Cross-Section Measurements @MicroBooNE

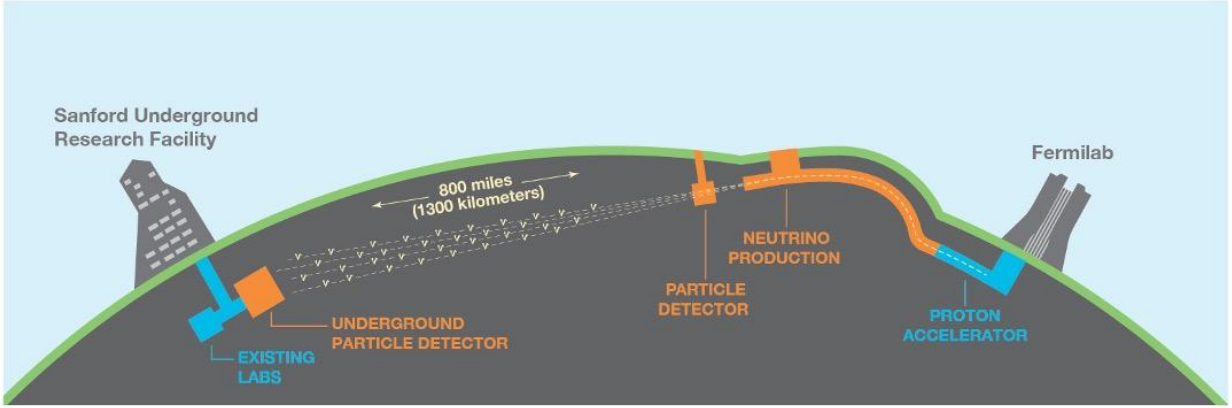
<u>Karolina Wresilo</u>
Philip Detje
Alexandra Moor
Natsumi Taniuchi

Overview

1. Why measure neutrino interactions?
2. MicroBooNE
   a. The Liquid Argon Time Projection Chamber
   b. BNB and NuMI beams
3. Cambridge Neutrino cross-section measurements

Motivation for Measuring Neutrino Interactions

- Current and future accelerator experiments measure neutrino oscillations in the **few-GeV energy regime**
- Example - DUNE physics program:
  - Definitive discovery of **neutrino mass ordering** and **CP-violation** in the lepton sector
  - **Precision measurements** of neutrino oscillations
  - Broad **BSM** and **low-energy physics** potential



Motivation for Measuring Neutrino Interactions

- Current and future accelerator experiments measure neutrino oscillations in the **few-GeV energy regime**
- Interactions are difficult to model (nuclear effects, FSIs, …) and **not well measured** (especially on Argon)

Near detector

oscillation probability

$$R(\vec{\mathbf{x}}) = \int_{E_{\min}}^{E_{\max}} \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \varepsilon(\vec{\mathbf{x}}) \times P(\nu_A \rightarrow \nu_B),$$

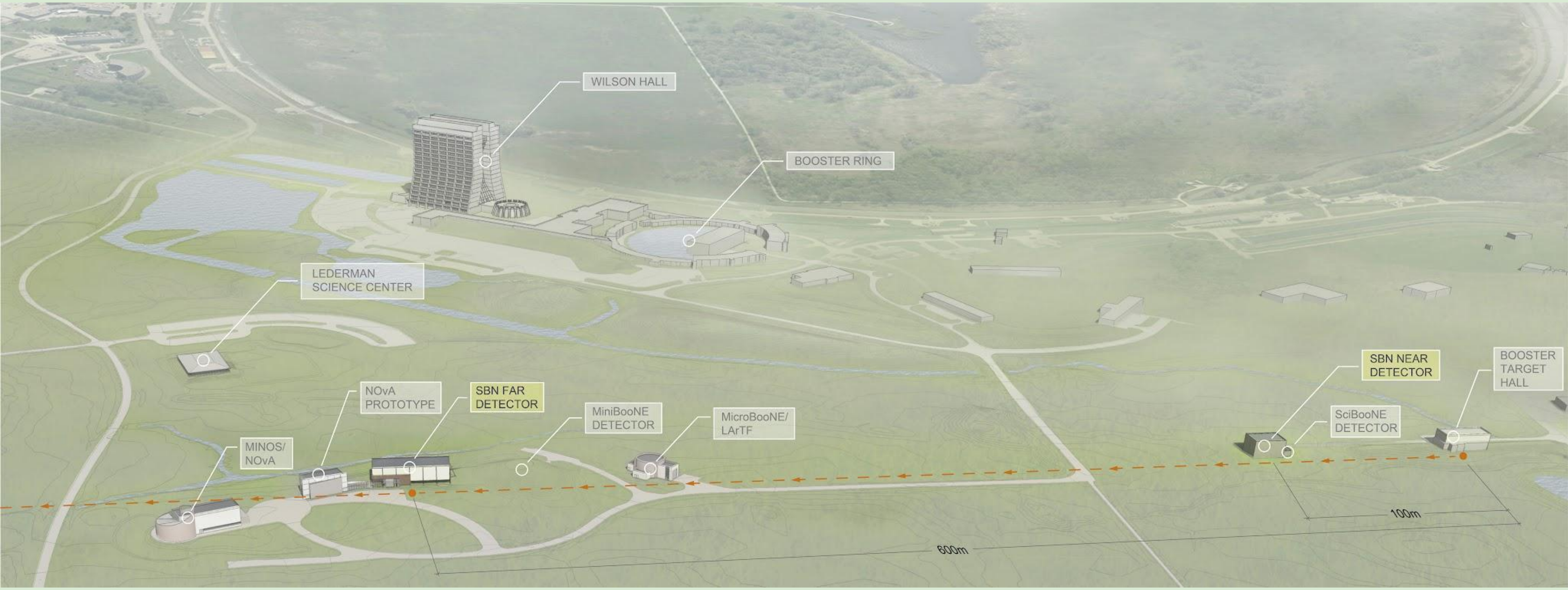
flux xsec efficiency

Far detector

- Energy spectrum and flavour components of the beam change significantly over the baseline -> systematics do not cancel in the near/far ratio
- **Cross-sections uncertainties dominate systematics**

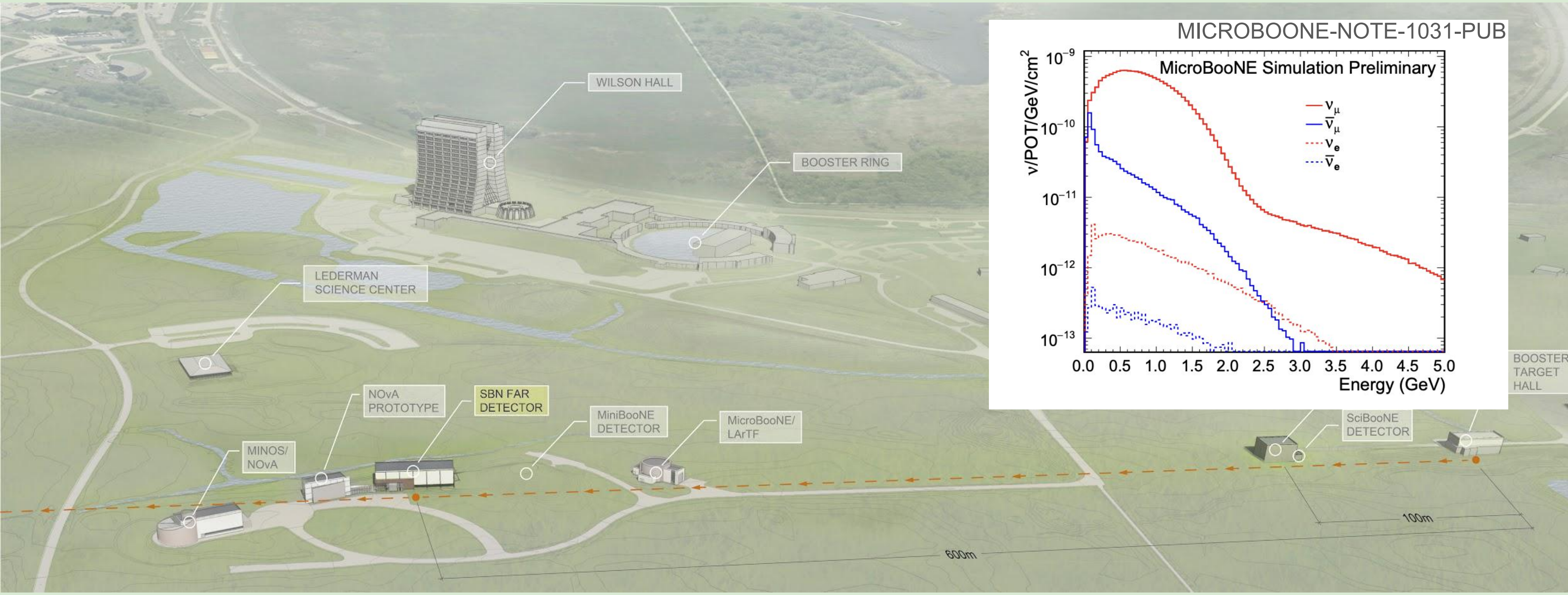
The MicroBooNE Detector, BNB and NuMI Beam

(The relevant part of the) Fermilab Accelerator Complex



MicroBooNE

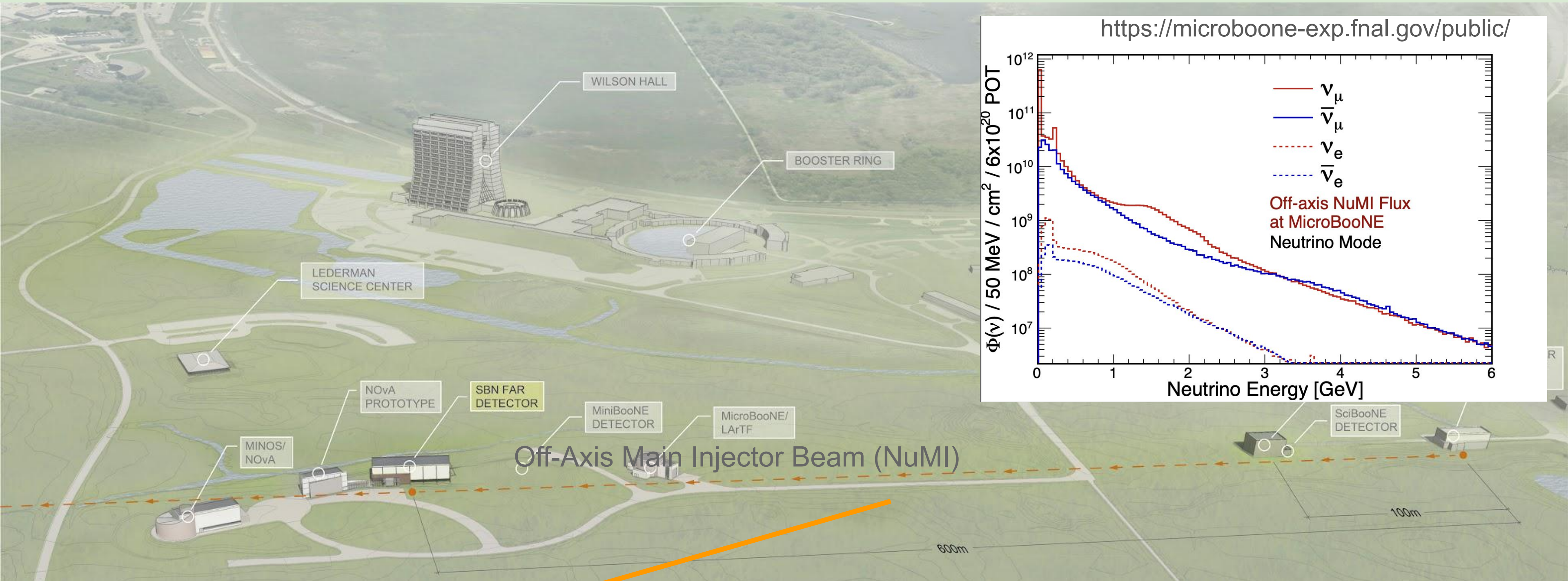
(The relevant part of the) Fermilab Accelerator Complex



Booster Neutrino Beam

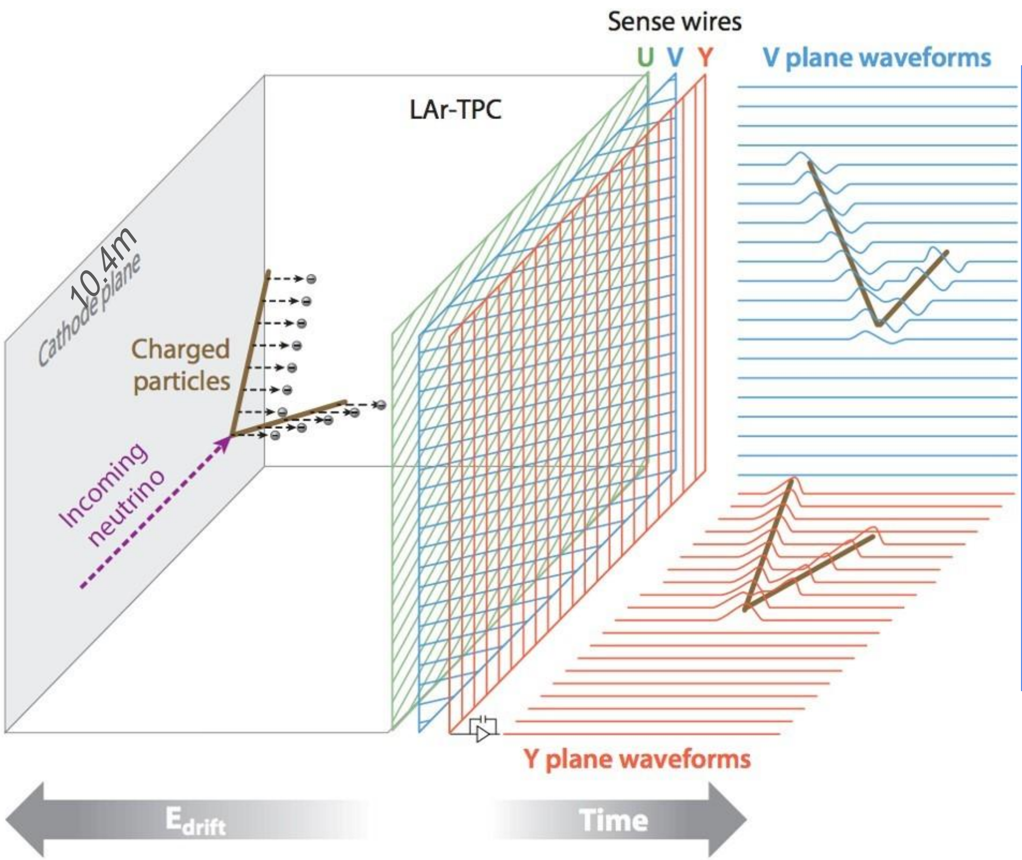
MicroBooNE

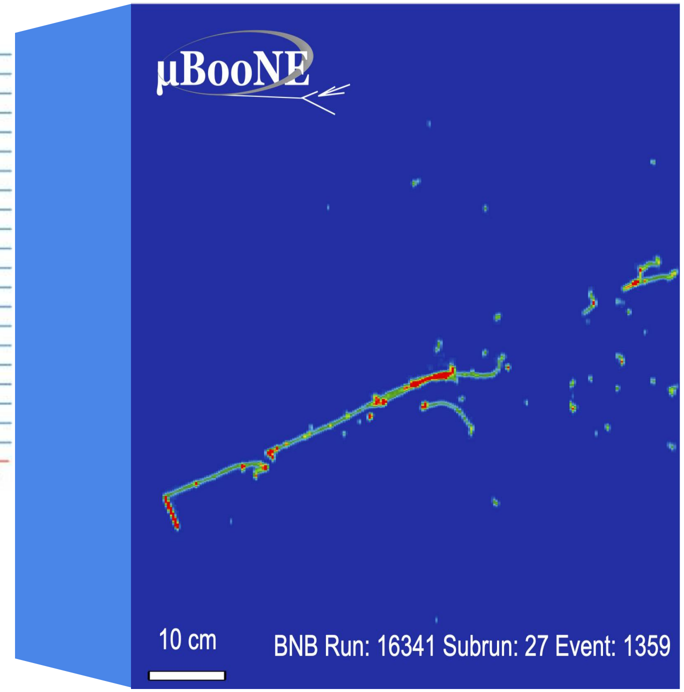
(The relevant part of the) Fermilab Accelerator Complex



MicroBooNE

MicroBooNE Liquid Argon Time Projection Chamber (LArTPC)

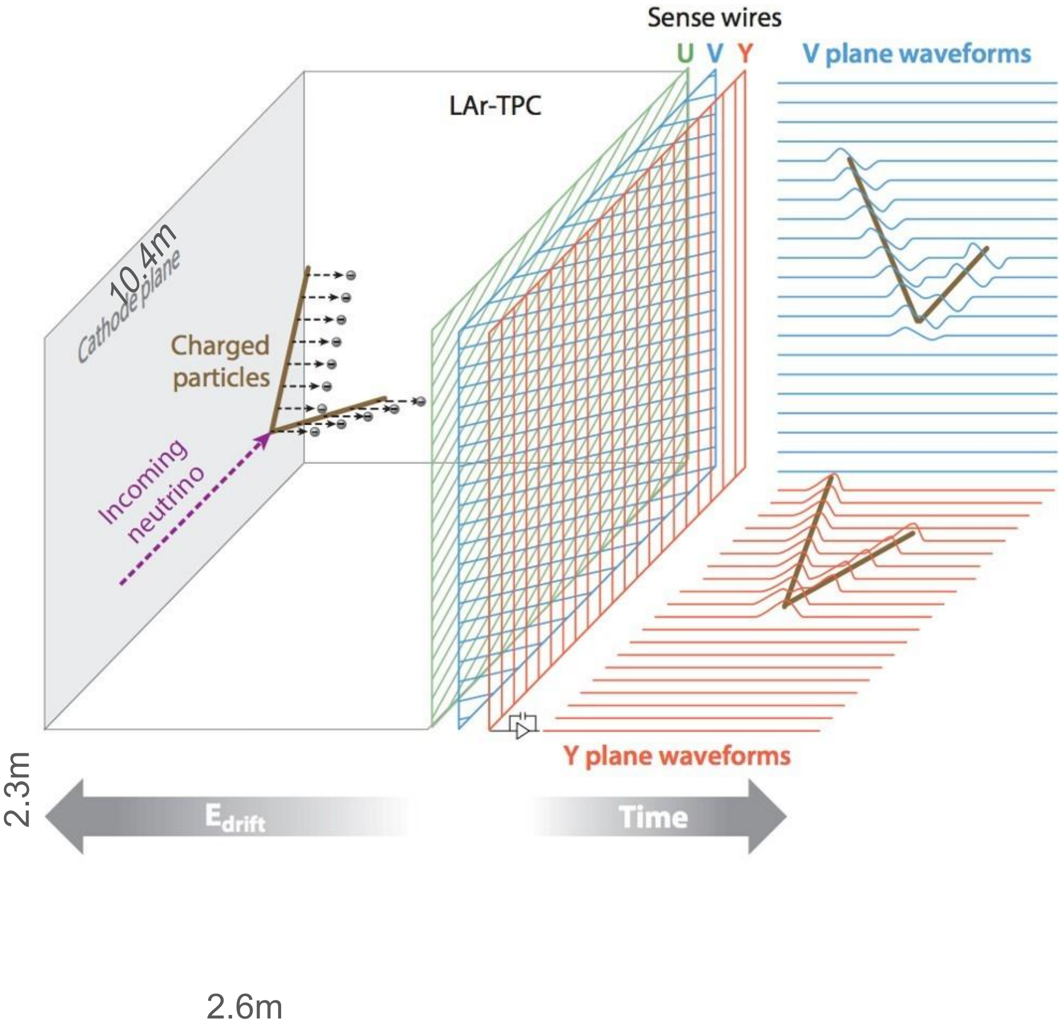




2.3m

2.6m

Why MicroBooNE?



- 170 tons of LAr (full volume)
- Full tracking calorimeter with "3D reconstruction"
- Unprecedented calorimetric and spatial resolution resolution (millimeter-scale)

Why MicroBooNE?

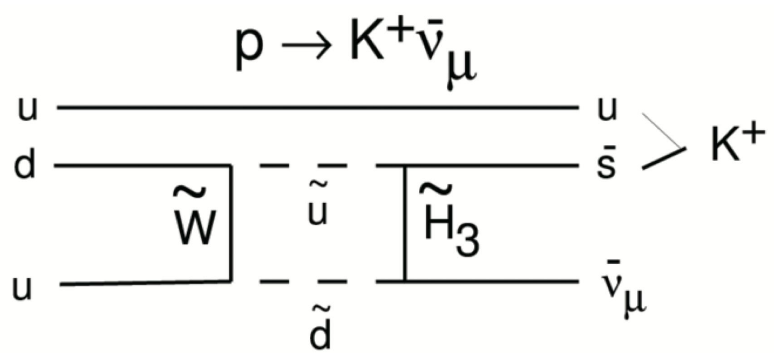
- Collected data between 2015 and 2021
  - ~1e21 POT for BNB, FHC NuMI and RHC NuMI (each)
- **Largest neutrino-Argon interaction data set in the world**
  - As of today, MicroBooNE has performed its duty and is currently being decommissioned :(

Cambridge Neutrino Cross-Section Measurements

* DISCLAIMER: no approved physics plots :(

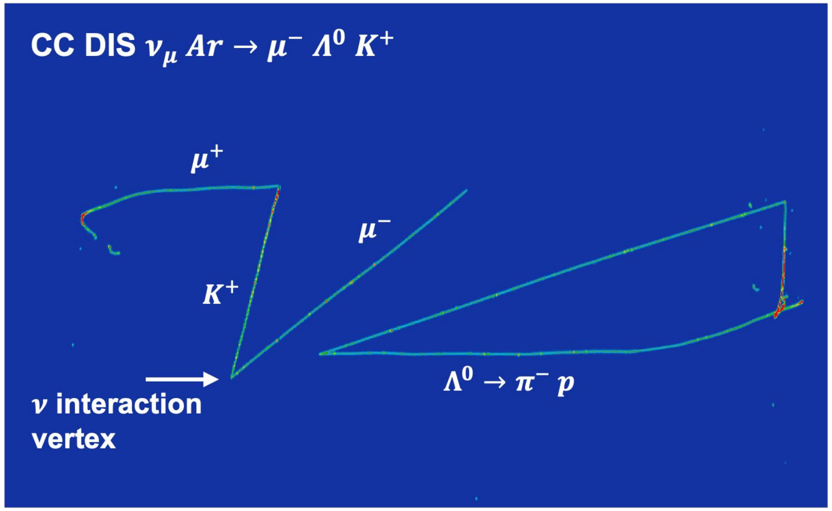
NuMI ν_μCC K^+

- GUTs predict baryon number violation
- Proton decay “golden channel”: ***p → νμ K+***
    - **Low energy threshold in LAr** compared to e.g. Cherenkov detectors -> possible to study with DUNE!
    - No existing K^+ - Ar cross-section measurement up to date



Natsumi Taniuchi

NuMI ν_μCC K^+: First Ar- K^+ Measurement in ~1GeV Regime



- Kaon production is a **rare process** with **complicated event topology** in LArTPC

$$\nu_\mu + n \rightarrow \mu^- + K^+ + \Lambda^0$$
$$\nu_\mu + p \rightarrow \mu^- + K^+ + p$$

$$K^+ \rightarrow \mu^+\nu_\mu \quad (\sim 63.6\%)$$
$$K^+ \rightarrow \pi^+\pi^0 \quad (\sim 20.7\%)$$

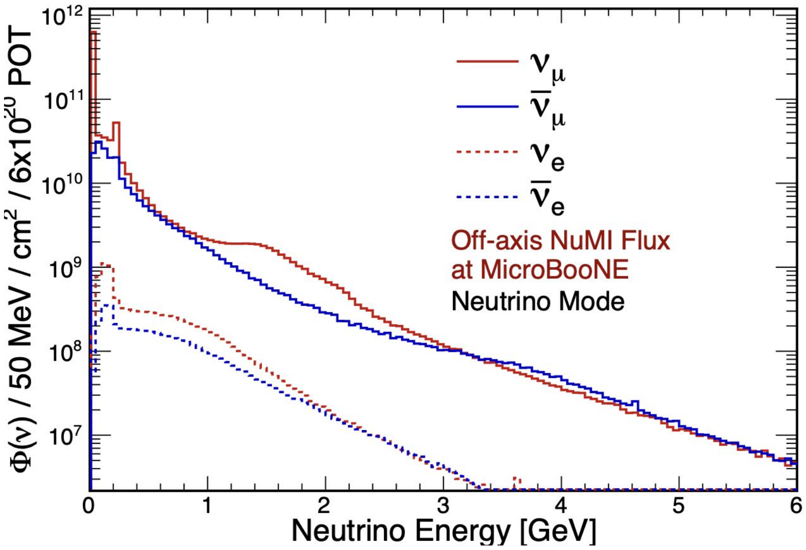
- Requires special reconstruction approach as well as BDT based selection

Natsumi Taniuchi

Alex Moor

NuMI ν_μ / ν_e Ratio

- Experimental value of the **ν_μ/ν_e cross-section ratio is poorly known**
- First measurement on LAr
  - Ratio binned in reconstructed energy and variables with large uncertainties e.g. lepton angle wrt neutrino direction
- Results can be used to **reduce systematics** in other analyses e.g. through a BNB flux constraint

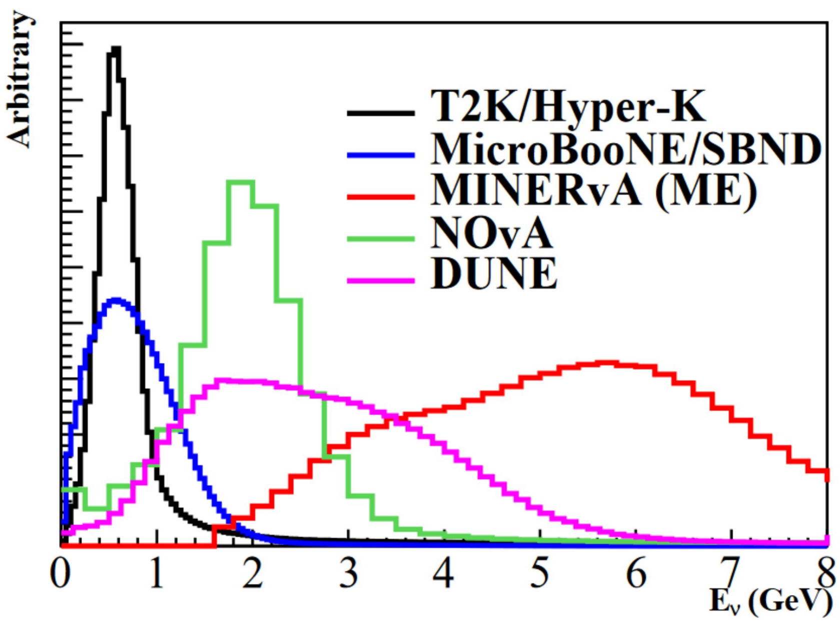


NuMI flux has a large ν_e component - perfect for studying electron neutrinos

Philip Detje
&
Karolina Wresilo

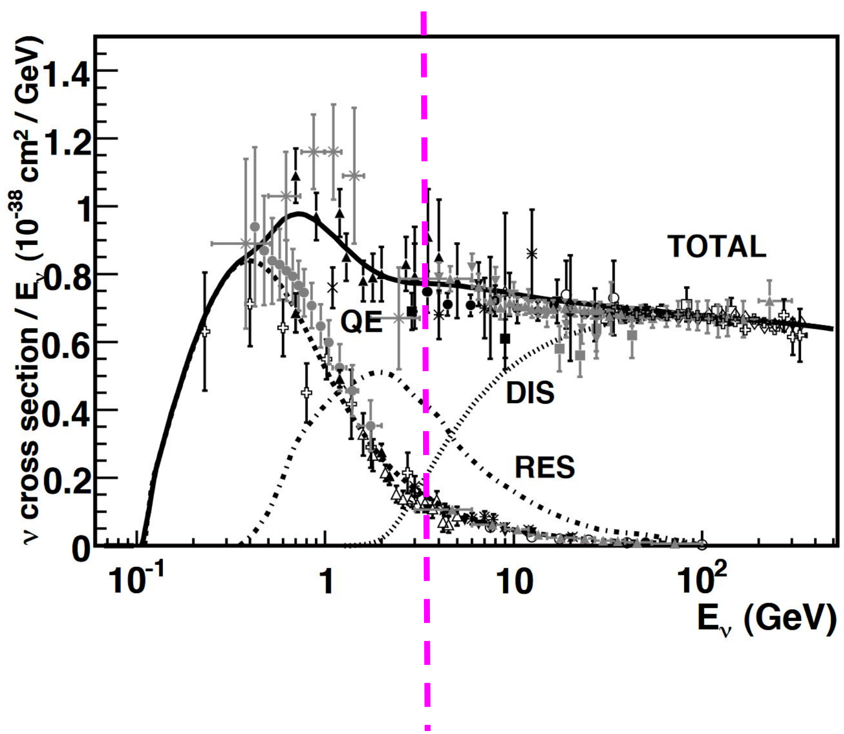
BNB ν_μCC1$\pi^\pm$ Np (N≥0) and ν_μCC1$\pi^\pm$Xp (X≥1)

- Single pion production channels are **one of the dominant topologies at DUNE**



arXiv:1611.07770

DUNE oscillation maximum



arXiv:1305.7513

Philip Detje
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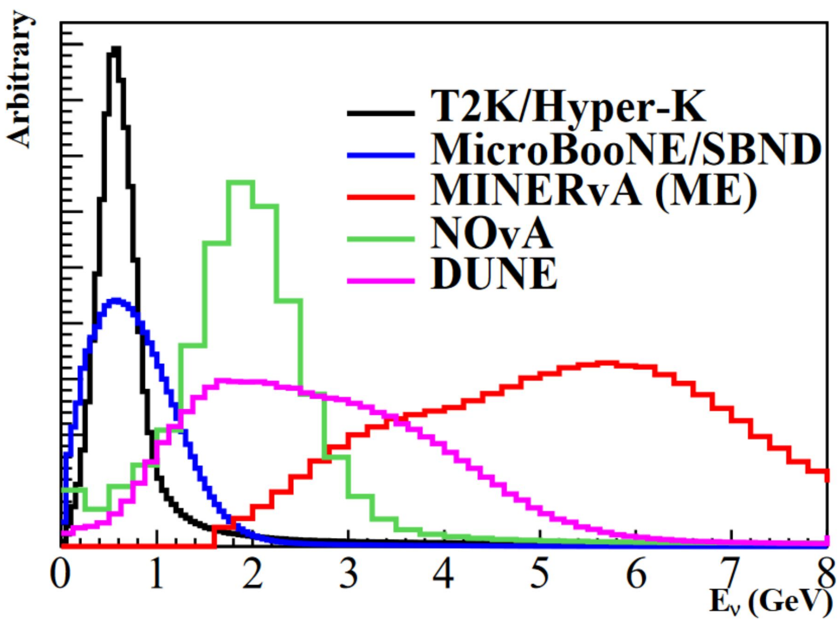
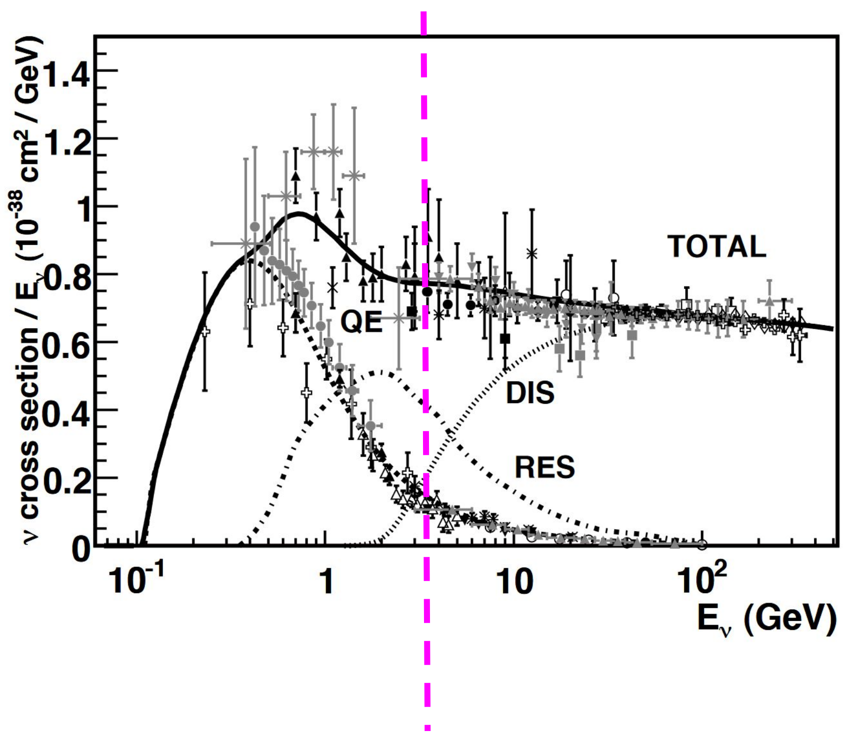
Karolina Wresilo

BNB ν_μCC1$\pi^\pm$ Np (N≥0) and ν_μCC1$\pi^\pm$Xp (X≥1)

- MicroBooNE has a **significant portion of flux in the relevant energy regime**



DUNE oscillation maximum



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arXiv:1305.7513

Philip Detje
&
Karolina Wresilo

BNB $\nu_\mu CC1\pi^\pm$ Np ($N \geq 0$) and $\nu_\mu CC1\pi^\pm Xp$ ($X \geq 1$)

Previous measurement:

- 0.23 tons active mass
- ~10^{20} POT exposure

arXiv:1804.10294

This measurement:

- 85 tons active mass
- ~10^{21} POT exposure

Summary

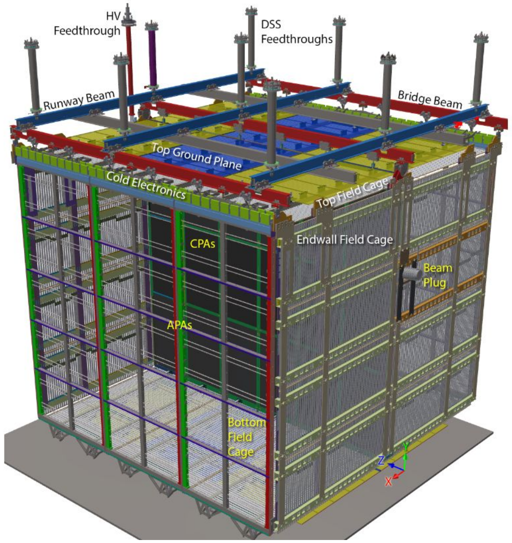
- Cross-section uncertainties dominate systematics in accelerator based neutrino oscillation experiments
- MicroBooNE detector's event reconstruction capabilities together with a large volume of neutrino-Ar data make it a perfect place to study neutrino interactions on Argon
- Number of cross-section measurements being done by the Cambridge group
    - Kaon production (Natsumi Taniuchi)
    - ν_μ/ν_e ratio (Alex Moor)
    - ν_μ CC single charged pion with visible proton (Karolina Wresilo)
    - proton -inclusive ν_μ CC single charged pion (Philip Detje)

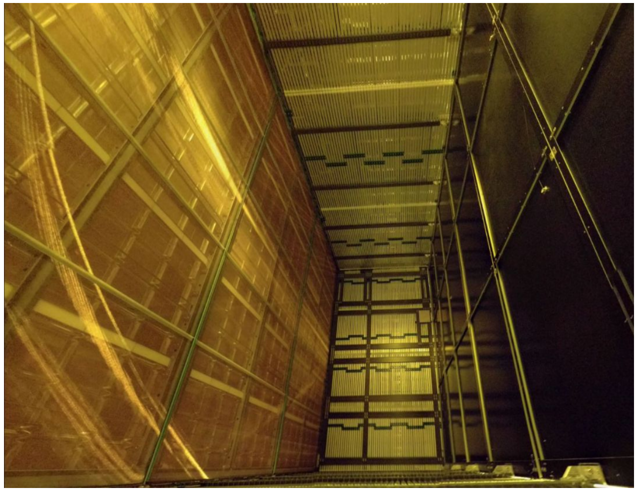
ProtoDUNE analysis

Jingyuan Shi, Leigh Whitehead, Stefano Vergani

ProtoDUNE Single Phase (SP) detector

- Test bed and full-scale prototype for the elements of DUNE.
- Located in CERN neutrino platform.
- 400t Liquid Argon Time Projection Chamber (LArTPC).





Pandora Event Reconstruction for ProtoDUNE-SP

- Paper detailing the Pandora reconstruction (finally) published!
  - Cambridge-led effort!

Eur. Phys. J. C (2023) 83:618
https://doi.org/10.1140/epjc/s10052-023-11733-2

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora

DUNE Collaboration

Pandora Event Reconstruction for ProtoDUNE-SP

- Paper detailing the Pandora reconstruction (finally) published!
    - Cambridge-led effort!
- Covers specific developments for ProtoDUNE-SP
    - First use case for Pandora in a LArTPC with more than one drift volume
    - Also the first use case of a hadron beam
- Cosmic ray reconstruction
- Beam particle reconstruction

Pandora Event Reconstruction for ProtoDUNE-SP

- LArTPCs have an intrinsic ambiguity between the drift coordinate (x) and the time that a particle arrives at the detector (t_0)
  - For beam particles, we know $t_0 = 0$
  - Cosmics arrive randomly during the readout window, so t_0 is unknown
- We can measure t_0 for cosmics that cross the cathode (or readout planes)

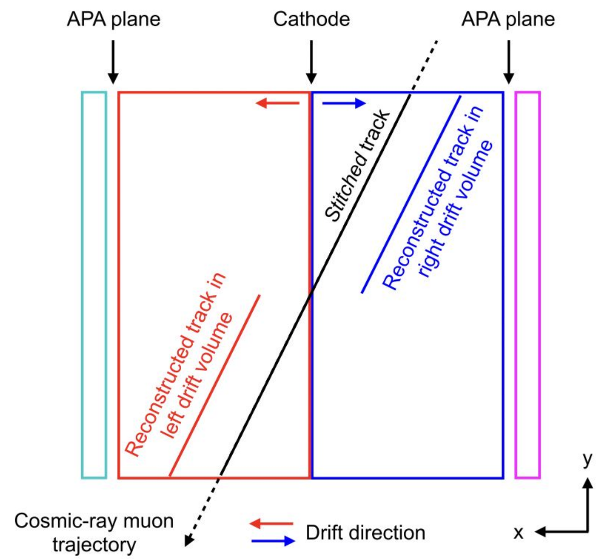
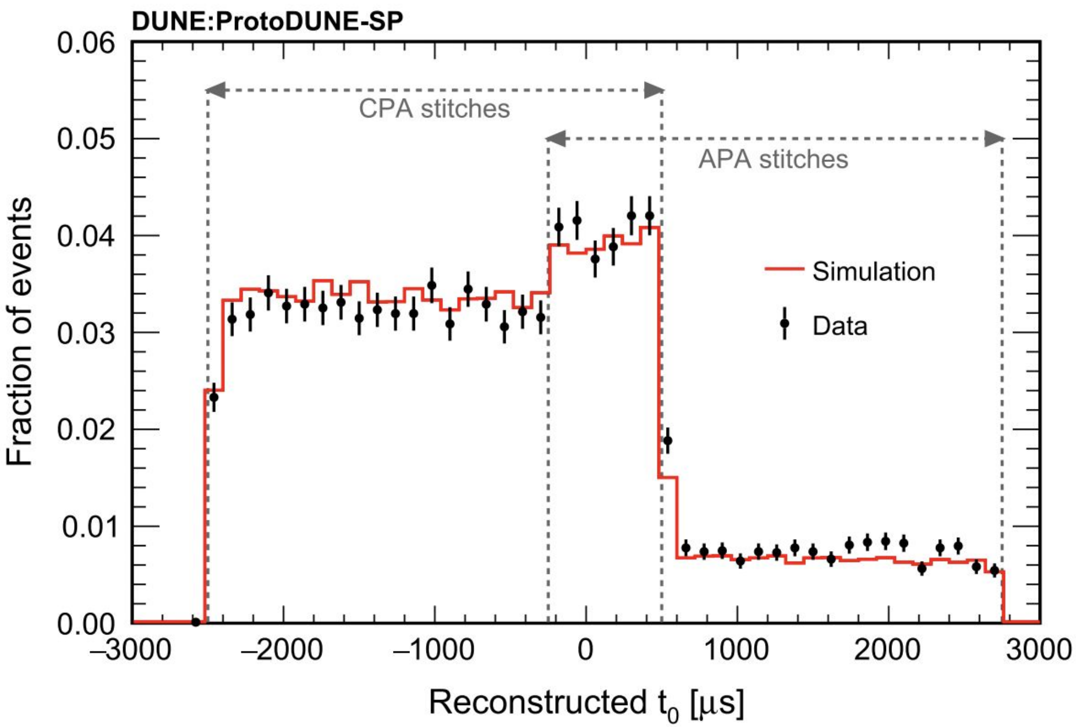


Fig. 3 An example of a cosmic ray crossing the detector from top to bottom and passing through the cathode. Under the initial (and incorrect) assumption of $t_0 = 0$ the energy depositions in the two drift volumes (red and blue lines) appear to be at the wrong position in the drift direction. The reconstruction can recover the correct t_0 by *stitching* the two tracks at the cathode by shifting the drift coordinate in each drift volume by an equal and opposite amount, resolving the ambiguity in the drift coordinate position

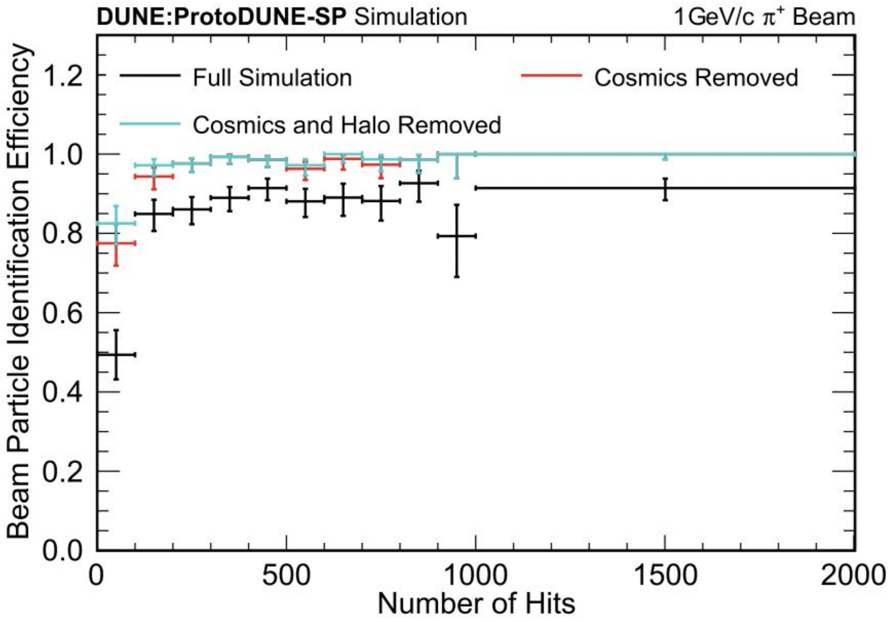
Pandora Event Reconstruction for ProtoDUNE-SP

- Time distribution agrees with expectation
- Nice agreement between data and MC
- These t_0-tagged cosmics for the base of much of the calibration work



Pandora Event Reconstruction for ProtoDUNE-SP

- Most of the ProtoDUNE-SP physics programme relies on reconstructing the hadron beam particle interactions
- Good efficiency even with large cosmic background
- Almost 100% efficient with cosmic and beam backgrounds removed



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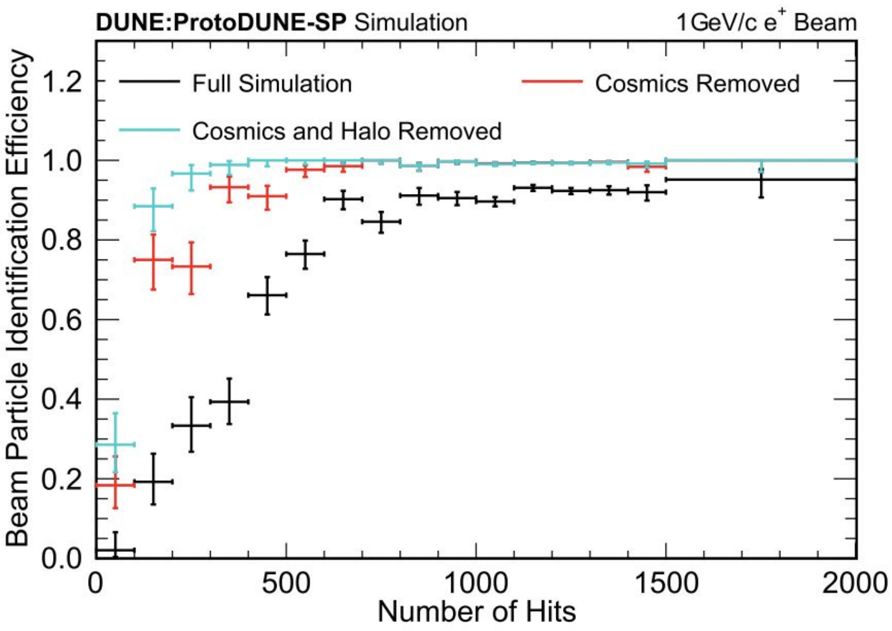
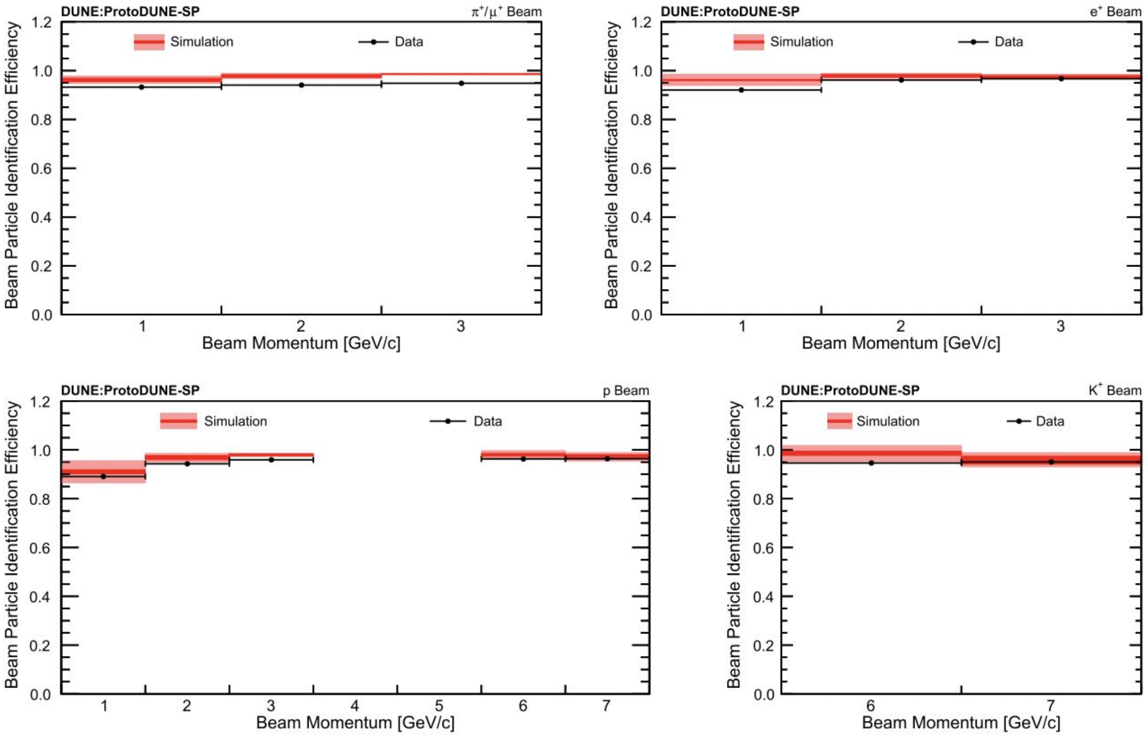


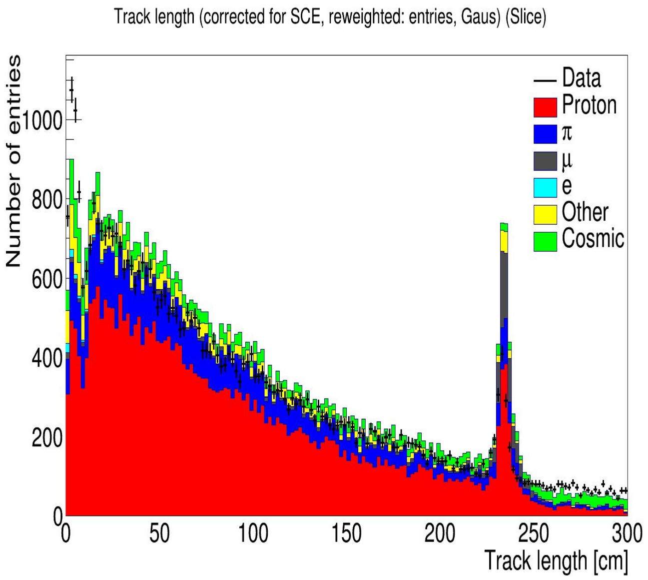
Pandora Event Reconstruction for ProtoDUNE-SP

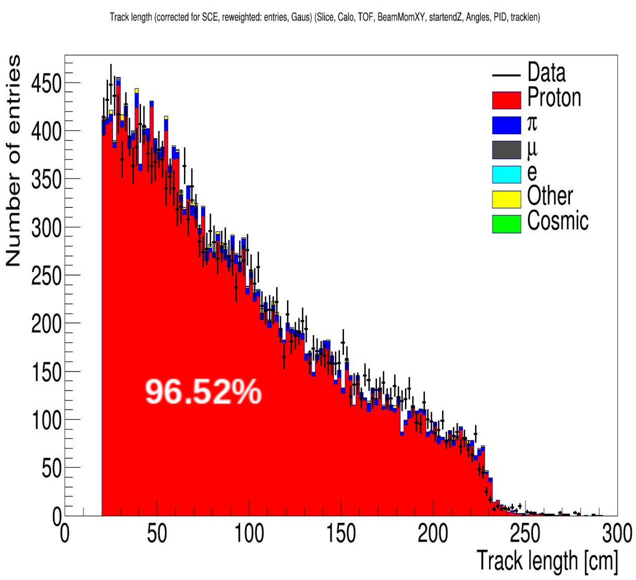
- To compare with data, look for fraction of beam triggered events with a reconstructed beam particle



ProtoDUNE 3 GeV proton cross-section measurement

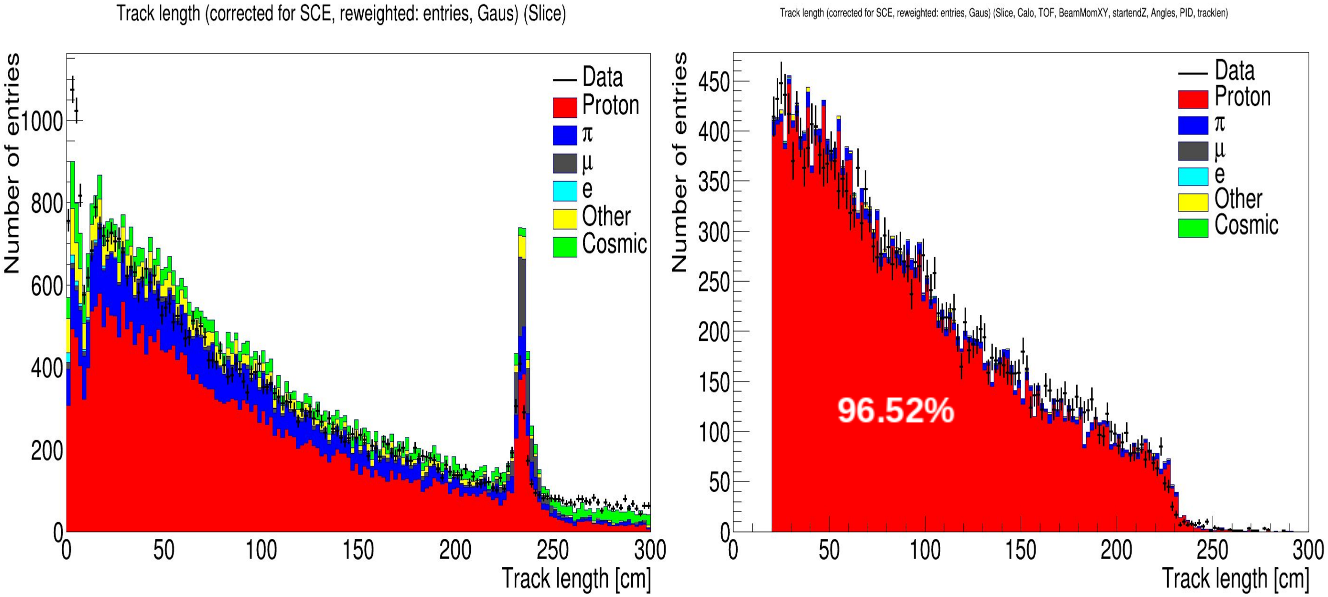
- Understanding proton interactions in DUNE.
- Test bed for event analysis.
- Precise measurement of proton cross-section in LAr is key to accurate ν interaction measurement.
- Isolate a pure proton sample.





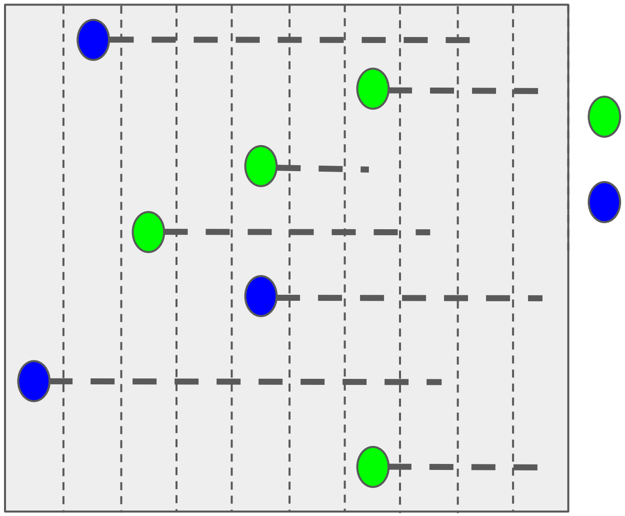
ProtoDUNE 3 GeV proton cross-section measurement

- The peak at ~220 cm is the edge of the first TPC and most tracks break there.
  At the moment, we will remove those events (~5% of the total).
  Over 90% of the particles in “Other” are kaons.
- Cuts:
  track or shower like
  is energy deposited
  TOF
  consistent with beam info
  reconstructed position
  Proton PID



The “thin-slice” method

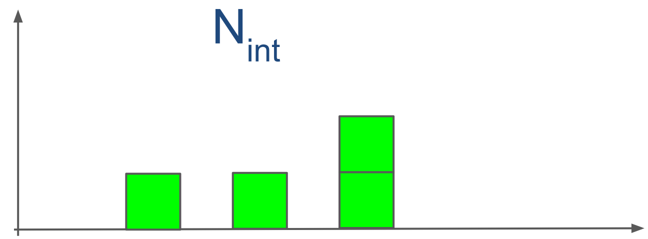
$$\sigma_i = \frac{m_{Ar}}{\rho N_A \delta E}\frac{dE}{dx}|_{E_i}\ln(\frac{N_{inc}}{N_{inc} - N_{int}})_i$$



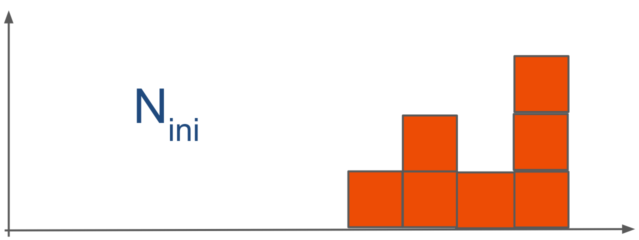
Proton inelastic collision

Proton other interactions

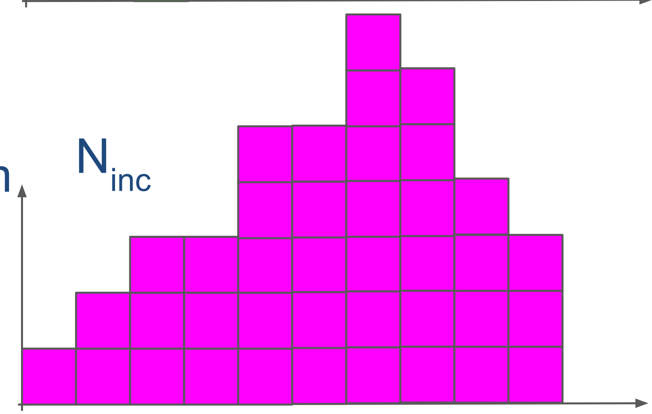
Interacting histogram



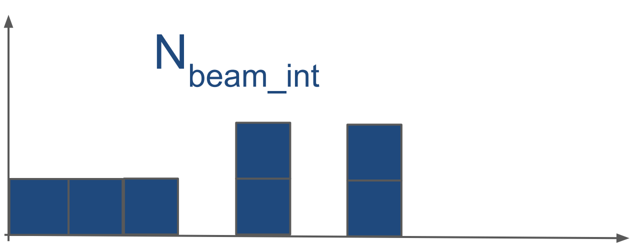
Initial histogram



Incident histogram



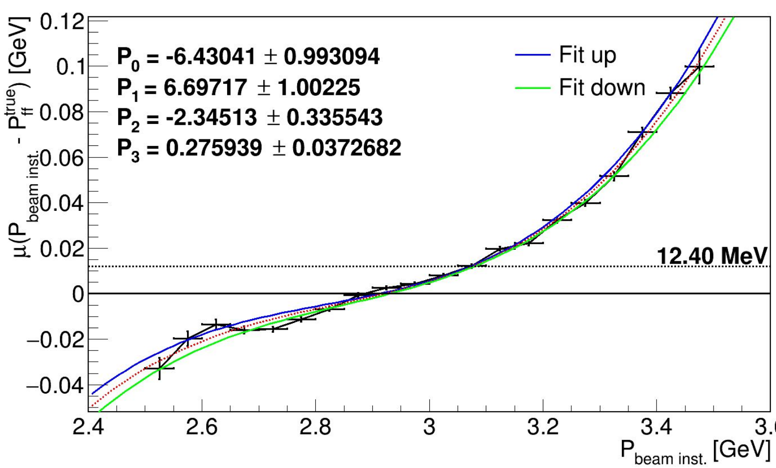
Beam int histogram

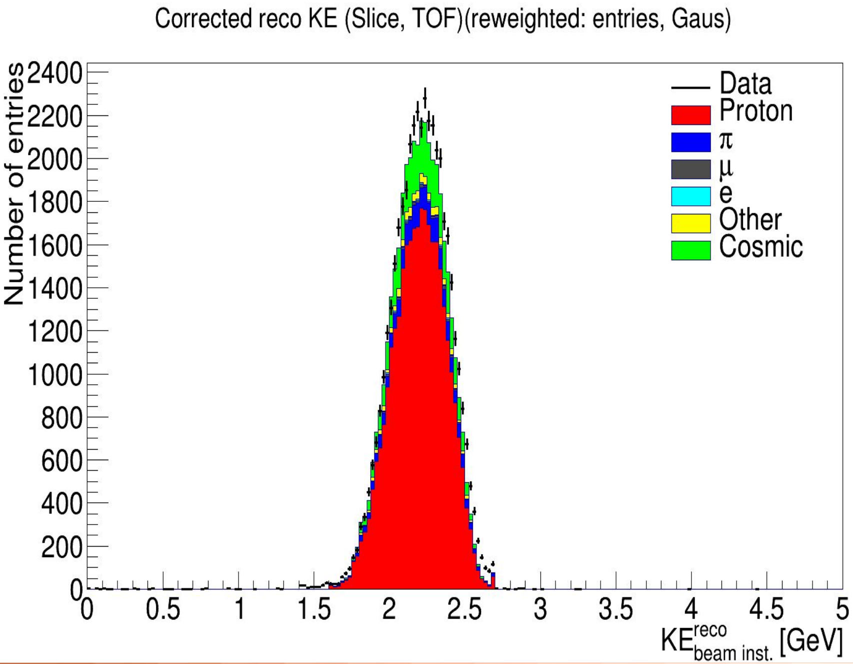


$$N^i_{inc} = \Sigma^N_i N_{ini} - \Sigma^N_{i+1} N_{beam\_int}$$

ProtoDUNE 3 GeV proton cross-section measurement

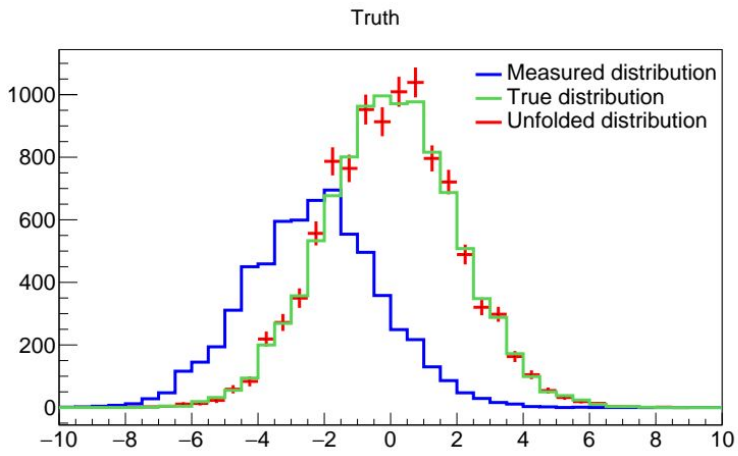
- Beam information is available in analysis as “pseudo” truth.
- Precise front face energy can be calculated using beam information and **upstream energy loss**.

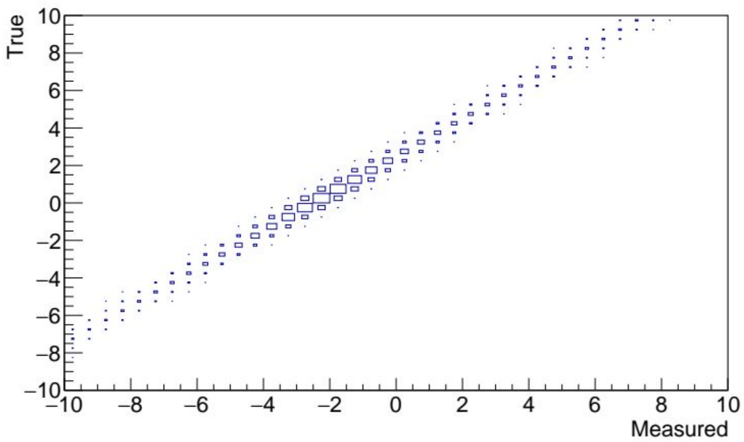




ProtoDUNE 3 GeV proton cross-section measurement

- Results will be presented in **truth** space.
- **Unfolding** is required to transfer reconstruction back to truth.
- Left: comparison of measured, true and **unfolded distribution**. Right: the **response** (reco-true) matrix.

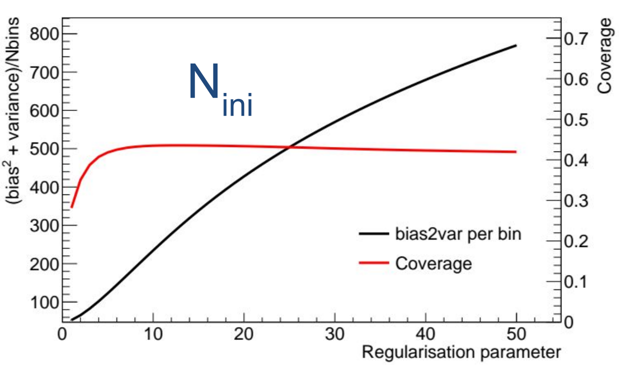


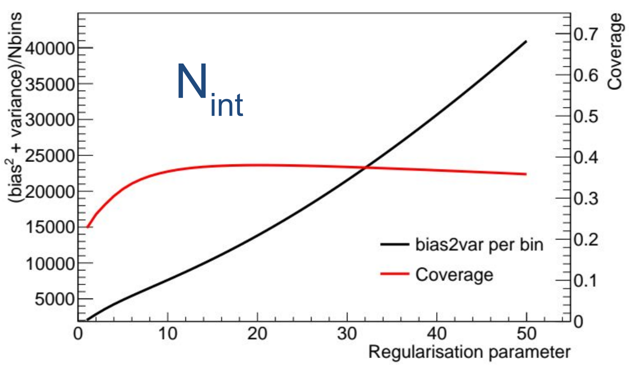


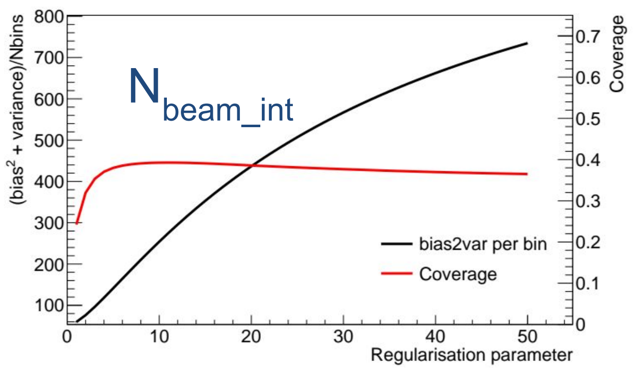
ProtoDUNE 3 GeV proton cross-section measurement

- Scanning the performance of different **unfolding regularisation** parameters.
- We define bias: difference between truth and unfolded.
  variance: (error/content)^2.
  coverage: probability to find true within one sigma of unfolded.

"N_{int}" has a much larger bias2var because it has 50 MeV per bin.

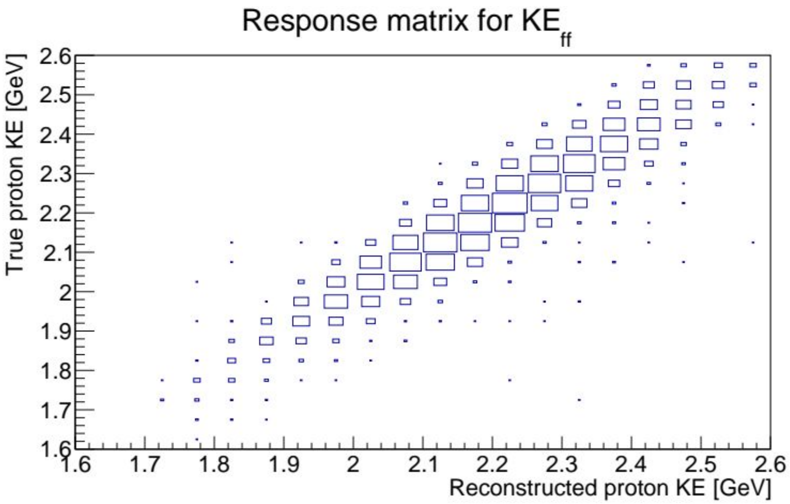


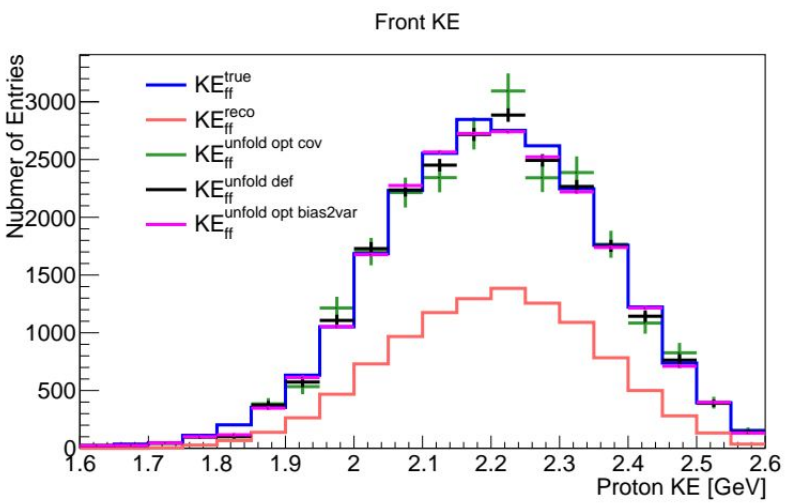




ProtoDUNE 3 GeV proton cross-section measurement

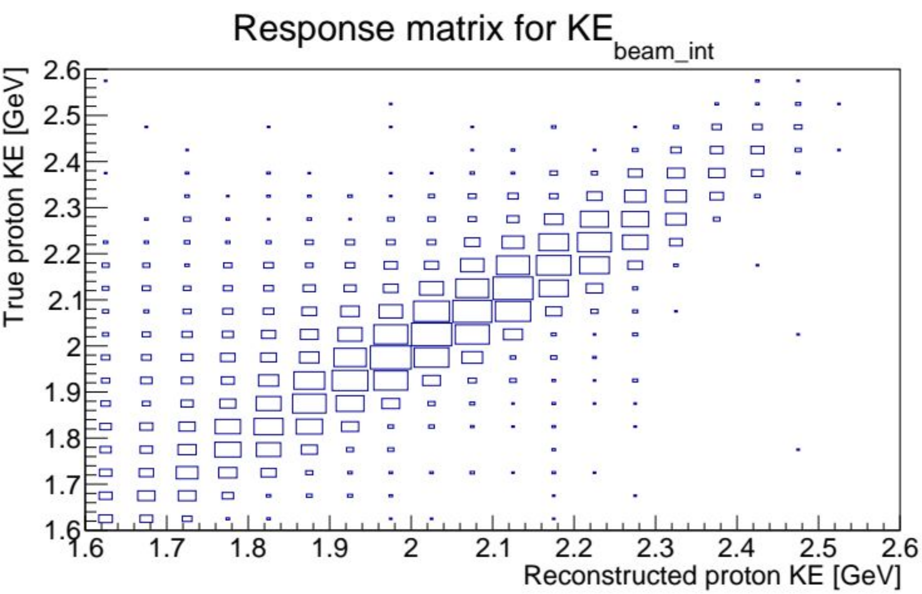
- The reconstructed front-face energy is calculated with beam_inst_P therefore it agrees well with the true front-face energy.
- “opt cov” is the unfolded histogram with maximum coverage.
- “def” is the unfolded histogram with default iterations.
- “opt bias2var” is the unfolded histogram with minimal bias^2 + variance.

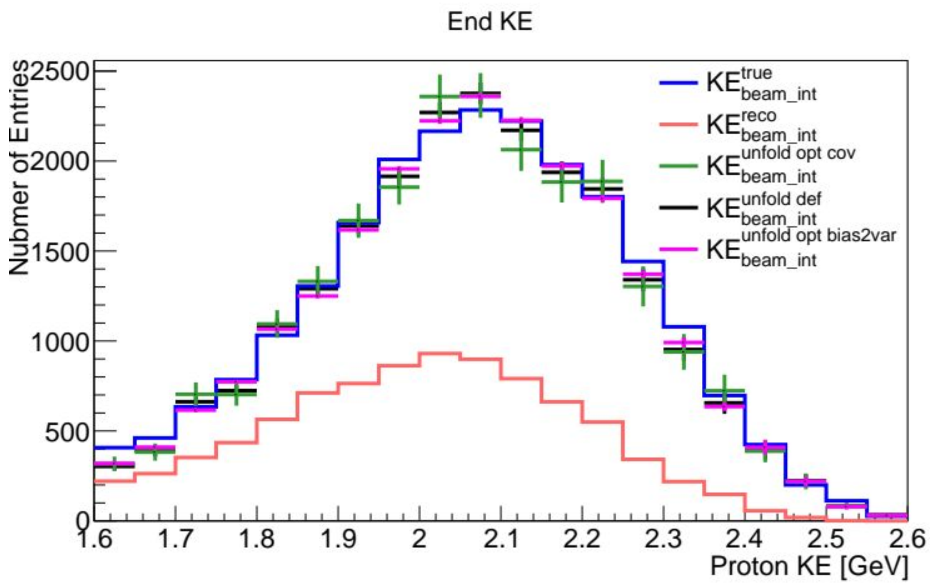




ProtoDUNE 3 GeV proton cross-section measurement

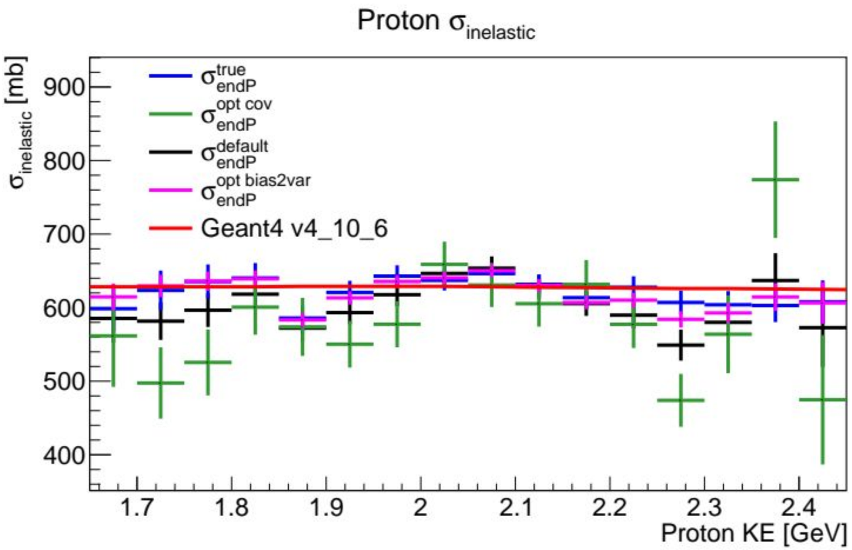
- Due to the high dE/dx values among some pitches, the reconstructed end KE has a long tail in the low energy region.





ProtoDUNE 3 GeV proton cross-section measurement

- The “opt cov” has the worst performance. Due to high number of iterations.
  ini: 13, int: 20, beam_int: 11.
- The “opt bias2bvar” has the best performance and it will be used on data.

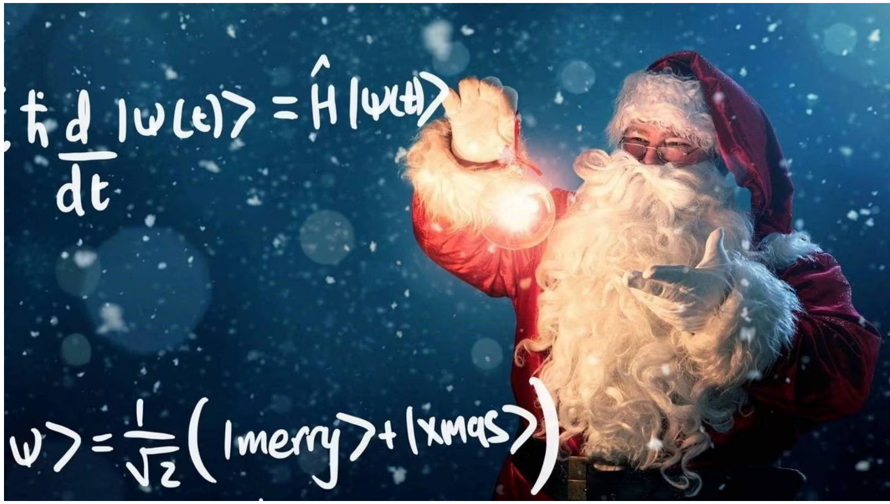


Neutrino Group - Next Year

- Many students graduating:
  - Alex - starting a postdoc at Sheffield.
  - Stefano - already taken up a postdoc at UCL.
  - Karolina
  - Jing
- Up and coming new talent:
  - Magnus
- Look forward to seminars next term from:
  - Karolina: 6th February - *Overview and Status of the 2x2 NDLAr Demonstrator*
  - Jing: 27th February - *Proton cross-section measurement in ProtoDUNE-SP*
  - Stefano: TBA - *Antarctic Impulsive Transient Antenna (ANITA)*
- Exciting new physics opportunities:
  - First ProtoDUNE-ND data collection and analysis.
    - First step to many papers.
  - ProtoDUNE-HD data taking.
    - Successor to ProtoDUNE-SP.

Santa and Neutrinos

- This is a very important time of year for neutrino physicists.
- Because as you all know, Santa is a lot like neutrinos.



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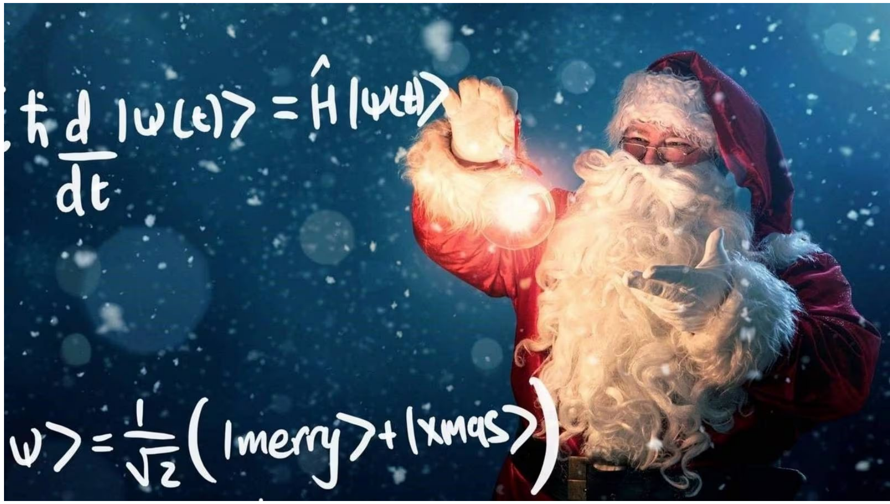

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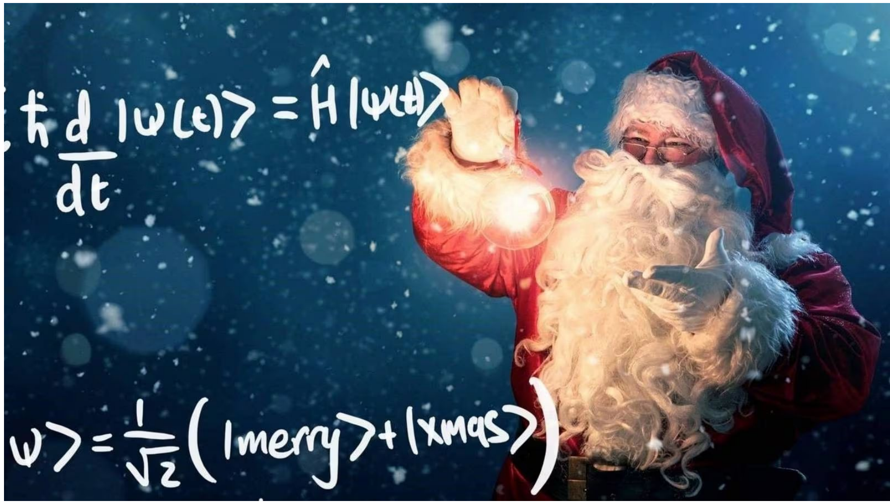

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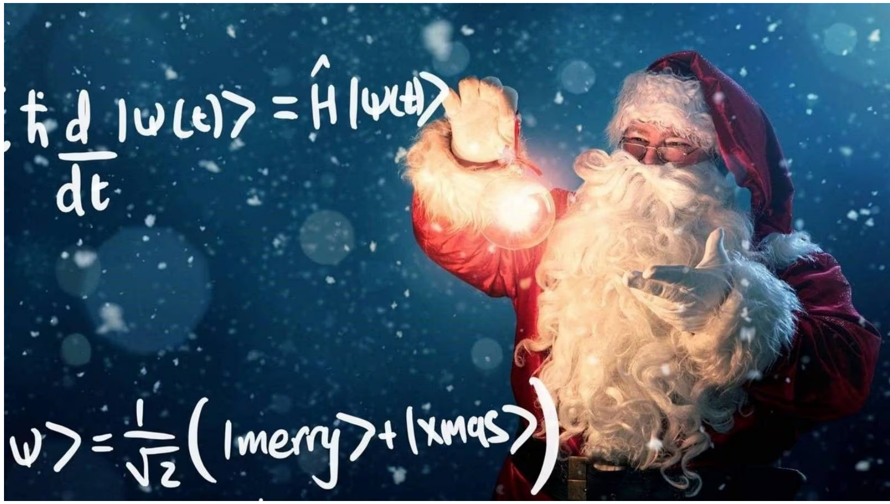
  - Goes through everyone's household on Christmas Eve.
  - Brings us exciting gifts.



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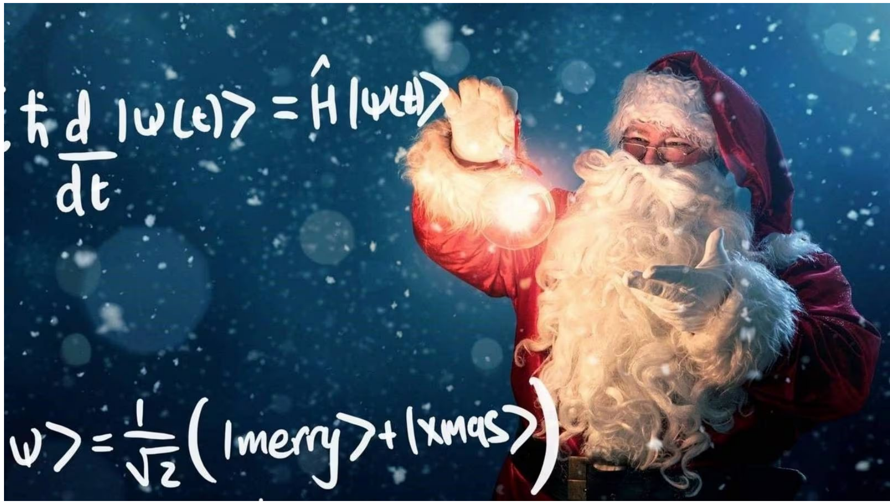
    - Brings us exciting gifts.
        - And sometimes coal.



Santa and Neutrinos

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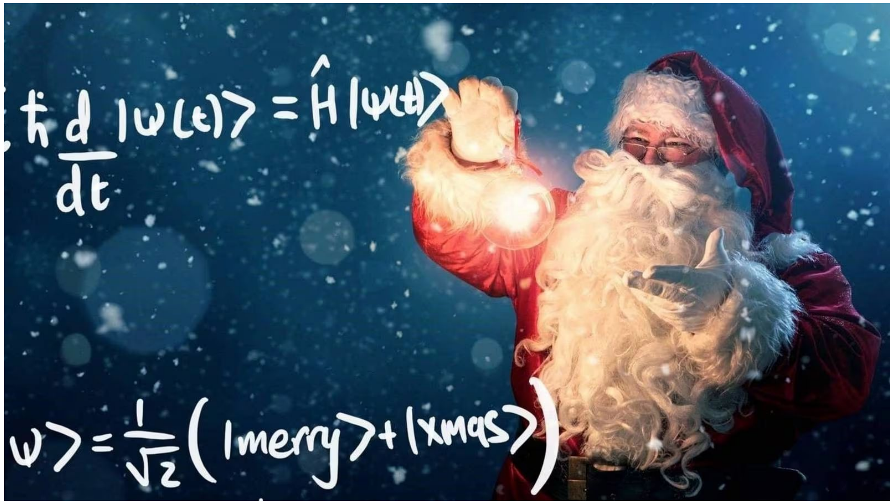

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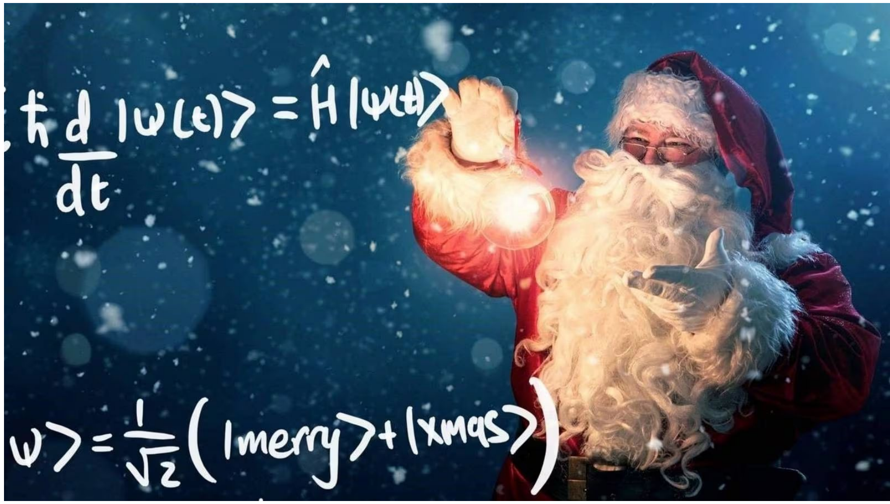

Thanks for listening.

Merry Christmas

and a

Happy Nu Year!