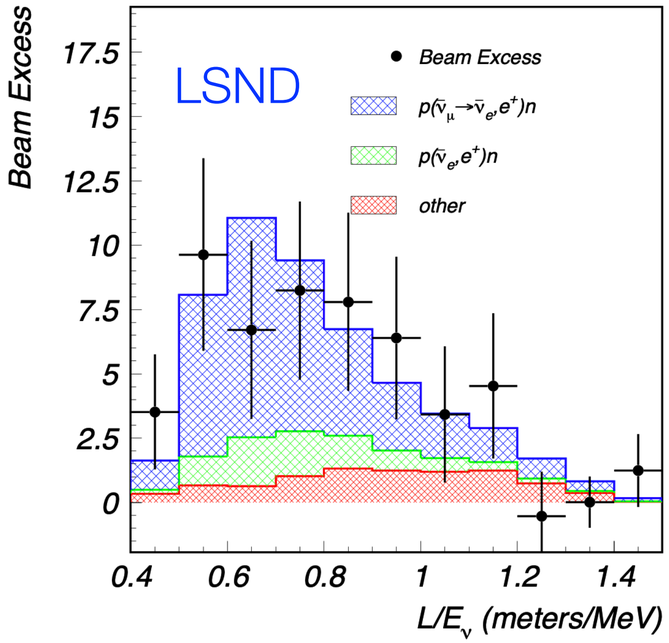
Latest results from the ICARUS experiment at the Short-Baseline Neutrino program

Alice Campani *on behalf of the* ICARUS collaboration

Vietnam Flavour Physics Conference, 21 August 2025

The sterile neutrino puzzle: hints of a 3+1 scenario?

- Well established 3-flavour neutrino mixing, but several anomalies in the past 20 years data

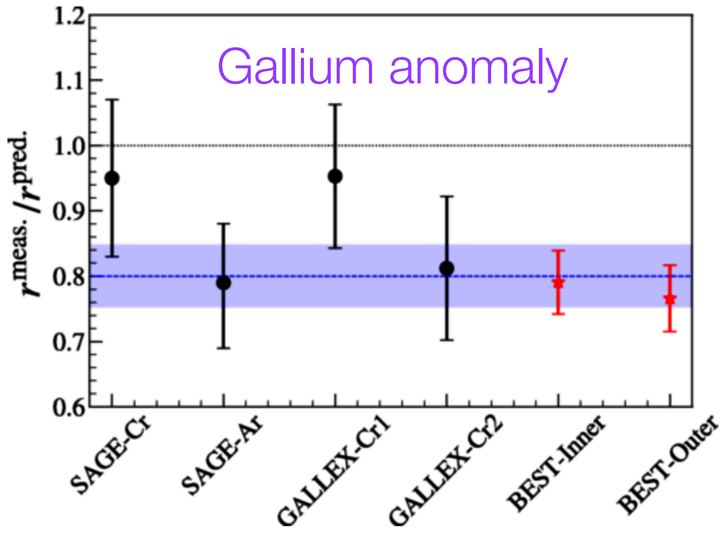


Anomalous signal of $\bar{\nu}_e$ excess at low energy:

best fit $\sin^2(\theta_{\text{new}}) = 0.003$

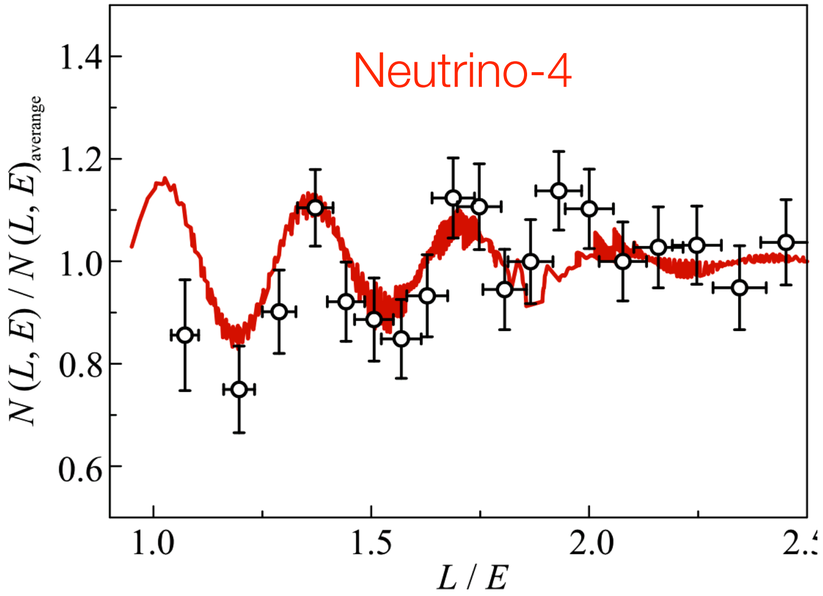
$\Delta m^2_{\text{new}} = 1.2\ \text{eV}^2$

Phys. Rev. D 64, 112007 (2001)



Phys. Rev. C 105, 065502 (2022)

These results could be explained with an additional $\Delta m^2_{\text{new}} \sim 1.0\ \text{eV}^2$ driving $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) oscillations at small distances and pointing towards the possible existence of **non-standard** heavier **sterile neutrino(s)**

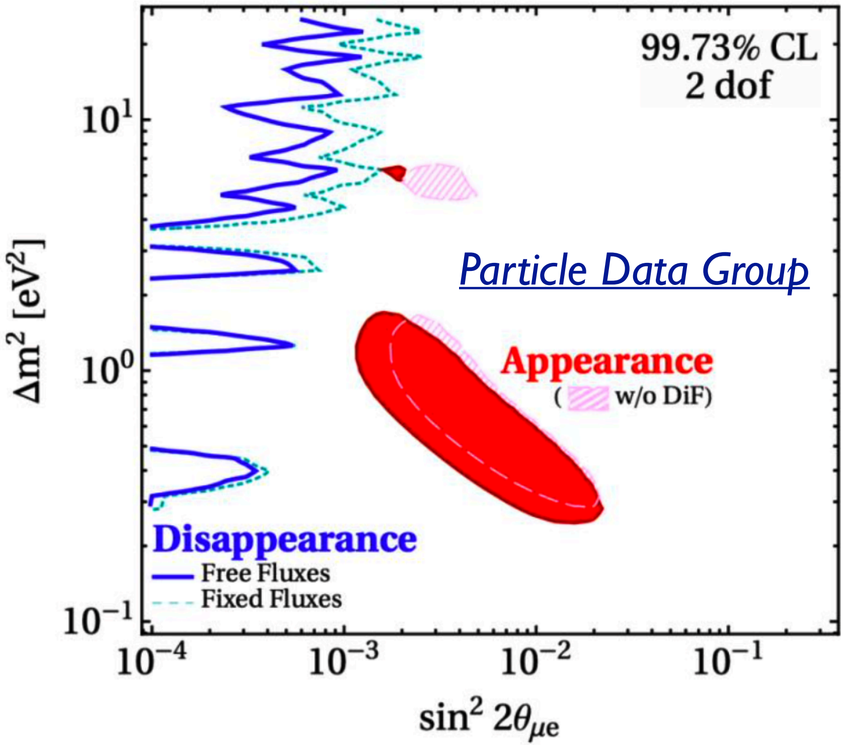


Oscillation signature compatible with $\Delta m^2_{\text{new}} = 7.3\ \text{eV}^2$ and $\sin^2(2\theta_{\text{new}}) = 0.36$ (5.8σ C.L.) and L/E ~1-3 m/MeV combining data from Neutrino-4, GALLEX, SAGE and BEST

Jetp Lett. 116, 669–682 (2022)

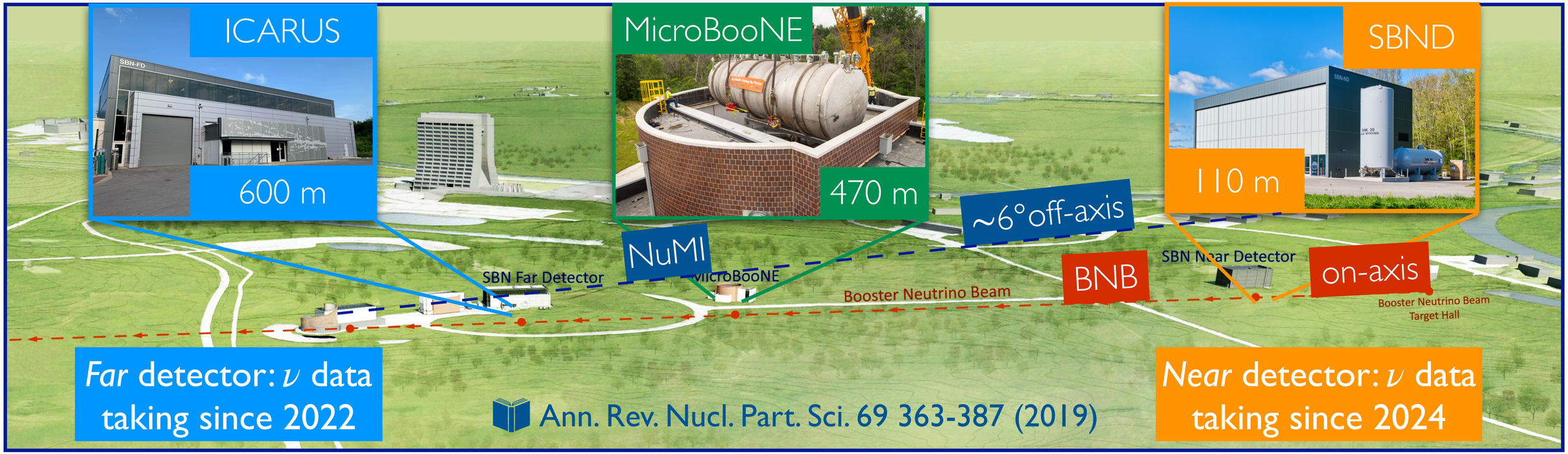
The sterile neutrino puzzle: hints of a 3+1 scenario?

- **Clear tension** between **appearance** and **disappearance** results from short baseline accelerator, reactor and radio-chemical experiments [Maltoni talk @ Neutrino 2024]
  - $\bar{\nu}_e$ **appearance**: weak hint of a signal from LSND
  - $\bar{\nu}_e$ **disappearance**: signal seen by Neutrino-4, ~5% discrepancy between Φ_{meas} and Φ_{theo} for SBL reactor experiments - recent results from Daya-Bay, RENO, STEREO reduce its significance
  - ν_e **disappearance**: radio-chemical experiments show a deficit in the measured rate $\mathbf{R = (0.82 \pm 0.03)}$
  - Many (accelerator and reactor) experiment results compatible with the null hypothesis & **no anomaly** seen in the ν_μ **disappearance** channel



We still **lack** a **global**, **clear** and **coherent picture** of all experimental data and the significant tension we observe comes from experiments with different technologies, detection techniques and energy ranges: performing a **simultaneous search in different channels** with the **same detection technique** is crucial.

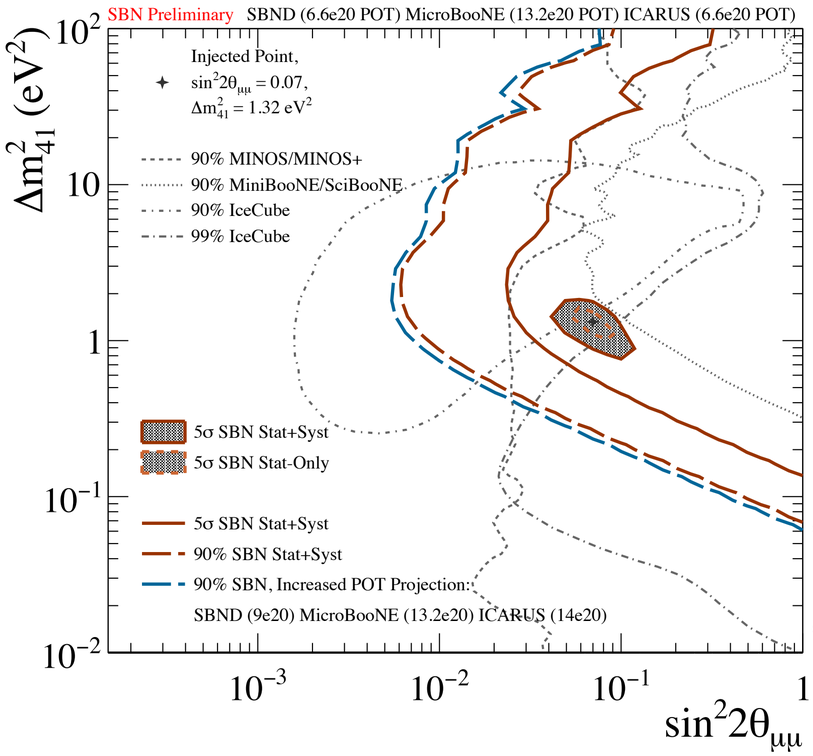
The Short Baseline Neutrino Program



- Same LArTPC technology (*near*→**SBND**, *far* detector→**ICARUS**), same nuclear target/beam source to constraint Φ and σ and reduce systematics to the level of %
- 0.8 GeV Booster Neutrino Beam (**BNB**) and for ICARUS also Neutrino at the Main Injector (**NuMI**) (6° off-axis)
- Sensitive search of **1eV** mass **sterile** ν in the ν_e (ν_μ) (dis)appearance channels to confirm/rule out past anomalies

  High statistics measurements of $\nu - Ar$ **cross sections** and event reconstruction studies in LArTPC in view of **DUNE:** $\sim 10^6$ events/yr <1 GeV in SBND from BNB - Beyond Standard Model (**BSM**) channels explored in ICARUS thanks to $\sim 10^5$ events/yr >1 GeV from NuMI beam

The Short Baseline Neutrino Program

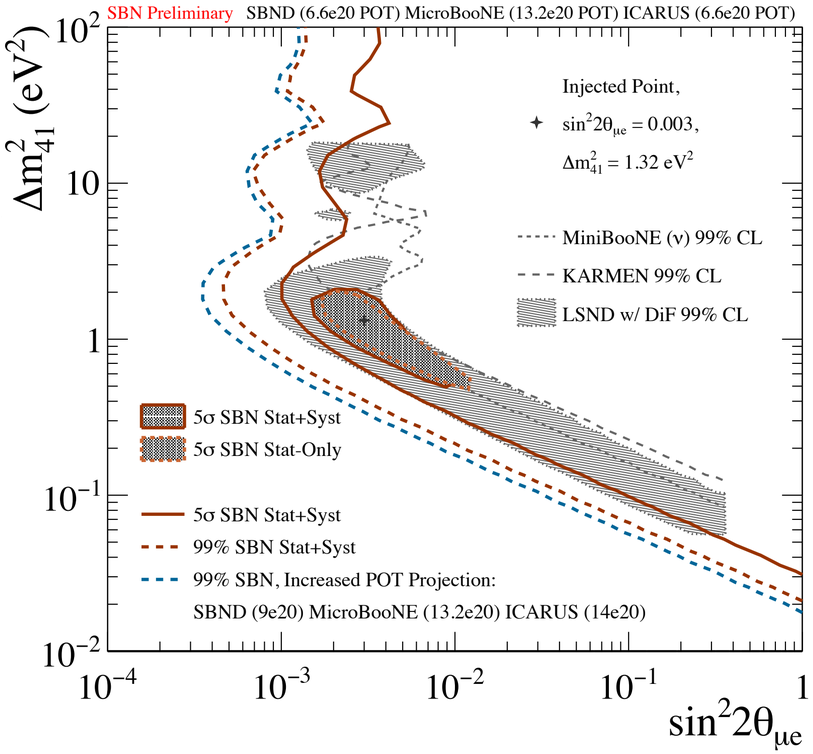


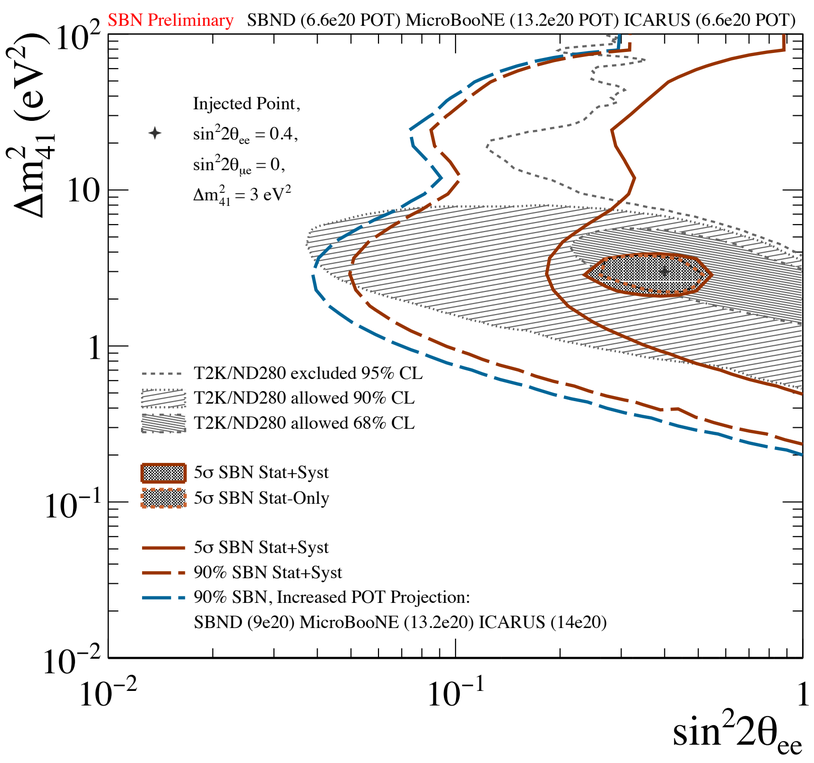
ν_μ disappearance channel

The **combined analysis** of near and far detector data grants the unique capability to study appearance and disappearance **channels simultaneously**

5σ sensitivity to LSND anomaly in **3 years of data taking** ($6.6 \cdot 10^{20}$ PoT) - reactor and gallium anomalies will be also probed

ν_e appearance channel





ν_e disappearance channel

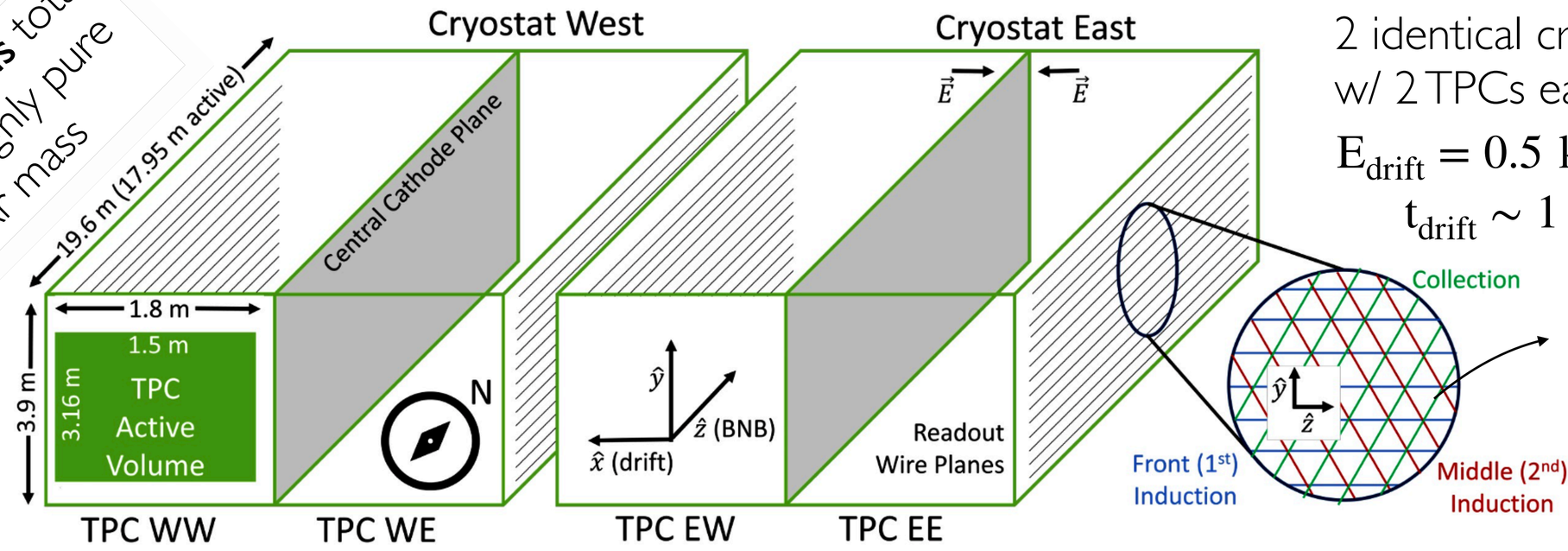
LArTPC imaging technology grants high sensitivity allowing high signal (ν_e) to background (NC) discrimination capability

The ICARUS experiment: LArTPC detector

- Liquid Argon Time Projection Chambers (LArTPCs)[1977, C. Rubbia]: self-triggering, continuously sensitive detectors with 3D topological and calorimetric reconstruction capability

ICARUS T600 is the **first** large scale **LArTPC** ever built!

760 (**470**) **tons** total (active) highly pure LAr mass



2 identical cryostats w/ 2 TPCs each

$E_{drift} = 0.5$ kV/cm

$t_{drift} \sim 1$ ms

3 wire planes: 54k wires, 3mm pitch

360 8" **PMTs** behind wires measure scintillation light thereby providing t_0 tagging (~ns) and trigger

External 4π Cosmic Ray Tagger (**CRT**) to tag incoming cosmic rays (11 μ tracks per trigger)

3 layer overburden to further suppress incoming cosmics

Eur. Phys. J. C 83:467 (2023)

ICARUS: detector operation and data acquisition

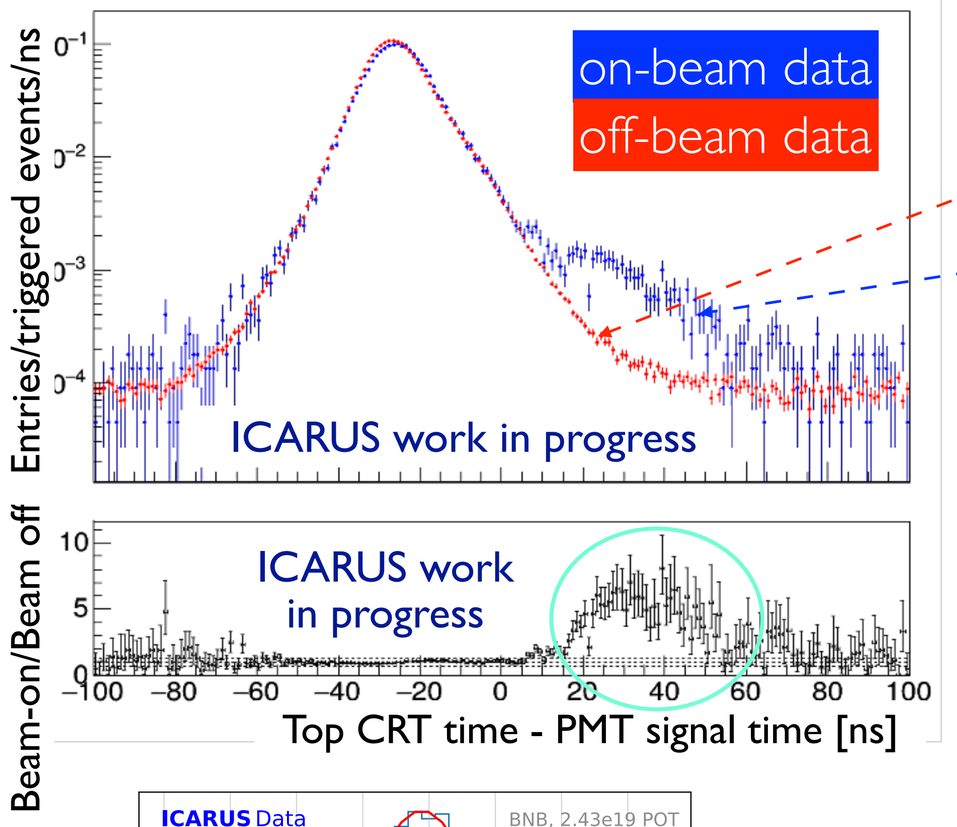
- Physics data taking started in June 2022 and we completed 4 physics runs so far
- Trigger: light recorded at the same time by 4 PMT pairs in a 6-m longitudinal section with BNB (1.6 μs), NuMI (9.5 μs) beam spills
- Steady data taking with great stability and BNB > 4 Hz, >90% efficiency @ Edep > 200 MeV, free τ_{ele}~7-8 ms

Collected statistics: Protons on Target (**PoT**)

Run	Duration	BNB (FHC) [*] positive focusing	NuMI (FHC) [*] positive focusing	NuMI (RHC) [*] negative focusing
1	Jun - July '22	0.42 10^{20}	0.69 10^{20}	-
2	Dec '22 - July '23	2.13 10^{20}	2.84 10^{20}	-
3	Mar - July '24	1.36 10^{20}	-	2.82 10^{20}
4	Dec '24 - Jul '25	3.63 10^{20}	-	-
Total	/	7.54 10^{20}	3.53 10^{20}	2.82 10^{20}

[*] FHC/RHC: Forward (Reverse) Horn Current

ICARUS detector performance: timing



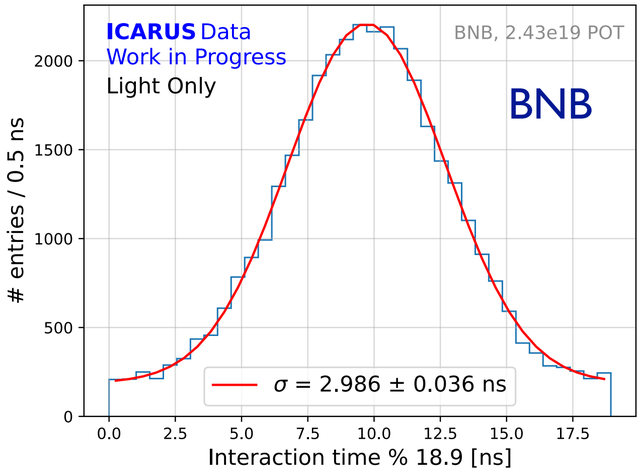
Time of flight **rejection of cosmic rays** using CRT & PMT

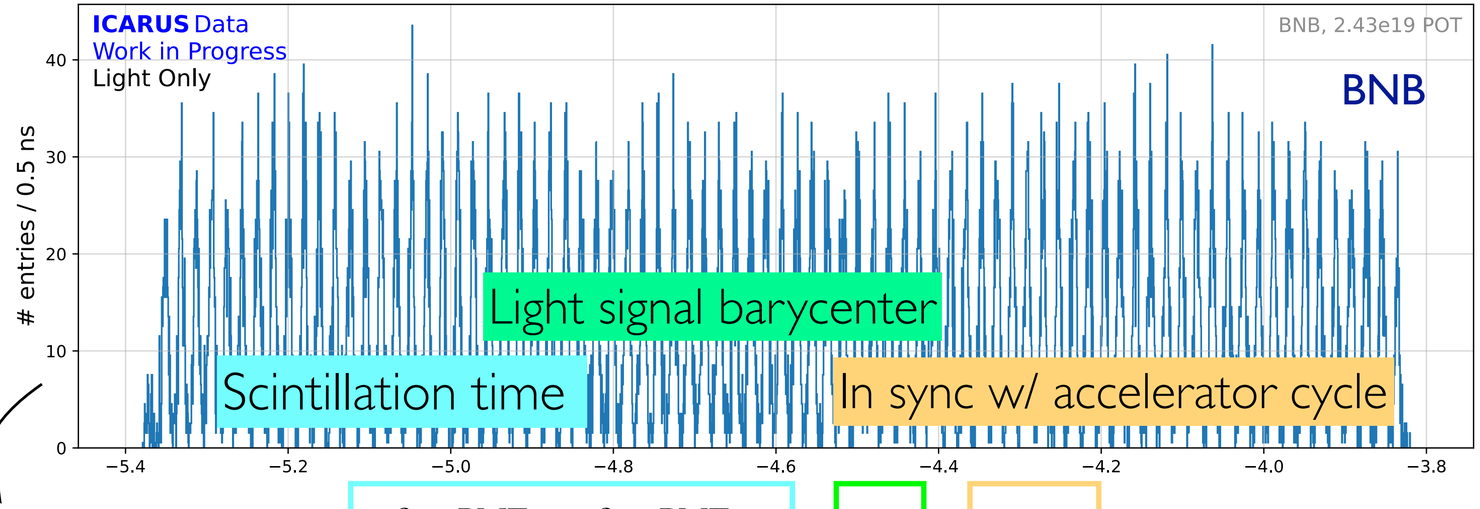
Cosmics entering from top CRT
$\Delta T_{CRT-PMT} < 0$ (bkg)

ν products exiting through top CRT
$\Delta T_{CRT-PMT} > 0$ (signal)

Excess due to ν beam (signal)

Bunched structure of BNB, NuMI **beam spill identified** with neutrino interaction time (scintillation, PMT) with respect to the proton beam extraction time after cosmics rejection (CRT) and correction for the neutrino time-of-flight (ToF) distance



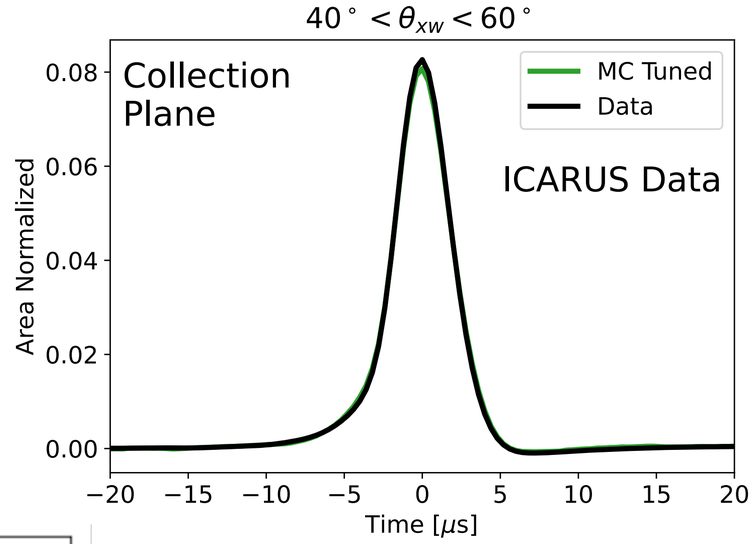


Relevant for BSM studies $(t_L^{\text{first PMT}} + t_R^{\text{first PMT}})/2 - \text{ToF} - T_{RWM}$ [us]

ICARUS detector performance: TPC signal modelling and calibration

- Accurate TPC wire signal characterisation and modeling in Monte Carlo simulations:
  Average electronics wire signal response per plane per track angular bin extracted

JINST 20 P01032 (2025)

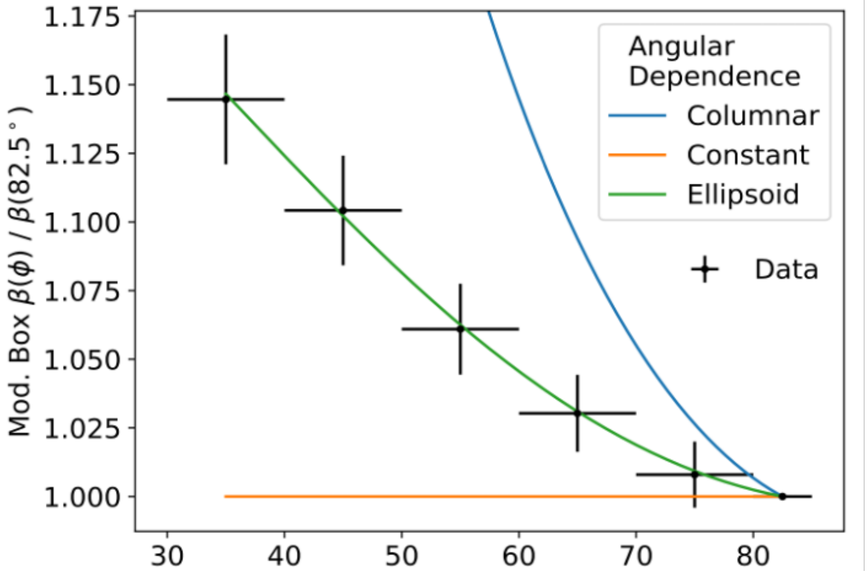


- Detector response **calibration** to extract front-end (TPC) electronic gain factors and electron lifetime corrections, using
  - Cosmic muons (MIP particles)
  - Protons from ν interactions
- New angular dependent modified (*ellipsodal*) **recombination model**

JINST 20 P01033 (2025)

$$\frac{dQ}{dx} = \frac{\log\left(\alpha + \mathcal{B}(\phi)\,\frac{dE}{dx}\right)}{\mathcal{B}(\phi)\;W_{ion}}$$

Modified Birks law: $\mathcal{B} = \mathcal{B}(\phi)$



$$\mathcal{B}(\phi) = \frac{\beta_{90}}{\varepsilon\rho\sqrt{\sin^2\phi + \cos^2\phi/R^2}}$$

$\alpha = (0.904 \pm 0.008)$

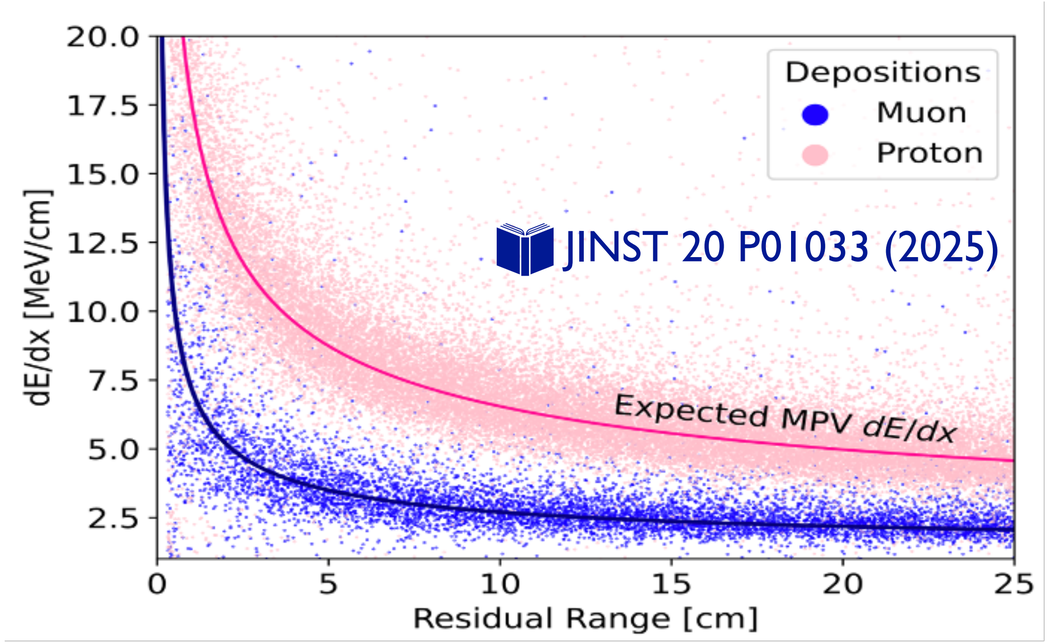
$\beta_{90} = (0.204 \pm 0.008)$ (kV/MeV)(g/mL)

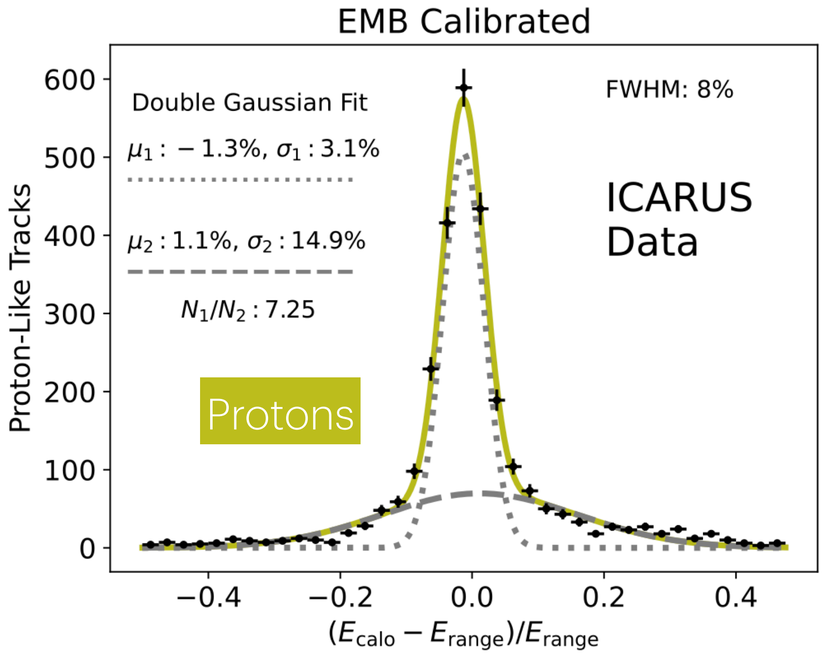
ε electric field, ρ LAr density

$R = (1.25 \pm 0.02)$

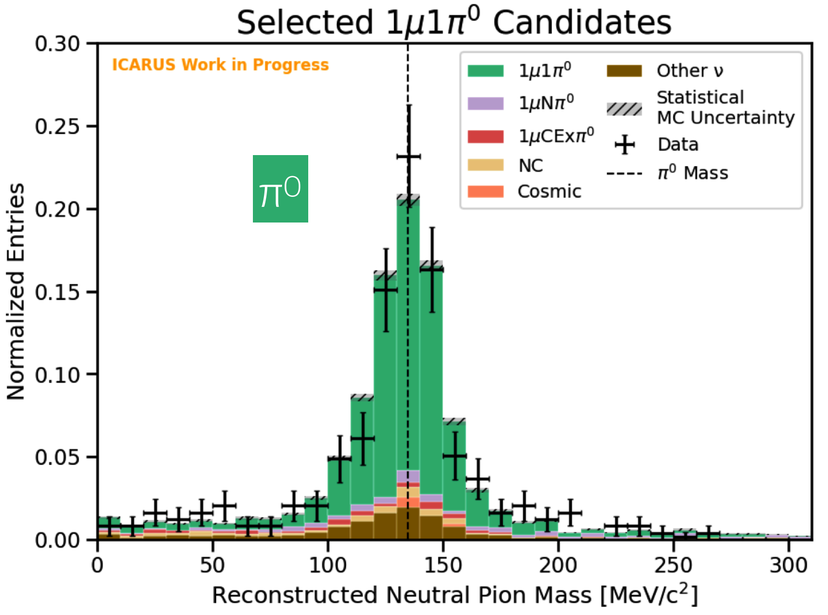
ICARUS detector performance: TPC signal modelling and calibration

- Energy loss per unit length (dE/dx) vs residual range crucial for (μ and protons) particle identification

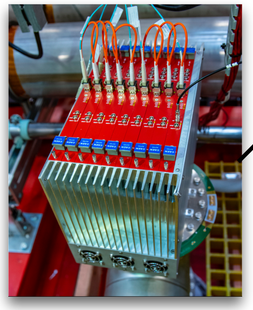




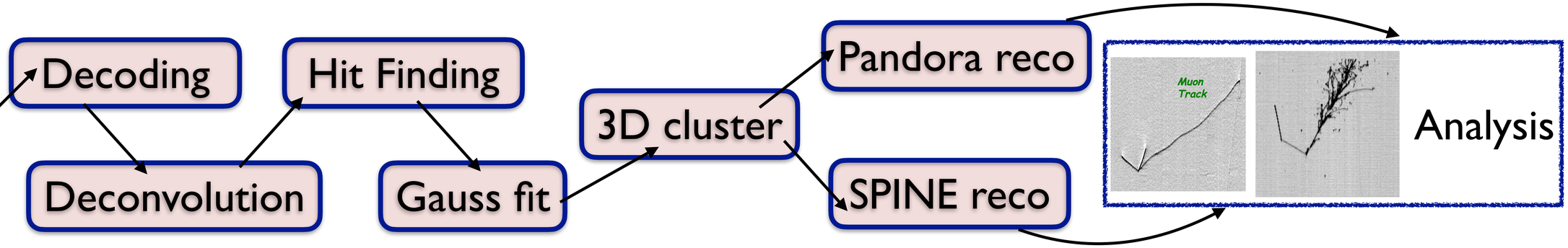
- Calorimetric reconstruction of the deposited energy was validated by means of several data samples:
  - Protons stopping in the active LAr volume from NuMI ν_μ CC interactions [8% energy FWHM]
  - π^0 from BNB ν_μ CC interactions [~10% resolution on $m_{\gamma\gamma}$]



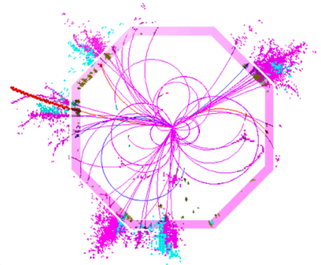
ICARUS event reconstruction



Raw data



- Two LArTPC event reconstruction frameworks:
  - **Pandora**, pattern recognition software widely used in LArTPCs
  - **SPINE**, entirely based on Machine Learning techiques (arxiv)
- Powerful tool to validate data processing and analysis and study data/MC agreement is the **visual scanning** of collected events:
  - reconstruction of the ν vertex using a BNB ν_μ CC sample
  - matching of light & charge signals: ~1m agreement along beam
  - test selection/reconstruction performance in view of analyses



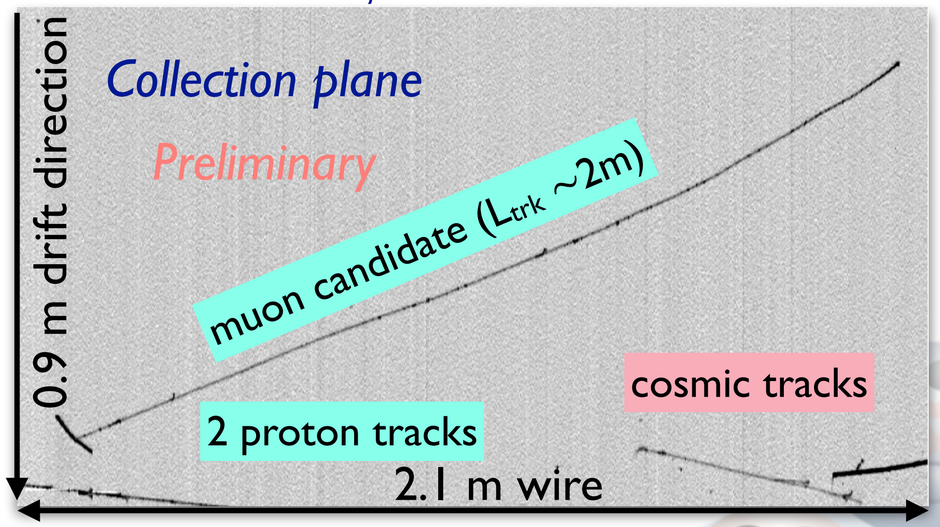
PANDORA SDK

SPINE

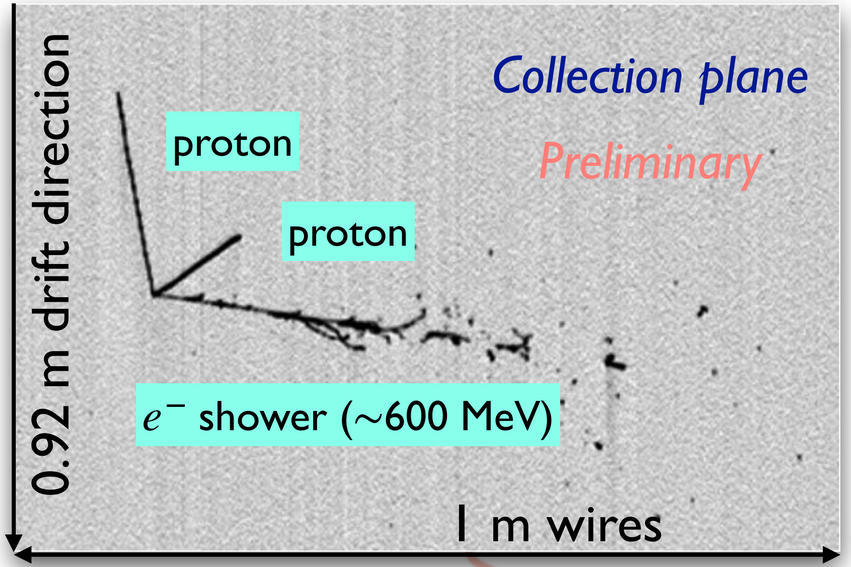
SPINE

ICARUS candidate neutrino events

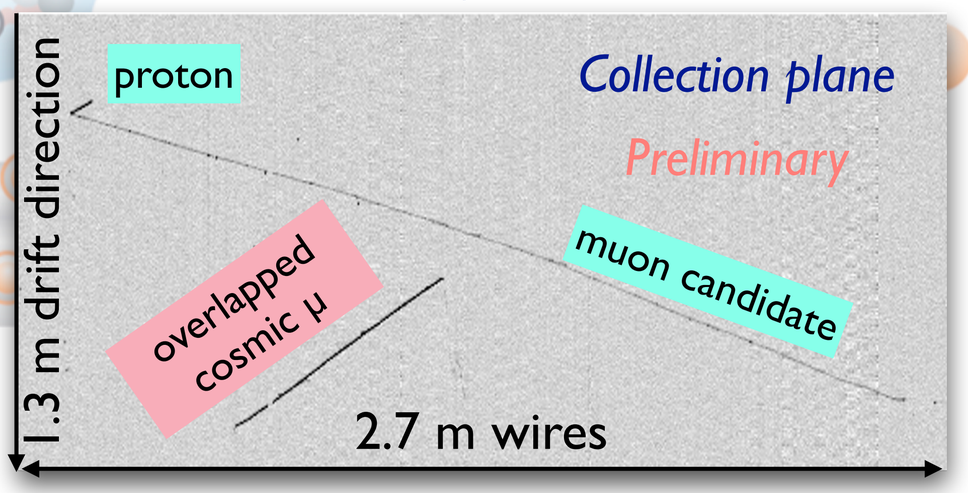
BNB ν_μ CC candidate



NuMI ν_e CC candidate



BNB ν_μ CC candidate



The ICARUS physics program

- **SBN physics program**: **sterile neutrino search** comparing ν_μ, ν_e interactions at a different distance from the BNB beam target thanks to SBND and ICARUS LArTPCs
- Before and in view of the joint-analysis with SBND, ICARUS focuses on a **standalone physics program:**
  - Analysis of the ν_μ **disappearance channel with BNB** to be complemented with ν_e **disappearance from NuMI** data - the goal is to verify the **Neutrino-4 claim**
  - Study of ν_μ, ν_e interactions from NuMI to **measure ν-Ar cross sections** and optimize reconstruction in the energy range that **DUNE** will explore
  - Search for **sub-GeV** Beyond Standard Model (**BSM**) **signals** using NuMI: $\mu\mu$ **decay channel** explored

Blinding policy to ensure robust and unbiased interpretation of the collected data:
analyses are validated using sidebands, a subset of the full dataset or variables insensitive to oscillation

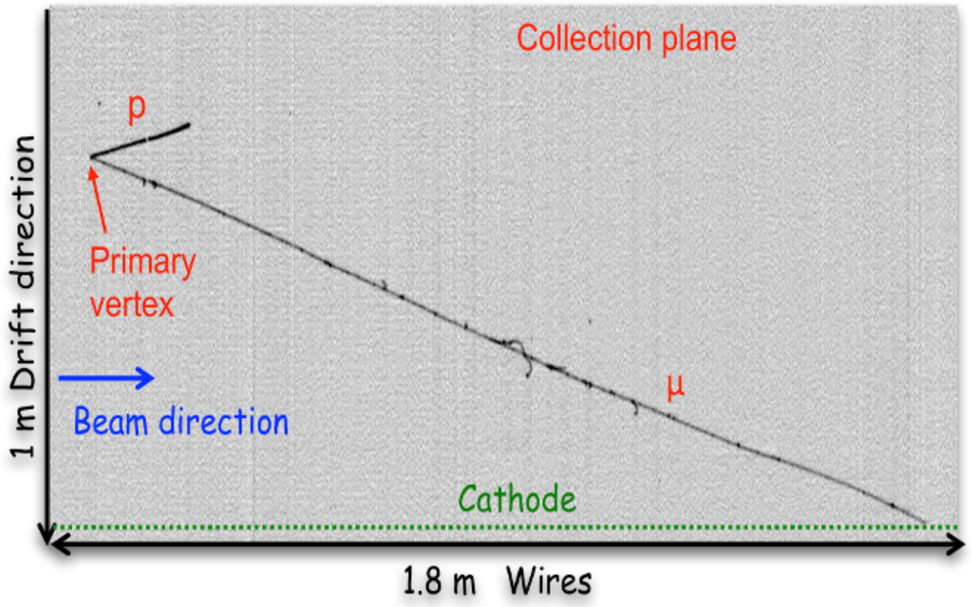
The ICARUS standalone ν_μ disappearance analysis: data selection

- Selection of fully contained ν_μ CC events with $1\mu + \mathrm{Np}$ with kinematic reconstruction and PID from range and the following requirements:

  (1) PMT light signal within 1.6 μs p beam spill in coincidence with reconstructed TPC tracks and no CRT signal

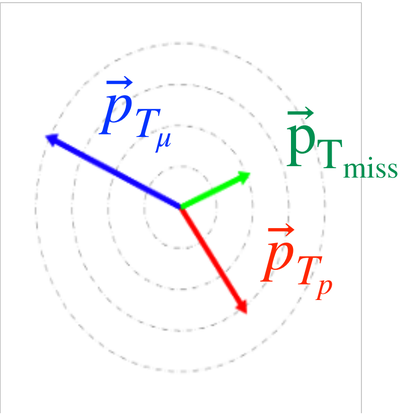
  (2) A muon with $\mathrm{L_{track}}$>50 cm, $\mathrm{N} > 1$ protons with $\mathrm{E_K}$>50 MeV ($\mathrm{L_{track}}$>2.3 cm), PID scores in range

  (3) No additional pion/photon



- Residual cosmic background evaluated using on- and off-beam data <1%
- Flux, cross sections and (conservative) detector **systematic uncertainties** included in the analysis:
  - comparison of (un)calibrated MC samples gives <u>preliminary estimates</u> of detector effects, while effort to improve simulations (light, TPC, dE/dx…) and reduce data/MC discrepancy continues

Momentum in the transverse plane



Substantial cancellation of Φ, σ effects and common detector effects is expected with a **joint** SBND/ICARUS analysis

The ICARUS standalone ν_μ disappearance analysis: selection results

- **10%** of RUN2 BNB data analysed (~20 x data available) showing good data/MC agreement within systematics

Two independent analyses

Pandora-based reconstruction

~**50%** efficiency, ~**80%** purity

1.93 x 10^{19} Proton on Target **(PoT)**

34000 events (Run1-3)

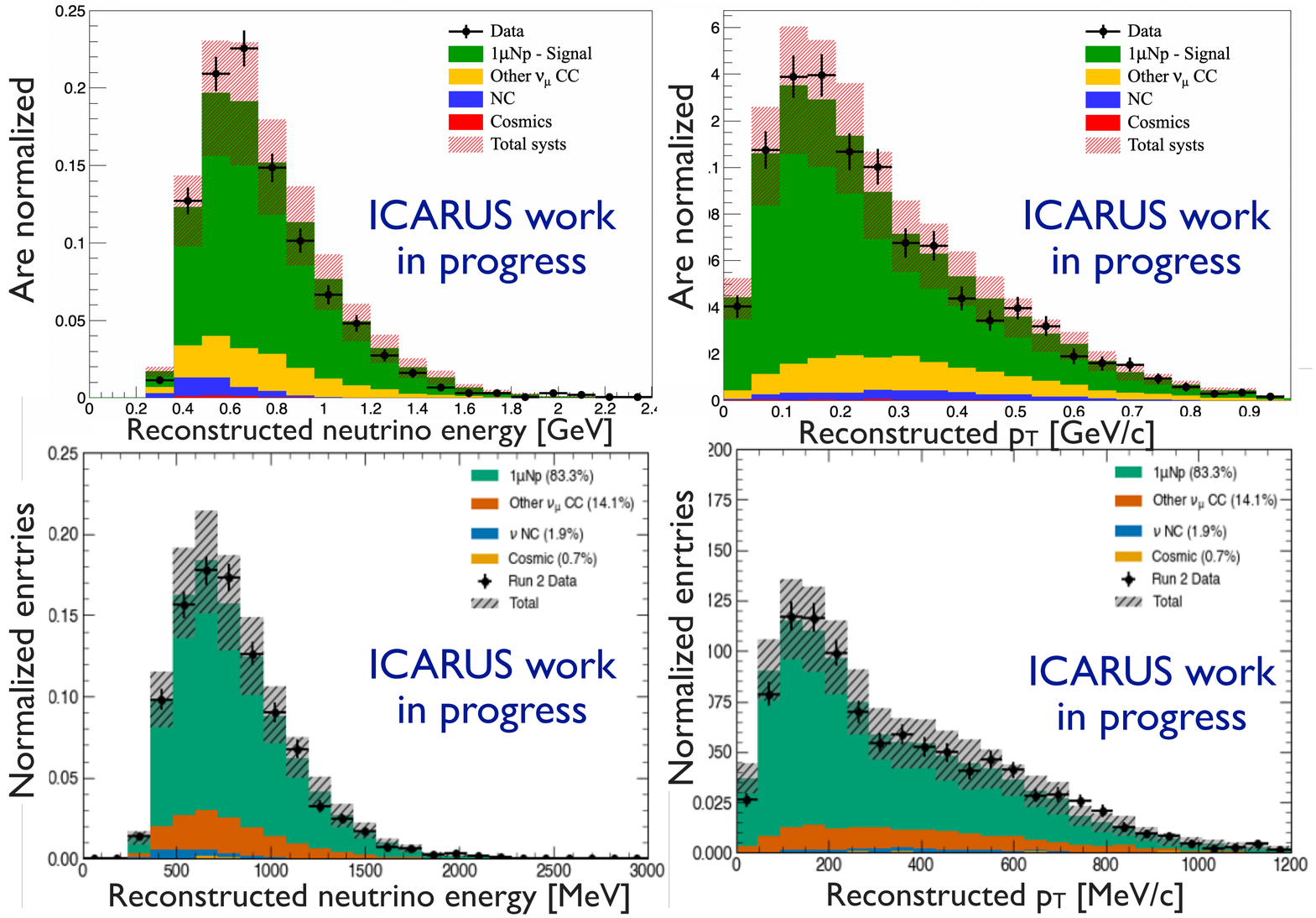
SPINE-based analysis

~**75%** signal efficiency, ~**90%** purity

1.92 x 10^{19} PoT

47000 events (Run 1-3)

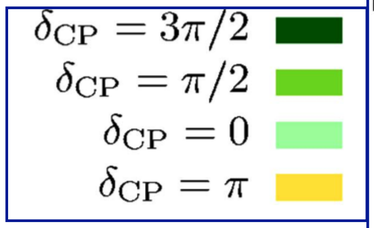
- Control sample enlarged to confirm the analysis is robust
- Systematics coverage verified
- Fitting framework developed

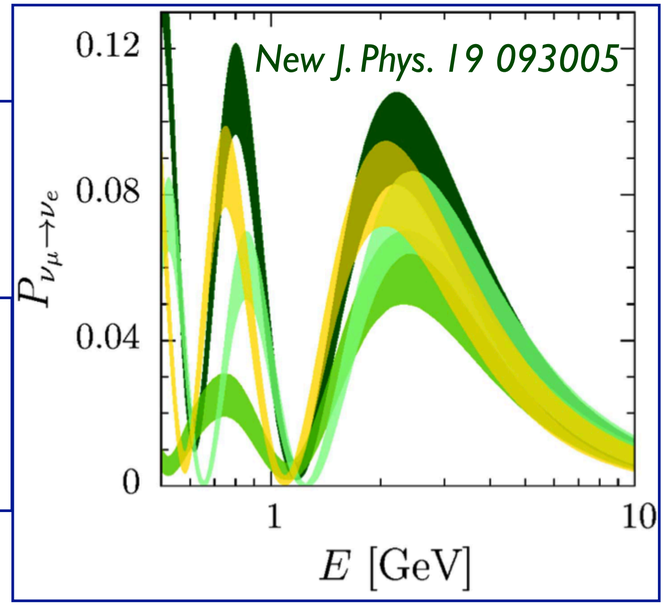


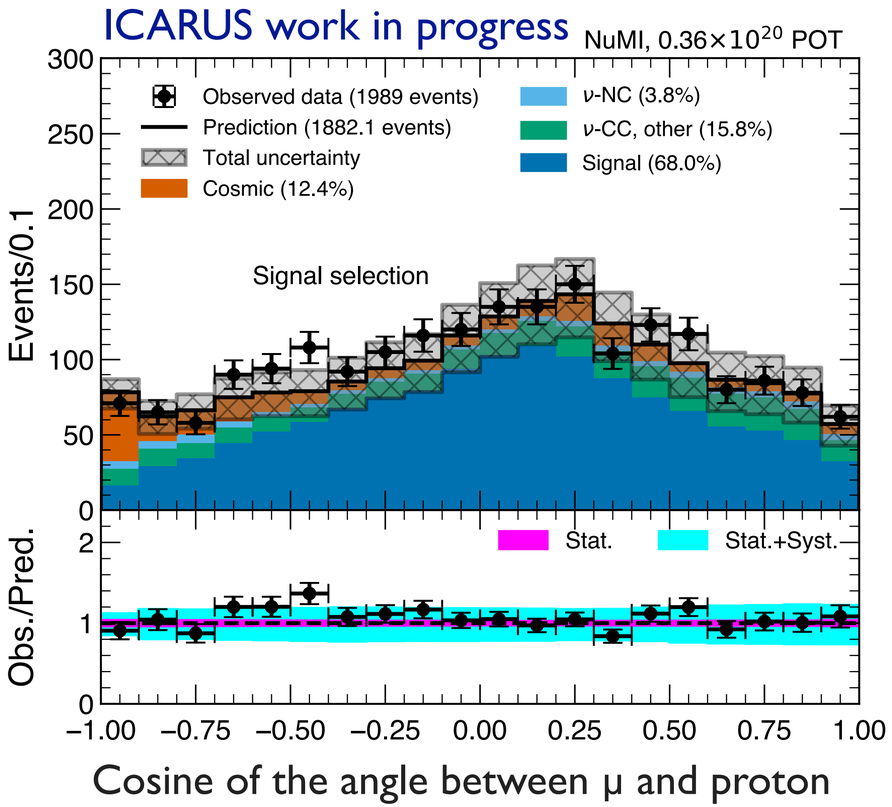
We are (almost) ready to proceed to full dataset unblinding and oscillation fit

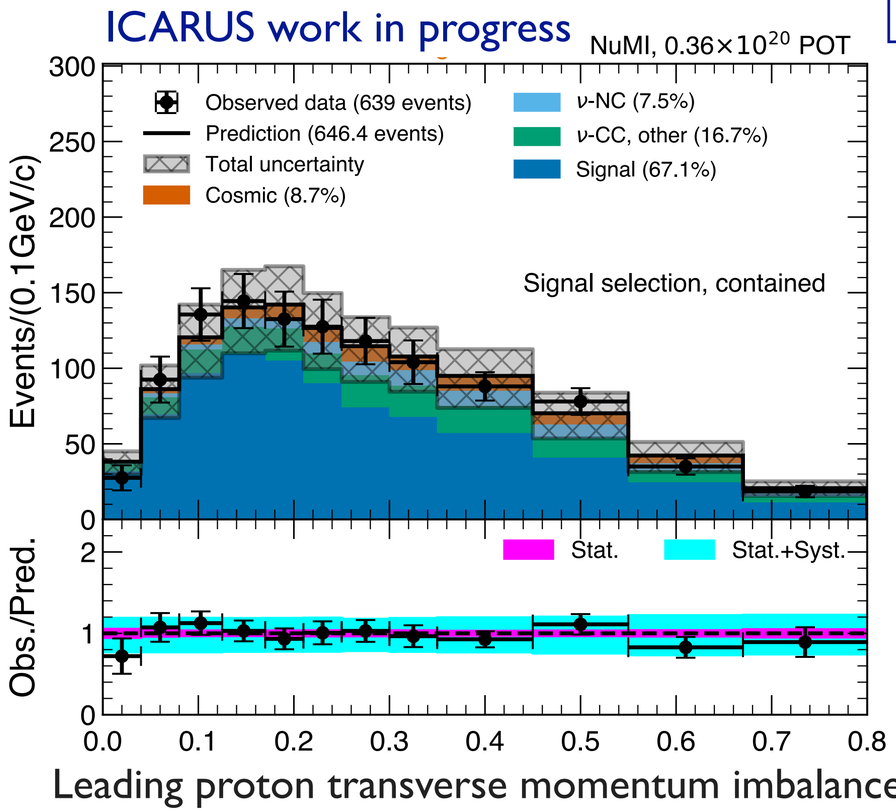
ICARUS physics program with NuMI data

- **Huge statistics** to measure quasi-elastic, resonance and deep inelastic scattering ν_μ, ν_e cross sections: CC events in 3.42 x 10^{20} PoT (*6 x 10^{20} PoT*)
  188 000 (*332 000*) ν_μ, 9600 (*17000*) ν_e
- Coverage of the first oscillation peak & relevant phase space for **DUNE**
- **BSM** physics program







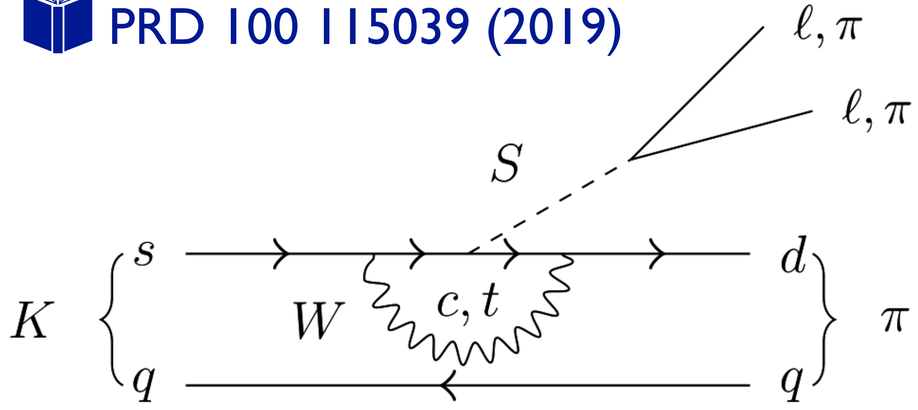


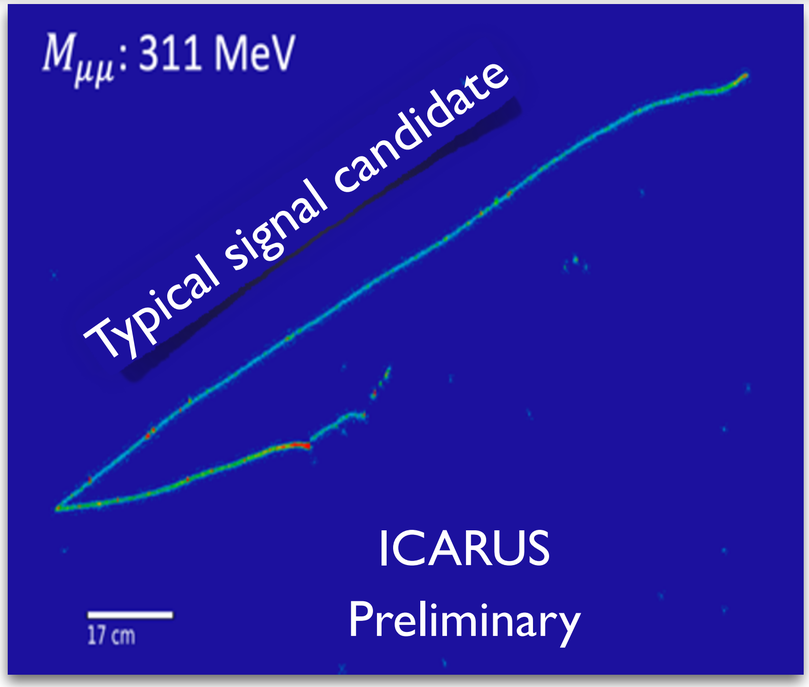
- First analysis targets **1μNp0π** sample <u>enhanced</u> in QE and 2p2h interactions
- Major background: undetected or misidentified π
- 15% of data & sidebands
- Results released soon

ICARUS dark sector model program with NuMI

Dominant signal production mode

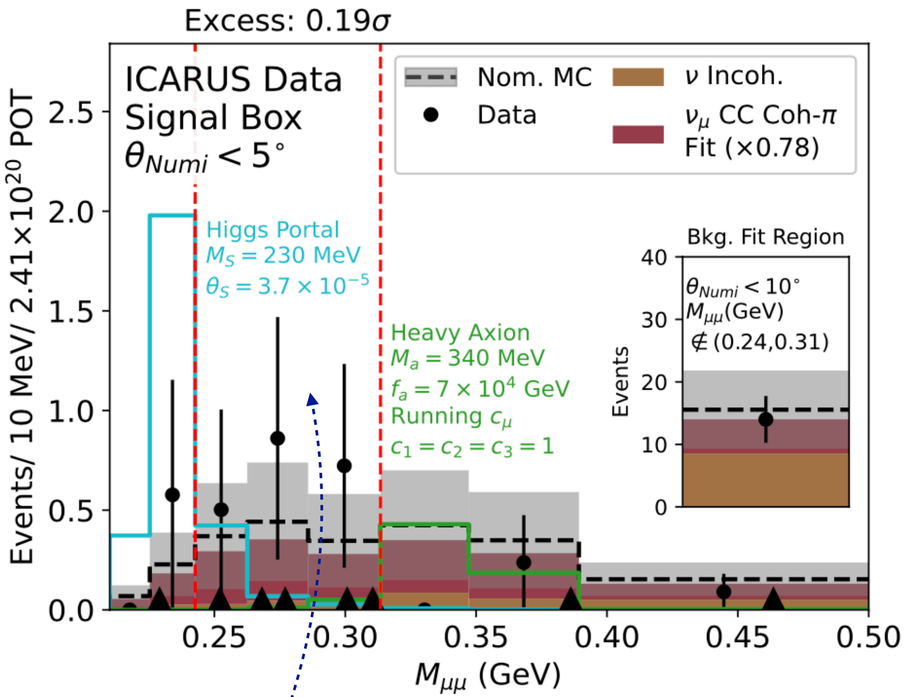
PRD 100 115039 (2019)

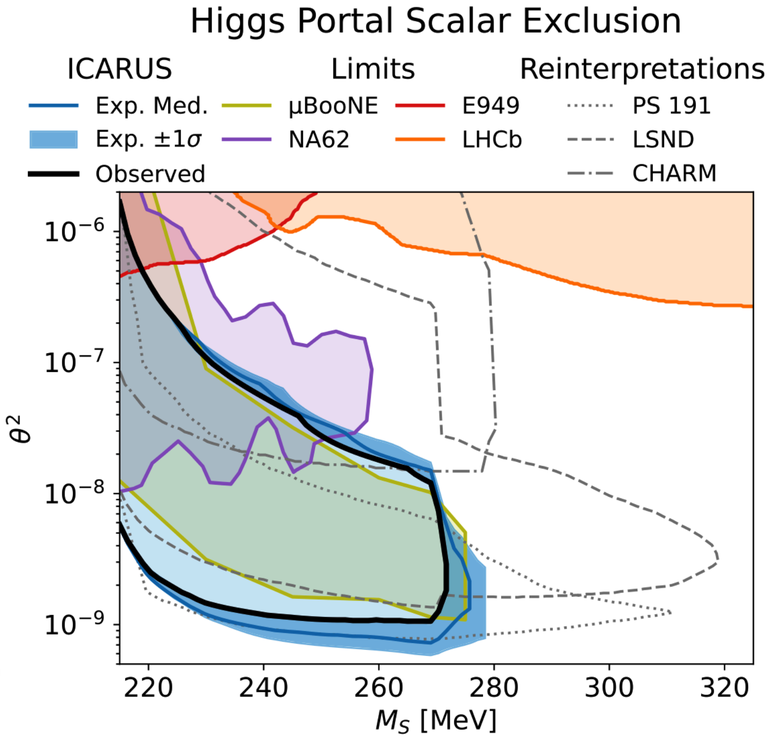




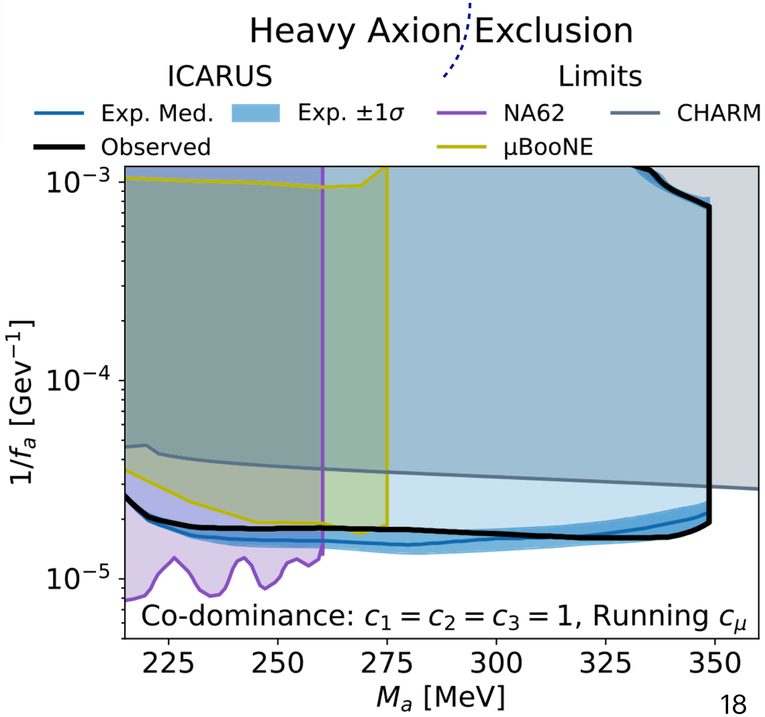
- Rich Beyond Standard Model (BSM) search program based on the off-axis **NuMI** beam
- **Models** currently explored feature dark particles coupling to SM via **Scalar** and **Pseudo-scalar Portal Interactions**
  - **Higgs Portal Scalar:** scalar dark particles, interacting via Higgs boson mixing
  - **Heavy QCD axion:** pseudo-scalar particles, interacting with SM ones via pseudo-scalar mesons
- First search for BSM particle decaying into **di-muon** state just **completed** with $2.41 \cdot 10^{20}$ PoT
  - Event selection: 2 stopping μ-like particles, fully contained & with resolvable mass peak, proxy of the scalar particle mass
  - Signal peak expected at small angles with respecto to the beam ($\theta_{\mathrm{NuMI}} < 5°$)
  - All systematics (flux, cross section and detector) included

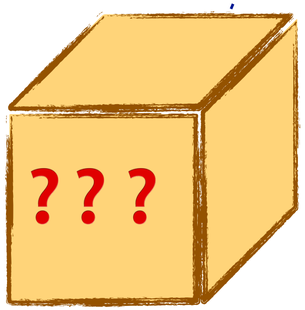
ICARUS BSM search in a di-lepton channel: final results





PRL 134, 151801 (2025)





Data **unblinding**: 8 events observed vs 8 events expected in the background-only hypothesis, mostly from ν_μCC coherent π production

No evidence of a signal observed:

maximum excess is **0.19σ**

Conclusions and next steps

- ICARUS is **running stably** and acquiring physics runs since summer 2022,
  esposed to both on-axis BNB (ν-mode) and off-axis NuMI (ν- and $\bar{\nu}$-mode) neutrino beams
- **Accurate** detector **calibration** and response **modelling** (electronic and calorimetric) extracted
  exploiting cosmic μs and protons from ν interactions and now fully embedded in our simulations
- Both waiting and in view of the upcoming joint-SBN analyses, several **single detector studies**
  are progressing and **quite advanced**:
  - ν_μ **disappearance** channel with **BNB** beam → after final checks we will proceed with data unblinding
  - ν**-Ar cross section measurements** with **NuMI** beam, first selection includes 1μNp0π events
    → sidebands with the full statistics available studied, almost ready to proceed with full unblinding
  - Search for **sub-GeV dark matter particles** with **NuMI** beam data
    - Search for ***di-muon*** fully contained final state topology available → analysis completed
- Interesting results are foreseen soon and ν_e analyses on BNB, NuMI data are starting so **stay tuned!**

Thanks for your attention

Cảm ơn sự chú ý của bạn

The sterile neutrino puzzle: hints of a 3+1 scenario?

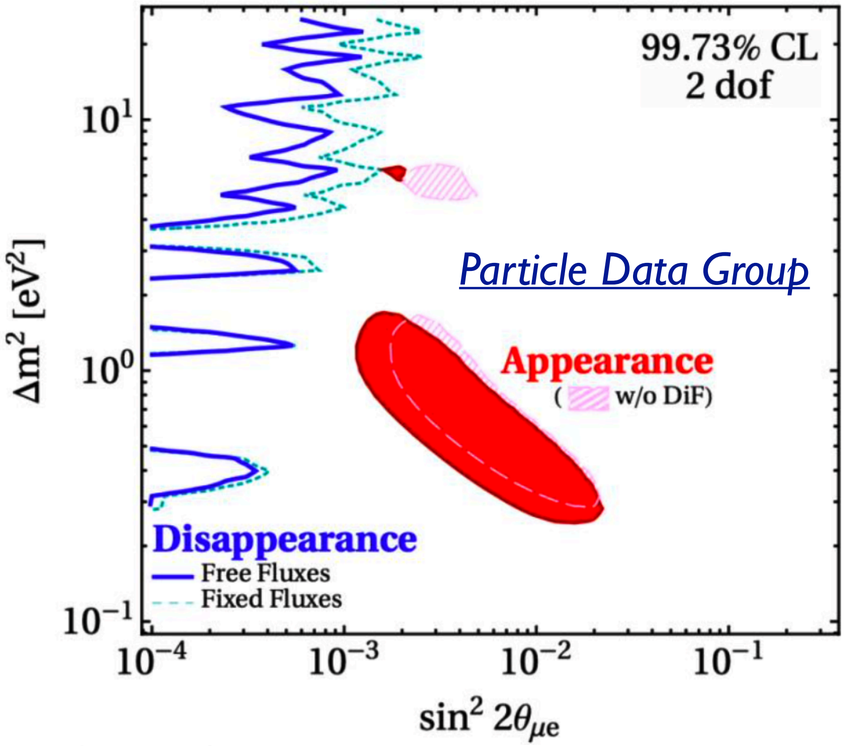
- **Clear tension** between **appearance** and **disappearance** results from short baseline (SBL) accelerator, reactor and radio-chemical (high intensity radioactive source) experiments [Maltoni talk @ Neutrino 2024]

  - $\bar{\nu}_e$ **appearance**: weak hint of a signal from LSND

  - $\bar{\nu}_e$ **disappearance**: signal seen by Neutrino-4, ~5% discrepancy between Φ_{meas} and Φ_{theo} for SBL reactor experiments - recent results from Daya-Bay, RENO, STEREO reduce its significance

  - ν_e **disappearance**: radio-chemical experiments show a deficit in the measured rate $\mathrm{R} = (0.82 \pm 0.03)$

  - Many (accelerator and reactor) experiment results compatible with the null hypothesis & **no anomaly** seen in the ν_μ **disappearance** channel



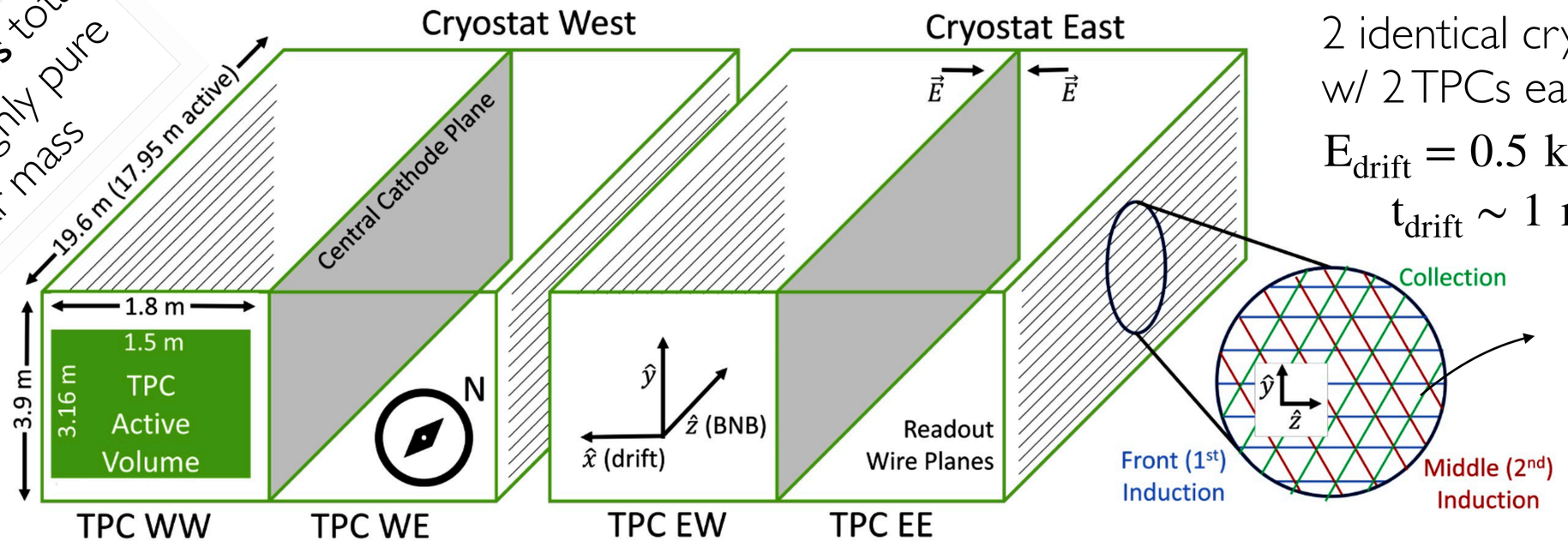
We still lack a global, clear and coherent picture of all experimental data and the significant tension we observe comes from experiments with different technologies, detection techniques and energy ranges: performing a simultaneous search in different channels with the same detection technique is crucial.

The ICARUS experiment: LArTPC detector

- Liquid Argon Time Projection Chambers (LArTPCs)[1977, C. Rubbia] are self-triggering, continuously sensitive detectors with 3D topological and calorimetric reconstruction capability

ICARUS T600 is the **first** large scale **LArTPC** ever built!

760 (**470**) **tons** total (active) highly pure LAr mass



2 identical cryostats w/ 2 TPCs each

$E_{drift} = 0.5$ kV/cm

$t_{drift} \sim 1$ ms

3 wire planes: 54k wires, 3mm pitch

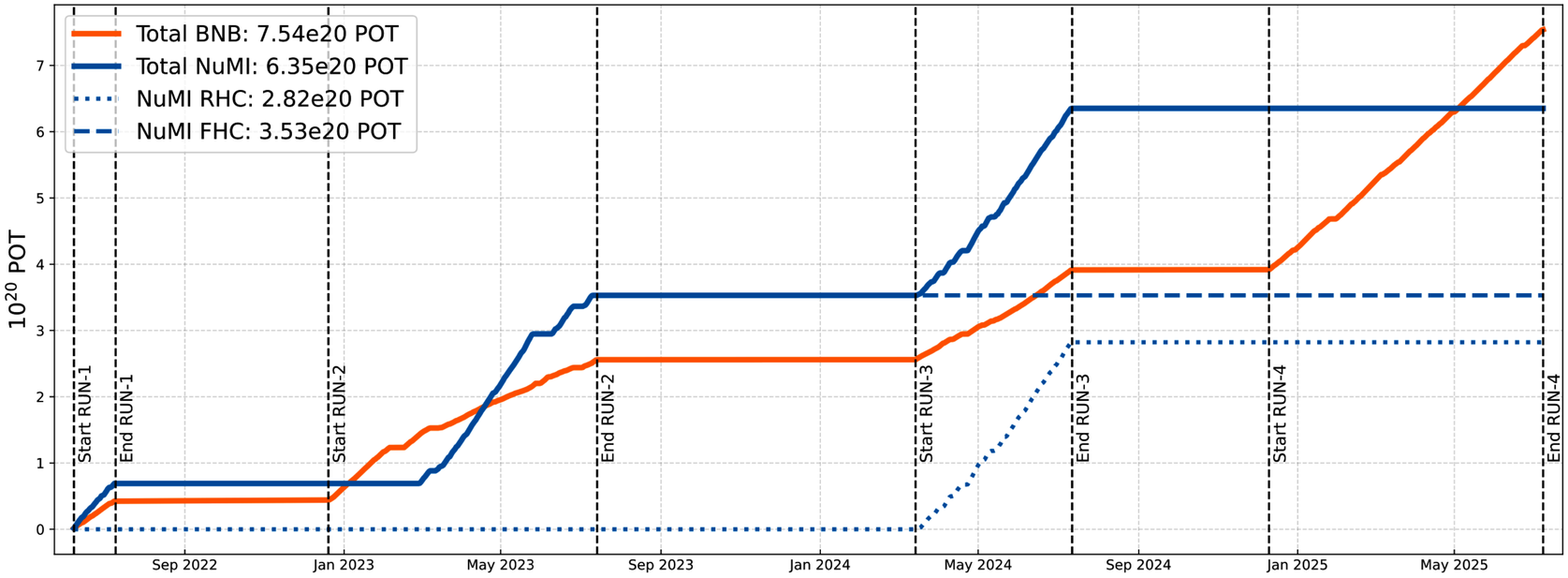
360 8" **PMTs** behind wires measure scintillation light thereby providing t_0 tagging (~ns) and trigger
External 4π Cosmic Ray Tagger (**CRT**) to tag incoming cosmic rays (11 μ tracks per trigger)

Comparison with **SBND**: ≠ light sensors - SBND has an hybrid setup of PMTs and ARAPUCAs - warm FE TPC electronics and additional 2.85, 3-layer **overburden** to further suppress incoming cosmics

Successful 3-yr physics run at LNGS (2010-13), intensive overhaul at CERN, ν data taking since June 2022

ICARUS: detector operation and data acquisition

- Physics data taking started in June 2022, 4 physic runs run 4 (only BNB beam): 10 December '24- 8 July '25
- Trigger: light recorded at the same time by 4 PMT pairs in a 6-m longitudinal section w/ BNB (1.6 μs), NuMI (9.5 μs) beam spills



- Steady data taking with great stability BNB > 4 Hz, >90% efficiency @ Edep > 200 MeV, free τ_{ele}~7-8 ms

Collected statistics:

Protons on Target (**PoT**)

[*] FHC/RHC:

Forward (Reverse)

Horn Current

Run	Duration	BNB (FHC) [*] positive focusing	NuMI (FHC) [*] positive focusing	NuMI (RHC) [*] negative focusing
1	Jun - July '22	0.42 10^{20}	0.69 10^{20}	-
2	Dec '22 - July '23	2.13 10^{20}	2.84 10^{20}	-
3	Mar - July '24	1.36 10^{20}	-	2.82 10^{20}
4	Dec '24 - Jul '25	3.63 10^{20}	-	-
Total	/	7.54 10^{20}	3.53 10^{20}	2.82 10^{20}

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The ICARUS physics program

- **SBN physics program**: **sterile neutrino search** with the comparison of ν_μ, ν_e interactions measured at different distances from the BNB beam target thanks to SBND and ICARUS LArTPCs

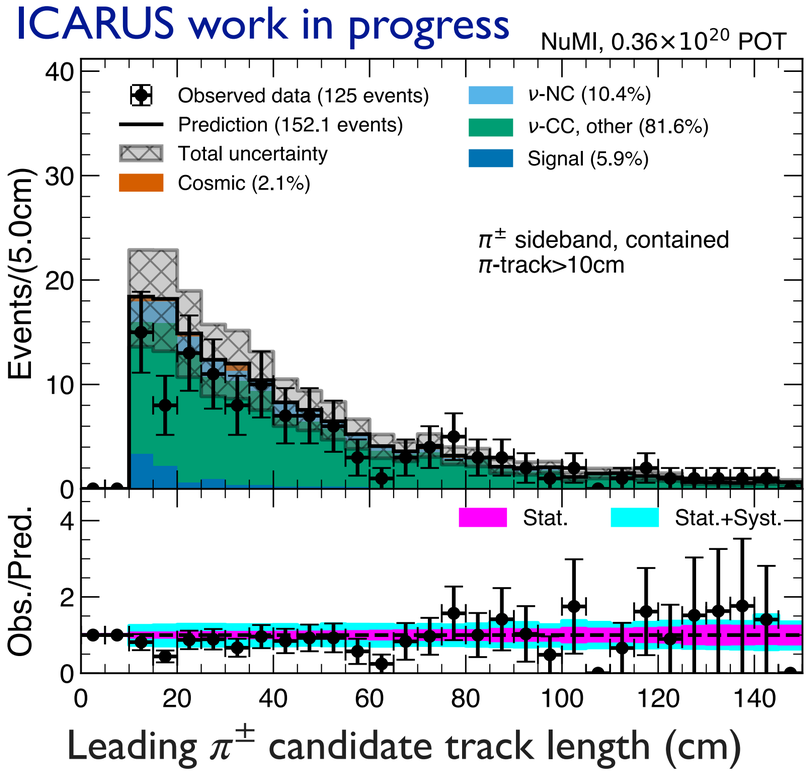
- Before and in view of the joint-analysis with SBND, ICARUS focuses on a **standalone physics program:**
  - Analysis of the ν_μ **disappearance channel with BNB** (selection ready and validated), to be complemented with ν_e **disappearance from NuMI** data - the goal is to verify the **Neutrino-4 claim** [CCQE events fully contained in LAr active volume to explore the same $\mathbf{L/E}$ range as Neutrino-4]
  - Study of ν_μ, ν_e interactions from NuMI to **measure ν-Ar cross sections** and optimize reconstruction in the energy range that **DUNE** will explore (selection ready, sidebands studied on a fraction of data)
  - Search for **sub-GeV** Beyond Standard Model (**BSM**) **signals** using NuMI: $\mu\mu$ **decay channel** explored

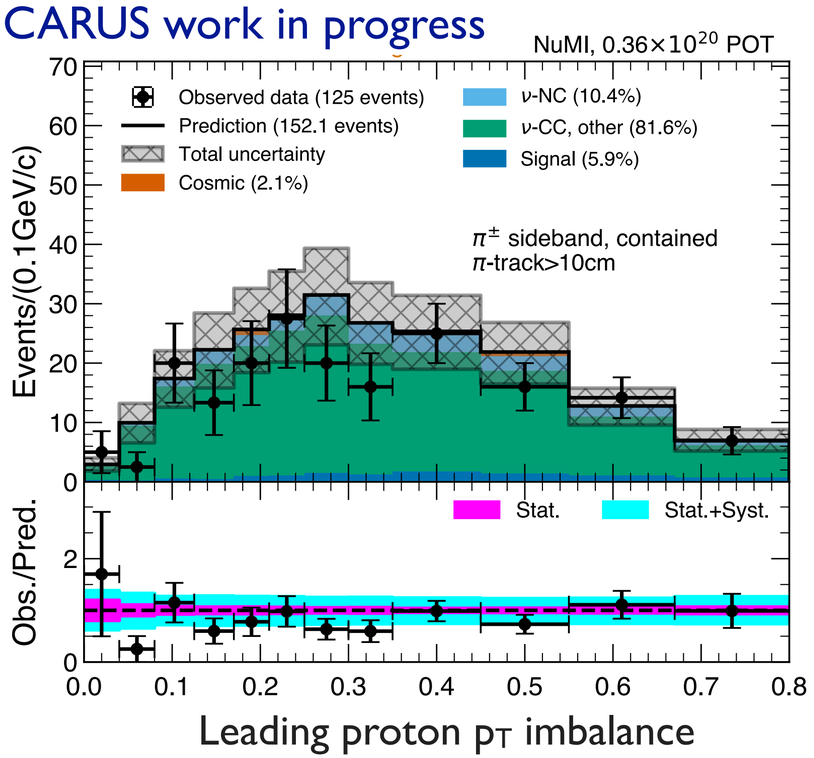
Blinding policy defined to ensure robust and unbiased interpretation of the collected data: analyses are validated using sidebands, a subset of the full dataset or variables insensitive to oscillation

NuMI $1\mu - (N \geq 1)p - 0\pi$ analysis: data selection

- **Signal definition**: at least 1 μ with p>226 MeV/c and proton(s) with $p \in$ [0.4, 1] GeV/c (from PID), no $\pi^{\pm}, \pi^{0}, \gamma$ in the final state - transverse kinematic variables are sensitive to initial/final state interactions $\cos\theta_{\mu,p}$ (*see plot on the previous slide*) should encode all information about **Final State Interactions**

- **Major background:** events with undetected or misidentified **pions**
- **Control sample** with $\pi^{\pm}$ and secondary μ-like track to model it
- Initial study using **15%** of the **data**
- **Sidebands** including full Run1 & Run2 statistics explored



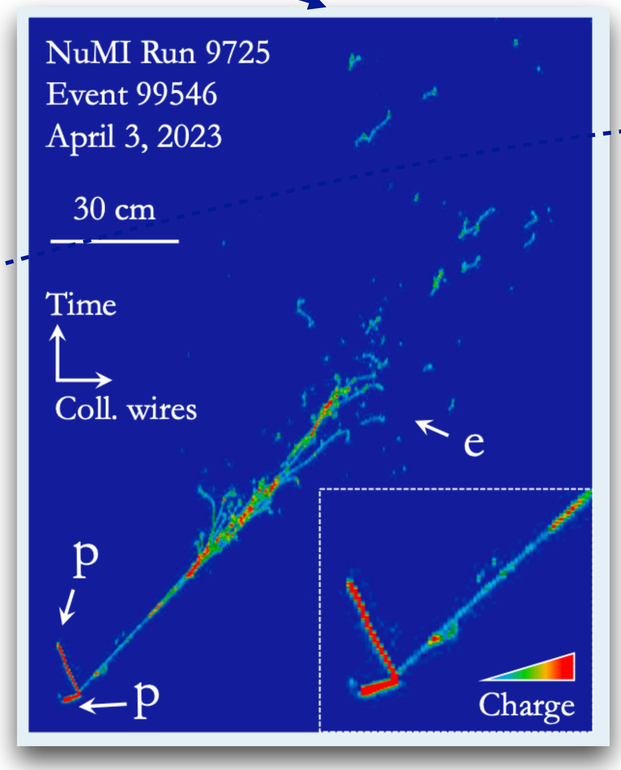


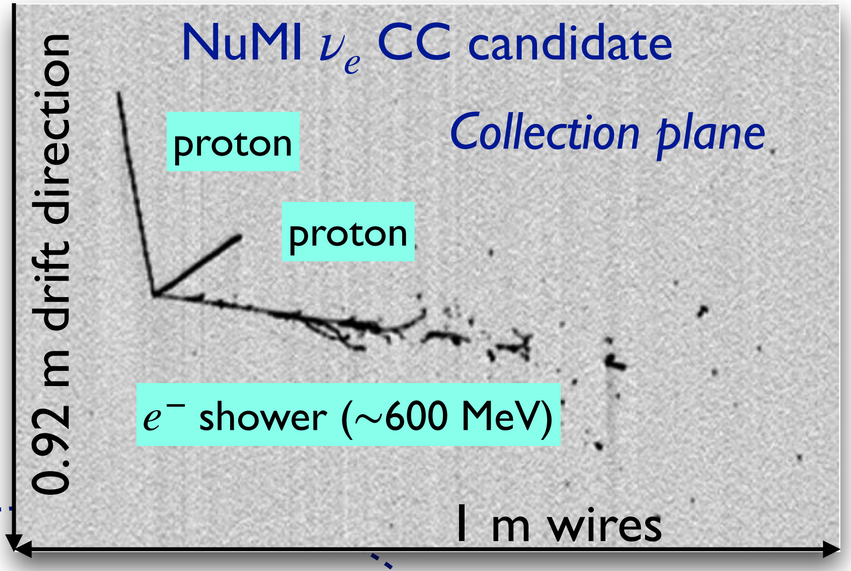
Results for the full (unblinded) $1\mu - (N \geq 1)p - 0\pi$ dataset to be released soon!

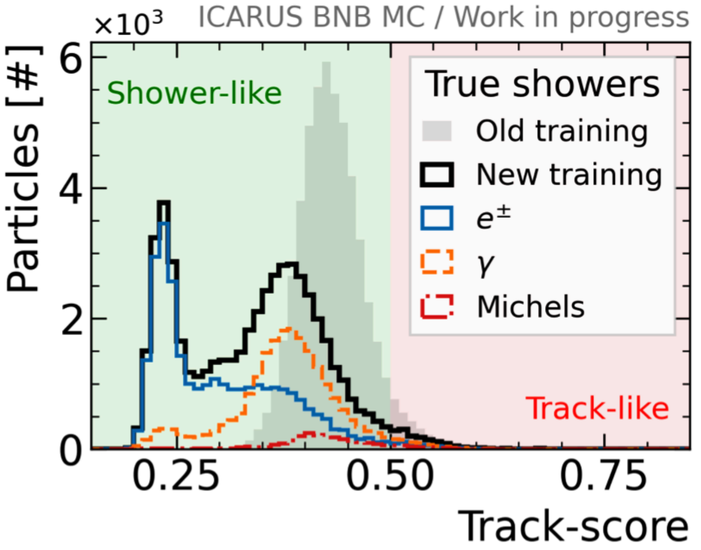
Reconstruction and selection of electron neutrino events

- Several efforts ongoing within simulation and reconstruction working group and a task force dedicated to shower event reconstruction with the goal to improve reconstruction and selection tools in view of ν_e analyses with both BNB and NuMI beam data

  - Inclusion of shower-growing algorithms to collect sparse hits
  - Retraining of algorithms to discriminate track-like and shower-like particles
  - New tools to improve dE/dx calculation and calorimetry







R. Triozzi @ EPS 2025