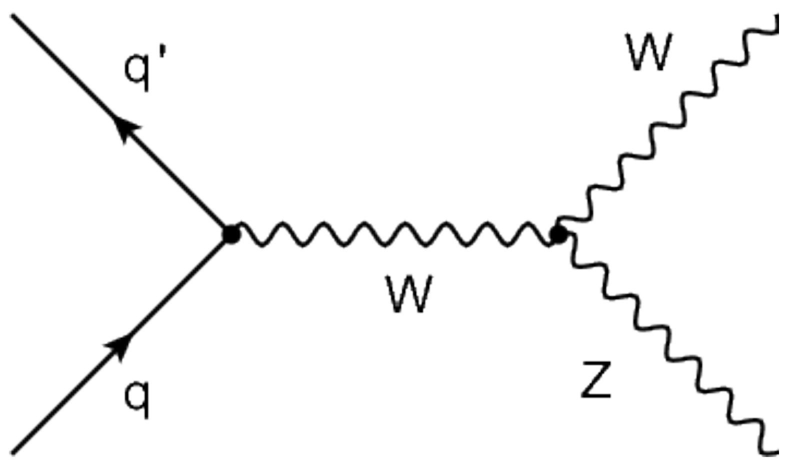
From [4]

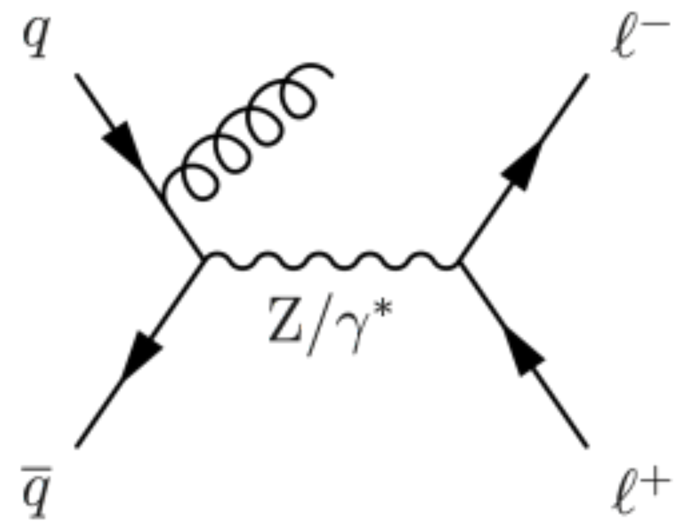
Challenges:

- Reconstruction efficiency and identification of displaced tracks
  -tau reconstruction at CMS is not optimised for very displaced tracks
  -Development of the neural network based tau reconstruction and identification algorithms for the Run 2 dataset.
- Trigger acceptance and thresholds
  -Development of displaced tau triggers at HLT for the LHC Run 3.
- Background understanding and estimation
  -WZ and jets
  -$t\bar{t}$ production
  -Drell-Yan
  -W

From [7]



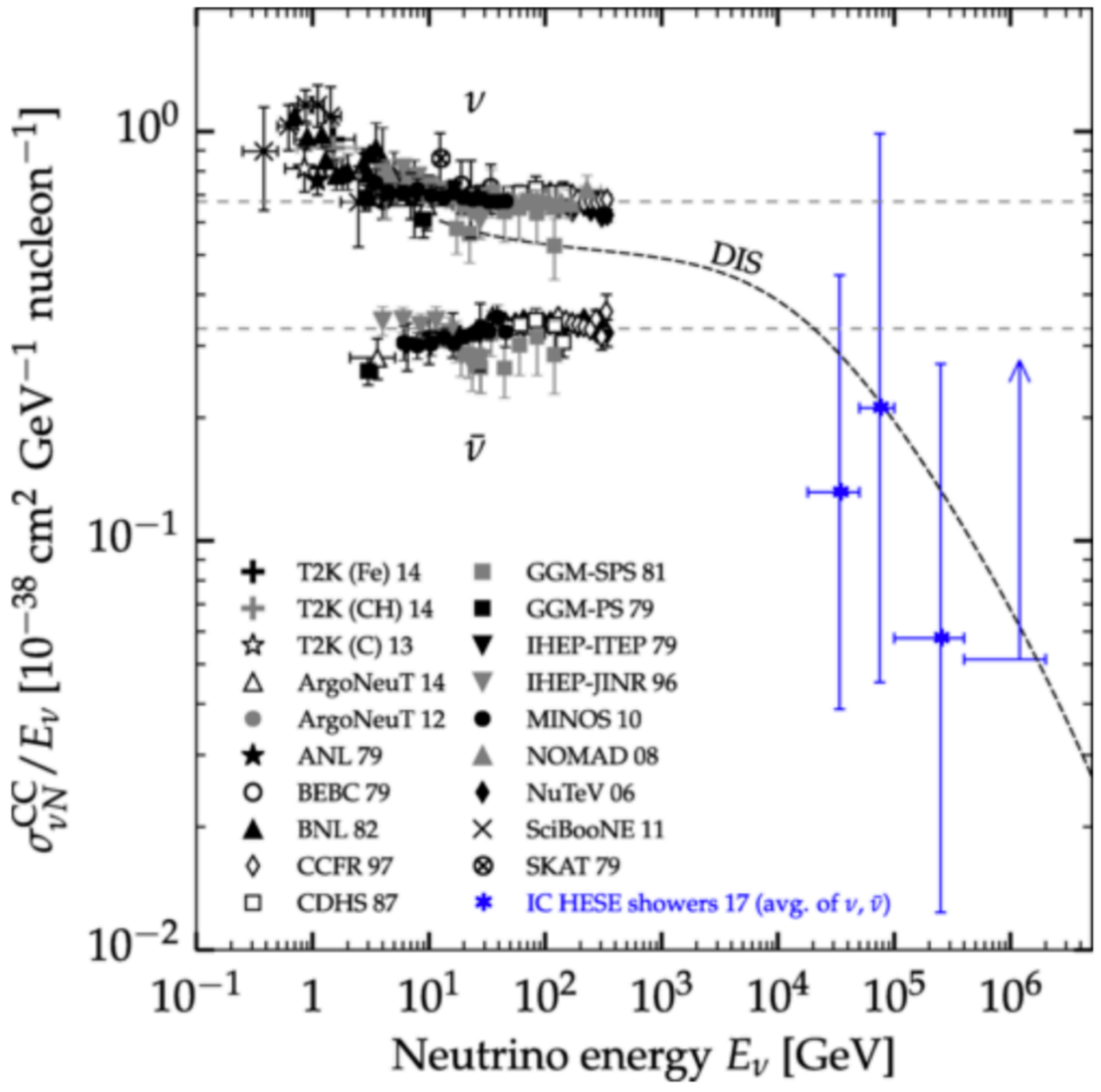




SND@LHC: Physics goals

Neutrino physics:

- Allows the detection of all three neutrino flavours in the pseudo-rapidity range of $7.2 < \eta < 8.6$ (350GeV-10TeV), currently unexplored [8]
- Precise tests of the Standard Model
  -Measure Charmed-hadron production in pp collisions
  -Lepton flavour universality test in ν interactions
  -Measurement of the neutral-current/charged-current ratio



From [9]

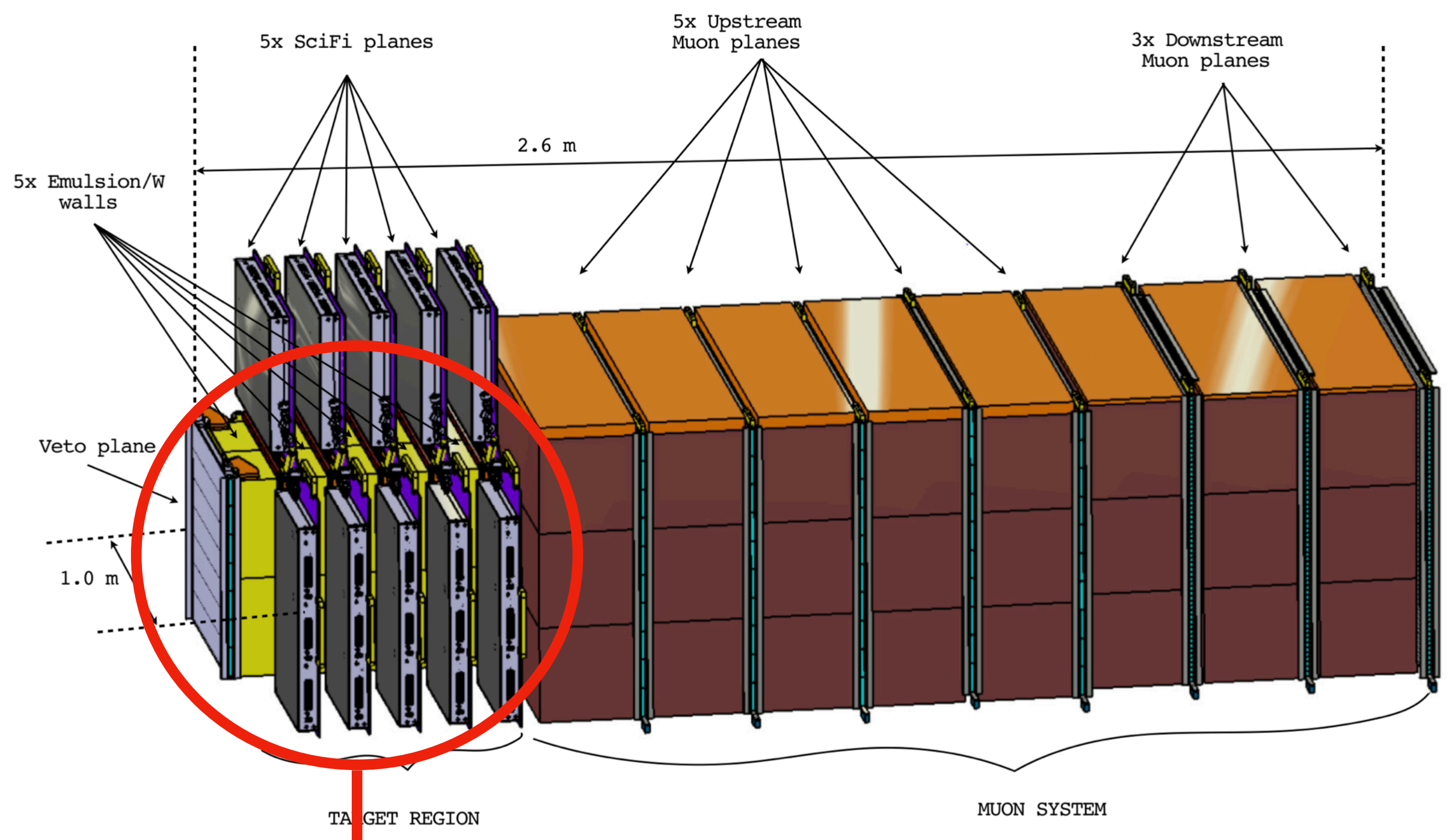
FIPs physics:

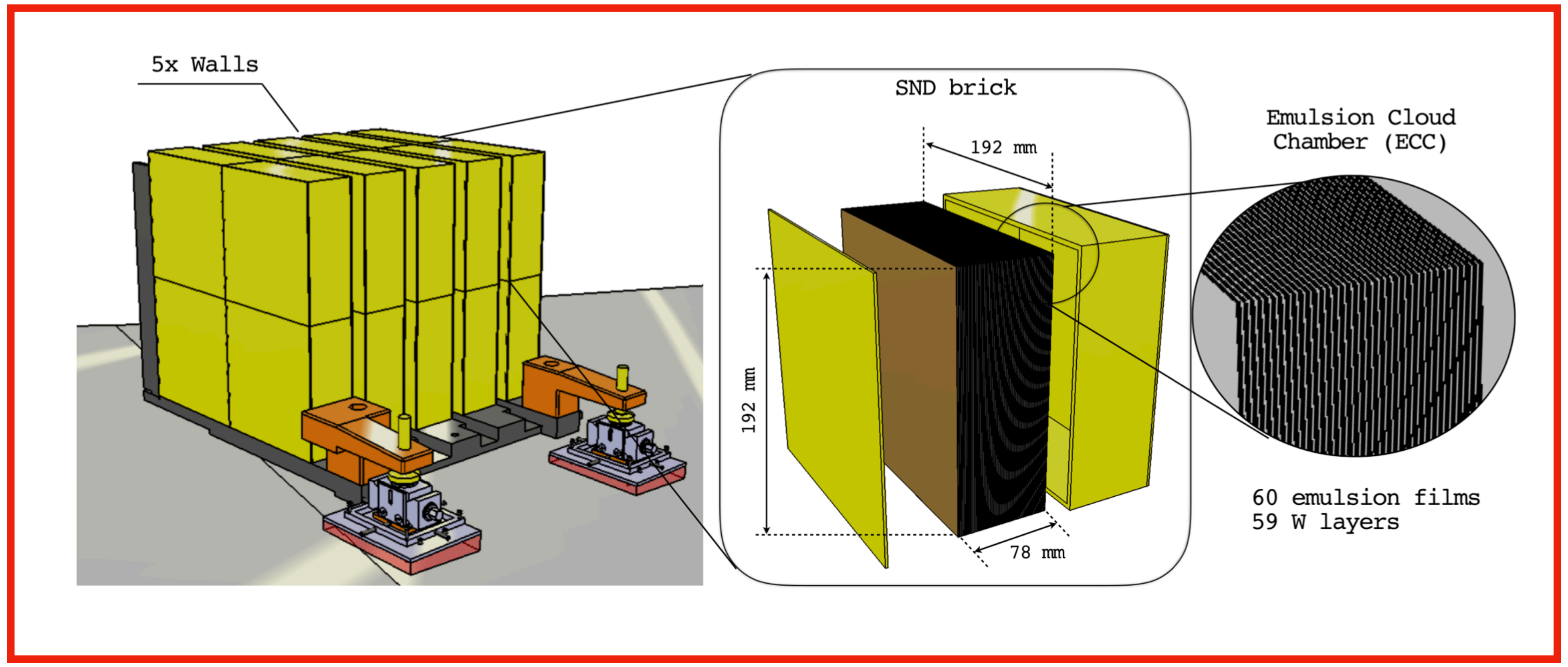
- Predicted by new physics theory
- Potential dark matter candidate
- FIPs detection via signatures of scattering (electrons or nucleons) in the detector target

Working principle

Tracker system:

- Each of the 5 emulsion walls brick is made 4 emulsion bricks, which is composed of 60 emulsion films interleaved with 59 1mm-thick tungsten layers. A brick correspond to $\sim 17\ X_0$





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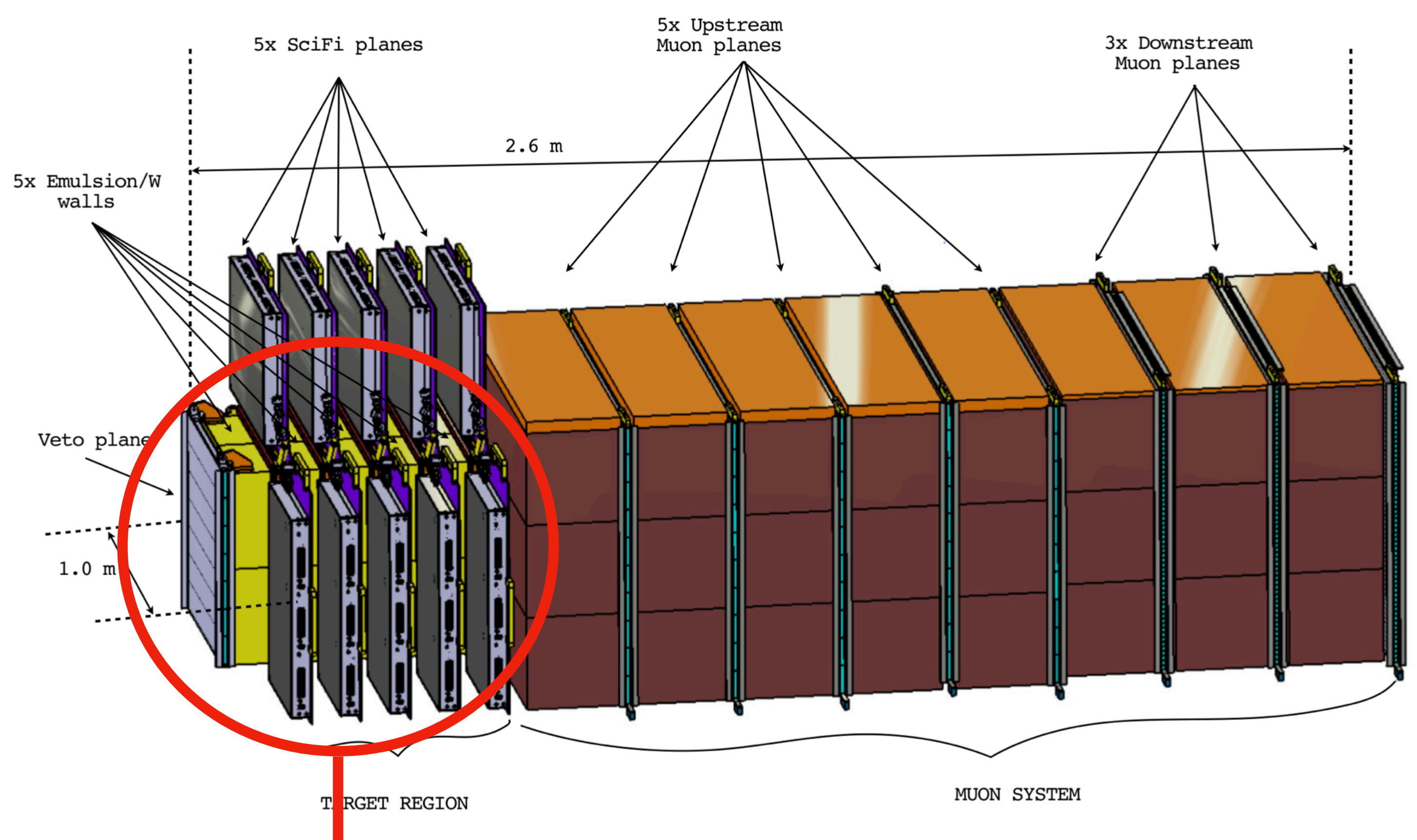

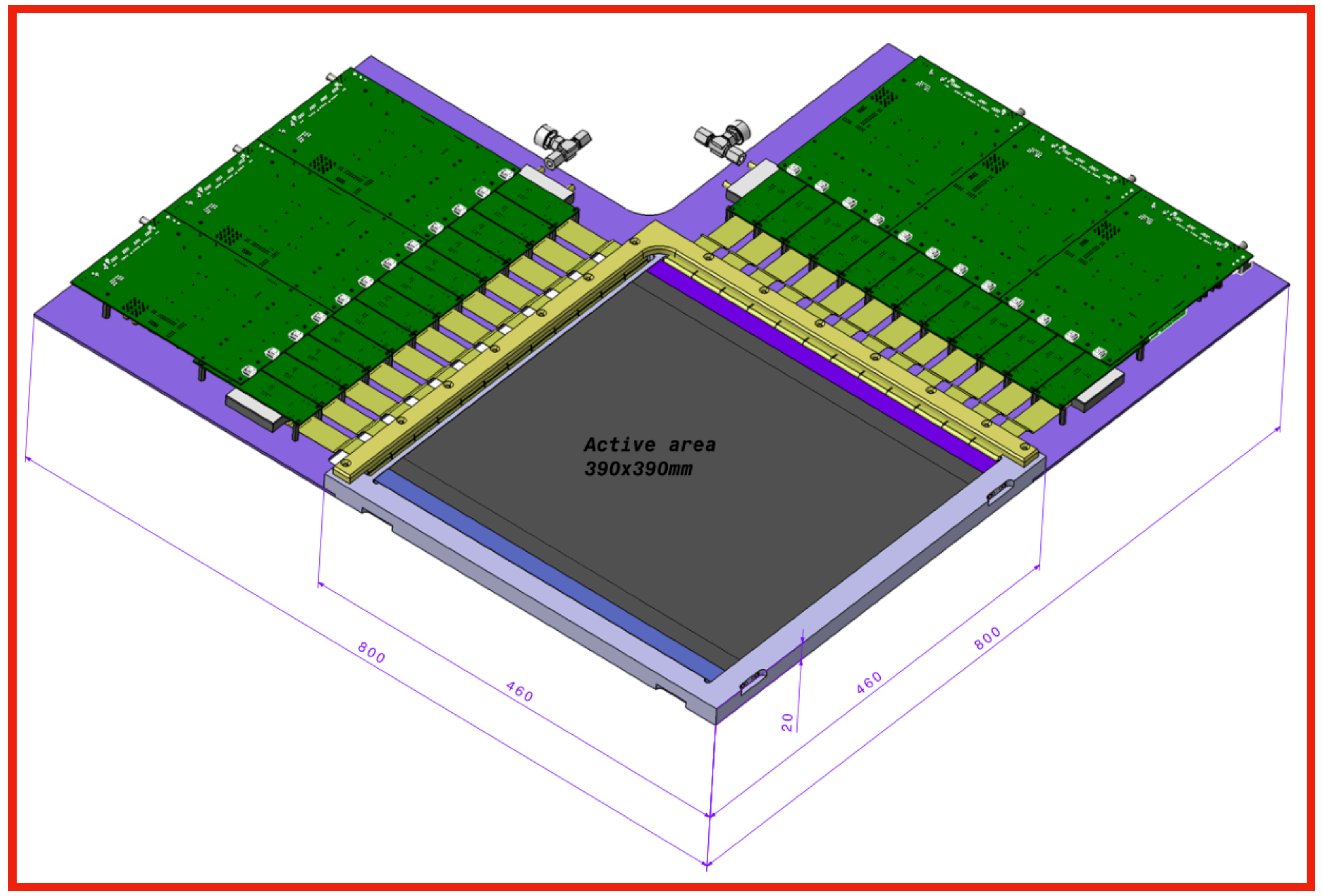

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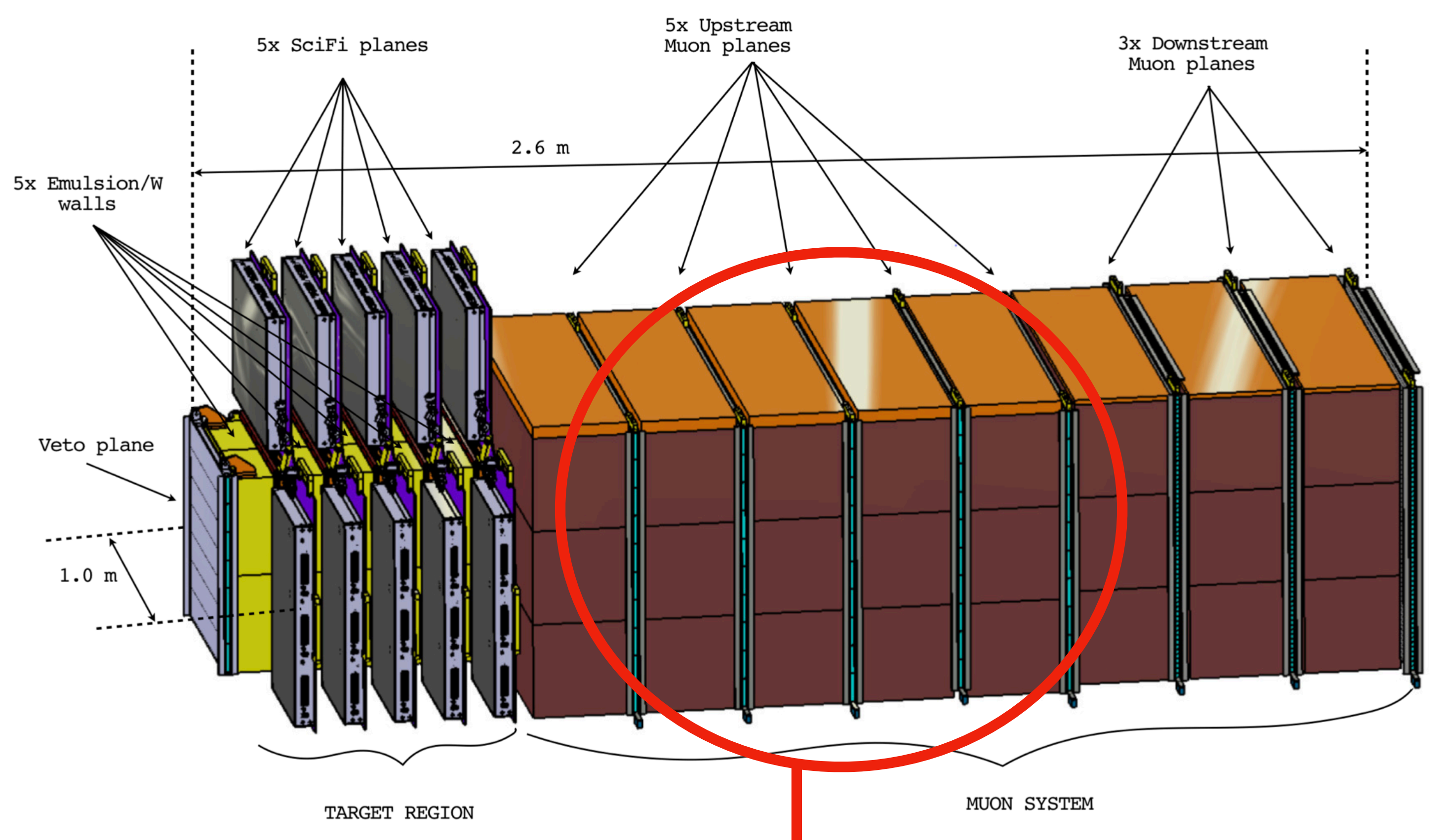

Muon system:

- Eight scintillating planes will be interleaved between layers of iron slabs 20 cm thick, which will act as passive material
  -The first five upstream planes will be used as a timing detector for traversing particles. One layer comprises ten bars, each with dimensions 81 × 6 × 1 cm

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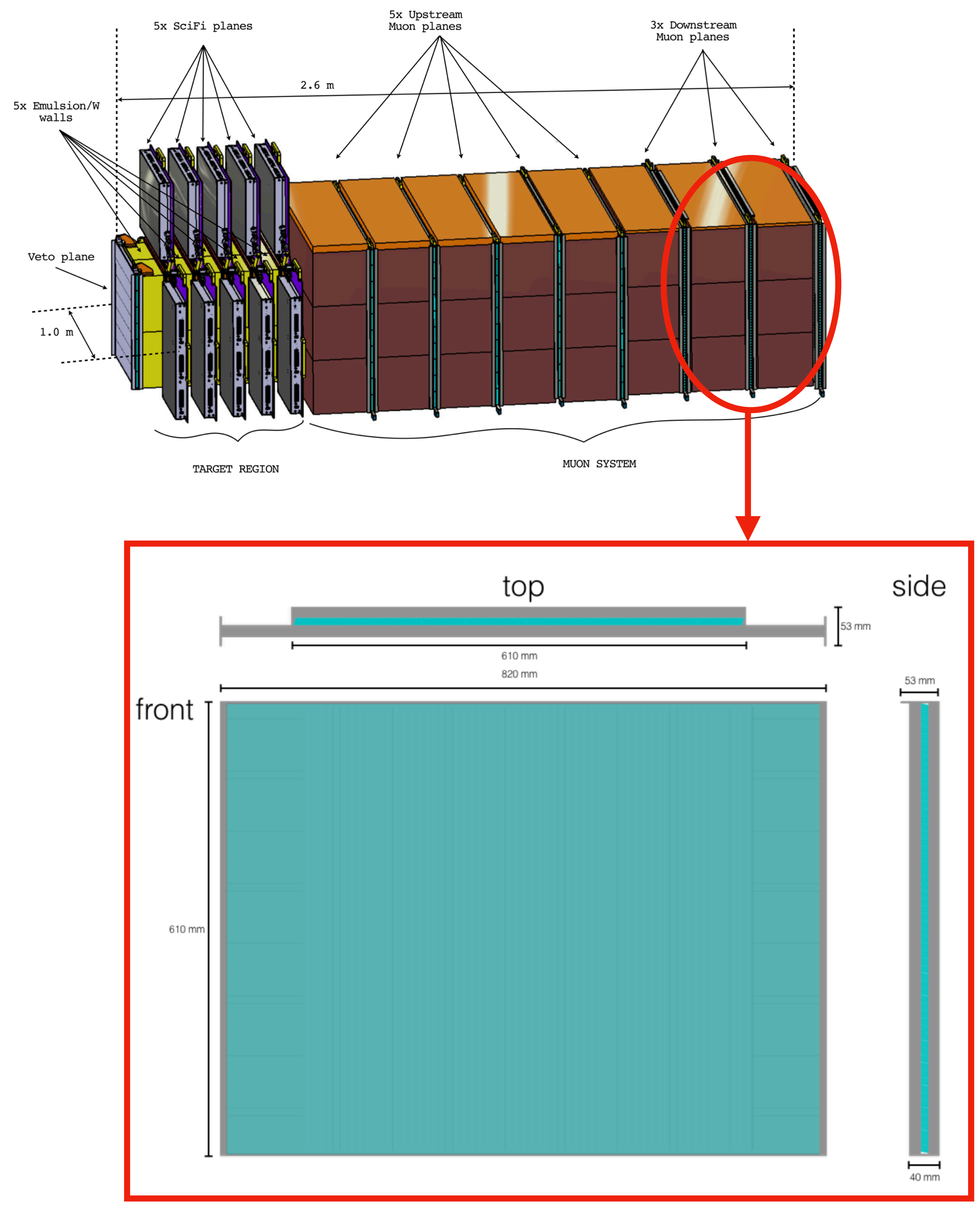
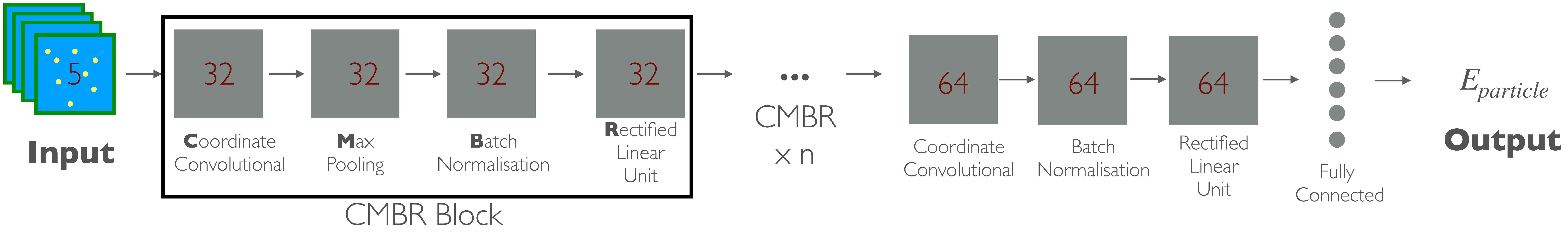
  -The last three downstream planes consist of two layers of thin bars, one arranged horizontally and one arranged vertically, allowing for a spatial resolution of less than 1 cm.



CNN used

Architecture:



Loss functions:

mse_loss

$$l(x,y) = L = \{l_1, \dots, l_n\}^T, \quad l_n = (x_n - y_n)^2$$

smooth_l1_loss

$$l(x,y) = \sum_n z_n$$

$$l(x,y) = \begin{cases} \dfrac{0.5\,(x_n - y_n)^2}{\beta} & if \ |x_n - y_n| < \beta \\ |x_n - y_n| - 0.5\beta & otherwise \end{cases}$$

mse_loss: larger mistakes result in more error than smaller mistakes, which mean that the model is punished for making larger mistakes.

smooth_l1_loss: less punitive for larger mistakes (linear and not quadratic)