CERN NP contributions to T2K, lessons learned and the road to the future

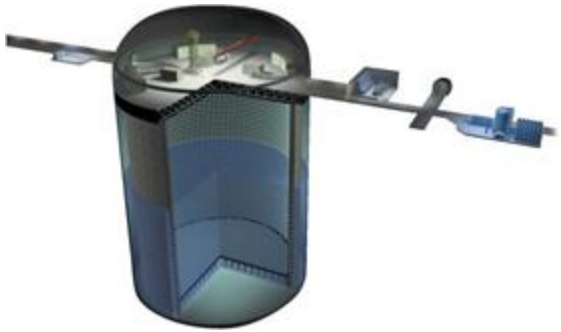
Laura Munteanu (CERN)

Workshop on Neutrinos@CERN

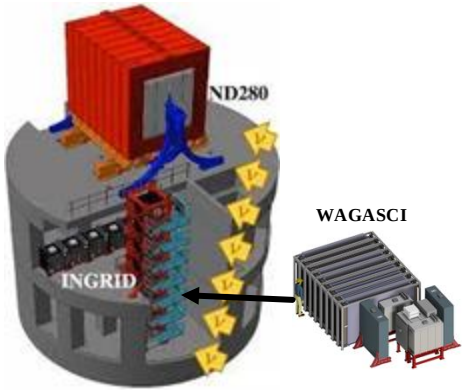
23 January 2025

The T2K Experiment

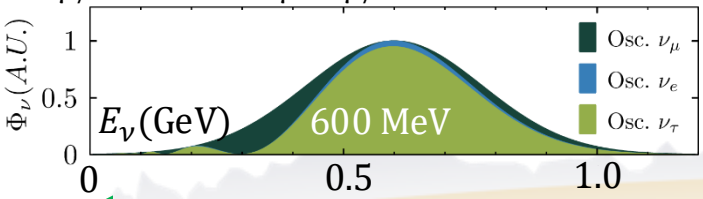
Far detector: Super-Kamiokande



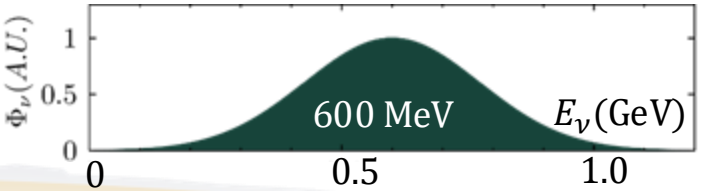
Near detector complex

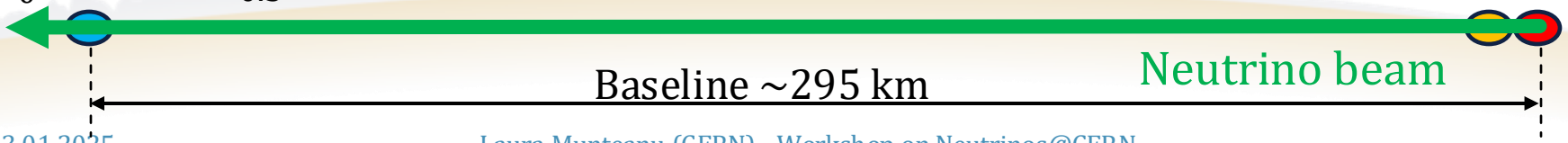


$$N_{\nu_{\mu/e}}(E_\nu) = P_{\nu_\mu \to \nu_{\mu/e}}(E_\nu)\Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)$$



$$N_{\nu_\mu}(E_\nu) = \Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)$$

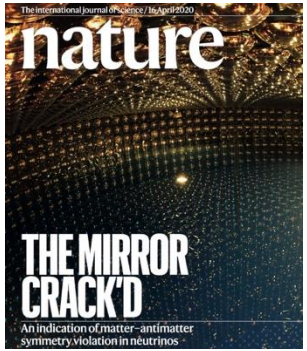


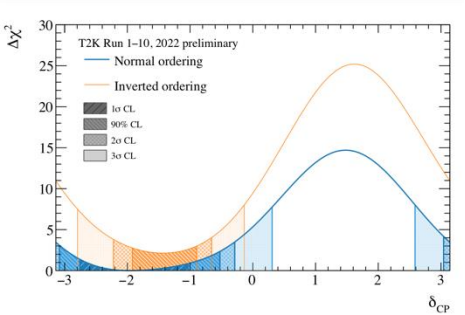


571 members from **74 institutions** from **15 countries**
(we count CERN as a country ☺)

Photo from T2K Collaboration Meeting in November 2024 @ J-PARC

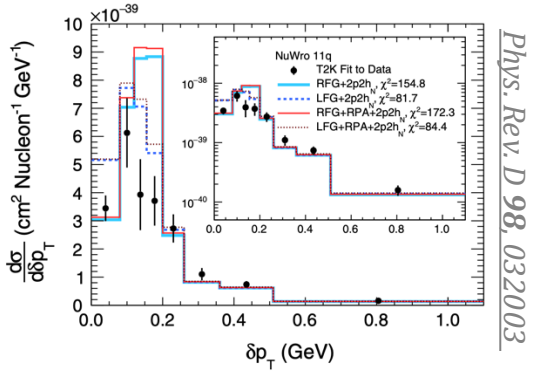
Neutrino oscillations





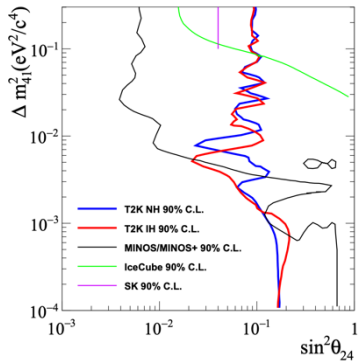
Nature 580, 339–344 (2020)

Neutrino cross-sections



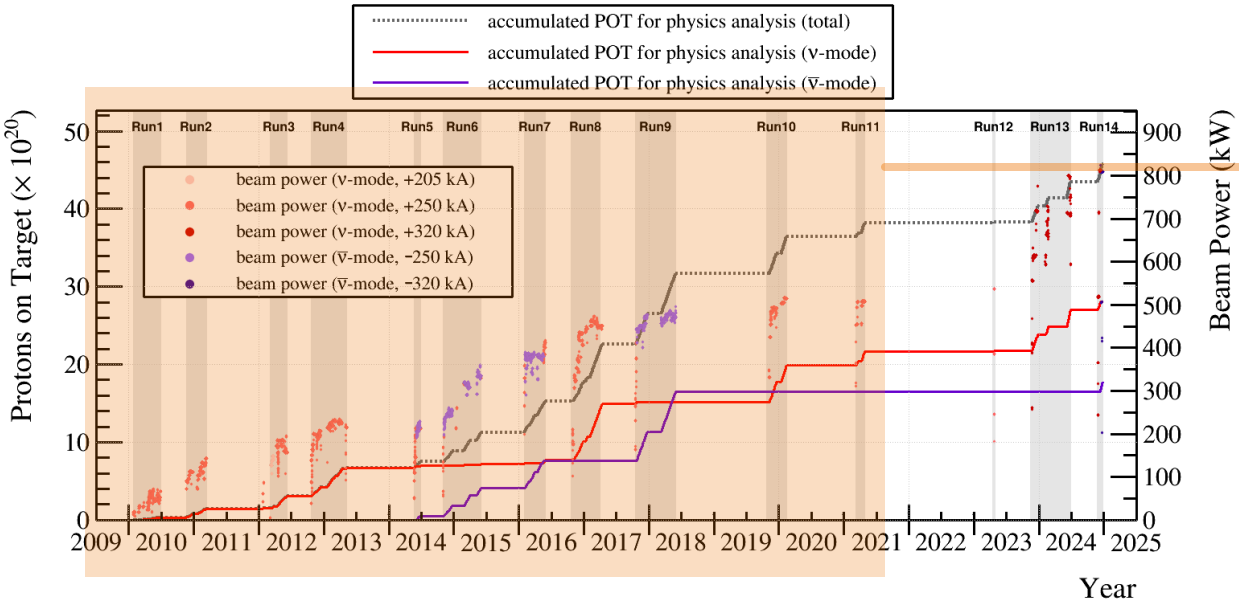
Phys. Rev. D 98, 032003

Exotic searches



Phys. Rev. D 99, 071103(R)

T2K accumulated data



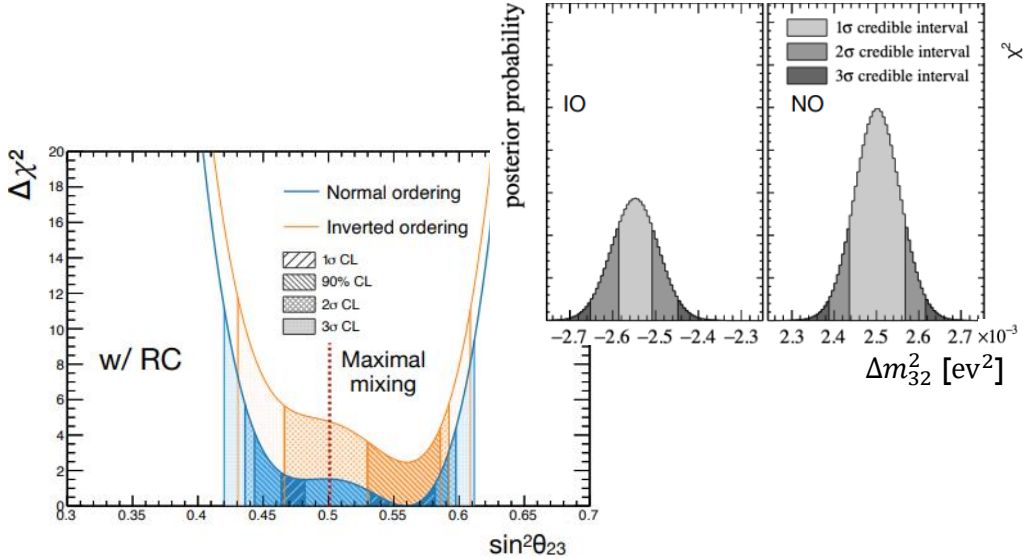
Oscillation events candiates at SK

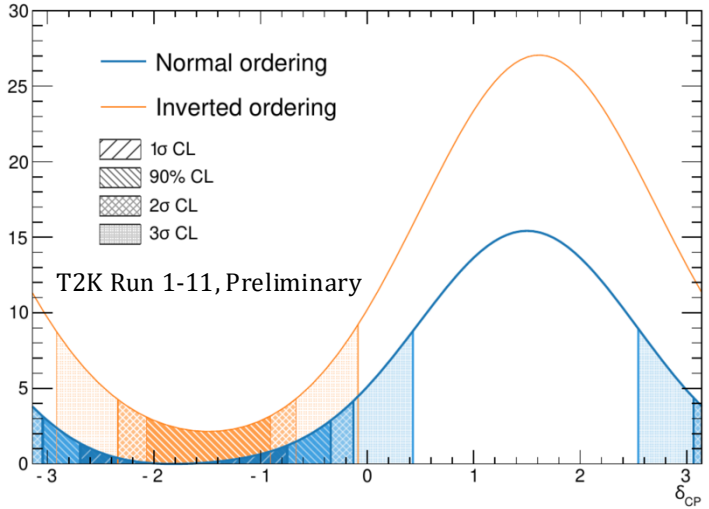
	Sample	Data candidates
ν-mode	1-Ring ν_μ	357
	Multi-Ring ν_μ	140
	1-Ring ν_e	102
	1-ring ν_e + decay electron	15
$\bar{\nu}$-mode	1-Ring $\bar{\nu}_\mu$	137
	1-Ring $\bar{\nu}_e$	16

T2K has been taking physics data since 2010
→O(10^5 events at the near detector)

T2K's latest oscillation results

World leading constraints





Weak preference for Normal Ordering and Upper Octant

Entering precision measurement era

CP-conserving values of δ_{CP} excluded at ≃90% C.L.

Hint of CP violation in the lepton sector

Measuring neutrino oscillations with T2K

Oscillation parameters are inferred from event spectra **as a function of reconstructed neutrino energy***

Systematic uncertainties

$$N_{\nu_\beta}(E_\nu^{reco}) = P_{\nu_\mu \to \nu_\beta}(E_\nu^{true})\Phi(E_\nu^{true})\sigma(E_\nu^{true})\epsilon(E_\nu^{true})S(E_\nu^{true}, E_\nu^{reco}) \quad \beta = e, \mu$$

- Oscillation parameters
- Neutrino flux
- Interaction cross-section
- Detection efficiency
- Energy smearing matrix

We rely on

- Our **near detectors** – *to obtain an in-situ constraint of* $\Phi \times \sigma$
- **External/support experiments** – *to inform flux and cross-section models*
- Reliable **models** – *to extrapolate near detector constraint to far detector prediction*

*full analysis uses additional sample-dependent kinematic variables to improve sensitivity

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- $P_{\nu_\mu \to \nu_\beta}(E_\nu^{true})$: Oscillation parameters
- $\Phi(E_\nu^{true})$: Neutrino flux
- $\sigma(E_\nu^{true})$: Interaction cross-section
- $\epsilon(E_\nu^{true})$: Detection efficiency
- $S(E_\nu^{true}, E_\nu^{reco})$: Energy smearing matrix

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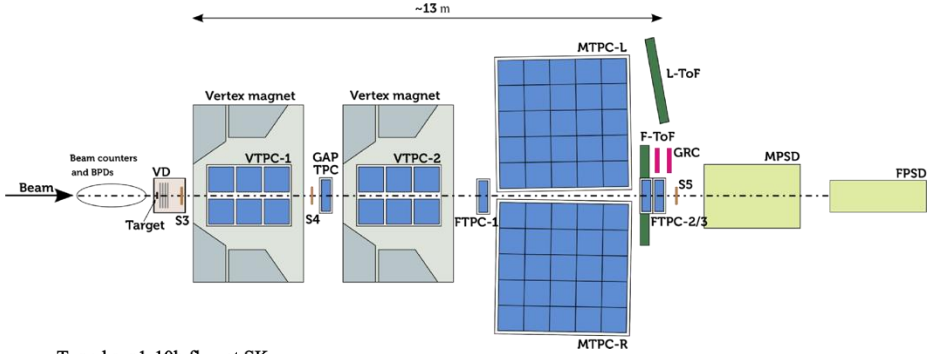
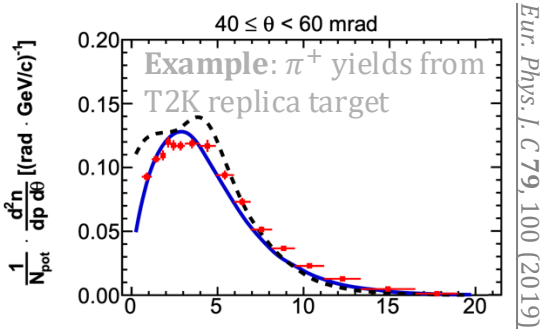
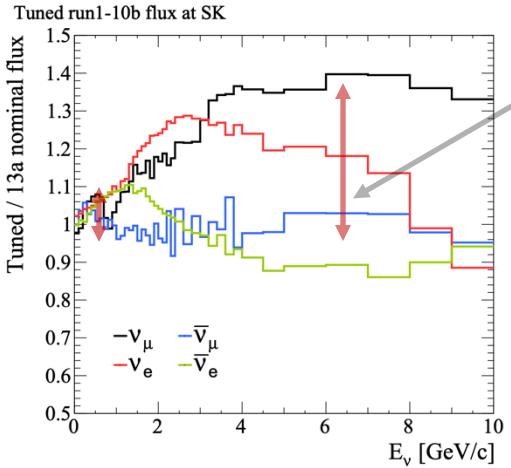
Role of support experiments – NA61/SHINE



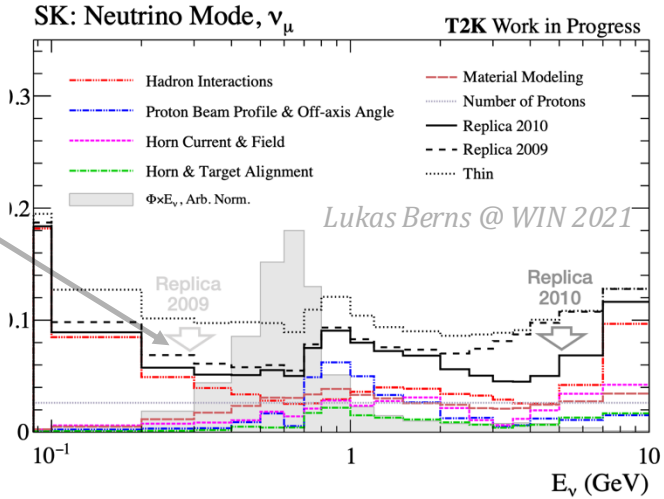


Eur. Phys. J. C 79, 100 (2019)



Tuned flux shape
(10% in peak region, 30% in tails)

Reduced uncertainties
(10%→5% in peak region)



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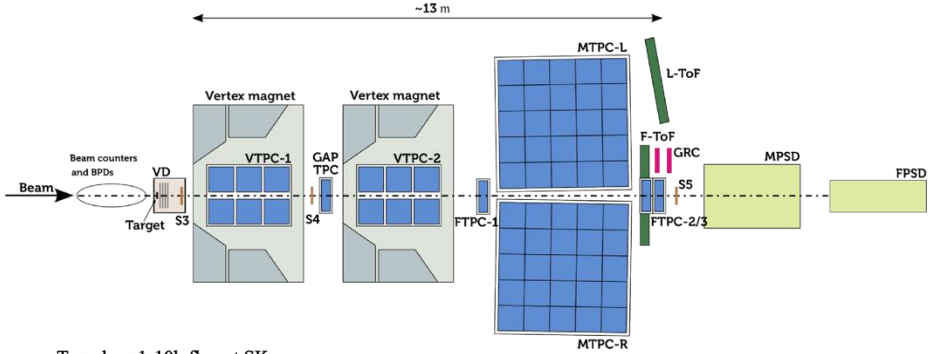

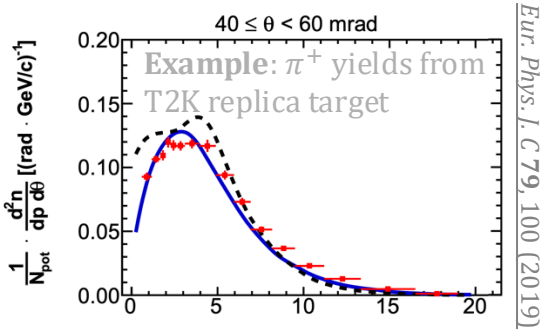

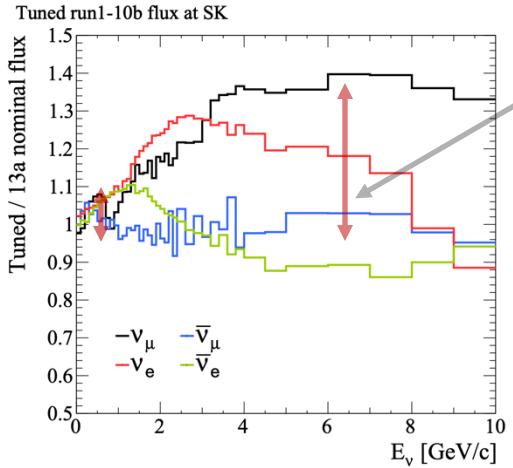

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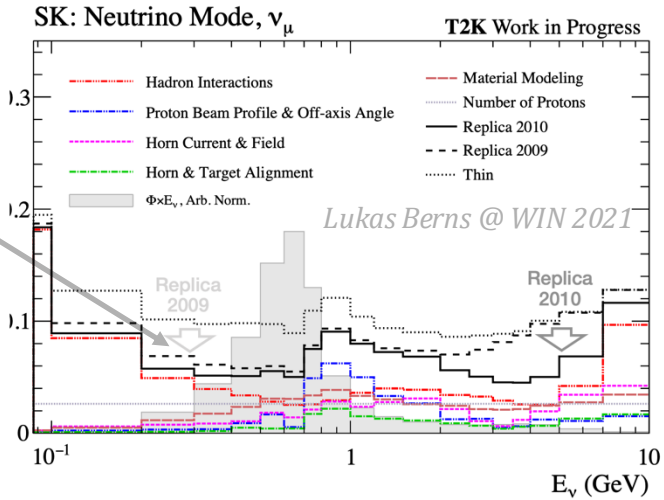
Critical input to T2K physics results



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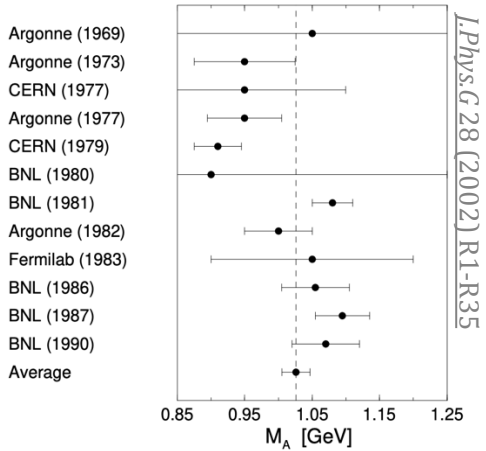
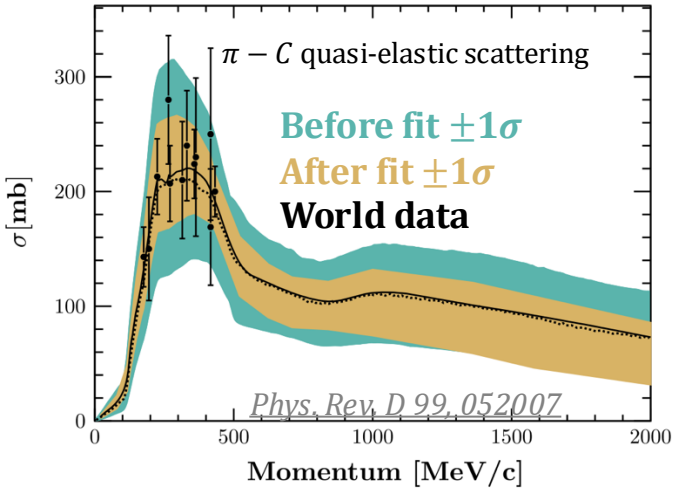
Role of support experiments – scattering experiments

Neutrino scattering



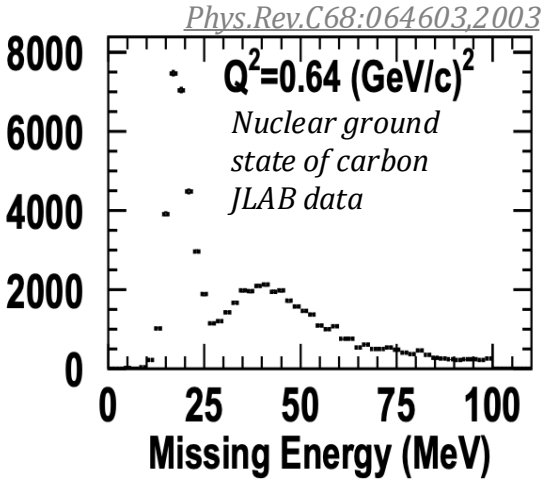
Inform our constraints on e.g. **nucleon form factors**

Hadron scattering



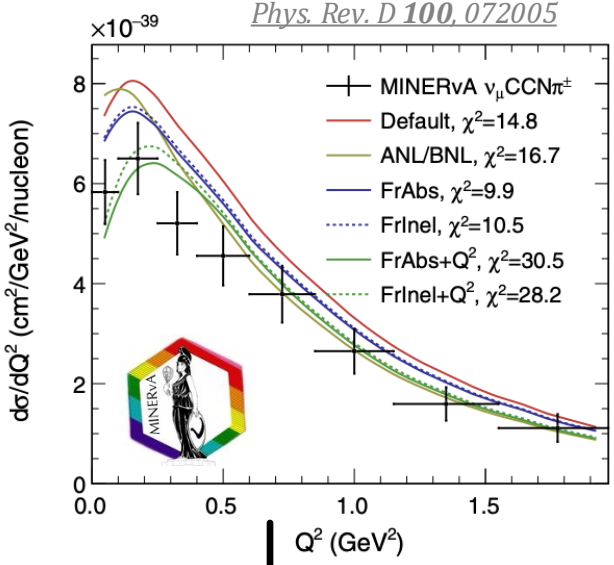
Help constrain **hadron transport models**

Electron scattering

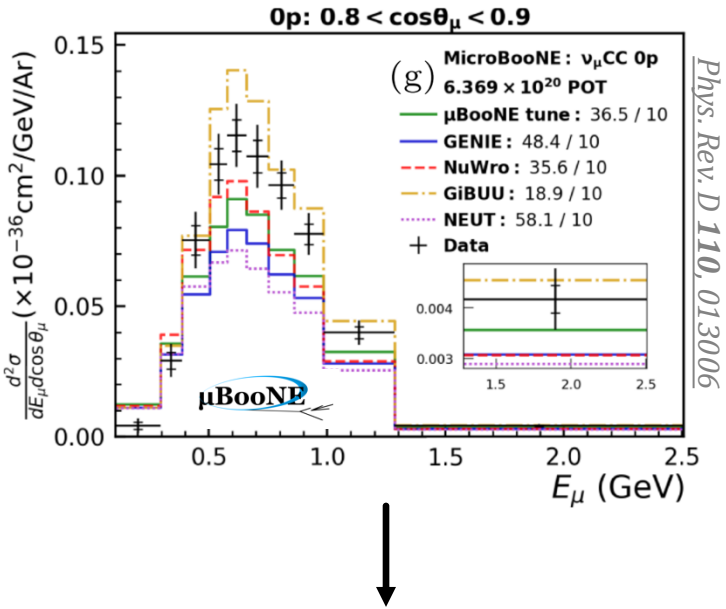


Determine uncertainties on the **nuclear ground state**

Role of support experiments – scattering experiments



Extract data-driven alteration to our MC and **check robustness of our analysis**



Use external results as motivation to **add new sources of systematic uncertainty**

No single experiment covers the full phase space of neutrino interactions

Complementary measurements from other neutrino scattering experiments are **vital to inform our choices**

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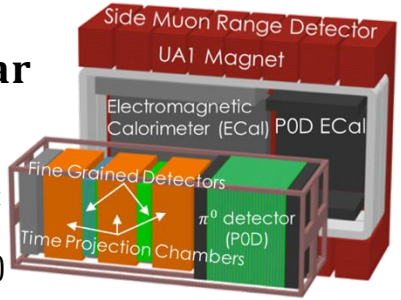
Constraining uncertainties with near detector data

ND280 Near Detector

(Magnet & support for control system provided by CERN!)



Run a fit to constrain syst. for the oscillation measurment

- 22 near detector samples
- 4000+ bins in $(p_\mu, cos\theta_\mu)$
- ~700 parameters

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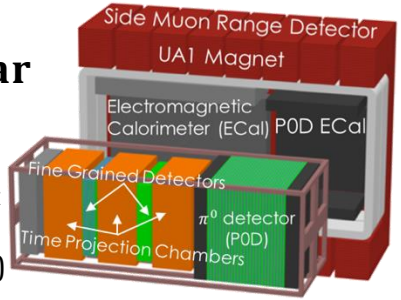

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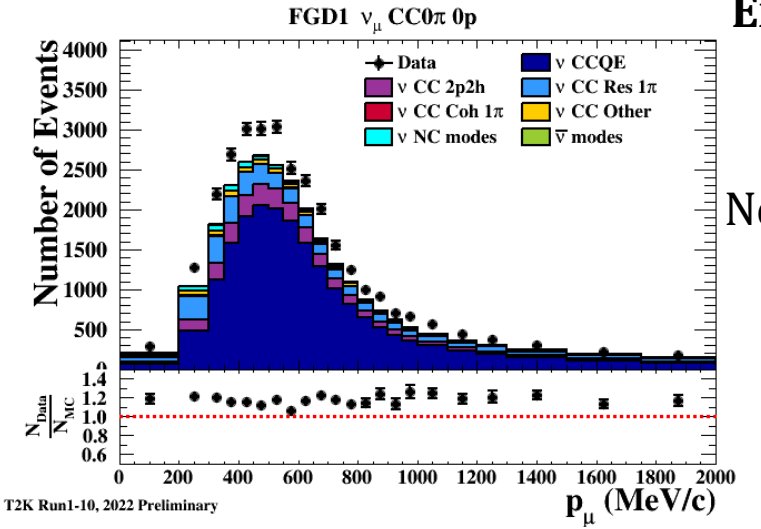
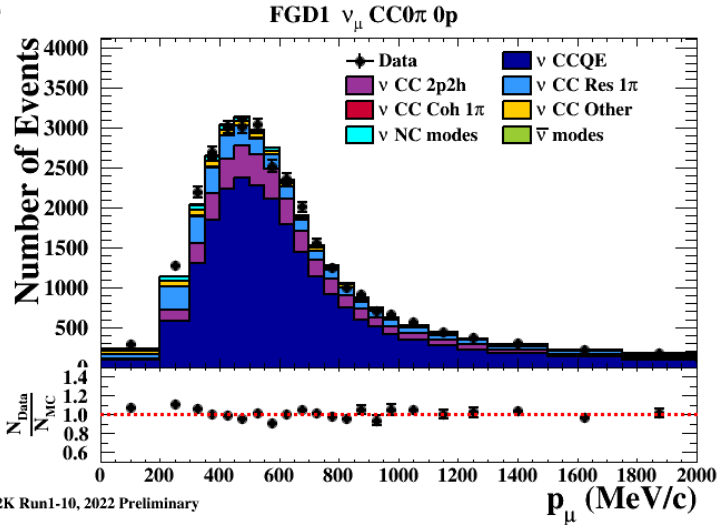
Example sample



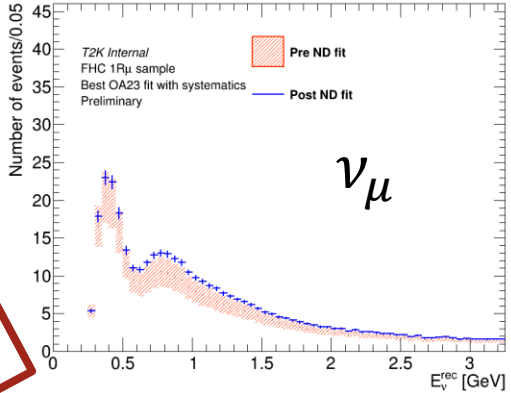
Near detector fit

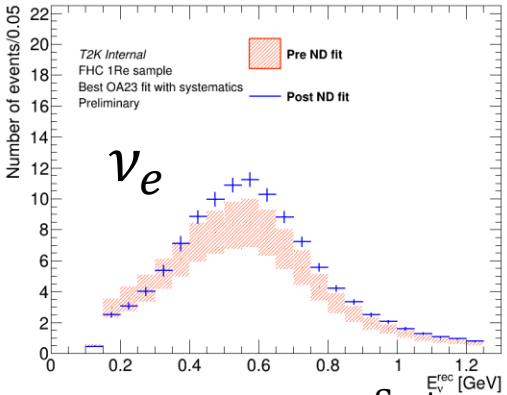
Varies parameters related to flux, detector and **cross-section model**



Impact of ND constraint on FD spectra and errors

T2K preliminary





Before ND fit

Systematic errors

Error source (units: %)	1R FHC e	1R FHC μ	1R RHC e	1R RHC μ	1R/MR CC1π e CC1π^+	1R/MR CC1π μ CC1π^+	ratio e FHC/RHC
BeamFlux	4.9	5.0	4.6	4.7	5.1	5.1	4.5
Xsec (all)	16.6	15.9	13.3	13.8	15.7	10.7	10.7
SK	3.7	1.4	5.2	3.6	4.5	3.1	4.1
Total	17.4	16.5	14.9	14.8	16.8	12.1	12.3

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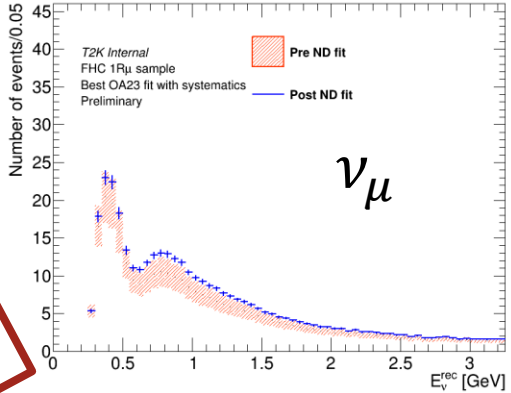

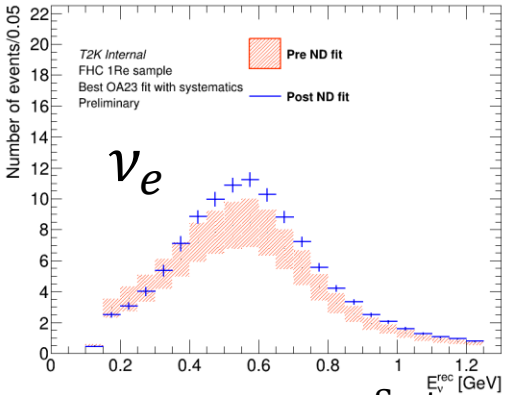

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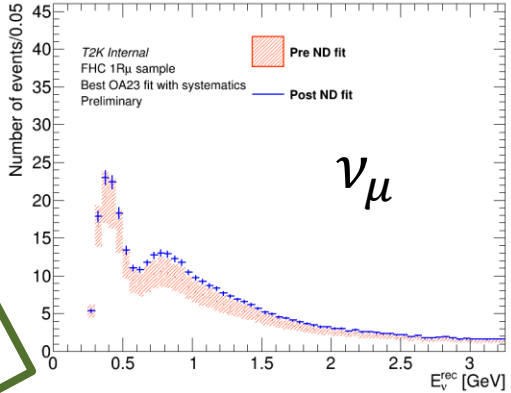

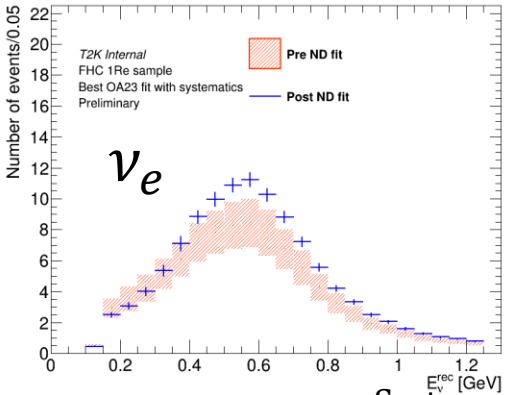

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BeamFlux	2.8	2.8	3.0	2.9	2.9	2.9	2.2
Xsec (ND constr)	3.8	3.6	3.5	3.5	4.3	3.0	2.4
Flux+Xsec (ND constr)	2.9	2.8	2.7	2.6	3.7	2.2	2.3
Xsec (ND unconstr)	2.9	0.6	3.4	2.4	2.8	1.3	3.8
SK	2.7	1.4	5.1	3.6	4.3	2.9	4.0
Total	4.9	3.2	6.7	5.0	6.3	3.9	5.9

Impact of ND constraint on FD spectra and errors

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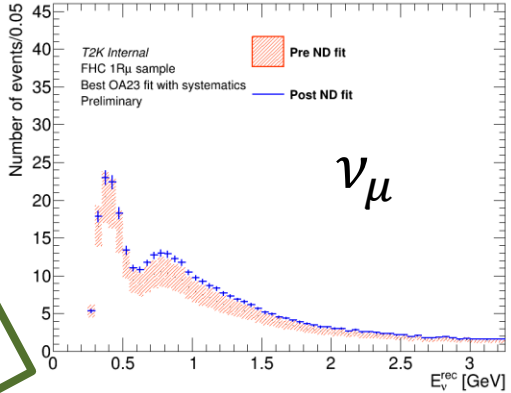

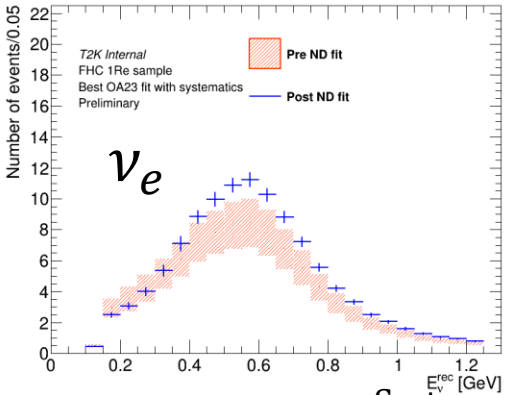

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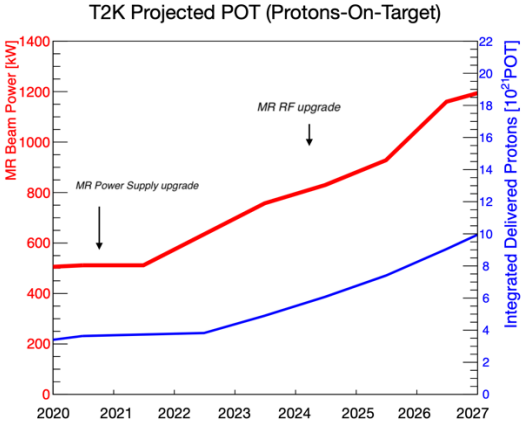
How can we do better?



800 kW reached in summer 2024!

Increased beam power

Expect O(10^{22}) POT by the end of 2027

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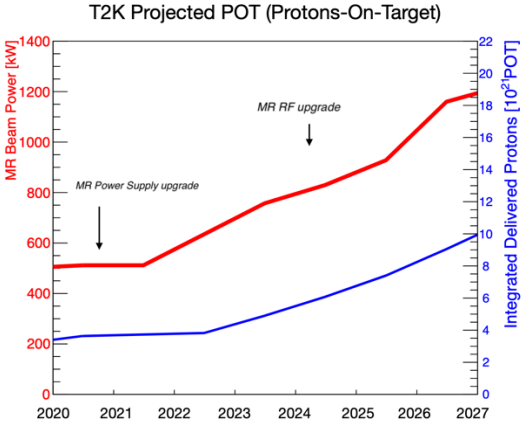


Increased beam power

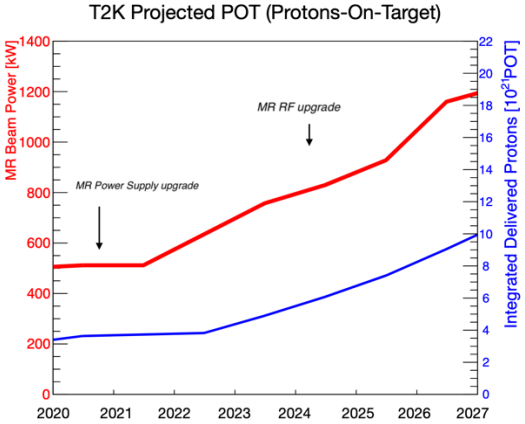
Expect O(10^{22}) POT by the end of 2027

800 kW reached in summer 2024!

(Our work is never over)

We need
- Bigger, better near detectors
- Continued support from external experiments
- Closer collaboration between experiment and theory

How can we do better?



Increased beam power

Expect O(10^{22}) POT by the end of 2027

800 kW reached in summer 2024!

(Our work is never over)

We need

- Bigger, better near detectors
- Continued support from external experiments
- Closer collaboration between experiment and theory

The NP07 Project

1

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

Major developments from the 2013 Strategy

B. The existence of non-zero neutrino masses is a compelling sign of new physics. The worldwide neutrino physics programme explores the full scope of the rich neutrino sector and commands strong support in Europe. Within that programme, the Neutrino Platform was established by CERN in response to the recommendation in the 2013 Strategy and has successfully acted as a hub for European neutrino research at accelerator-based projects outside Europe. ***Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).***

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NP07

Upgrade of the T2K Near Detector

Synonym: ND280
Research Programme: NEUTRINO
Approved: 05-03-2019
Beam:
Status: Completed

Overview | Teams | Participations

Spokesperson:	SANCHEZ NIETO, Federico Joaquin LUX, Thorsten GIGANTI, Claudio	**Number of Institutes:**	22
Contact person:	BENVENUTO, Elena CATANESI, Maria Gabriella	**Number of Countries:**	11
Technical Coordinator:	RESNATI, Filippo LUX, Thorsten	**Number of Participants:**	109
Resources Coordinator:	MIRALLES VERGE, Lluis Secundino	**Number of Authors:**	53
Experimental Safety Officer (EXSO):	BORDONI, Stefania		
Experiment secretariat e-mail:	neutrino.secretariat@cern.ch		

Status History

Status	Start Date	End Date
Preparation	05-03-2019	16-06-2024
Completed	17-06-2024	

The NP07 Project

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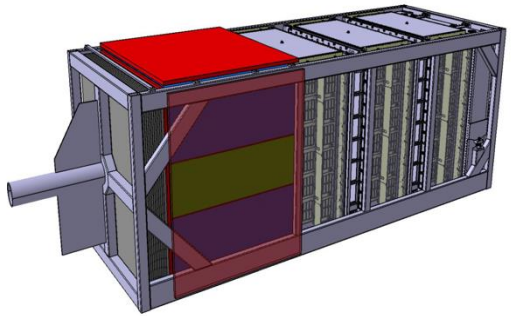


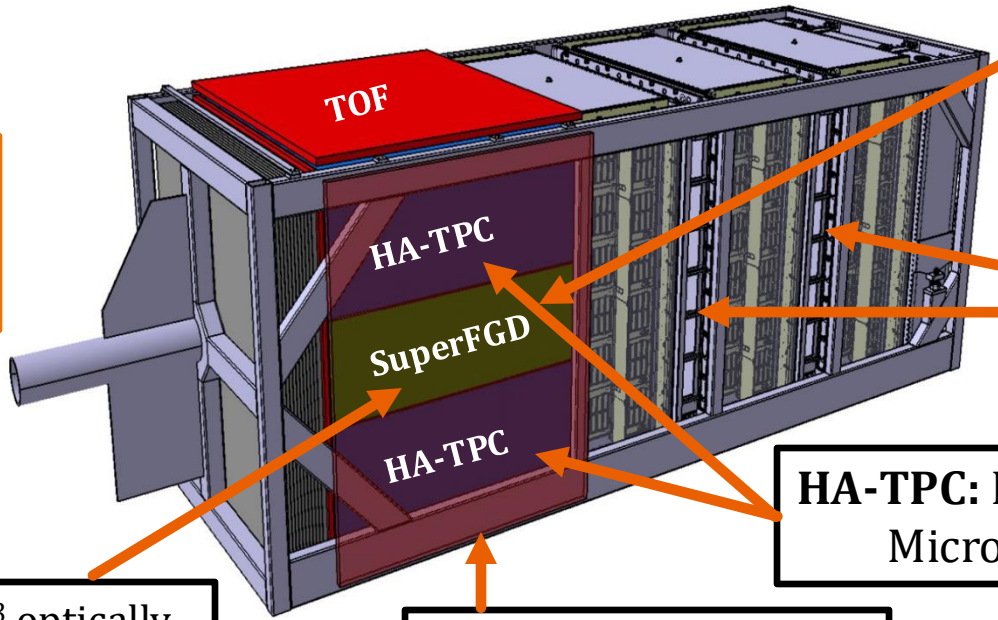
The T2K ND280 Upgrade project

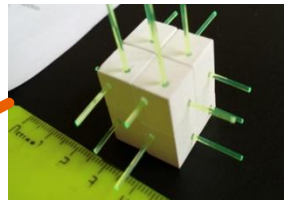
ND280 Upgrade TDR

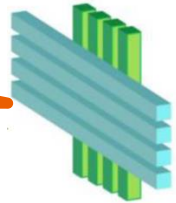
Replace P0D by new suite of detectors

>100 researchers
37 institutes
8 countries

ν beam







HA-TPC: Employ new resistive Micromegas detectors

Super-FGD: 2M 1cm^3 optically isolated scintillator cubes

TOF: 150 ps timing resolution for PID

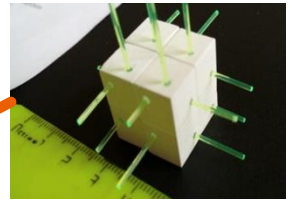
The T2K ND280 Upgrade project

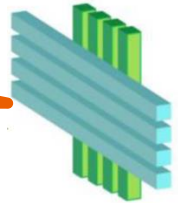
ND280 Upgrade TDR

Replace P0D by new suite of detectors

Significantly upgraded performance

4π acceptance
300 MeV/c proton tracking threshold
Neutron kinematics via time-of-flight
Two ton SuperFGD target: more events





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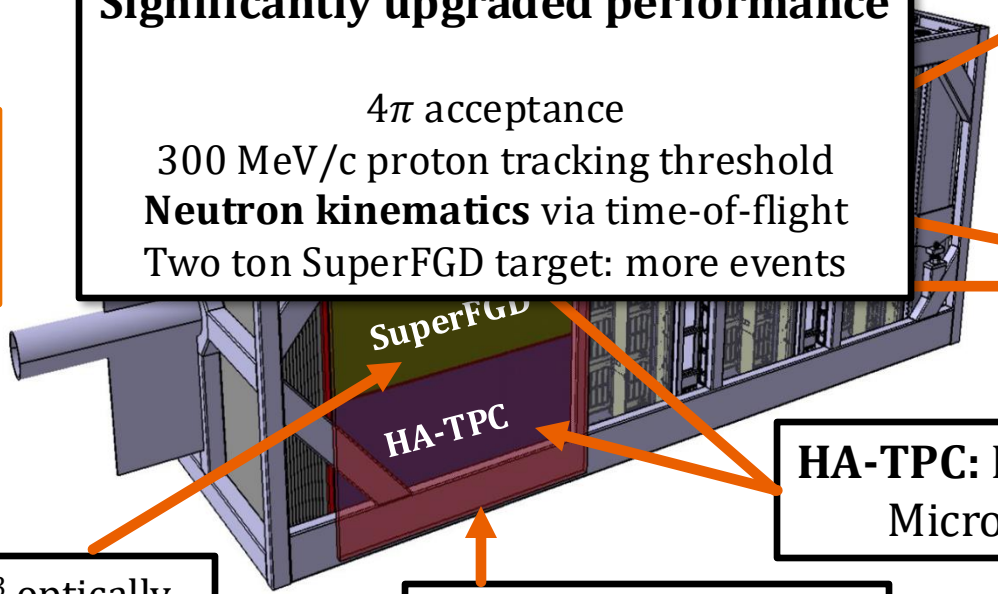

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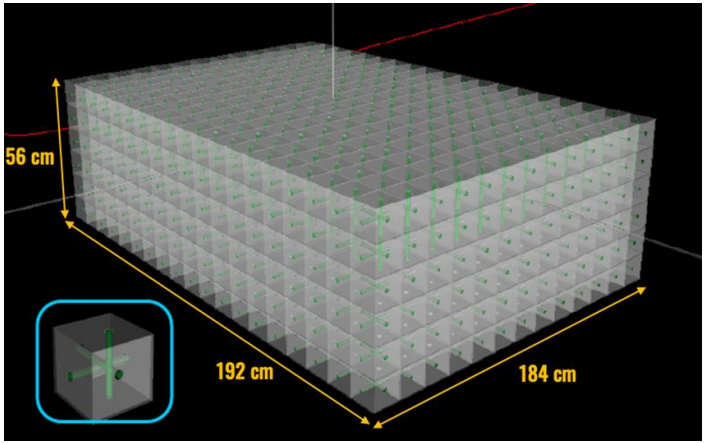
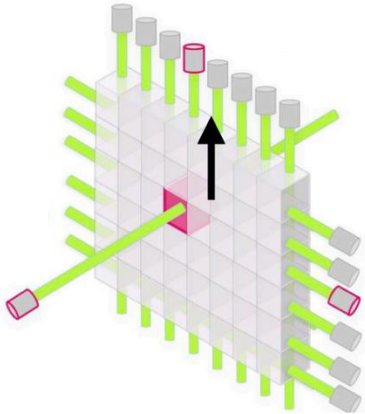
Super-FGD: 2M 1cm^3 optically isolated scintillator cubes

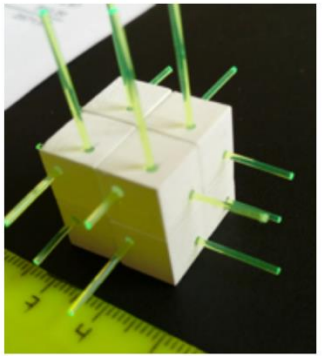
TOF: 150 ps timing resolution for PID

The SuperFGD detector

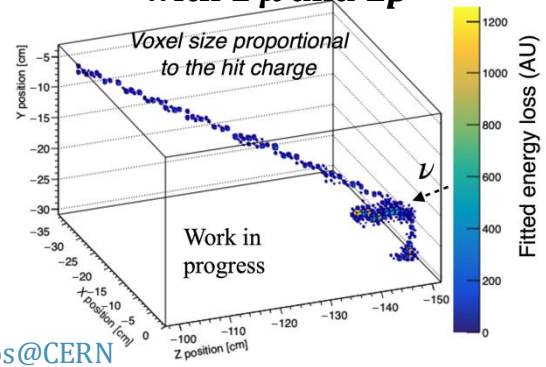




JINST 13 P02006 (2018)



Candidate ν interaction event with 1 μ and 2p



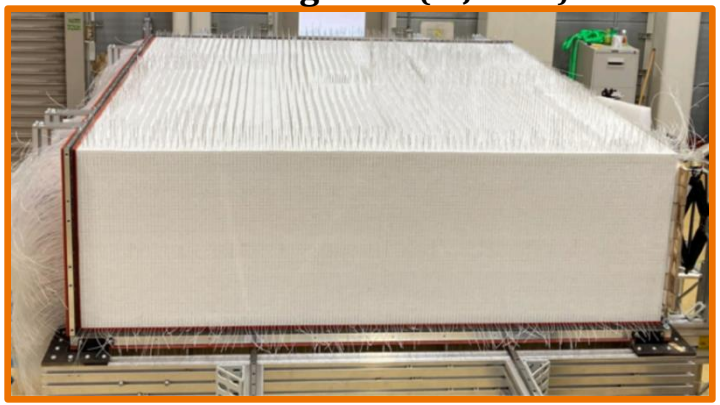
- ~**2 000 000** (56x182x192) optically isolated scintillating cubes ≃ **2 tons** of extra fiducial mass
- **55 888 readout channels** using WLS fibers & SiPMs

The SuperFGD@CERN

- First assembled and transported using fishing lines (then replaced with WLS fibers)
- Mechanical box assembled and tested at CERN
- Optical connectors for fibers/SiPMs bought by CERN

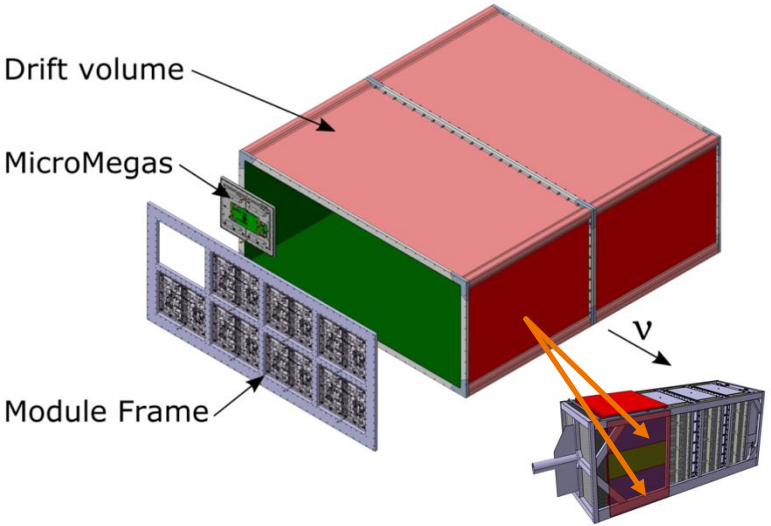
Mechanical box tests at CERN Neutrino Platform

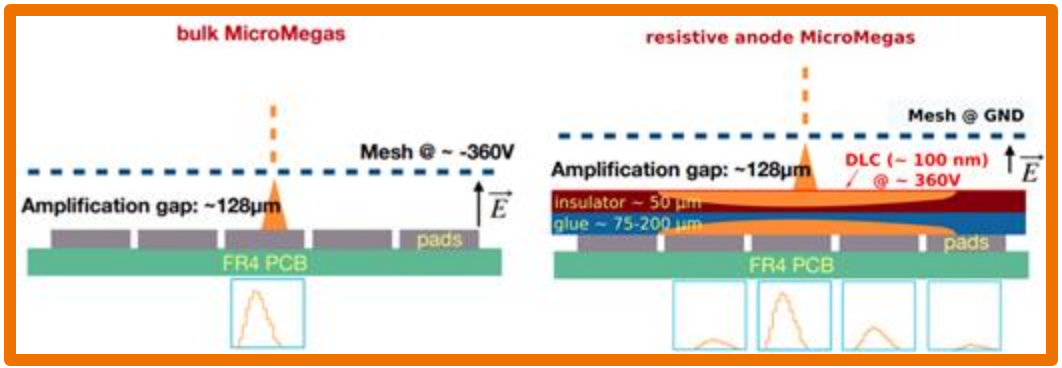
Cubes with fishing lines (at J-PARC)



Mechanical box (Assembled at CERN)

The High Angle Time Projection Chambers (HA-TPC)

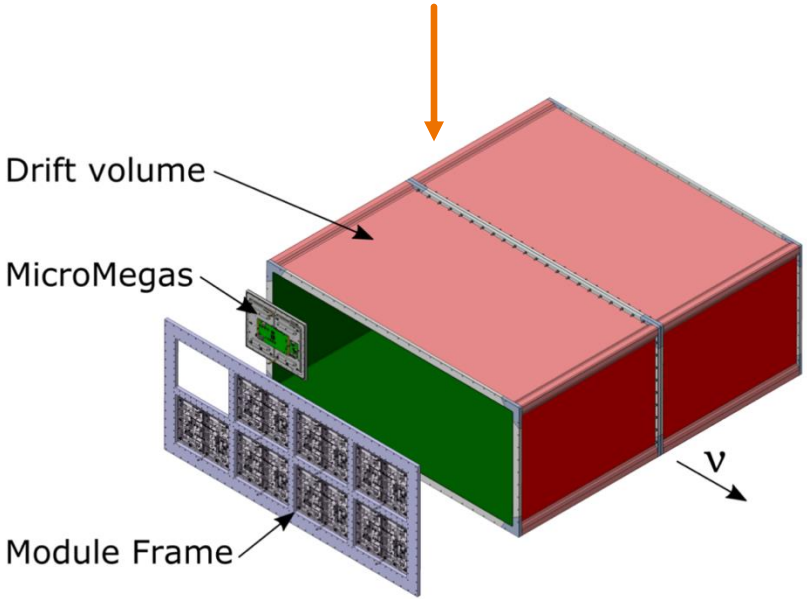


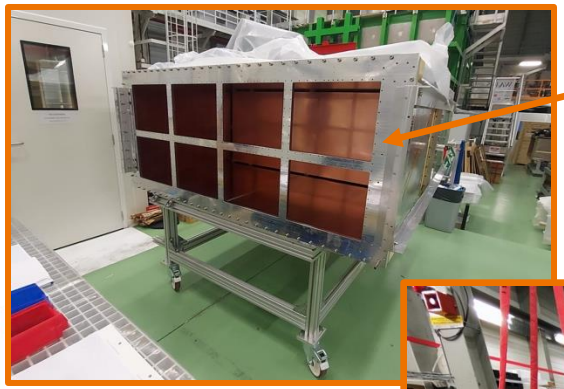


- Gaseous Ar TPC – **new gas system provided by CERN**
- Central cathode with 1m drift distance
- Readout anodes instrumented with **32 Resistive MicroMegas detectors (ERAM)**
- **First time this technology is used in a large scale experiment**

Building the HA-TPCs

@ CERN - Bld. 182



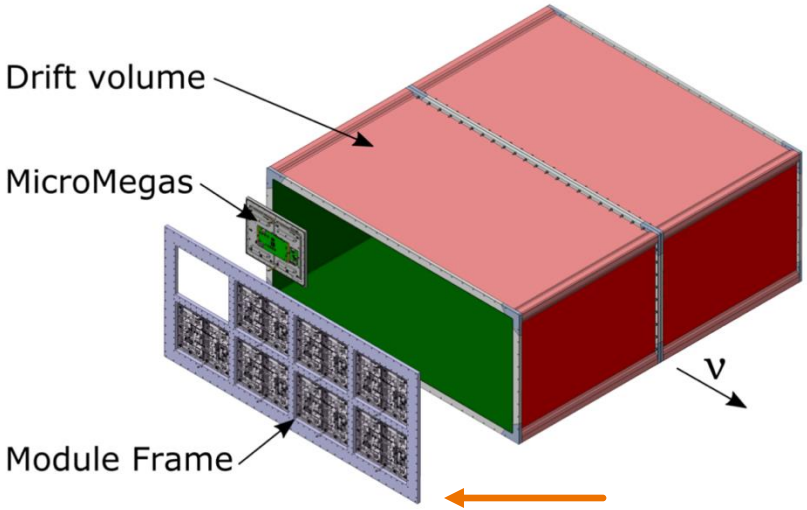


Inside of first field cage

Arrival of second field cage

Building the HA-TPCs

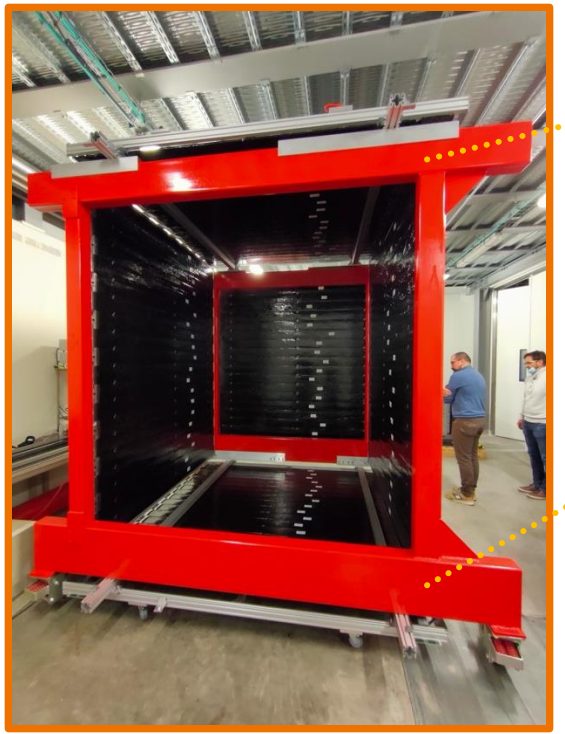
@ CERN - Bld. 182

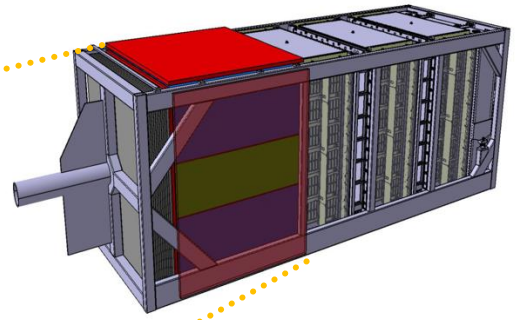


Resistive MicroMegas detectors installation in clean room

Quality control test bench

ToF detector @ CERN

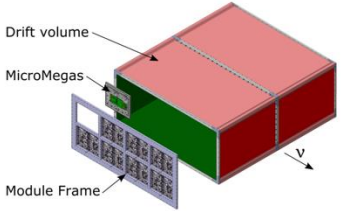


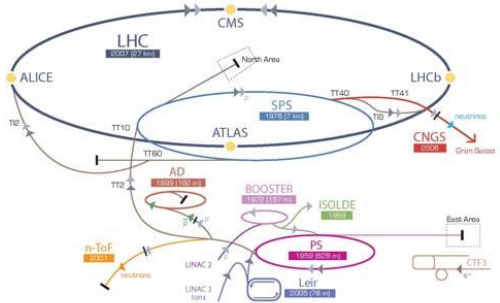


Testing, assembly and commissioning of six scintillator planes for Time-of-Flight measurements
@ Neutrino Platform

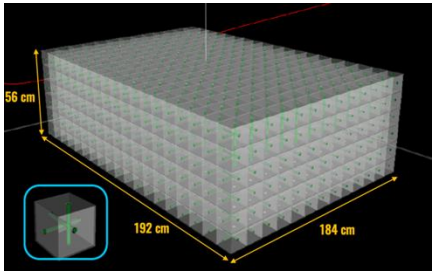
Test beams @ CERN

HA-TPC

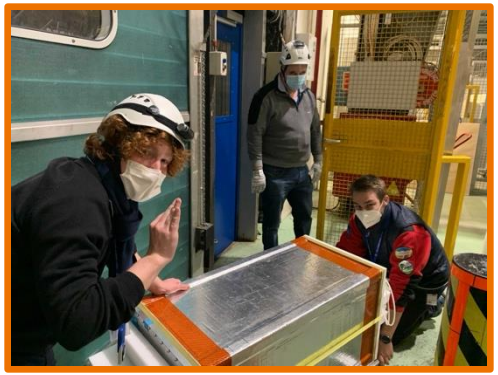




SuperFGD



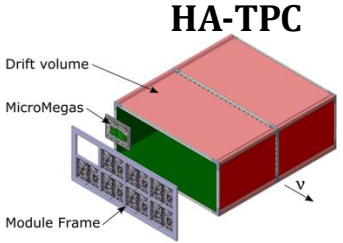
Preparation for prototype tests at NA SPS beam dump

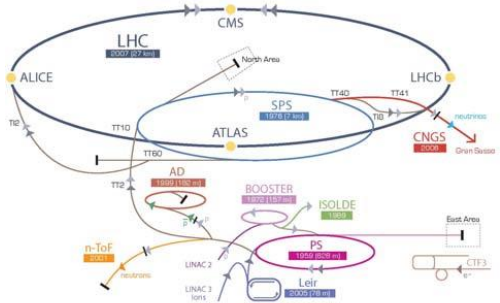


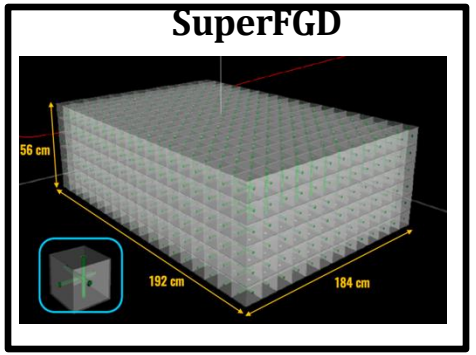
Test beam at T9 area for first complete field cage

Test beam at T9 area for first SuperFGD prototype

Test beams @ CERN

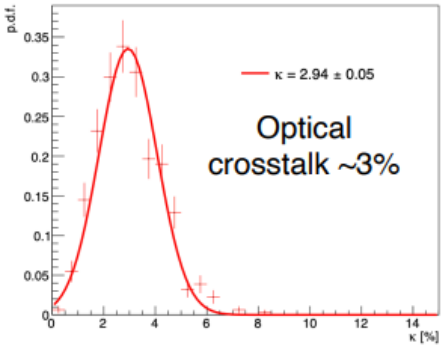




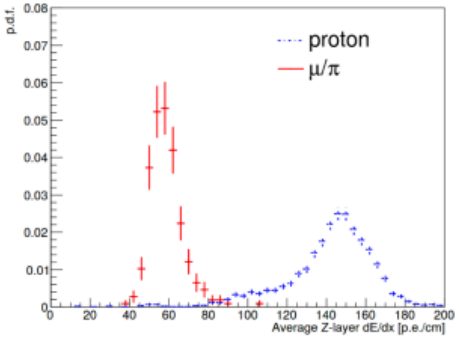


JINST 15 (2020) 12, P12003

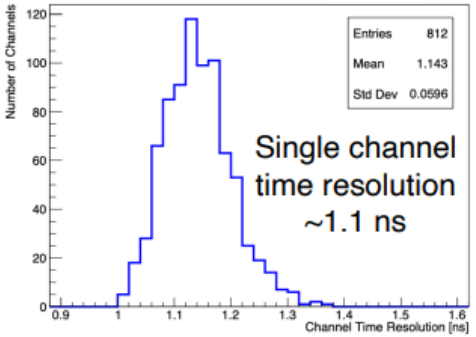
Low crosstalk



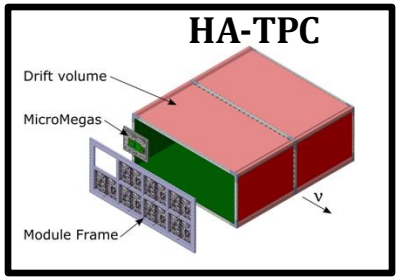
Excellent PID

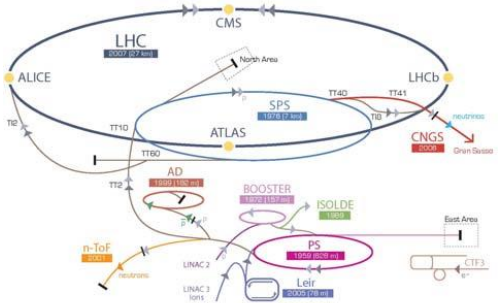


Fast timing



Test beams @ CERN





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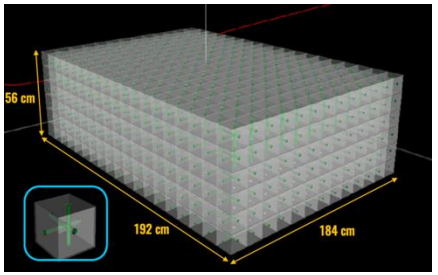
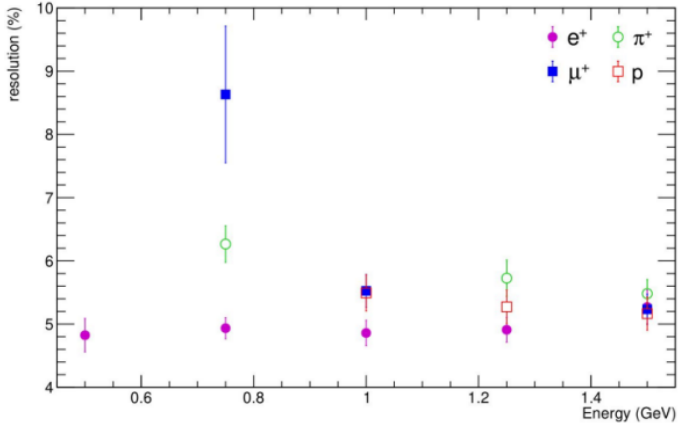
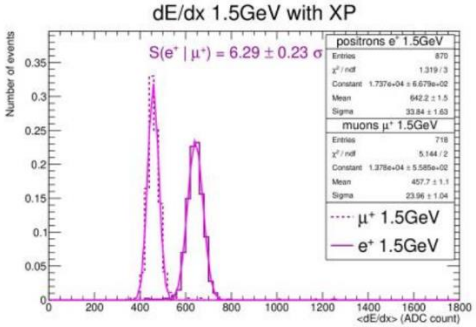


Previous CERN test beam analysis: *NIMA* 1052 168248



dE/dx resolution typically <6%

Unambiguous μ^+, e^+ separation



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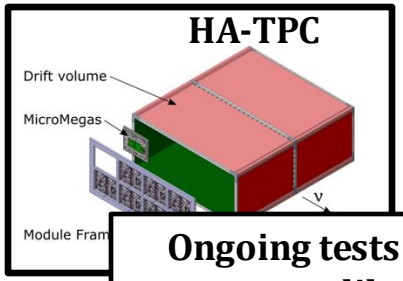
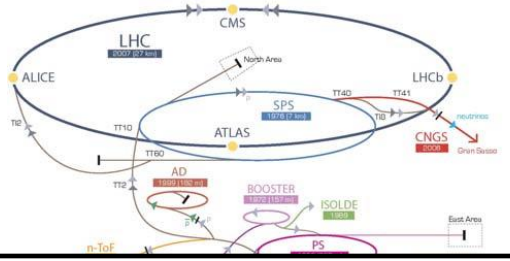
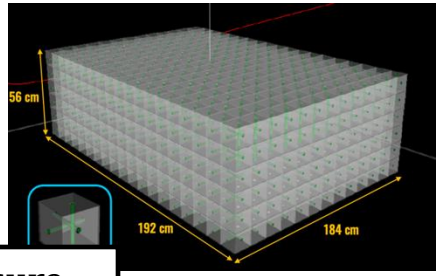


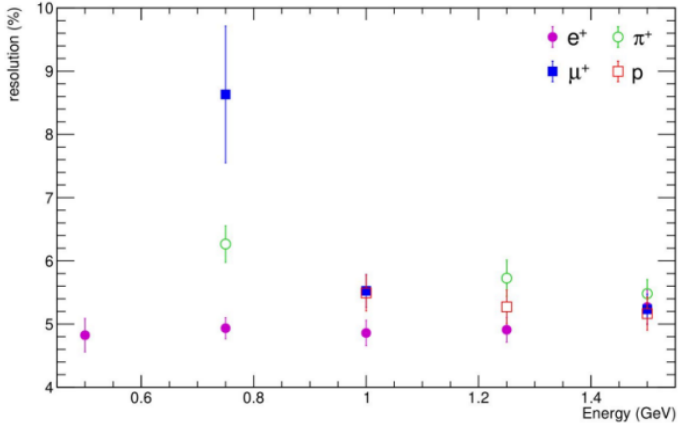


SuperFGD



Ongoing tests of HA-TPC clone @CERN to ensure accurate calibrations and charicterisation of track reconstruction

Previous CERN test bea



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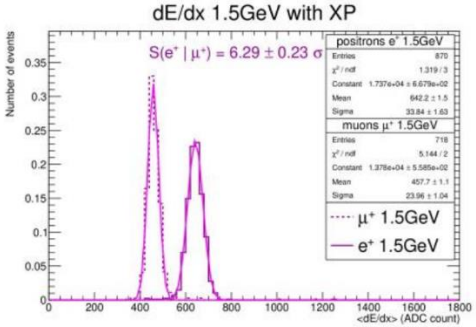
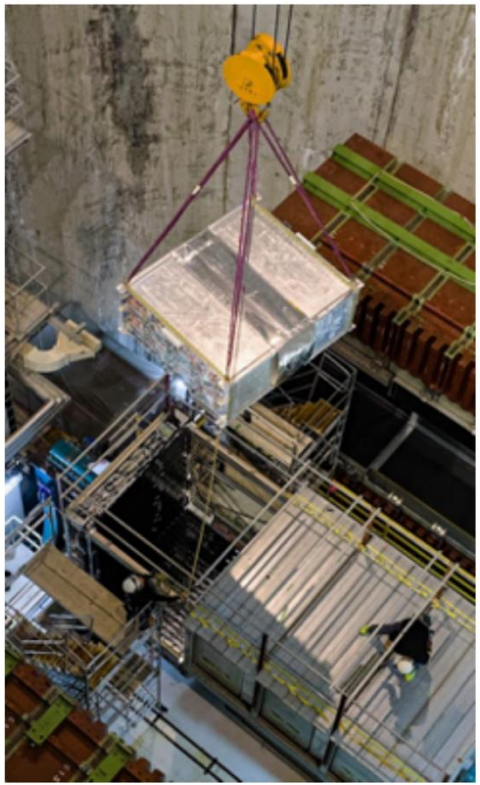
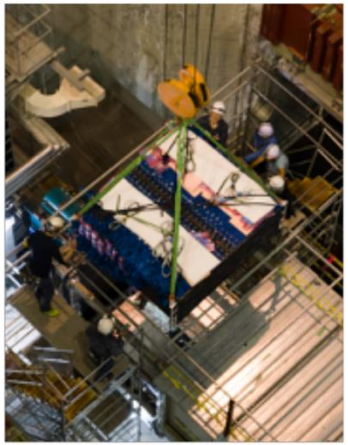
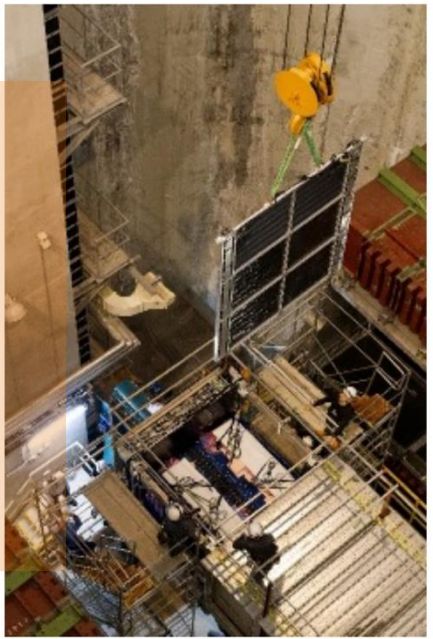


Installation in Japan

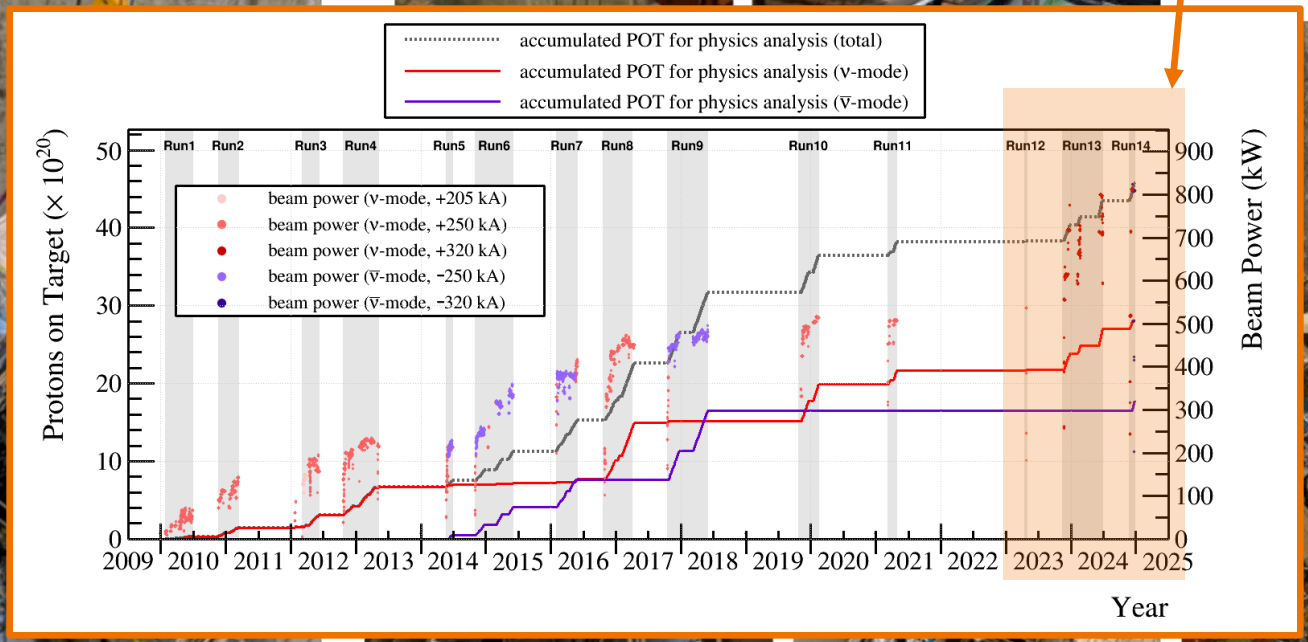




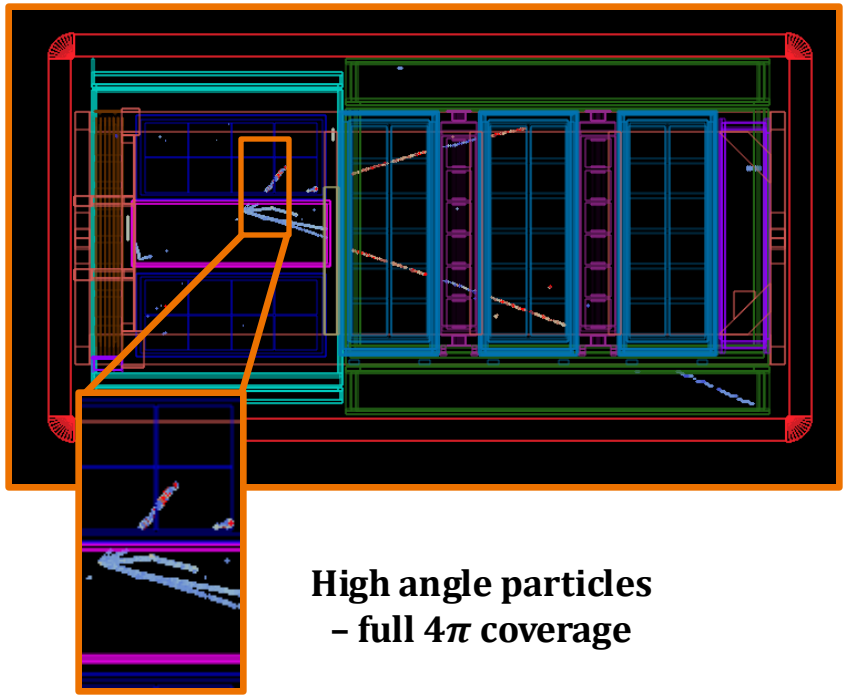


Installation in Japan

Now taking data!

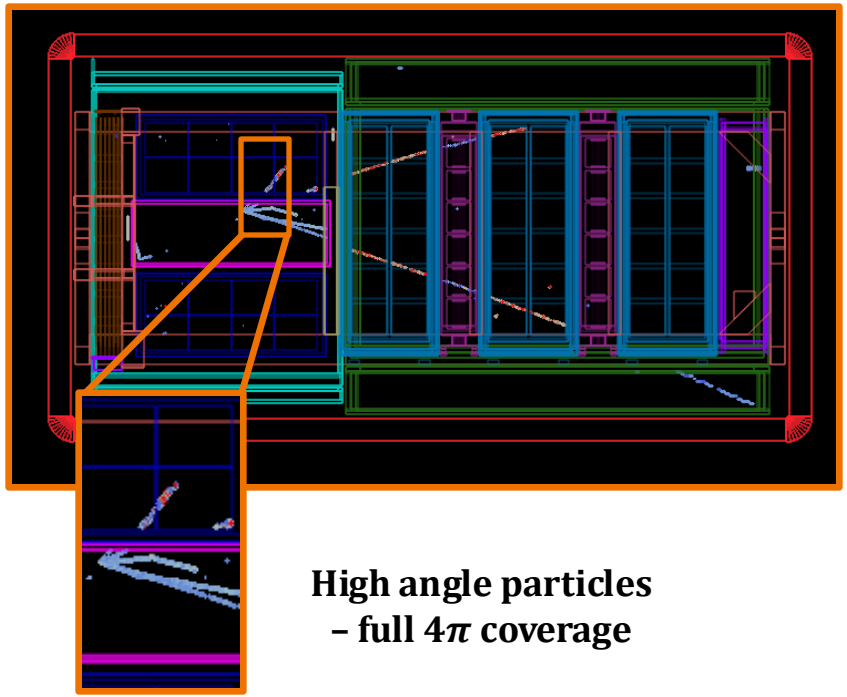


Event displays

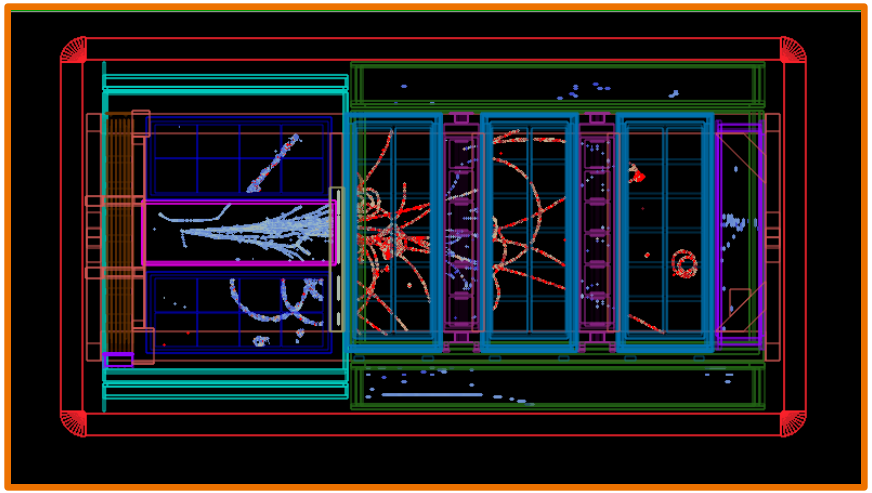


High angle particles
– full 4π coverage

Event displays

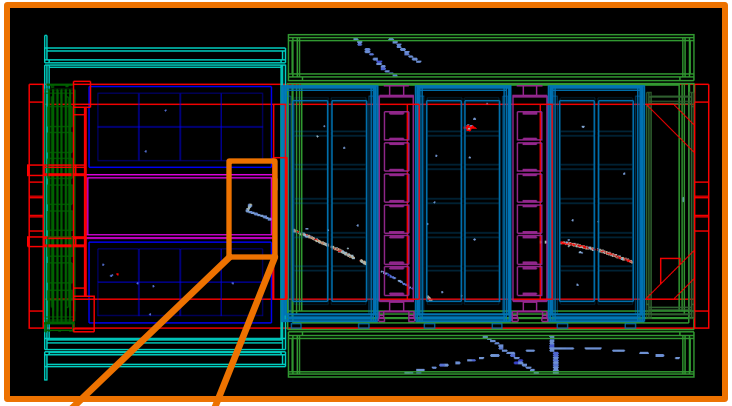


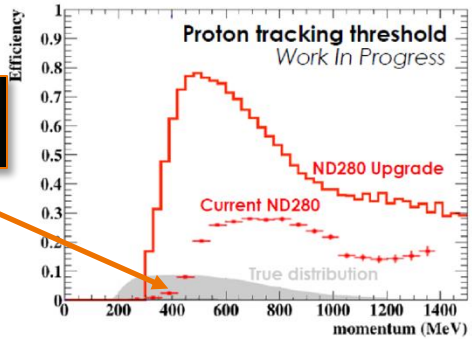
High angle particles – full 4π coverage

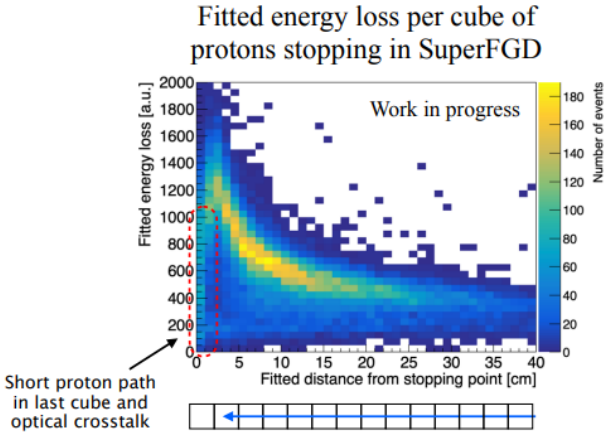


High multiplicity event

Event displays

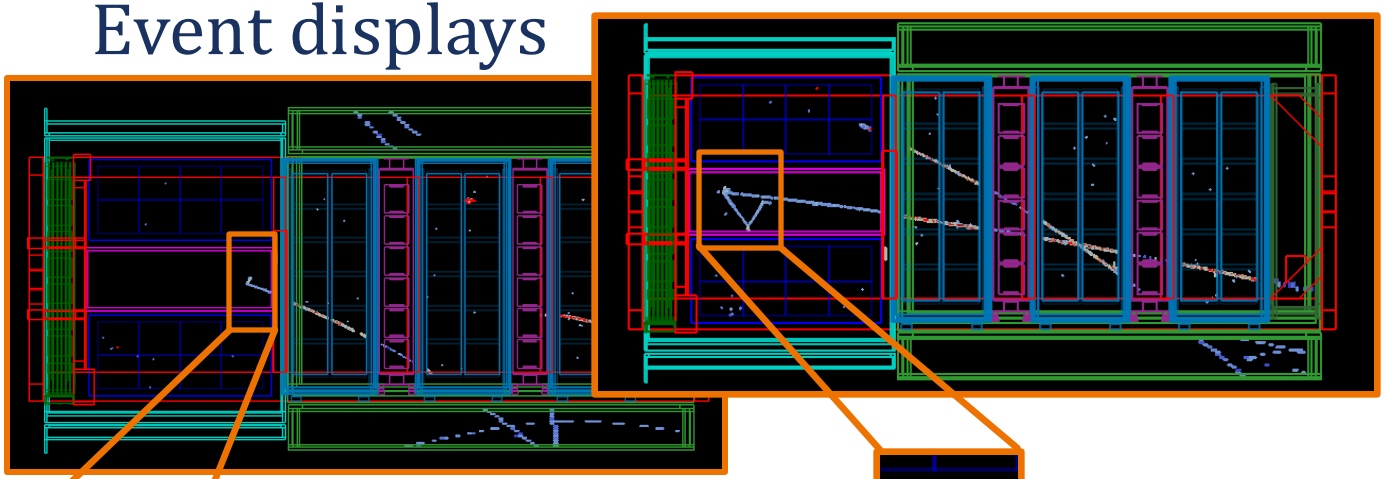


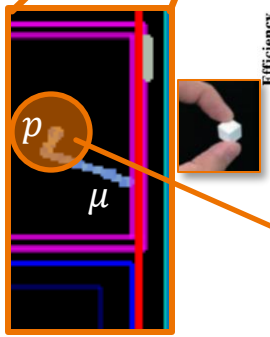


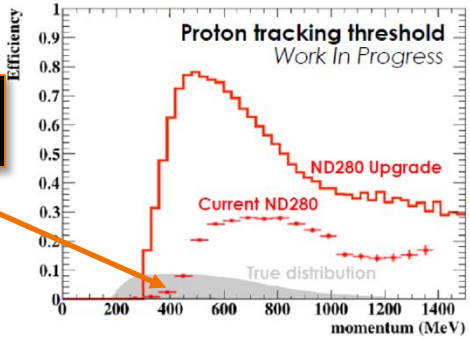


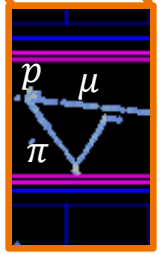
Allows us to access **low momentum protons**!

Event displays





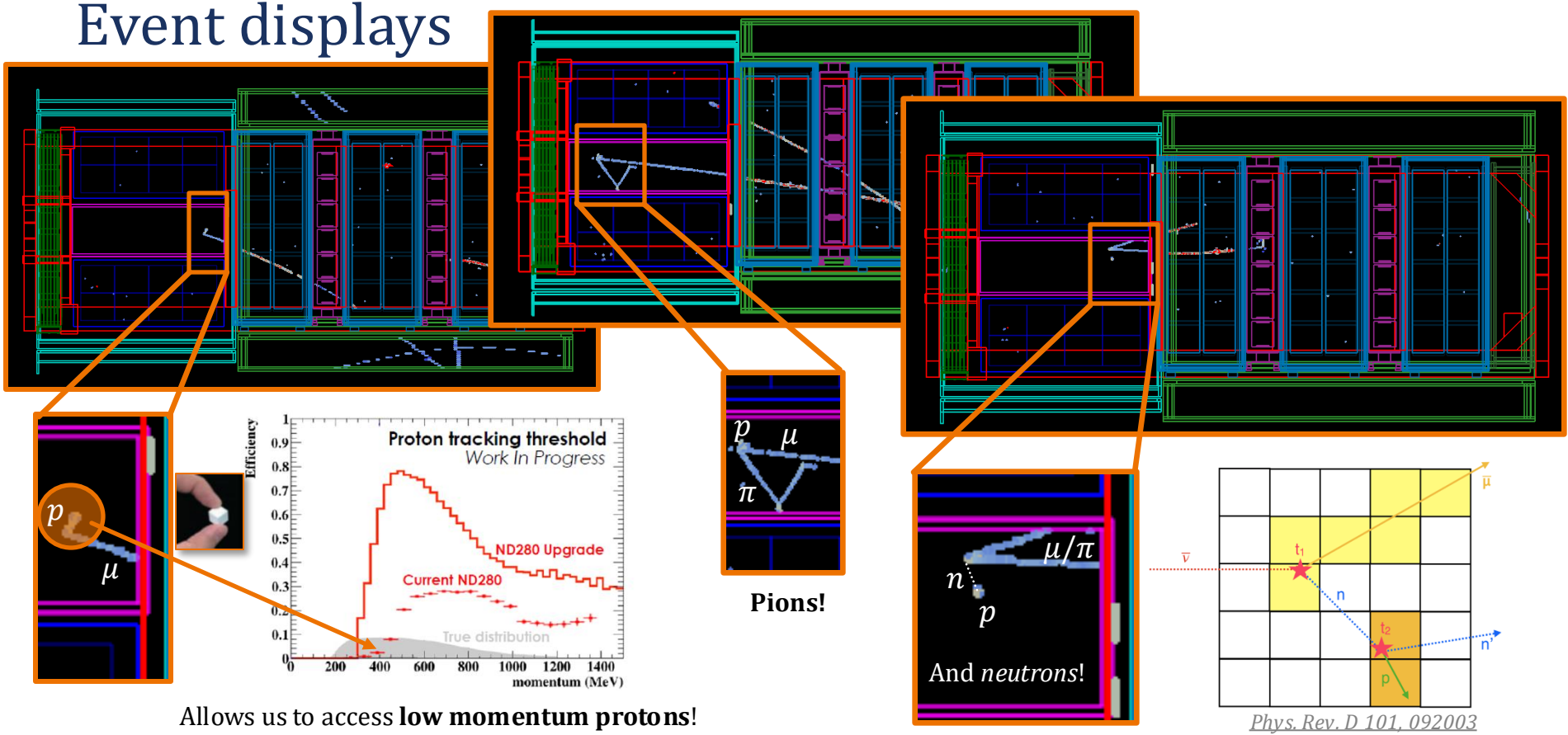




Pions!

Allows us to access **low momentum protons**!

Event displays



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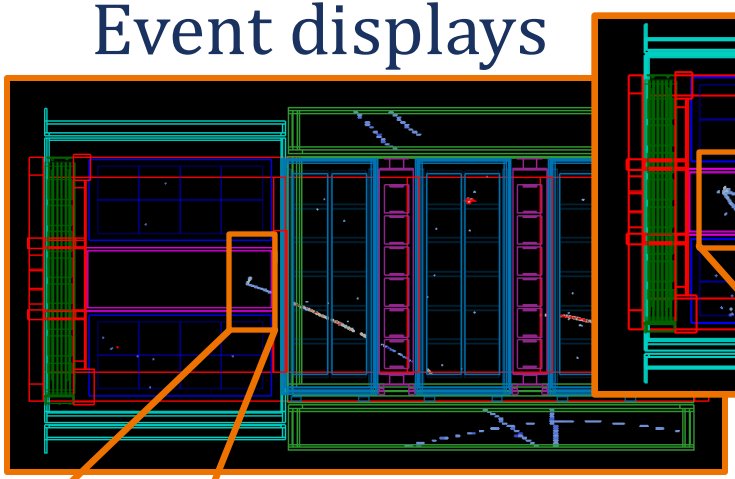
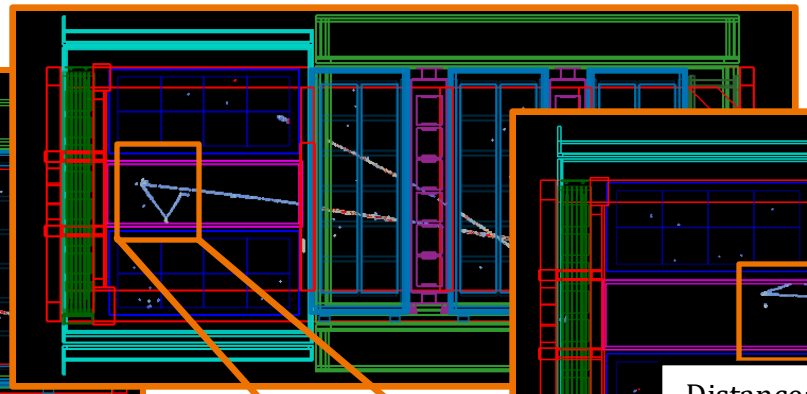
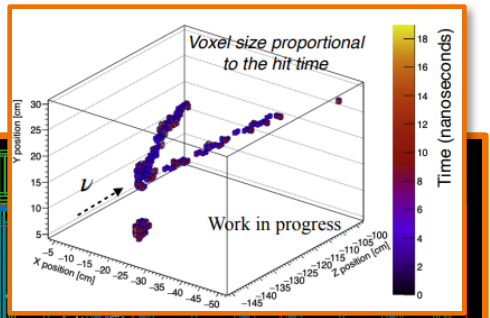
Phys. Rev. D 101, 092003

Event displays

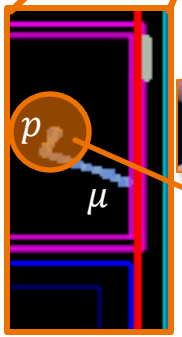


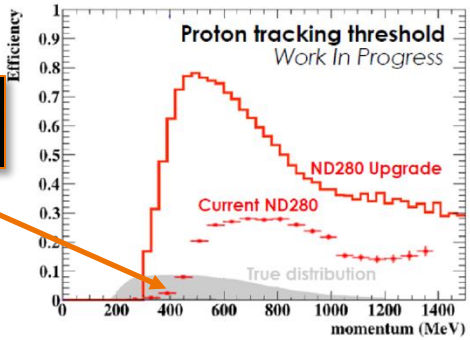


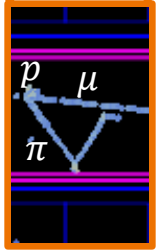


Distance: 122 mm; Time of flight: 1.7 ns

Kinetic energy: 27 MeV







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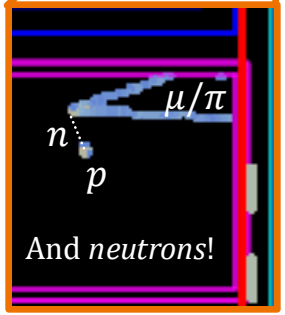

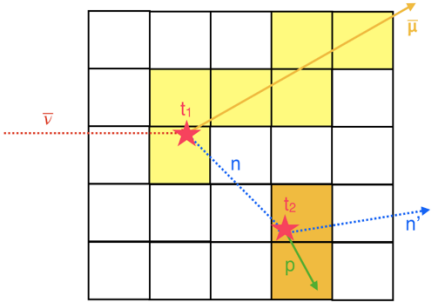

Phys. Rev. D 101, 092003

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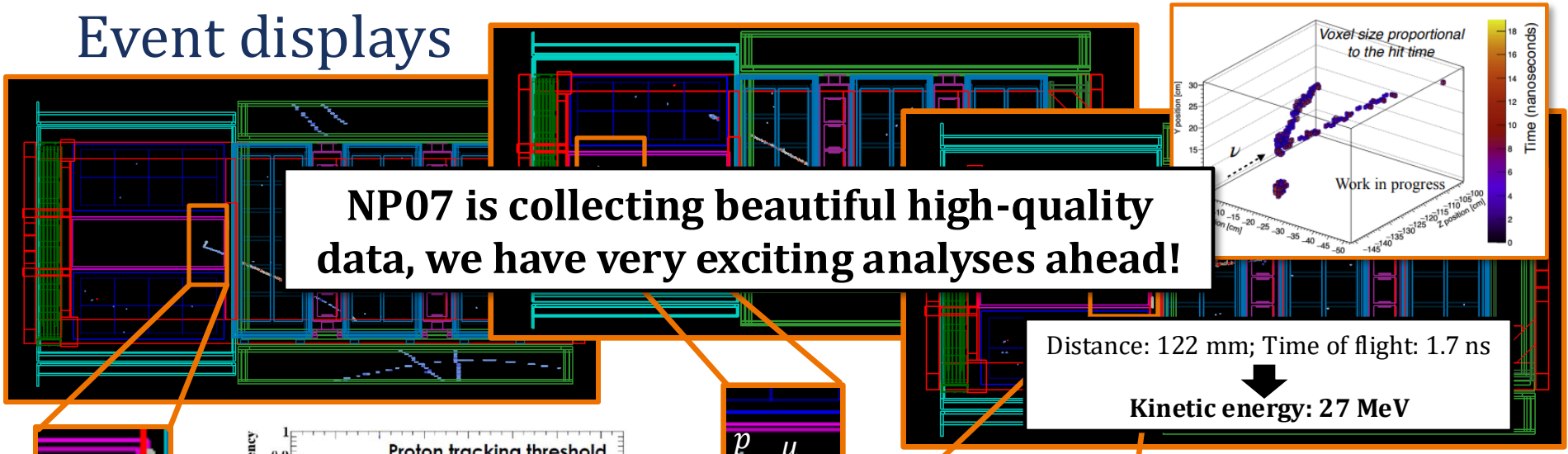

NP07 is collecting beautiful high-quality data, we have very exciting analyses ahead!

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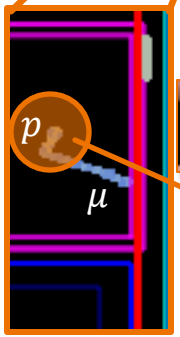

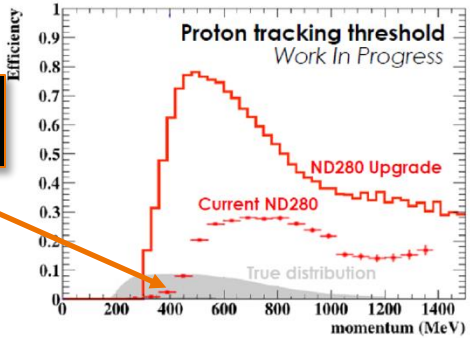

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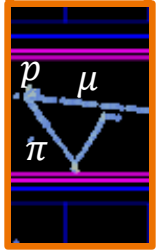

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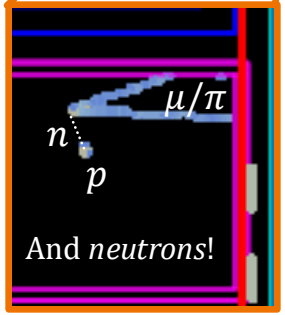
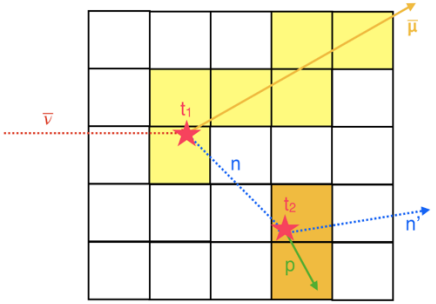
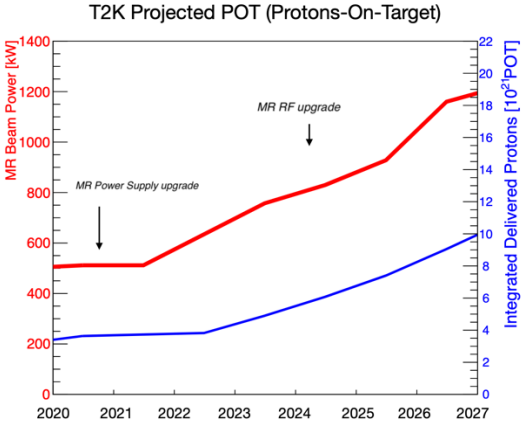




Phys. Rev. D 101, 092003

How can we do better?



Increased beam power

Expect O(10^{22}) POT by the end of 2027

800 kW reached in summer 2024!

(Our work is never over)

We need
- Bigger, better near detectors
- Continued support from external experiments
- Closer collaboration between experiments and theory

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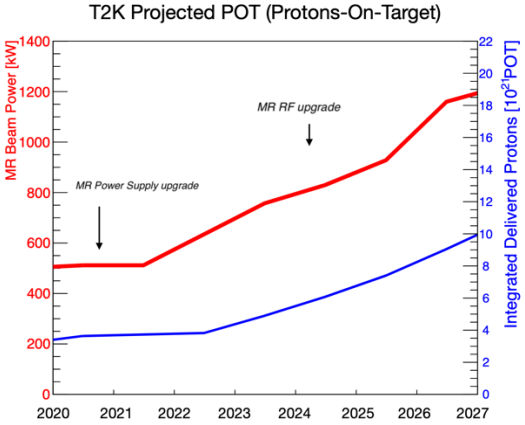

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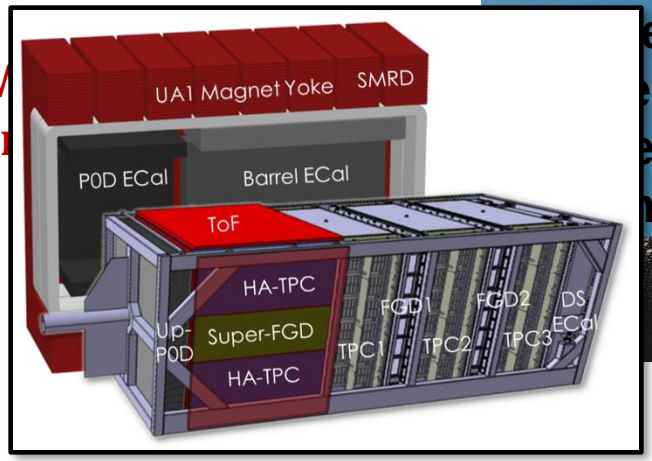
sum



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NA61/SHINE has taken new data for T2K in 2022

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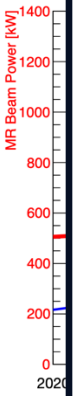

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

B. The existence of non-zero neutrino masses is a compelling sign of new physics. The worldwide neutrino physics programme explores the full scope of the rich neutrino sector and commands strong support in Europe. Within that programme, the Neutrino Platform was established by CERN in response to the recommendation in the 2013 Strategy and has successfully acted as a hub for European neutrino research at accelerator-based projects outside Europe. ***Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).***

Tangible outcome of the 2020 ESPPU

(Our work is never over)

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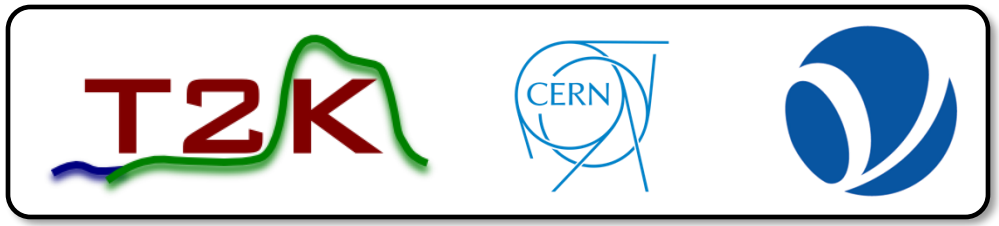
T2K and CERN/the Neutrino Platform

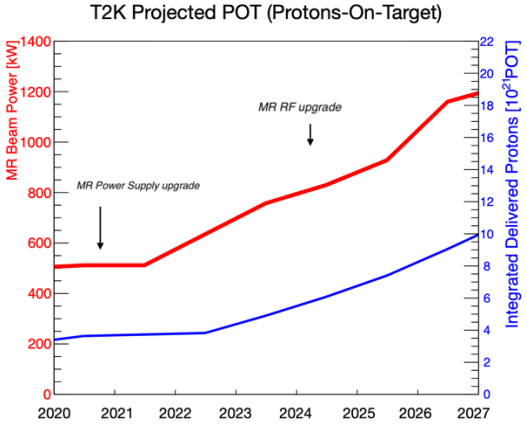
T2K acknowlges invaluable support provided by CERN and the Neutrino Platform in realizing its physics goals

- The ND280 Upgrade project (realization, testing, R&D etc…) has greatly benefited from CERN's support, facilities and financial contributions through the NP07 project
- T2K relies on support experiments (such as NA61), hosted at CERN
- But also on harnessing the analysis expertise developed at CERN



T2K's experience shows how crucial support from CERN and the Neutrino Platform will be for the next generation of long-baseline experiments

How can we do better?



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Bridging the gap between theory and experiment

In the last ~6 years, the CERN EP-NU group has informally become a European hub for facilitating communication between nuclear physicists and experimentalists. **Examples:**

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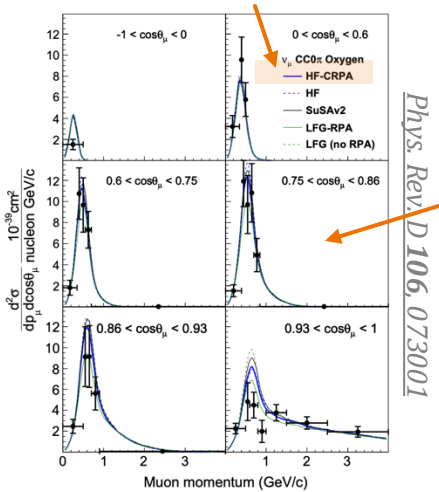
(with theorists from U. Ghent and Fermilab)



Phys. Rev. D **106**, 073001

Used in latest T2K Oscillation analysis and **highlighted largest source of systematic uncertainty**

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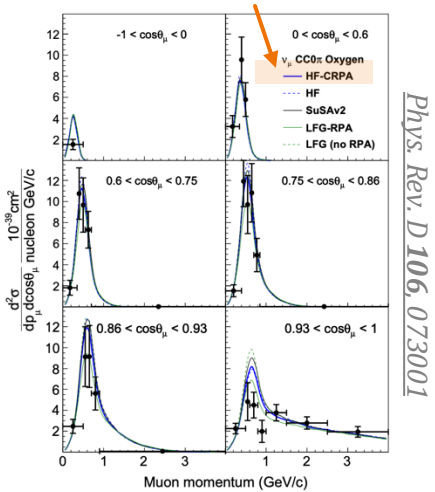

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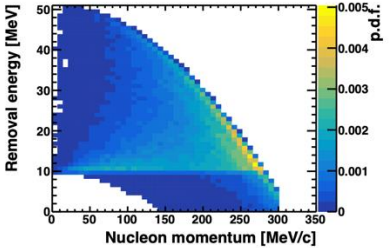

Using T2K experience to inform DUNE interaction uncertainty model

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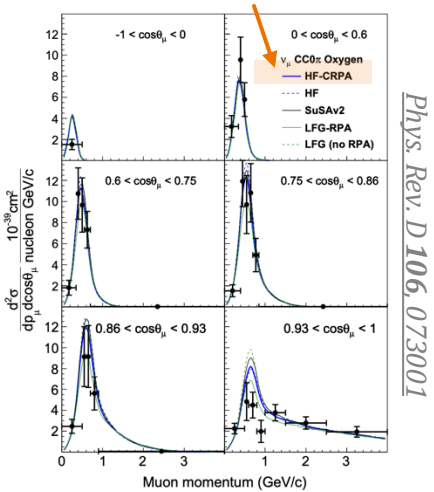

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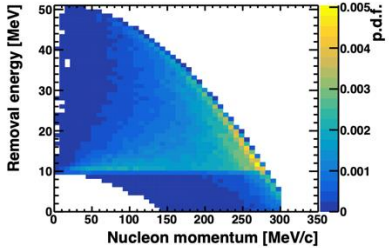

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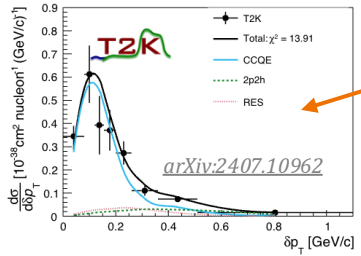

Benchmarking models against measurements

Used T2K model to **compare** to T2K, MicroBooNE and MINERvA measurements to **lift degeracies between experiments**

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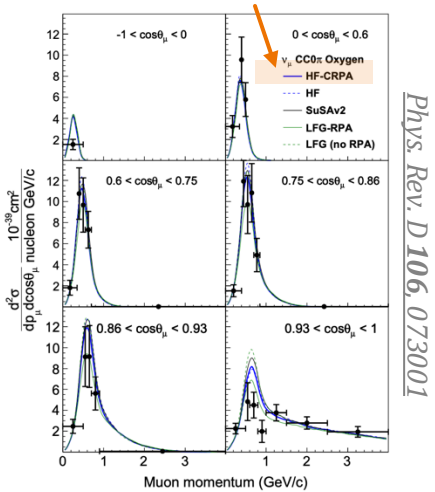

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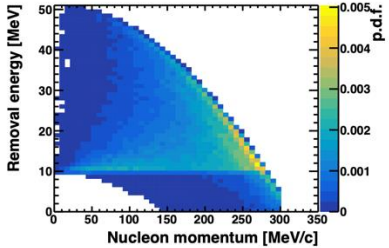

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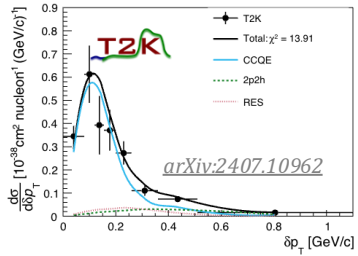

Benchmarking models against measurements

Collaborations with nuclear theorists

Implemented models & uncertainties (e.g. CRPA, SF, Martini etc.) in generators which are **used in T2K oscillation analyses**

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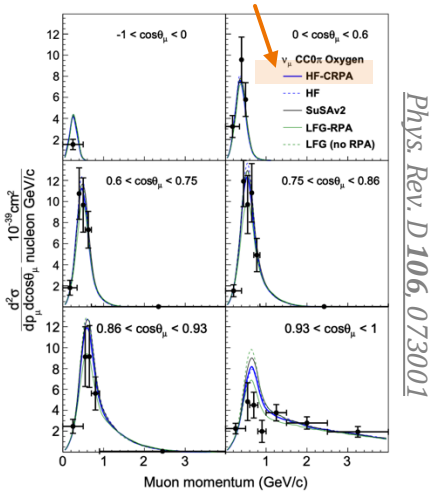

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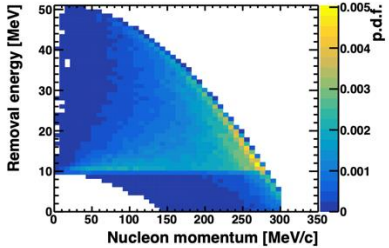

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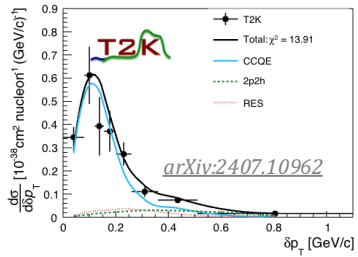

arXiv:2407.10962

Benchmarking models against measurements

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Organization of NuXTract Workshop

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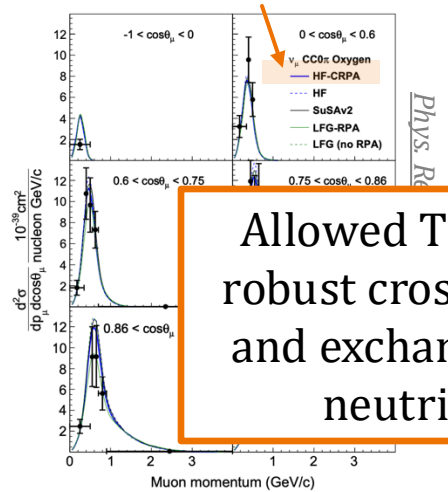

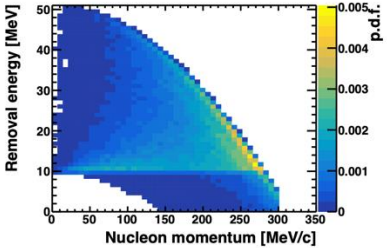

Using T2K experience to inform DUNE interaction uncertainty model

Allowed T2K to share its experience in robust cross-section extraction methods and exchange on statistical problems in neutrino cross-section physics

Benchmarking models against measurements

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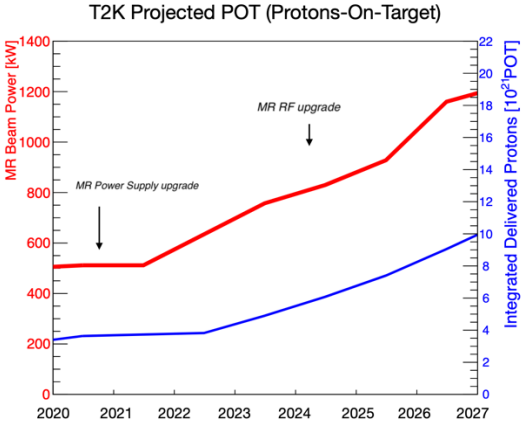
How can we do better?



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Bringing theory and experimental communities closer

- The robustness and quality of **T2K analyses have benefited greatly from this informal effort**
- Next generation experiments will be **limited by systematic uncertainties** (largest will be related to neutrino cross sections)
  - They would benefit even more heavily from such a structure
- Possible ways:
  - Reviving previous efforts (e.g. CENF WG2 Cross-section (Theory) and Generators)?
  - Establishing a new European platform with support from NP/CERN
  - Supporting regular topical workshops/events

What we can do with/for Neutrinos@CERN?

Europe has a key role in the future of oscillation experiments

CERN & the NP should continue supporting long-baseline neutrino experiments with

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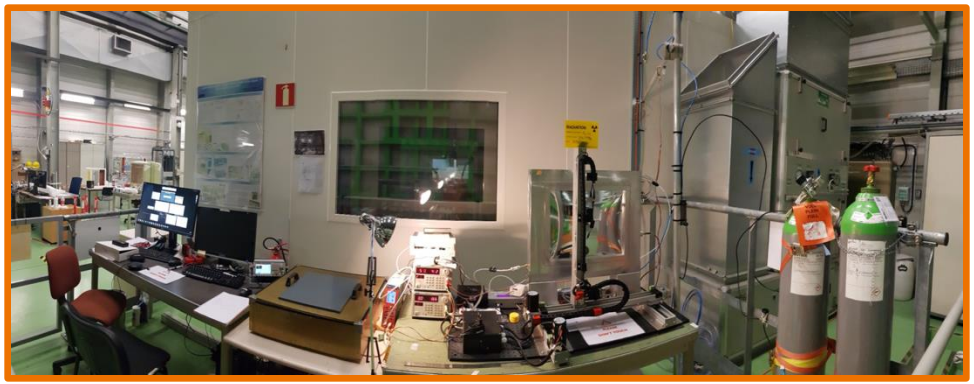
- **Facilities/expertise to develop detectors** for future experiments



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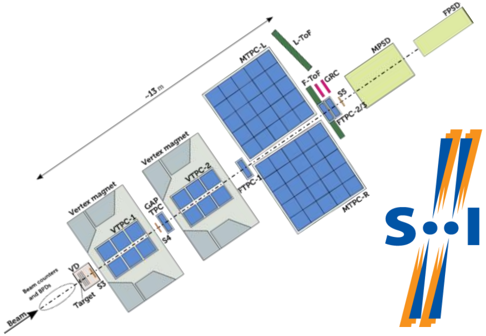
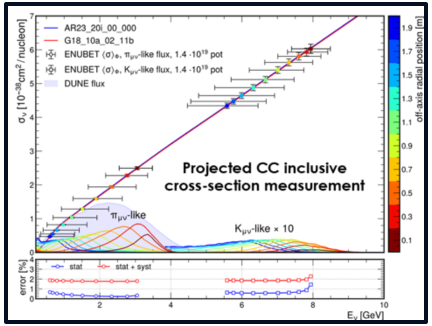
CERN & the NP should continue supporting long-baseline neutrino experiments with

- **Facilities/expertise to develop detectors** for future experiments
- **Support experiments** to control flux and cross-section systematics



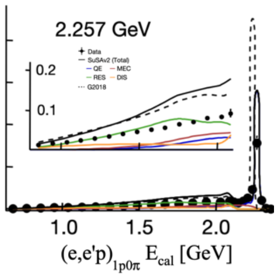
Hadroproduction measurements

SBN@CERN
(See S. Dolan's talk)



ν cross-section measurements

Nature 599, p. 565–570 (2021)



Potential electron scattering measurements?

What we can do with/for Neutrinos@CERN?

Europe has a key role in the future of oscillation experiments

CERN & the NP should continue supporting long-baseline neutrino experiments with

- **Facilities/expertise to develop detectors** for future experiments
- **Support experiments** to control flux and cross-section systematics
  - E.g. by continuing NA61/SHINE measurements, dedicated neutrino cross-section experiments (such as SBN@CERN), potential electron scattering experiments
- Providing a **platform for experimentalists and theorists** to work together on reducing systematic uncertainties