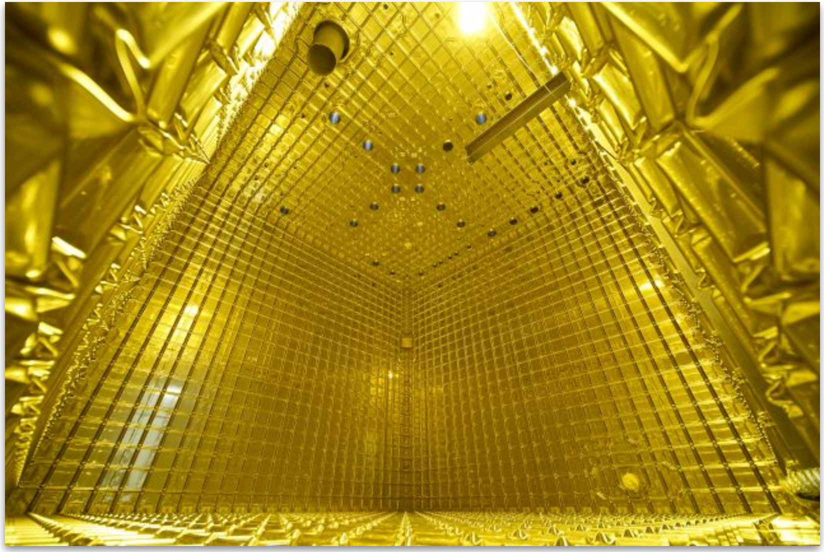
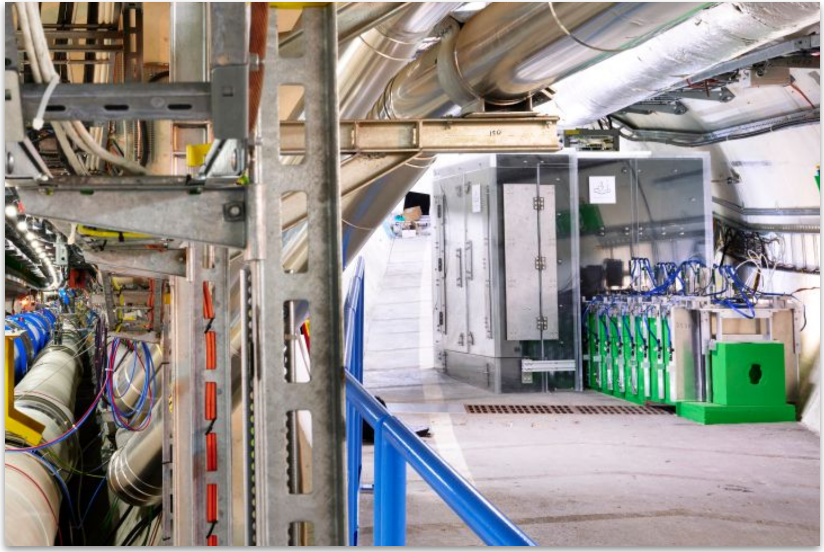
Neutrinos at the Intensity and Energy Frontiers

ProtoDUNE cryostat at the CERN neutrino platform



SND@LHC installed in the LHC TI18 tunnel



DEEP UNDERGROUND NEUTRINO EXPERIMENT

LHC
Scattering and Neutrino Detector at the LHC

CERN

LIP Assistant Researcher Call Public Presentation
November 3rd, 2022

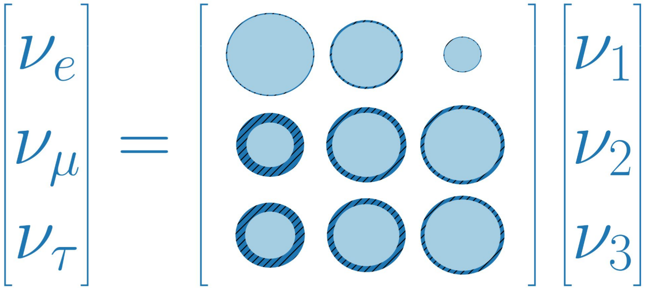
Cristóvão Vilela

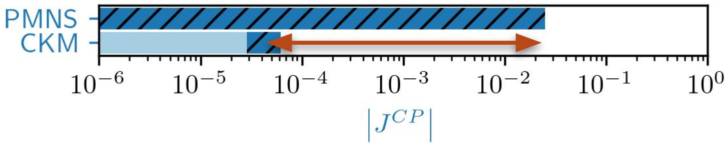
Flavour, mass and ~~CP~~

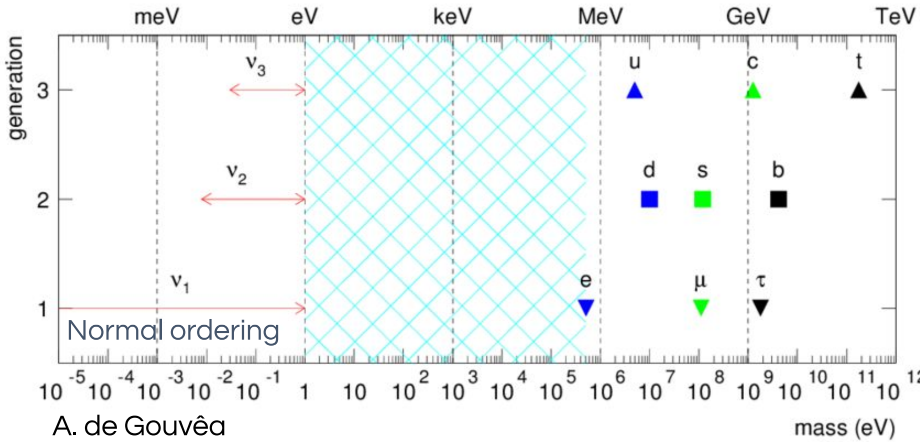
- Neutrino oscillations → $m_\nu \neq 0$ → rich ν phenomenology
- Standard Model puzzles need neutrino experiments!
  - The origin of **matter**: last chance for large ~~CP~~ in the SM **[1]***
  - The nature of **mass**: why are m_ν so small? $m_1 > m_3$? $\nu = \overline{\nu}$ **[10]** ?
  - The **flavour** structure of the SM:
    - Lepton **mixing** very **different** from the quark sector
    - Lepton Flavour Universality **never tested** with νs
      - Hints of ~~LFU~~: B decays, μ g-2

2015

PMNS NuFit 5.1 (2021)

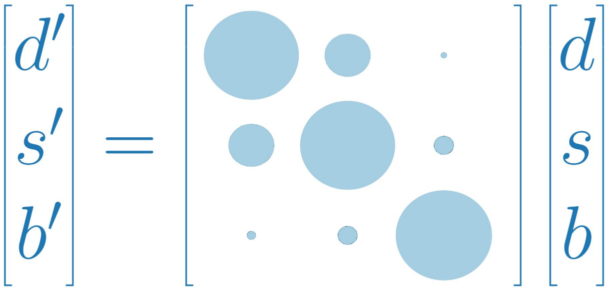






A. de Gouvêa

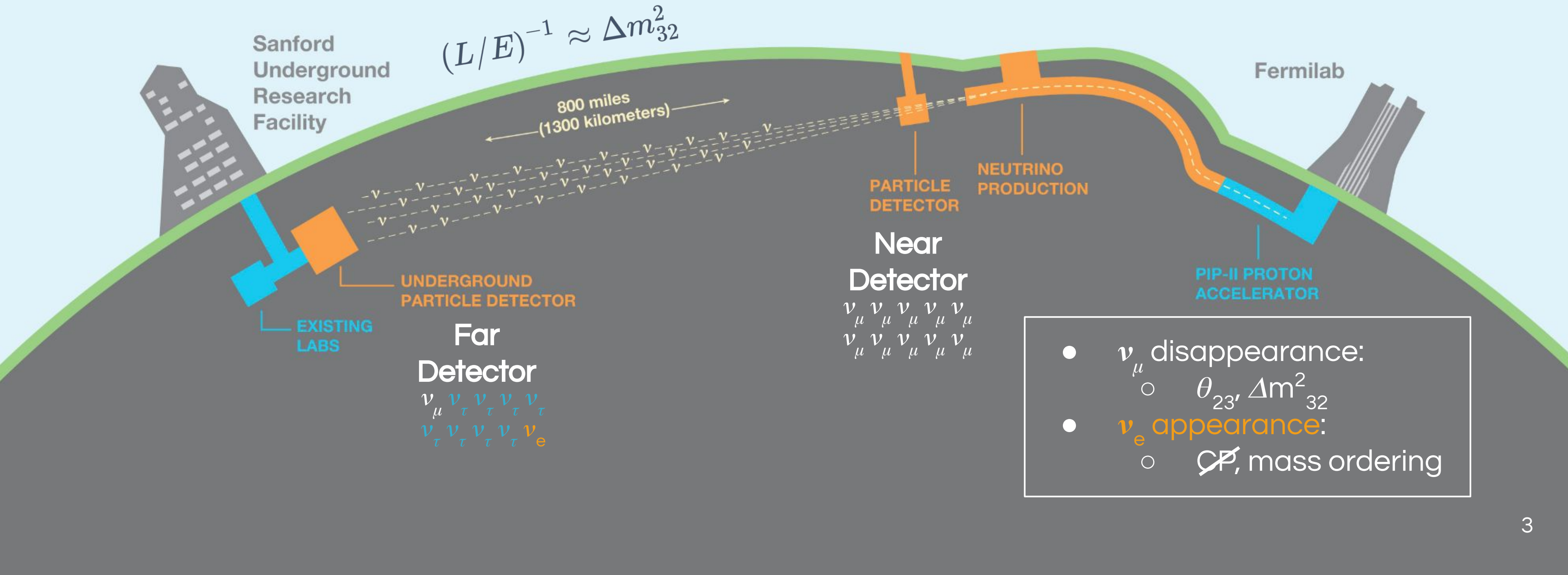
CKM CKMfitter Spring 21



* Numbers in brackets refer to my publications, listed in the last slide.

Long-baseline neutrino oscillations

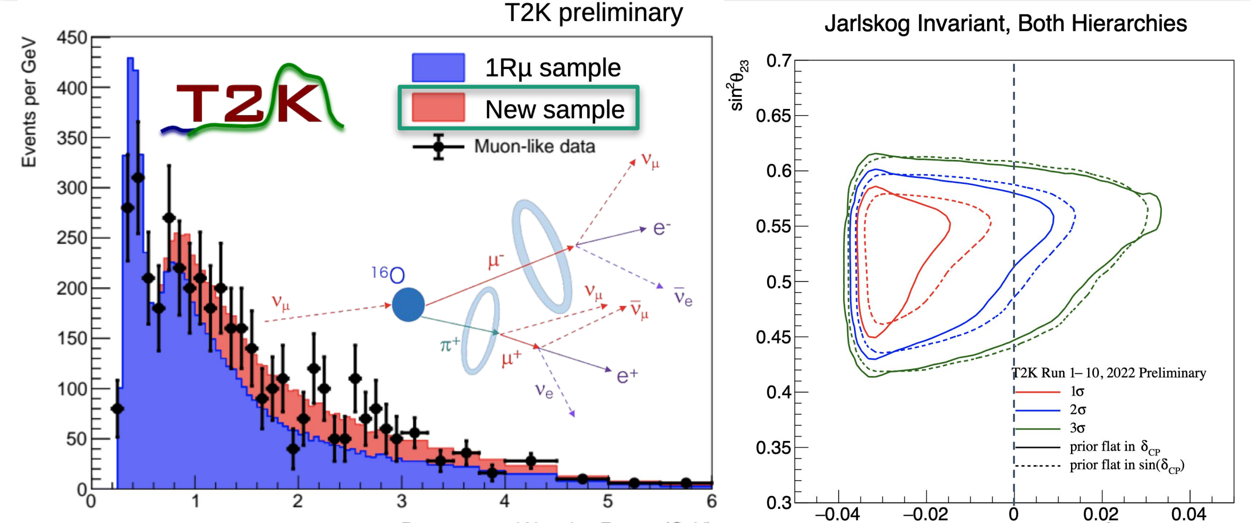
DEEP UNDERGROUND NEUTRINO EXPERIMENT



- ν_μ disappearance:
  - θ_{23}, Δm^2_{32}
- ν_e appearance:
  - ~~CP~~, mass ordering

Neutrino oscillation state-of-the-art

- T2K **world-leading** results enabled by substantial improvements in FD analysis methods:
  - Updated **reconstruction** and expansion of the fiducial volume **[1, 2, 3]**
  - New **sample**, with 2 resolved final-state particles (**Neutrino 2022**)
- I have **convened** the T2K FD working group for the last 3 years



Presented at Neutrino 2022

[1] 2020

- **DUNE** will **conclusively** determine the **mass ordering** and measure ~~CP~~
- With great **statistics** come great **systematic uncertainty** challenges!

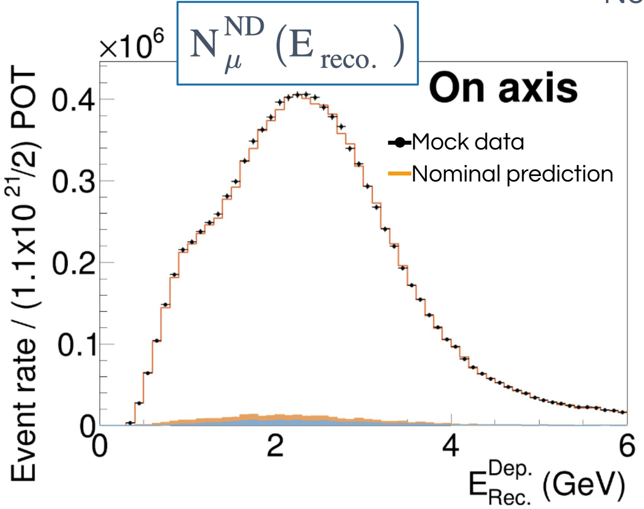
Understanding **bias** in ν oscillation experiments

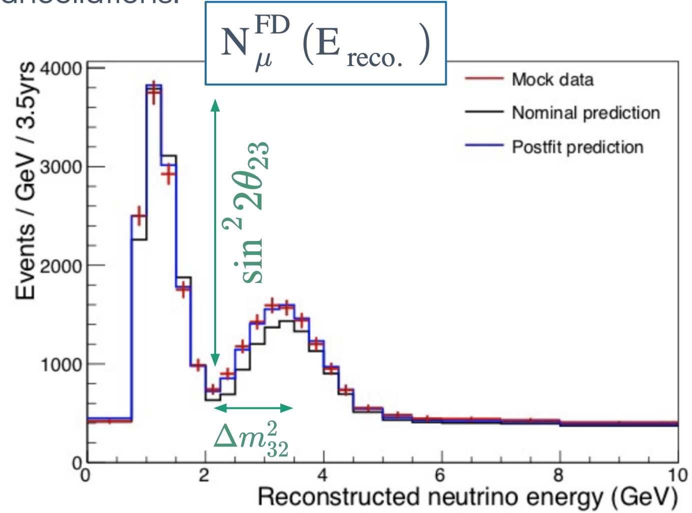
What we observe

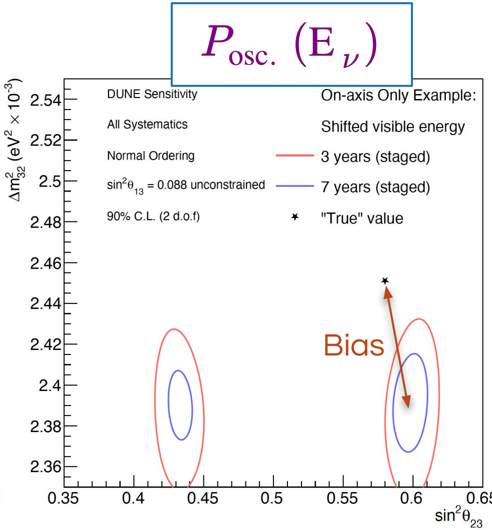
$$\frac{N^{FD}_{e,\mu}(E_{reco.})}{N^{ND}_{\mu}(E_{reco.})} = \frac{\int dE_{\nu}\, R^{FD}(E_{\nu}, E_{reco.})\, \phi_{\nu_\mu}(E_{\nu})\, \sigma_{\nu_{e,\mu}}(E_{\nu})\, P_{osc.}(E_{\nu})}{\int dE_{\nu}\, R^{ND}(E_{\nu}, E_{reco.})\, \phi_{\nu_\mu}(E_{\nu})\, \sigma_{\nu_\mu}(E_{\nu})}$$

What we want to know

No cancellations!







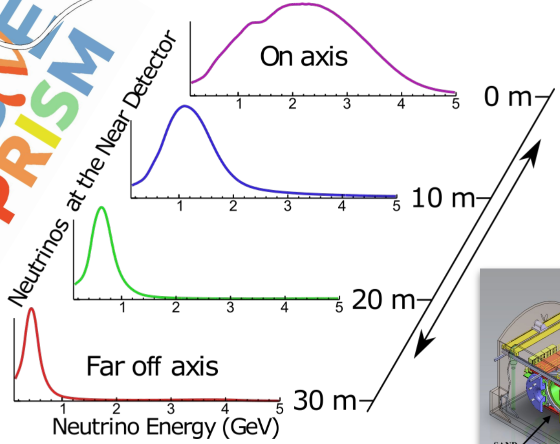
I demonstrated the potential for bias with an on-axis near detector for the DUNE design reports **[4, 5]**:

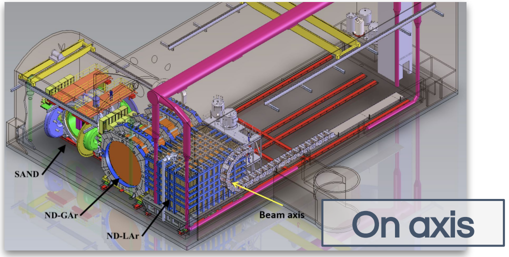
Use machine learning to generate mock data with "adversarial" interaction model.

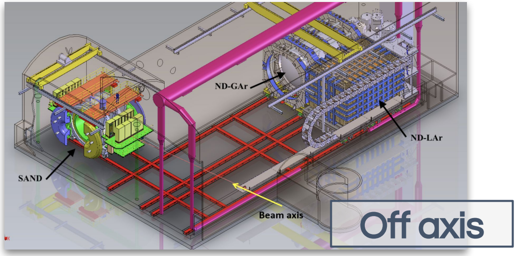
Mis-modeling is invisible in on-axis near detector.

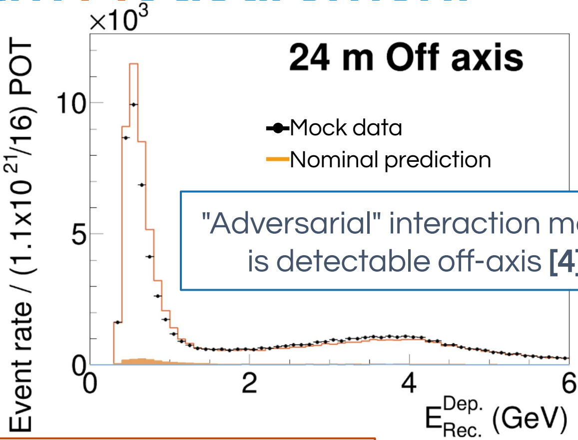
Produces biased oscillation measurements when far detector mock data is fitted with nominal model.

Precision Reaction-Independent Spectrum Measurement





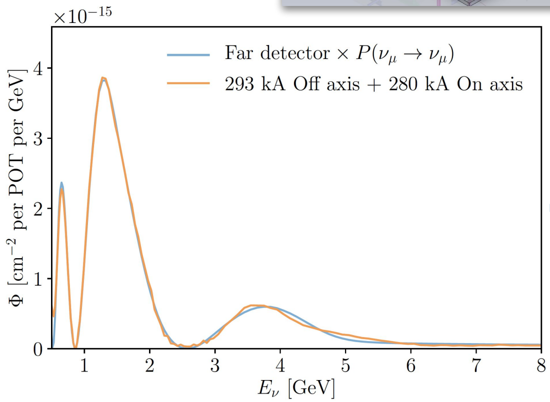




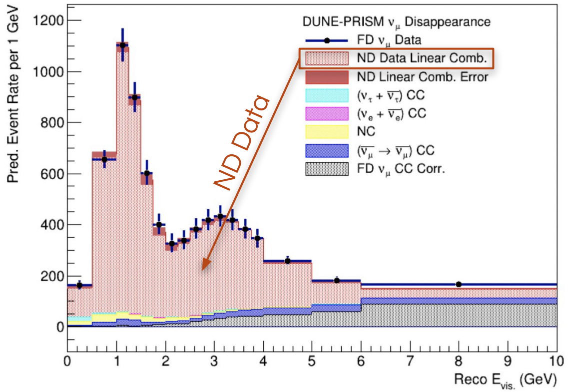
"Adversarial" interaction model is detectable off-axis **[4]**.

DUNE-PRISM reviewed as a **top priority** in the ND complex.
Now part of the DUNE **baseline**.

Combine DUNE-PRISM **fluxes**



Combine DUNE-PRISM **data**



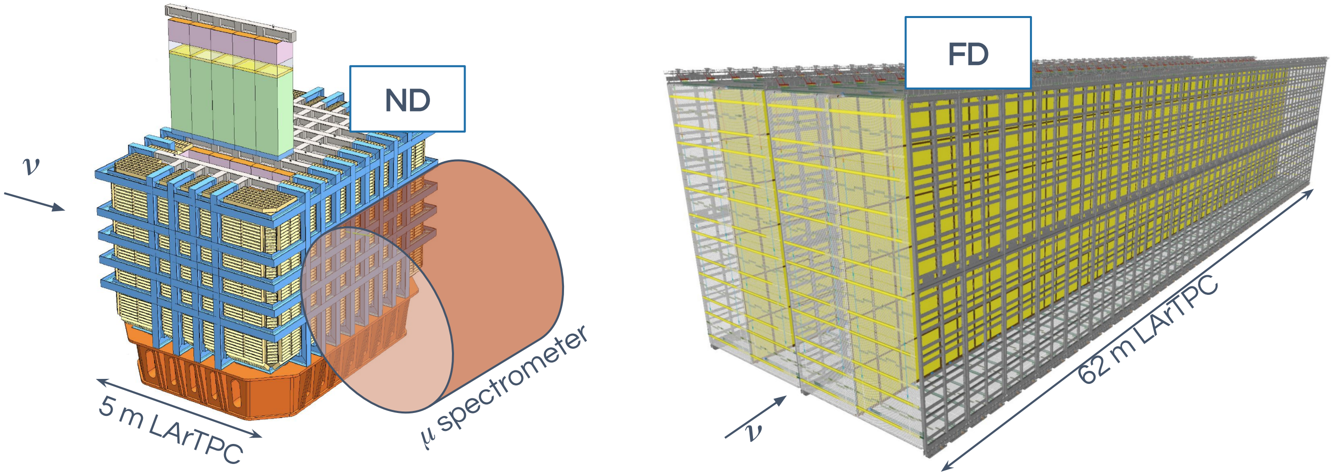
I was part of the small team (two postdocs and three faculty) that proposed DUNE-PRISM in 2017.

Detector response in data-driven analyses

67 ton LArTPC with 3D **pixel** read-out, **segmentation,** and downstream **muon spectrometer**

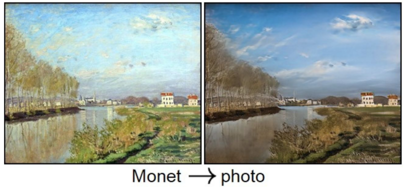
$$R^{\mathrm{ND}}(\mathrm{E}_{\nu}, \mathrm{E}_{\mathrm{reco.}}) \neq R^{\mathrm{FD}}(\mathrm{E}_{\nu}, \mathrm{E}_{\mathrm{reco.}})$$

10 kton LArTPC with 3 x 2D **wire** read-out and very large drift volumes



- I developed a data-driven method to correct for **acceptance** differences using the event geometry **[4].**
  - Implementation of the method is ongoing in collaboration with one postdoc and students at Stony Brook University, where I am a Visiting Scholar.
- Need a **model-independent** method to account for differences in the **detector responses.**
  - If an **ND** event had occurred instead in the **FD,** what would be its reconstructed energy at the FD?

Learning the differences between ND and FD



CycleGAN arXiv:1703.10593 (2017)

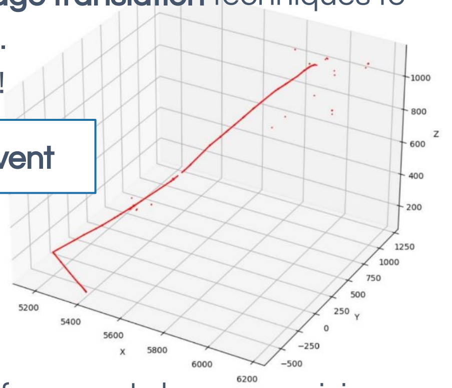
- Traditional approach: response matrices out of high-level reconstructed variables.
  - Leads to model dependence.

Model dependence ⟷ Curse of dimensionality

Trade-off

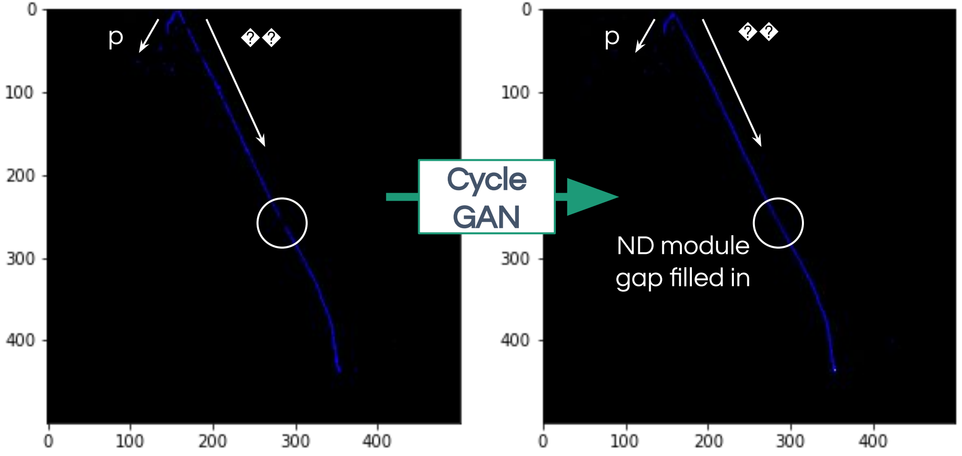
- Reduce model dependence by using **image-to-image translation** techniques to generate FD-like events from ND events at **hit level.**
  - Nothing like this was ever attempted in HEP!

3D ND Event



ND response 2D projection

FD response for the same event

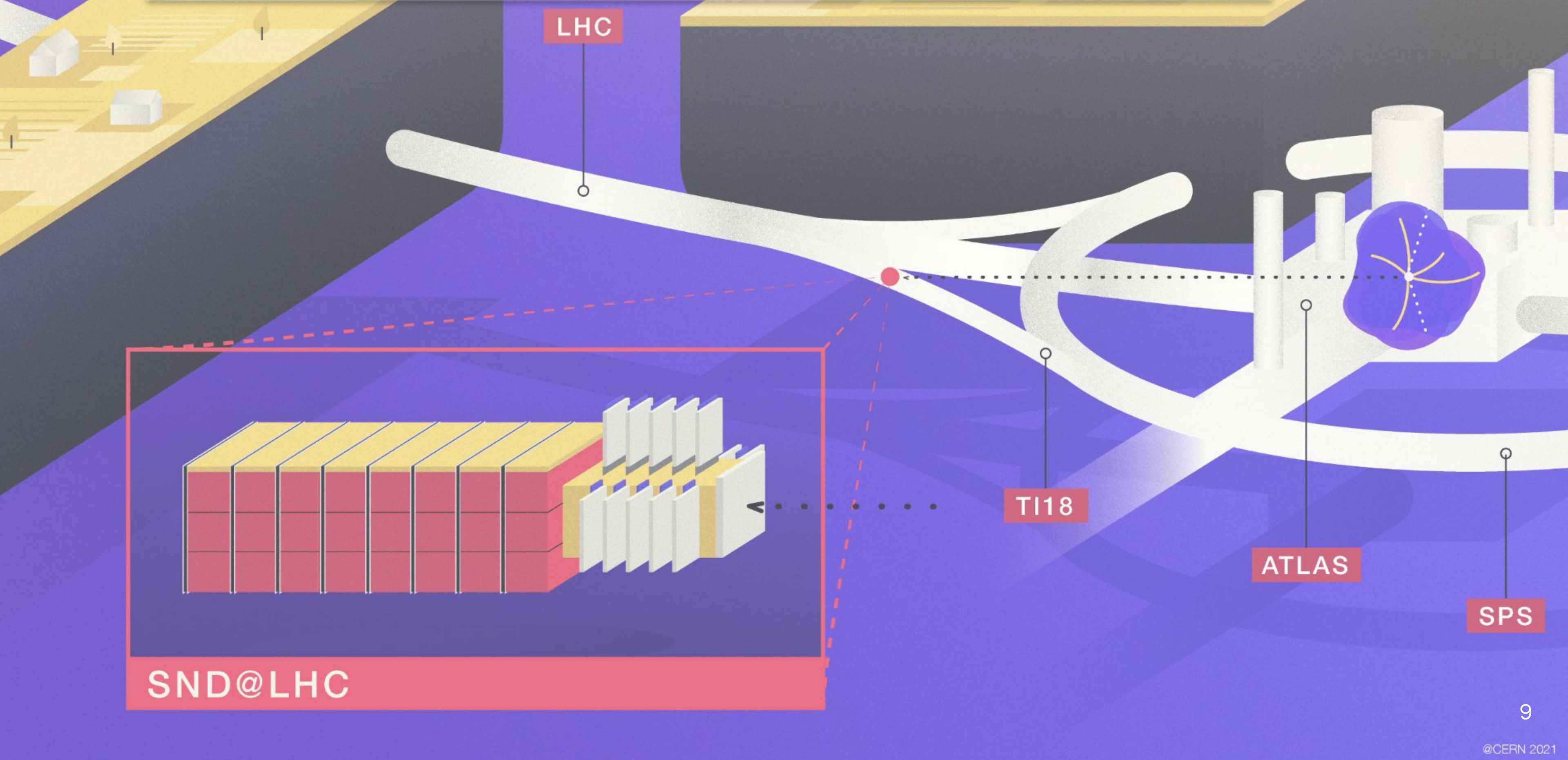


- 2D proof-of-concept shows promising results.
- Next step:
  - ND 3D readout → FD 3x2D readout
  - Needs novel neural network **architectures**

Data-driven analysis will **enable percent-level** systematic uncertainty requirement in DUNE

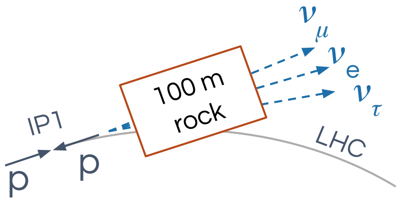
I am Supervising two **CERN Junior Fellows** on DUNE machine learning project. Taking advantage of generative models expertise **[6].**

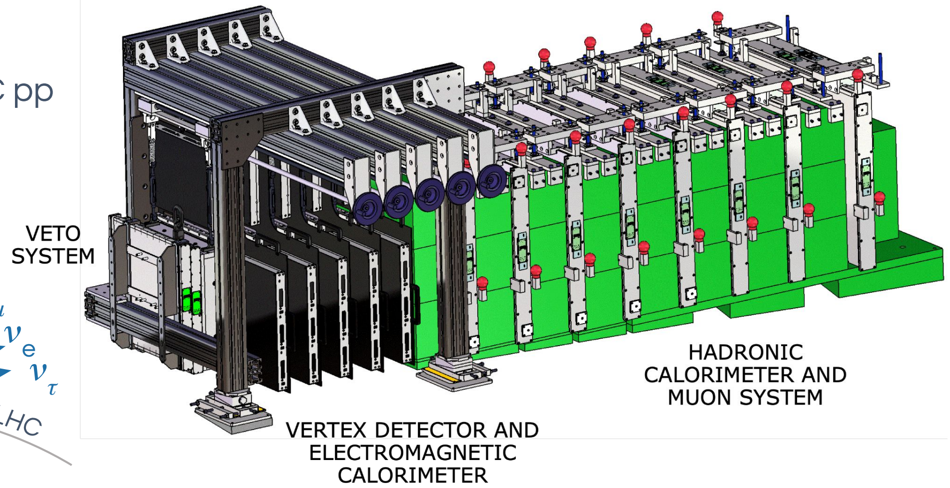
Observing neutrinos at the LHC



Scattering and Neutrino Detector at the LHC

- The possibility of observing neutrinos from LHC pp collisions was pointed out in the early 90's
  - Large flux in forward region
  - Very high neutrino energy
    - $\sigma_\nu \propto E_\nu$



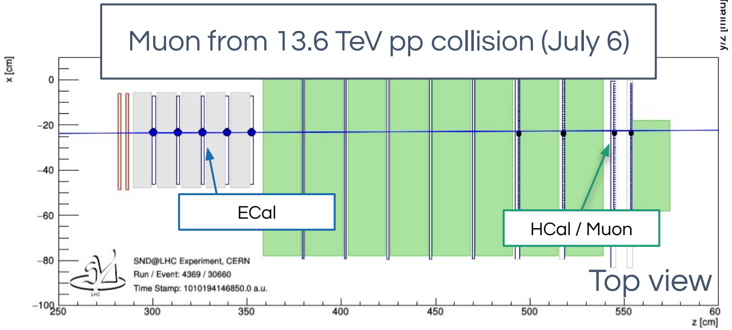


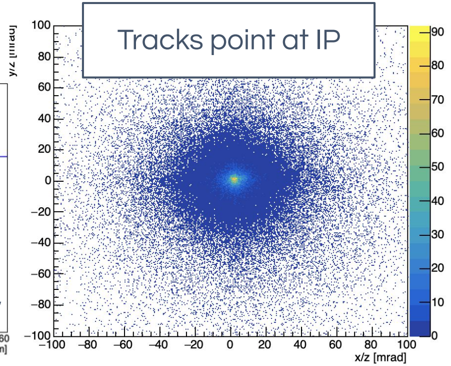
- Wide physics reach:
  - ~~νLFU~~ tests with ν_e/ν_τ and ν_e/ν_μ ratios
  - Forward **charm production** measurement
    - Gluon PDF at very low x
  - Beyond the **S**tandard **M**odel searches
    - Long-lived / feebly-interacting new particles

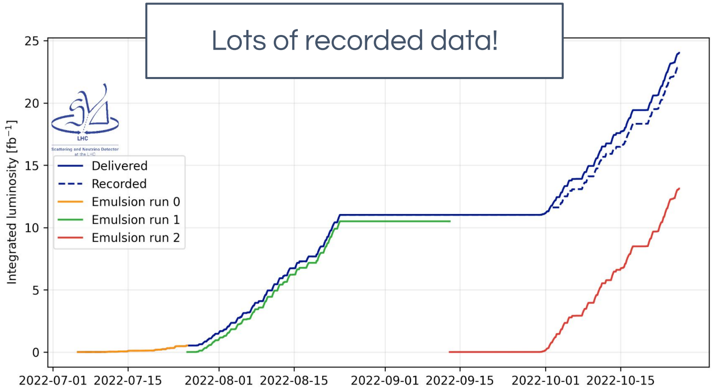
- Detector technology:
  - **Emulsion** and tungsten target (800 kg)
  - Scintillating Fibre **EM calorimeter / tracker**
  - Scintillator and iron **hadron calorimeter / muon system**

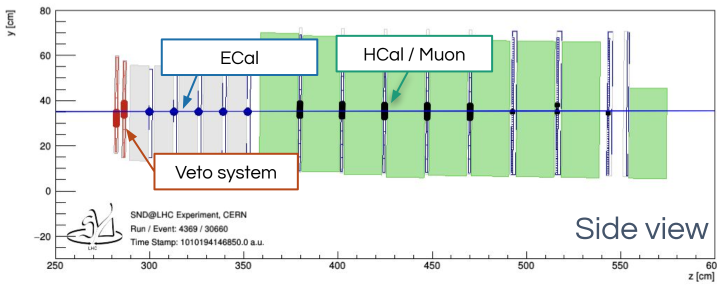
Letter of Intent
August 2020
→
Approval
March 2021
→
Physics data
June 2022

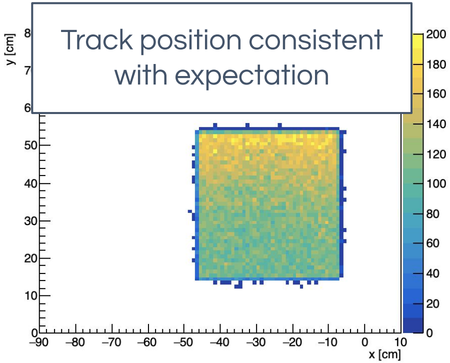
SND@LHC Data!

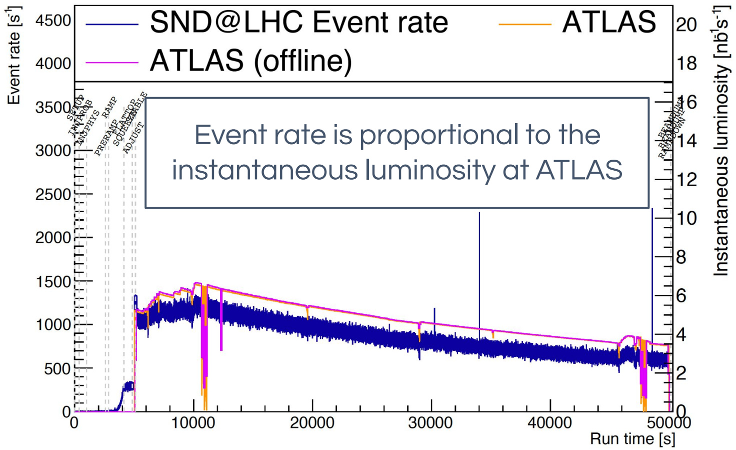










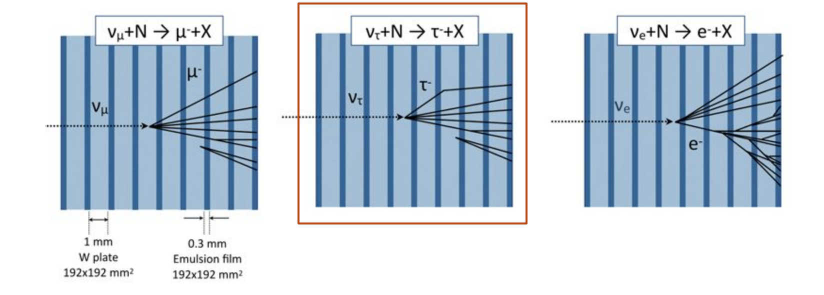


- I have critical **data-taking** responsibilities in the experiment:
  - **Luminosity** estimation – crucial for planning emulsion changes.
  - **Raw data transfer** out of the DAQ server and **backup**.
  - I wrote the first draft of the **shifter manual.**

Neutrino identification in SND@LHC

- Neutrino identification strategy:
  - Identify candidates in the **electronic detector** data
  - Identify candidates in the **emulsion** data
  - **Match** candidates to each other to get complete event
- I have developed the **analysis tools** for the **electronic detectors.**

Flavour identification with emulsions



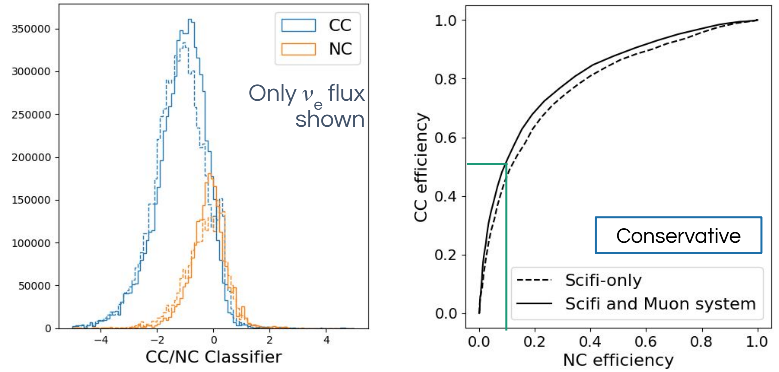
Pattern recognition with Muon System

	Fraction of correctly identified events
ν_μCC (1μ)	78.5%
ν_eCC (0μ)	87.3%
NC (0μ)	93.1%

- I demonstrated a high purity ν_μCC sample is achievable using only the electronic detectors.
  - Developed muon pattern recognition algorithm based on the Hough transform.

Charged-current ν_e identification with ECal

Statistical separation of ν_eCC and NC events using ECal hit pattern



Taking advantage of event reconstruction expertise **[6, 7, 8]**.

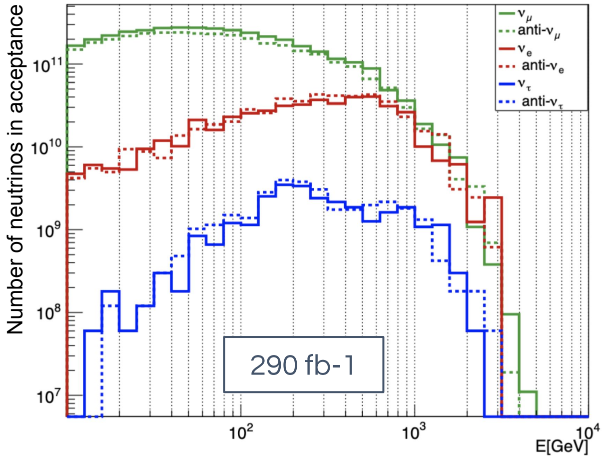
Electronic-detector-only **neutrino observation** possible!

SND@LHC Neutrino Measurements

Complex **interplay** of **flux** and **cross sections**

	Expected number of CC events / 290 fb^{-1}	Most common parent < 300 GeV	Most common parent > 300 GeV
$\nu_e+\bar{\nu}_e$	450	Light	**Charm**
$\nu_\mu+\bar{\nu}_\mu$	1447	Light	Light/**Charm**
$\nu_\tau+\bar{\nu}_\tau$	**34**	**Charm**	**Charm**

$N_{DONUT} + N_{OPERA} =$ 19



Unique ability to constrain charm production with high energy ν_e due to off-axis location

$7.2 < \eta < 8.4$

Significant correlations between parameters of interest

- Lepton Flavour Universality tests with ν_e/ν_τ and ν_e/ν_μ.
  - **Interaction**
- Forward charm production → gluon PDF at very low x.
  - **Flux**

Solution:

- Fit all samples **simultaneously** for all parameters of interest.
  - Same approach taken by T2K **[1, 2, 3]** and DUNE **[4, 5]**.

Current status:

- I have integrated the GENIE **neutrino interaction event generator** in the software framework.
- I am leading an effort to develop **neutrino event selection** criteria using the electronic detector data.

My research project at LIP

DUNE and SND@LHC at LIP

DEEP UNDERGROUND NEUTRINO EXPERIMENT

LHC
Scattering and Neutrino Detector at the LHC

- LIP effort focused on **calibration**
  - Consortium leadership
  - Development and construction of laser calibration source
    - To be tested in ProtoDUNE-II

- LIP is a founding member
- **Construction** of the mechanical structure of the hadron calorimeter
  - Detector alignment / data readiness

- In both cases, my research plans **leverage and expand** the existing efforts at LIP.
  - **DUNE** data-driven analysis ↔ LIP **calibration expertise**.
  - **SND@LHC** electronic detector data analysis ↔ LIP **detector expertise**.
- I bring to LIP world-class **expertise** in **accelerator-based neutrino** experiment **data analysis.**
  - There are no active experts on this subject in the country.

Opportunity to strengthen ties between neutrino and collider groups.

Six-year outlook

SND@LHC

Short-term → Long-term

- **First** robust **observation** of neutrinos from pp collisions!
  - Muon system partly built at **LIP** is a critical component of this analysis.
- First SND@LHC **physics results** with simultaneous fit of all neutrino data.
- Explore **BSM** searches with **SND@LHC.**
  - I am the LPCC Long-lived Particles **convener** for SND@LHC
  - I am the SND upgrade (AdvSND) **BSM contact** in the Forward Physics Facility
- **Final** Run III physics results and detector **upgrade** for **HL-LHC: AdvSND**

DUNE

Short-term → Long-term

- Develop **machine learning** tools for **near-to-far** detector event **translation**
- Validate **DUNE** near-to-far event translation using **ProtoDUNE II** real data.
  - Establish systematic uncertainty for DUNE **data-driven sensitivity.**
    - Direct impact of **LIP**-led DUNE **calibration** strategy on **physics** results.
- Data-driven oscillation analysis in place for **start of operations** (around 2030).
  - Opportunity for leading analysis role at **LIP**.

2022

ProtoDUNE II

LHC Run III

2028

Thank you for your attention!

[1] **Nature** 508:339 (2020) **T2K**
[2] **PRL** 121:171802 (2018) **T2K**
[3] **PRD** 103:112008 (2021) **T2K**
[4] **Instruments** 5:31 (2021) **DUNE** ND **CDR**
[5] FERMILAB-PUB-20-025-ND (2020) **DUNE** FD **TDR**
[6] **Front. Big Data** 5.868333 (**2022**) C. Vilela *et al.* [**corresp.**]
[7] KEK Preprint 2016-21 (2016) **Hyper-K** **DR**
[8] **PTEP** 053F01 (2019) **Super-K**
[9] **PRD** 99:032005 (2019) **Super-K**
[10] **PRD** 93:112008 (2016) **NEMO3** (PhD)