Energy Calibration of the SND@LHC and Search for the Dark Higgs

LIP Summer Internships 2025

João Galhardo Rodrigo Castanheira

Supervisors:

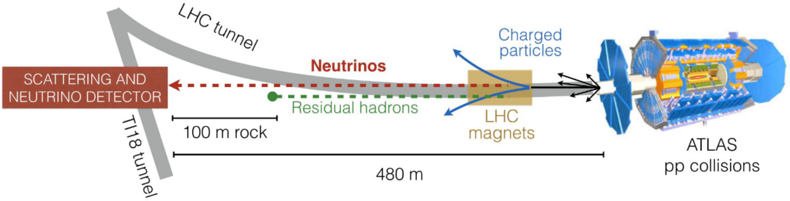
Cristóvão Vilela
Nuno Leonardo

Table of Contents

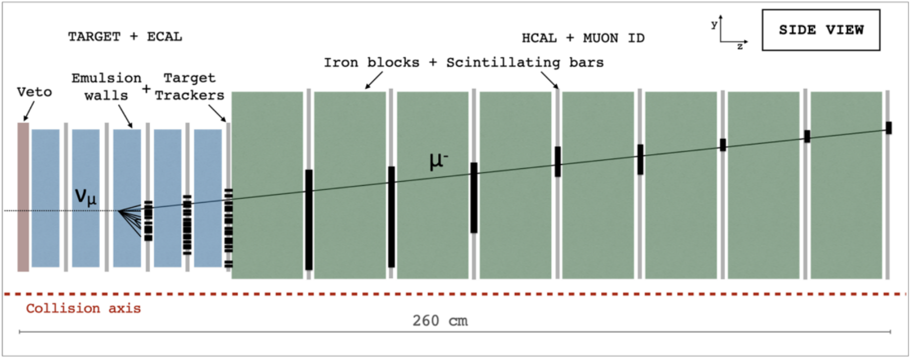
SND@LHC

The SND@LHC

- The Scattering and Neutrino Detector at the LHC studies high energy neutrinos and feebly interacting particles produced in LHC collisions.
- It is located in a tunnel 480 meters downstream of the ATLAS detector, approximately collinear with the collider beams.

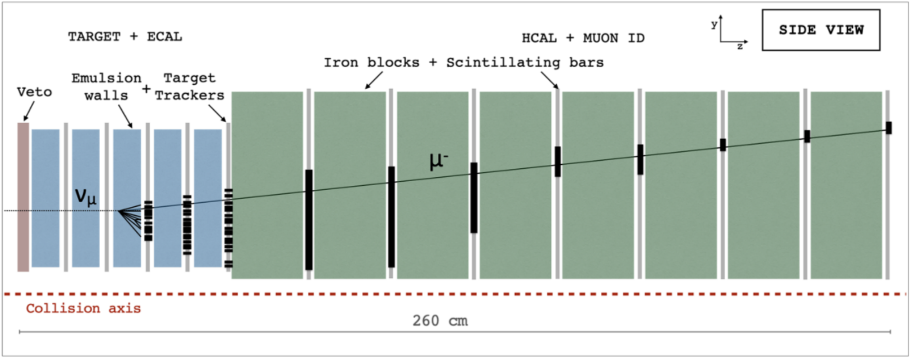


SND@LHC Components



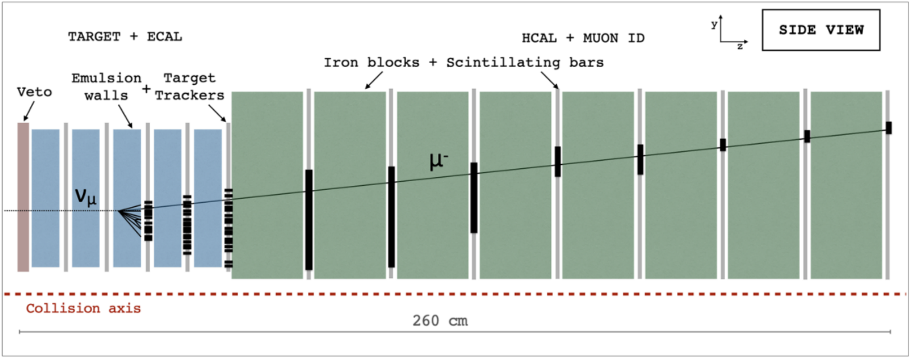
- Veto: Comprised of two scintillator planes, it detects any charged particles entering the detector.

SND@LHC Components



- Electronic Calorimeter and Target: Composed of emulsion Tungsten walls and scintillator fibers, it follows the electromagnetic showers with a temporal and spatial profile.

SND@LHC Components



- Hadronic Calorimeter and Muon System: Composed of Iron walls and scintillator bars, it develops the hadronic showers, detects their energy and identifies muons leaving the detector.

Birk's Law and Energy Calibration

Birk's Law

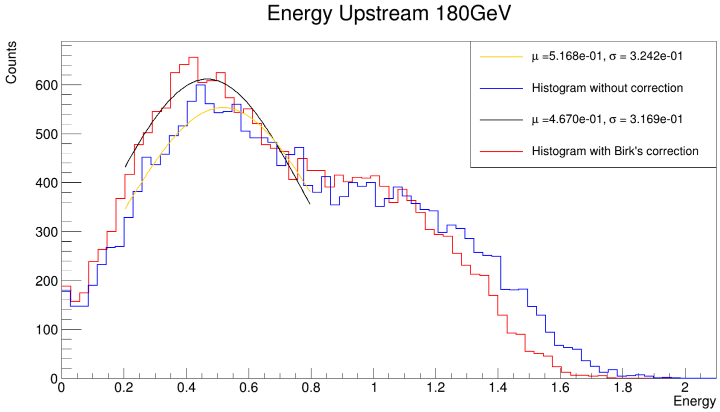
A particle that deposits energy in a scintillator bar will produce light, which in turn is converted into an electric signal, the QDC. This light yield doesn't relate linearly with the deposited energy and is described through Birk's law:

$$QDC \propto \frac{dL}{dr} = \frac{S \times \frac{dE}{dr}}{1 + kB \times \frac{dE}{dr}}$$

- QDC - Signal produced by the photo multipliers on the scintillators
- $\frac{dL}{dr}$, $\frac{dE}{dr}$ - Light yield and Energy deposited per unit of length travelled by the particle in the scintillator bar
- kB - Birk's coefficient
- S - Scintillator efficiency

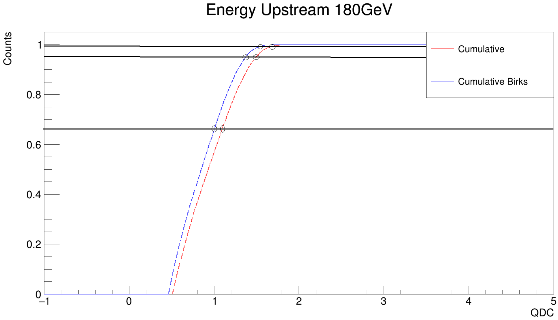
Simulation data

- Birk's Law was applied to a simulation software to observe whether or not its effect is impactful, bringing the simulation closer to reality.
- For numerous simulated events, all individual energy deposits were summed up simply or with Birk's correction, constituting the resulting energy of the event, and then gathered into a histogram:



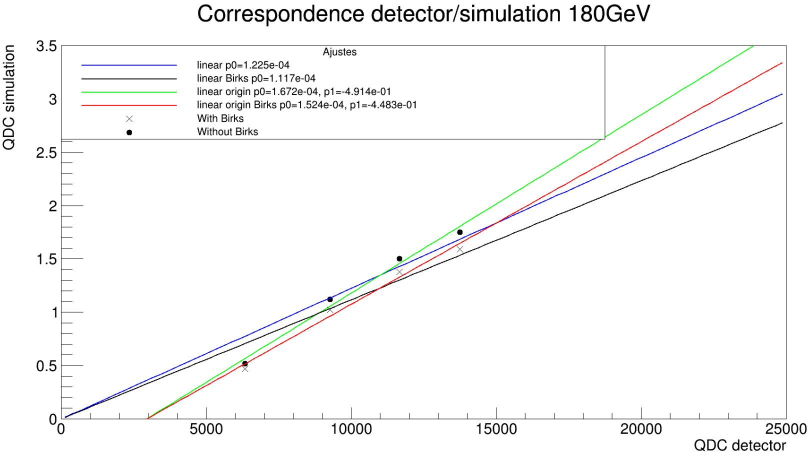
Analysis

From the highest point of both histograms, determined through a localized gaussian fit, the normalized cumulative distribution was made. Then, along with the zeroes, three more points were chosen for comparison with real data.



Comparison

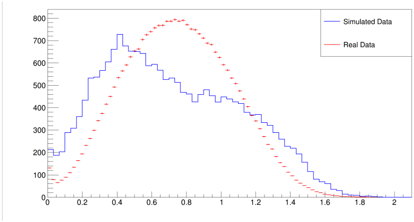
The simulated values are then joined with the real values in two sets of points. To evaluate the relation between them two linear fits are made for each set:

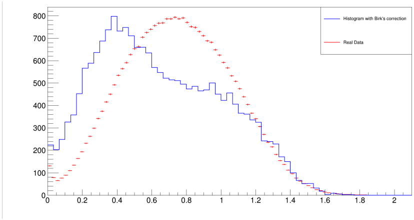


Histogram Comparison

We can now scale the data to compare the histograms directly:

- The most noticeable effect is the retraction of the tail accompanied by little to no movement of the peak.

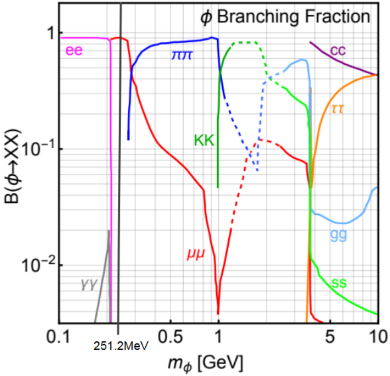




Search for Dark Higgs with SND@LHC

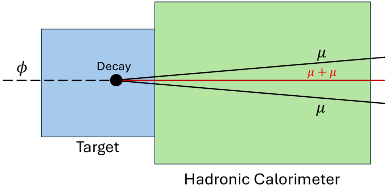
The Dark Higgs

- The Dark Higgs boson ϕ is the chosen Dark Matter candidate, a scalar particle that mixes with the Standard Model Higgs.
- It is produced from decays of mesons such as the B, the K and light mesons, in descending order of dominance.
- A mass of $m_\phi = 251.2\,\text{MeV}$ is chosen so that the only possible decay is to a dimuon pair, $\phi \to \mu^- \mu^+$.

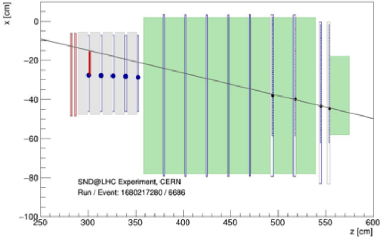


Dimuon Signal

- Due to the geometry of the detector, the two muon tracks cannot be resolved and the signal is collinear.



- The muon track is reconstructed to the Veto from hits in the last 3 planes of the Hadronic Calorimeter.



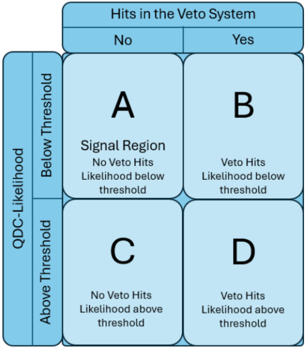
- Each Upstream (US) (5 first planes) hit has a QDC value that allows for the distinction between single muon background and dimuon signal.

Selection Cuts

To exclude the single muon and neutrino backgrounds:

Run 5000 ($N = 4.5 \times 10^7, L = 0.6\,\mathrm{fb}^{-1}$)	
Applied Cuts	Surviving Percentages
Veto XY limits ($[-44.5, -10.5], [18, 52]\,\mathrm{cm}$)	29.609 ± 0.007
Maximum distance squared ($0 < d \leq 3\,\mathrm{cm}^2$)	3.252 ± 0.003
Total upstream hits (≤ 10)	3.252 ± 0.003
Upstream hits per plane (≤ 1)	2.556 ± 0.002
Polar angle ($\leq 86.9\,\mathrm{mrad}$)	1.241 ± 0.002
Total SciFi hits (≤ 96)	1.241 ± 0.002
QDC Likelihood (≤ -7.5)	$(4.281 \pm 0.307) \times 10^{-4}$
Veto hit (false)	0 ± 0

Single Muon Background Selection



$$\frac{N_A^{bkg}}{N_B^{bkg}} = \frac{N_C^{bkg}}{N_D^{bkg}}$$

$$N_i^{bkg} \approx N_i, i = B, C, D \Rightarrow N_A^{bkg} \approx \frac{N_C}{N_D} N_B$$

Single Muon Background

Run 5000 ($N = 4.5 \times 10^7, L = 0.6\,\text{fb}^{-1}$)	
Region	Counts
B	194
C	487
D	562473

$$N_A^{bkg} \approx \frac{N_C}{N_D} N_B \approx 0.168 \pm 0.014$$

where the uncertainty is given by $\sqrt{N_B N_C (N_B + N_C)}/N_D$.

Neutrino Background

Applying the chosen selection cuts to a $30\,\mathrm{fb}^{-1}$ neutrino Monte Carlo simulation:

Neutrino Monte Carlo ($N = 10878$, $L = 30\,\mathrm{fb}^{-1}$)		
Applied Cuts	Muons (%)	Neutrinos (%)
Veto XY	26.609 ± 0.007	76.99 ± 0.40
Maximum distance	3.252 ± 0.003	1.89 ± 0.13
Total US hits	3.252 ± 0.003	1.49 ± 0.12
US hits per plane	2.556 ± 0.002	0.864 ± 0.089
Polar angle	1.241 ± 0.002	0.864 ± 0.089
Total SciFi hits	1.241 ± 0.002	0.855 ± 0.088
QDC Likelihood	$(4.281 \pm 0.307) \times 10^{-4}$	0.00919 ± 0.00919

Extrapolation and Results

- Extrapolating the results to $200\,\mathrm{fb}^{-1}$:

$$N_{\mu}^{bkg} \approx 56.00 \pm 4.67$$
$$N_{\nu}^{bkg} \approx 6.67 \pm 6.67$$

- The smallest number of counts that excludes the hypothesis that there are only background events, at a 5σ significance, is:

$$N_{5\sigma} = 106$$

- The high number of counts can be due to an abnormally large Veto inefficiency during run 5000.

Conclusions

Conclusions:

- Birk's Law has a measurable effect on the calibration of the SND@LHC detector allowing for a more accurate simulation.
- The SND@LHC is an experiment with potential for feebly interacting particle studies.
- The established selection cuts are very efficient at excluding background events.
- Over $200\,\text{fb}^{-1}$, $N_{5\sigma} = 106$ counts are needed for claims of a discovery.

Future work:

- The Dark Higgs analysis can be optimized and applied to a larger sample of SND@LHC data, including Birk's Law calibration.
- The signal selection efficiency can be determined using simulation and taken into account.

References

[1] F. Alicante, (2023).

[2] R. Albanese, A. Alexandrov, F. Alicante, A. Anokhina, T. Asada, C. Battilana, A. Bay, C. Betancourt, R. Biswas, A. Blanco Castro, M. Bogomilov, D. Bonacorsi, W. M. Bonivento, P. Bordalo, A. Boyarsky, S. Buontempo, M. Campanelli, T. Camporesi, V. Canale, ... J. Zamora Saa (SND@LHC Collaboration), Phys. Rev. Lett. **131**, 031802 (2023).

[3] H. Santos, (2024).