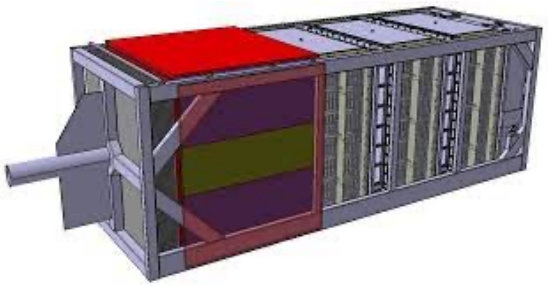


ND280 UPGRADE STATUS AND SENSITIVITY

PREPARING T2K NEUTRINO MEASUREMENTS FOR THE PRECISION ERA

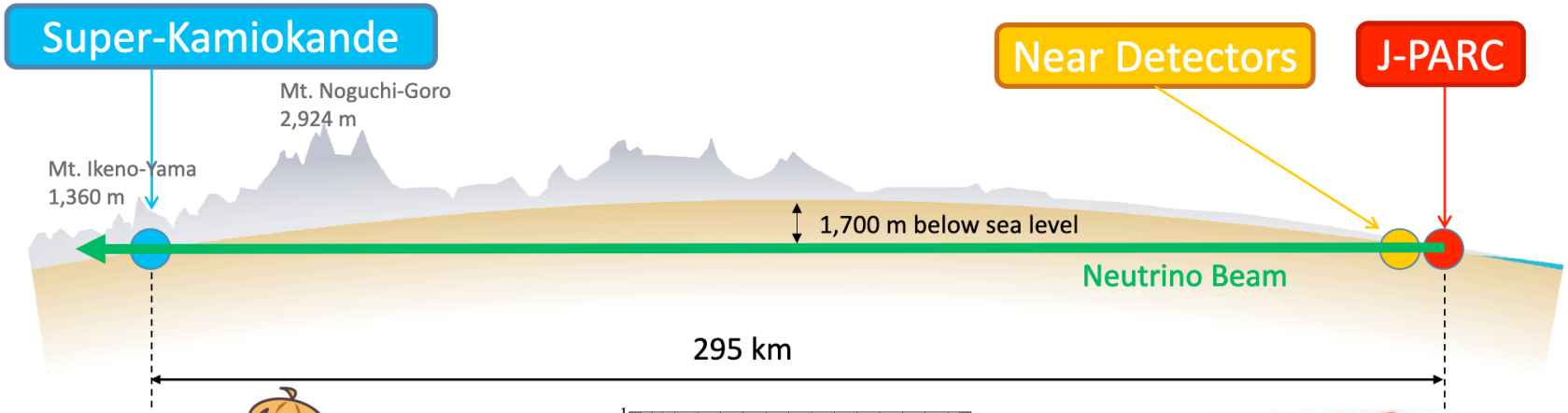
Laura Munteanu for the T2K Collaboration

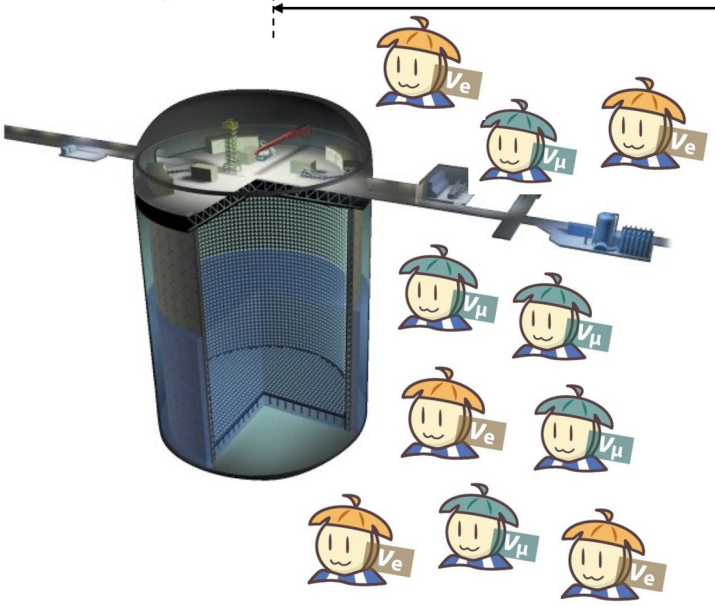
NuINT 2022

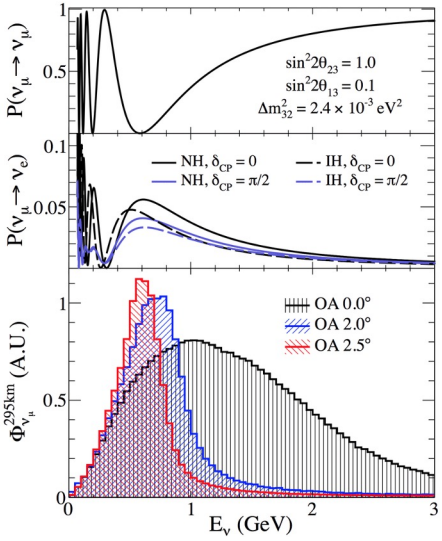
Seoul, South Korea

October 28 2022

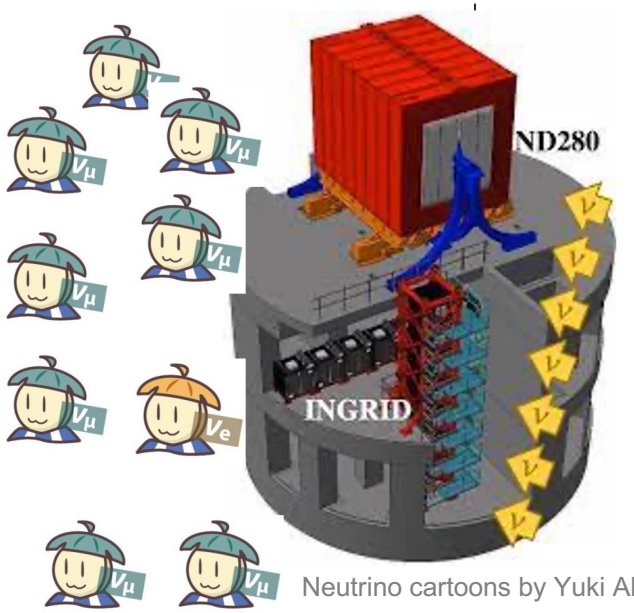
THE T2K EXPERIMENT







2.5° off-axis



Neutrino cartoons by Yuki Akimoto

T2K PHYISICS PROGRAM & RECENT ACHIEVEMENTS

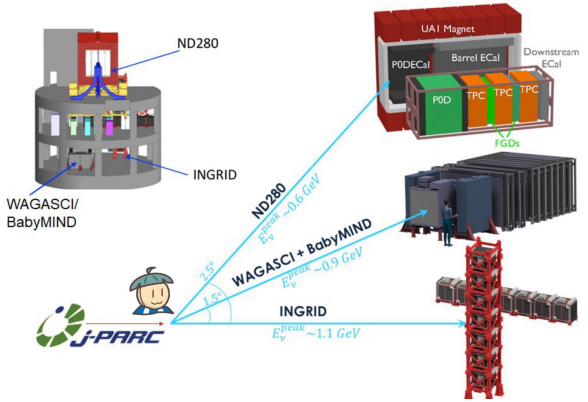
Neutrino oscillation measurements *[See talk by C.Wret]*

- Measuring neutrino oscillation parameters
  - **First hint of CP violation in the lepton sector!**

Nature 580, 339–344 (2020)

Neutrino cross-section measurements *[See talk by C.Jesus-Valls]*

- Particular focus on joint measurements:
  - On/off-axis [See talk by C. Schloesser]
  - C/O [Phys. Rev. D 101, 112004 (2020)]
  - $\nu/\bar{\nu}$ [Phys. Rev. D 101, 112001 (2020)]
  - $\nu_e/\bar{\nu}_e$ [JHEP 2020, 114 (2020)]
  - TKI in ν_μ CC1π^+ channel [Phys. Rev. D 103, 112009 (2021)]
  - CC1π 4π ν_μ interactions [See talk by D.Vargas Oliva]



Experimental Property	T2K	NOvA
Proton Beam Energy	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection Technology	Water Cherenkov	Segmented liquid sintillator bars
CP Effect*	32%	22%
Matter Effect	9%	29%

Sterile searches

Joint fits

- T2K + SK atmospherics joint fit
- T2K-NOvA joint fit

T2K EXTENDED RUN

- Thanks to the results of T2K and other leading neutrino experiments, we now know much more about neutrinos than when we started!
- Neutrino physics is entering the precision era
  - **T2K aims to determine CPV/CPC at the 3σ level in the coming years**
- To achieve its ambitious goals, T2K will continue taking data (2023-2026) and aims to gather 10×10^{21} protons-on-target (POT)

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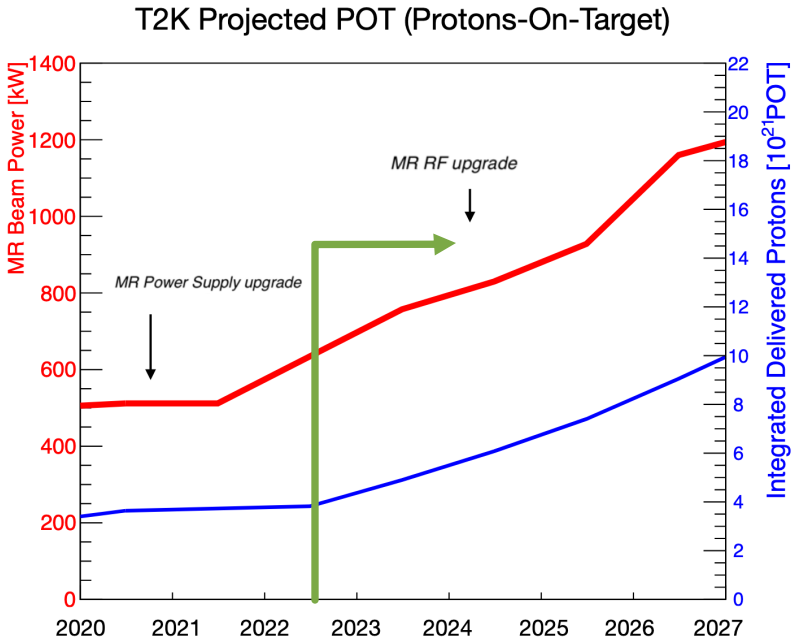
  - Increase beam power from 500 kW to 750 kW and then 1.3 MW (Hyper-K era) – intense neutrino beam, significant increase in event rate
  - Increase magnetic horn current (from 250 kA to 320 kA) – better separation of right/wrong sign component in the beam



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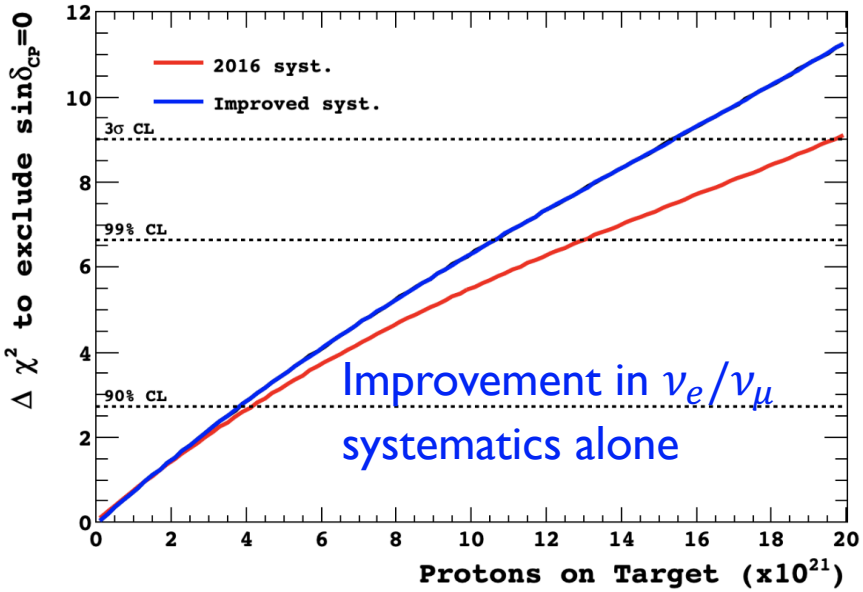
- **Systematics will become the limiting factor** at this level of statistics



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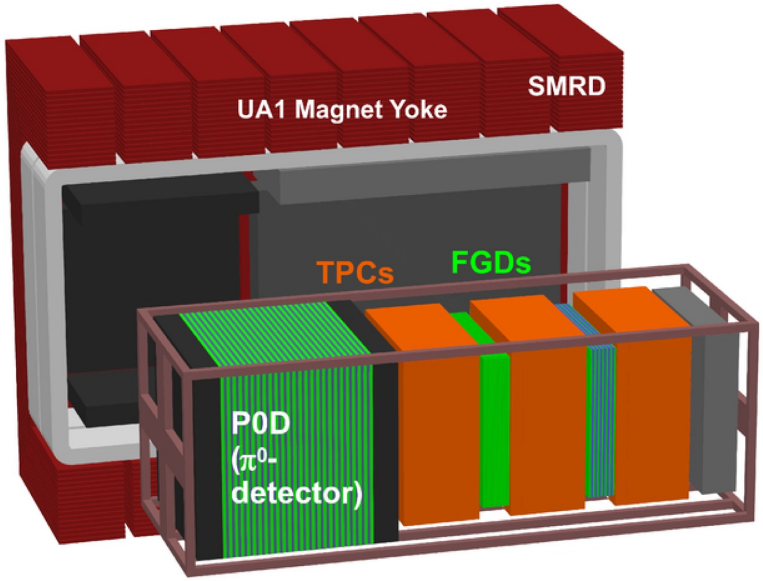
To control systematic errors for its desired goals, T2K has been planning an Upgrade of its off axis near detector, ND280

THE CURRENT ND280 DETECTOR *[See talk by C.Wret]*

Fine Grained Detectors (FGDs)

- Scintillating bars (CH target)
- 2 x 1 ton of mass
- FGD2 also contains water target



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- Instrumented with Bulk MicroMegas detectors
- Excelent tracking capabilities

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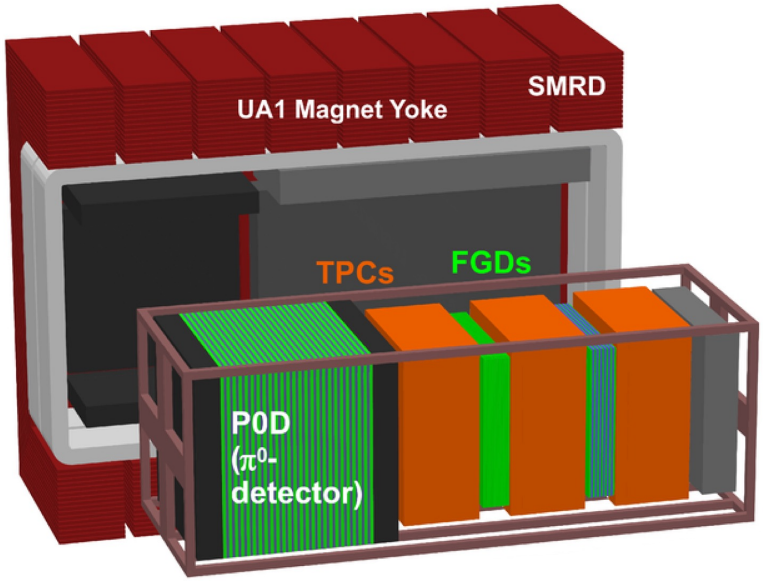

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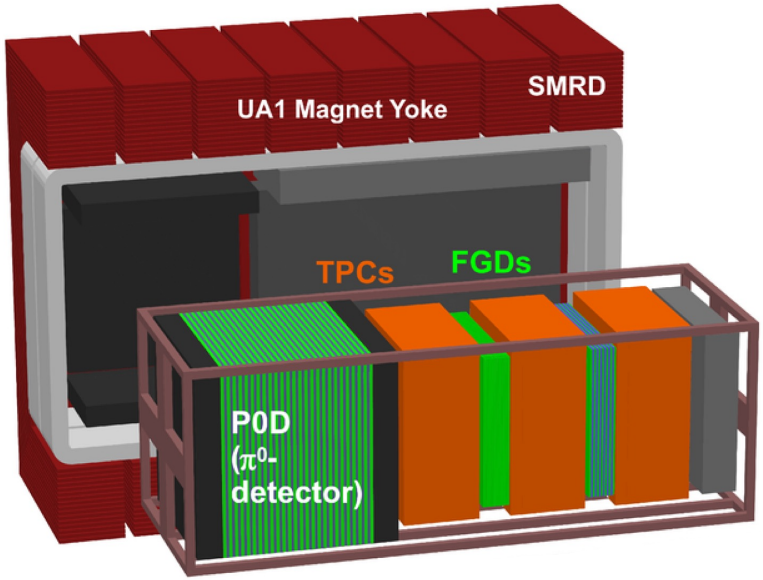

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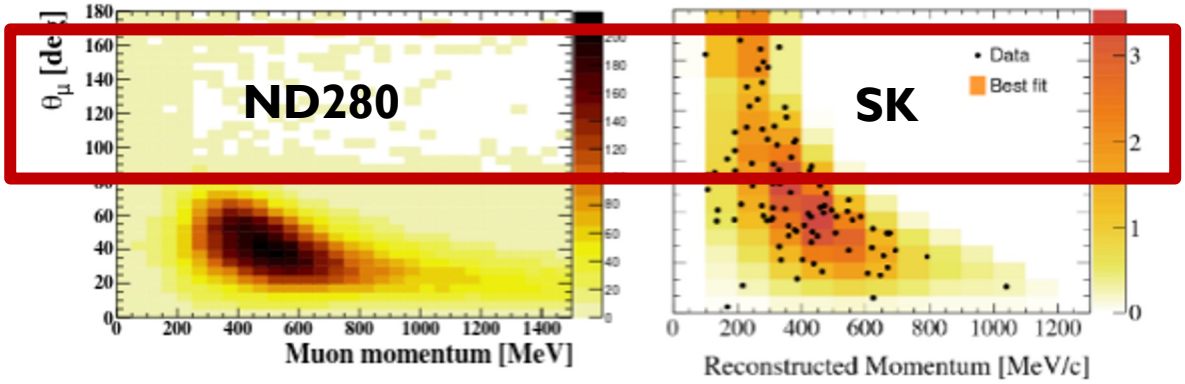

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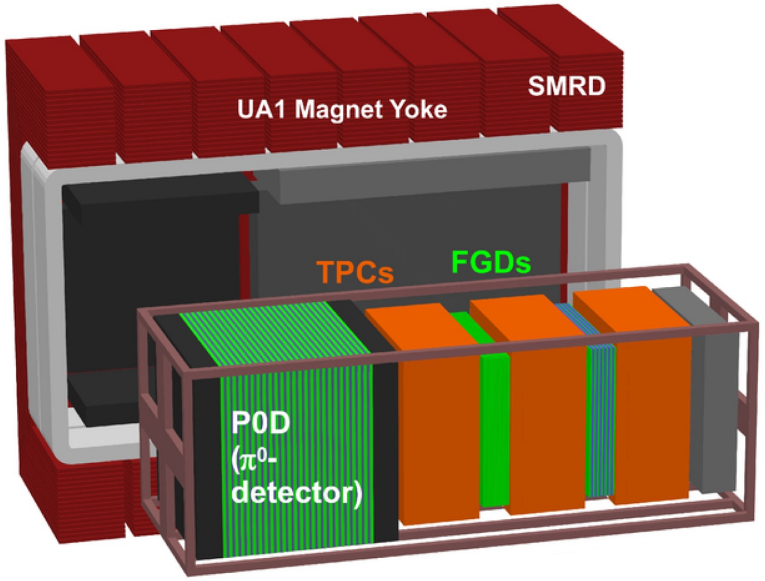

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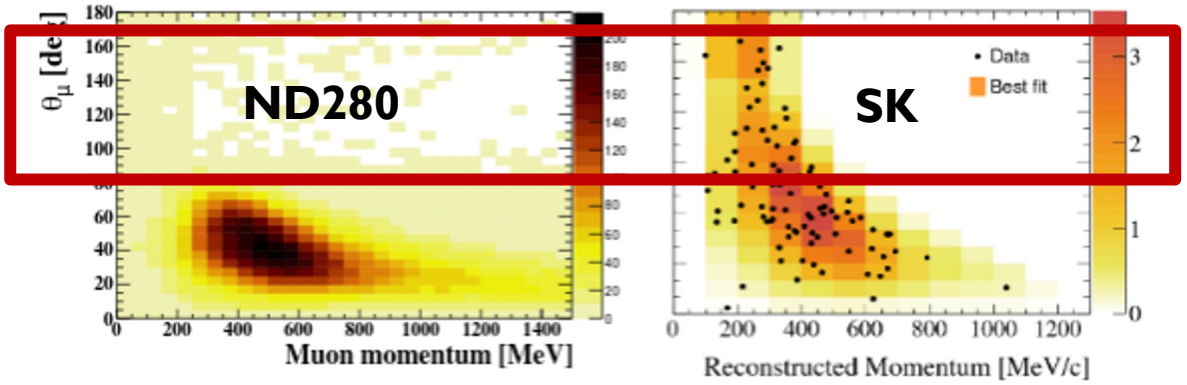
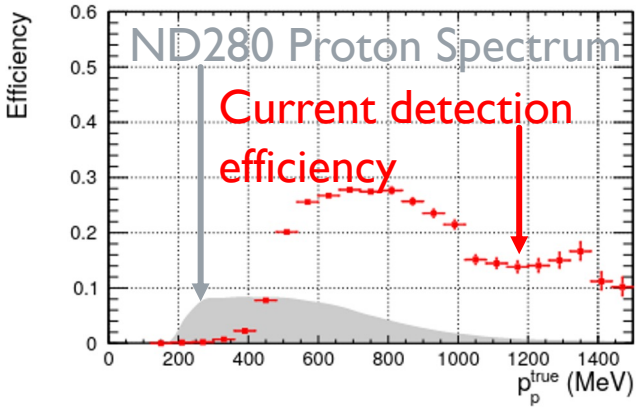
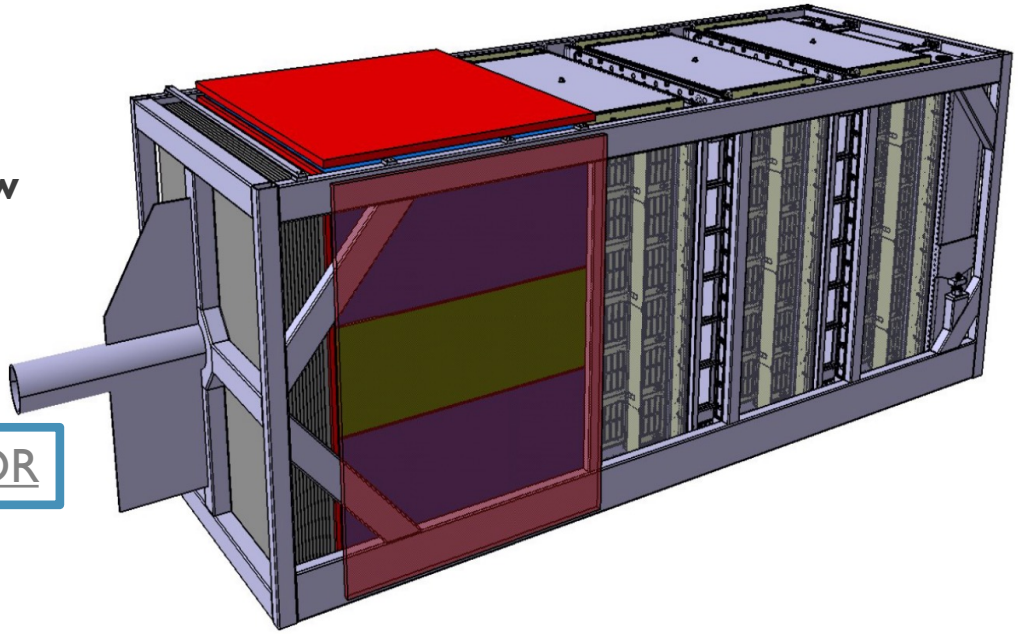




THE ND280 UPGRADE

Replace P0D by new suite of detectors



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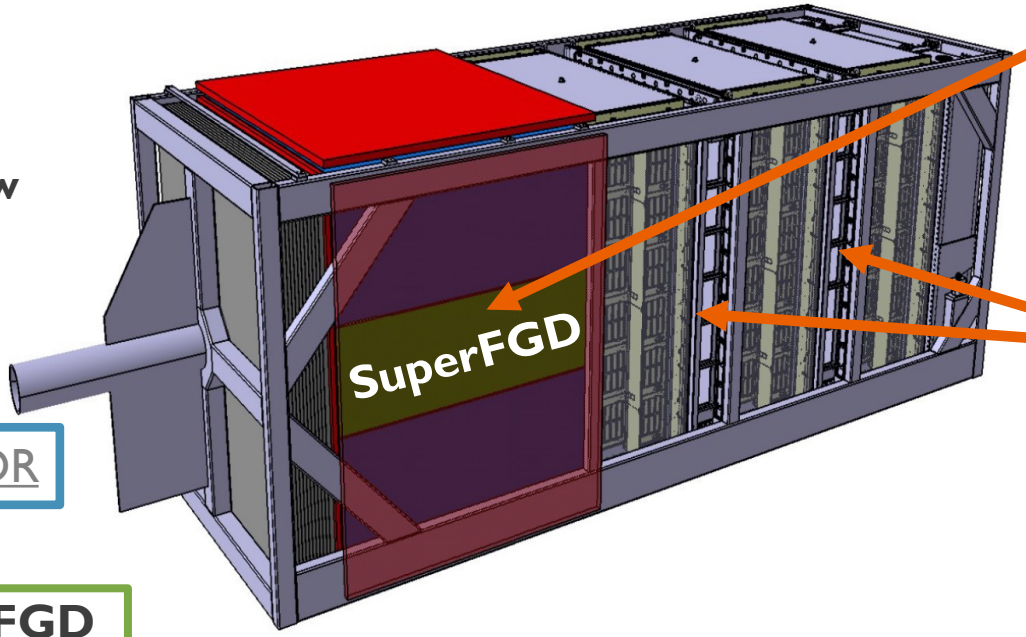
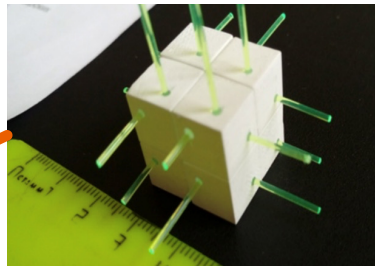
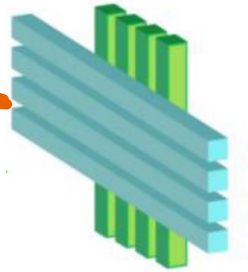




VS



ND280 Upgrade TDR

New Target: **SuperFGD**

- 2 tons fiducial mass
- **3x2D readout**
- 4π coverage
- Low thresholds
- Can detect neutrons!

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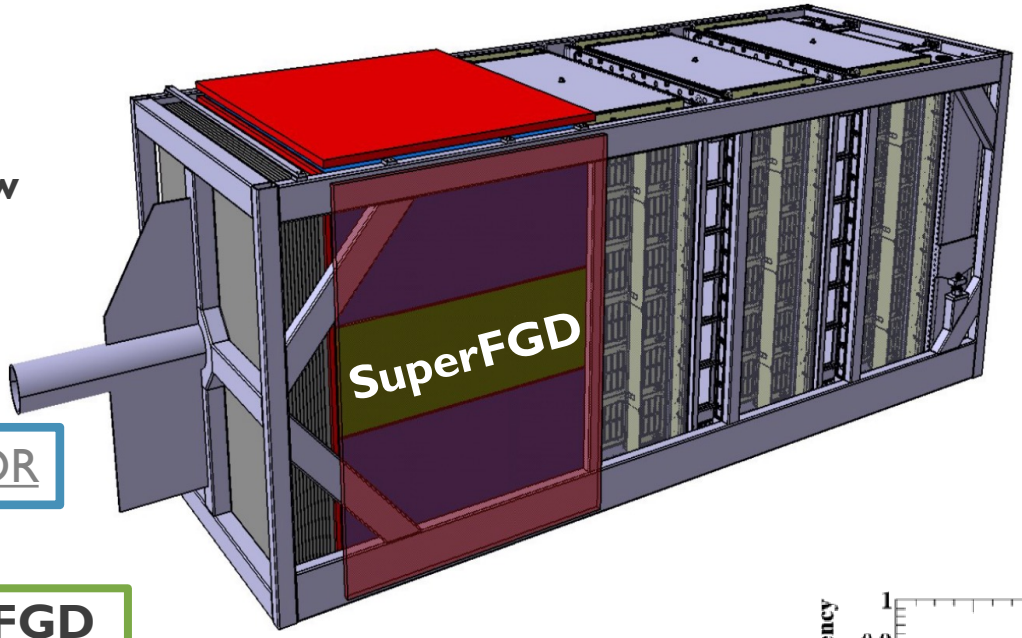

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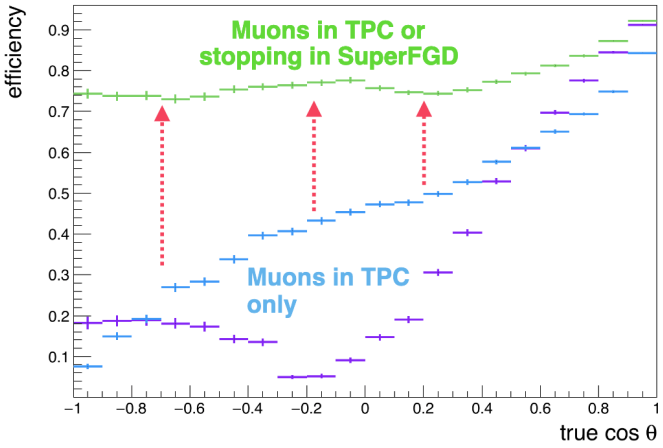

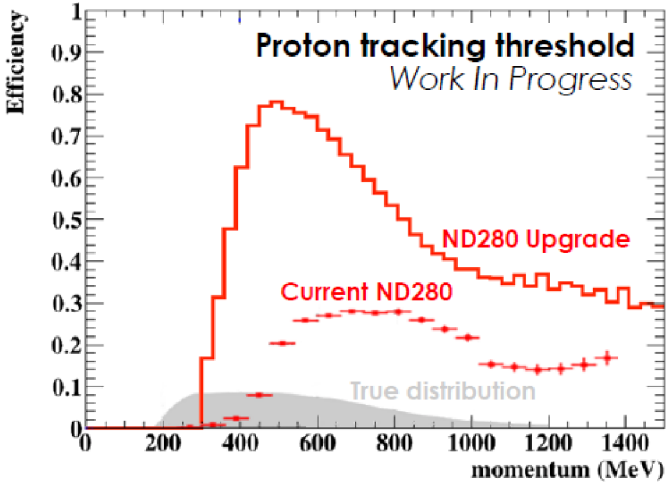

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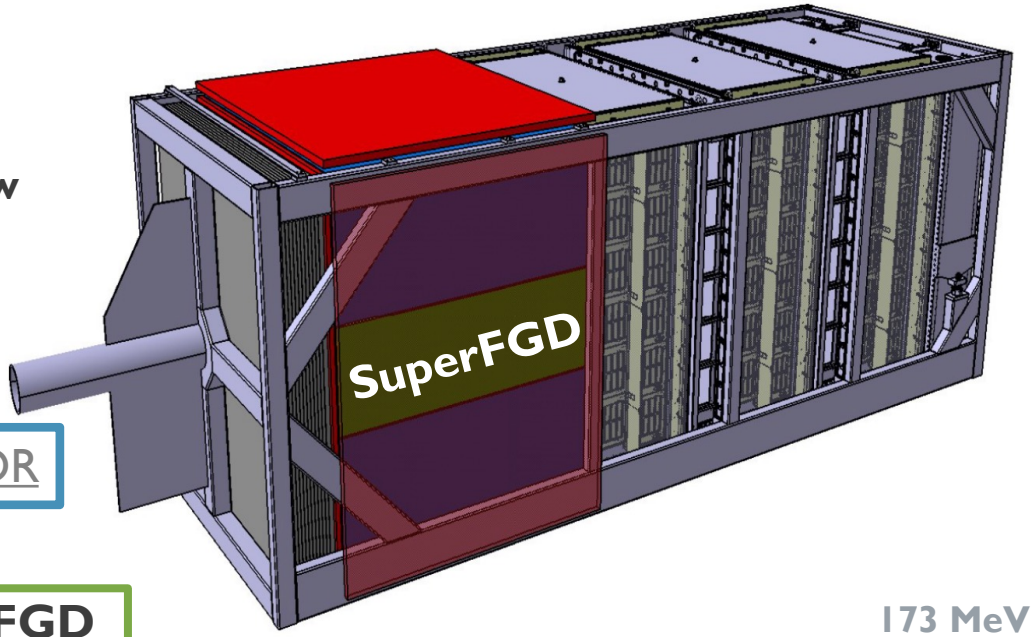
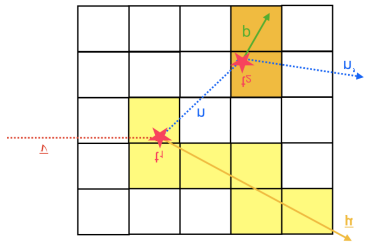


Phys. Rev. D 101, 092003



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[See talk by S. Gwon]

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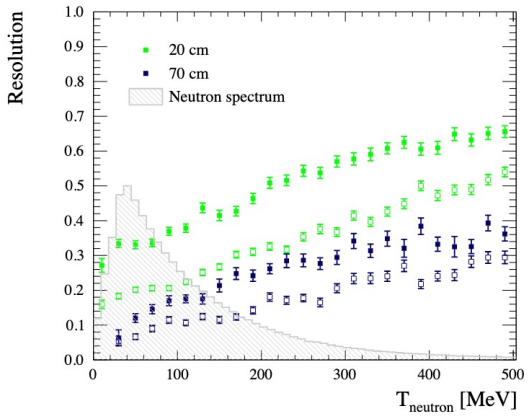
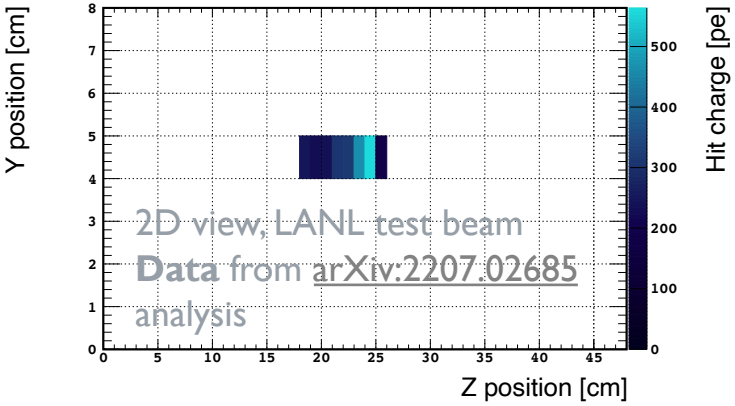


173 MeV Neutron candidate



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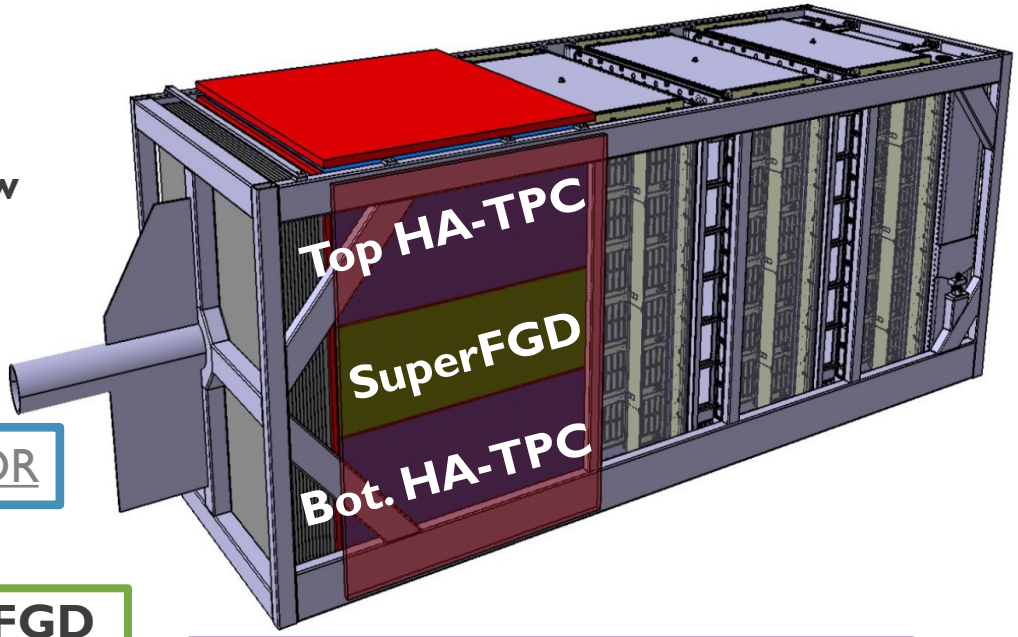

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(High-Angle TPCs)

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- Instrumented with novel resisitve MicroMegas detectors
- Excellent performance

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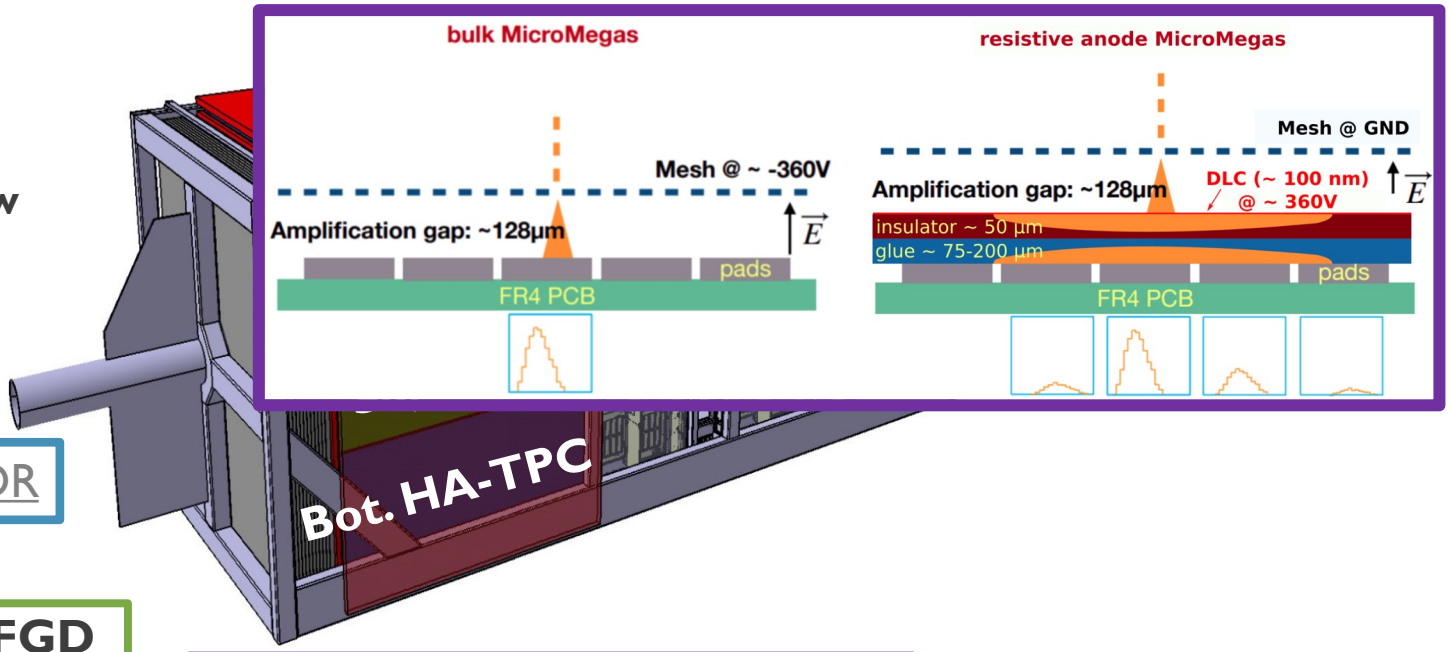

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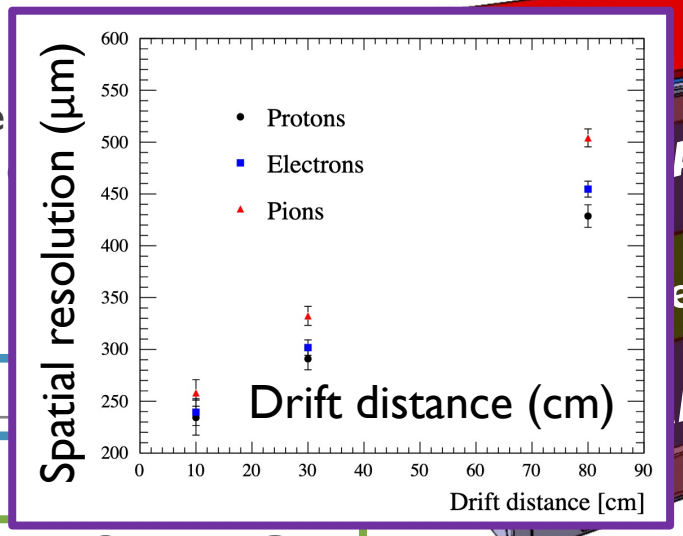
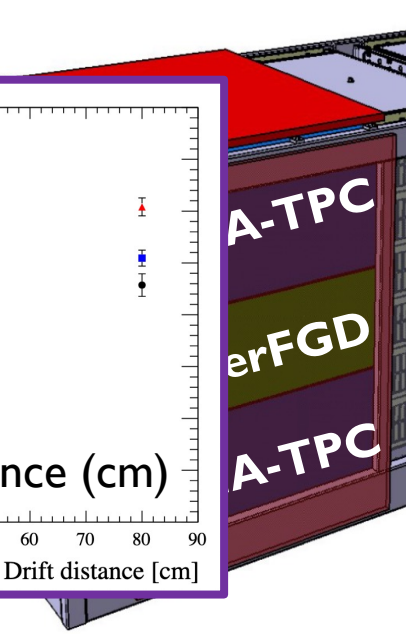
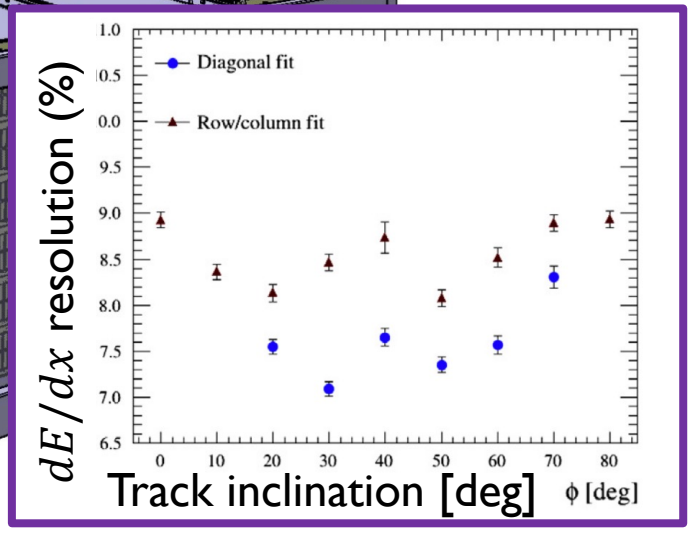
Nucl.Instrum.Meth.A 1025 (2022) 166109
Nucl.Instrum.Meth.A 957 (2020) 163286

Replace
suite of

ND280







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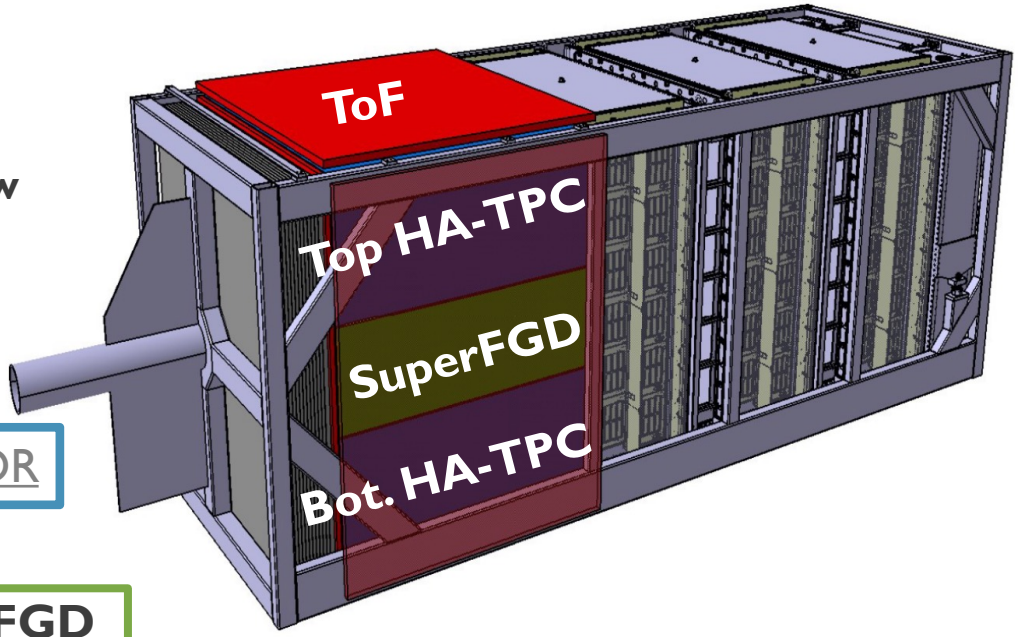

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- **6 scintillator planes**
- 150 ps time resol.

THE ND280 UPGRADE

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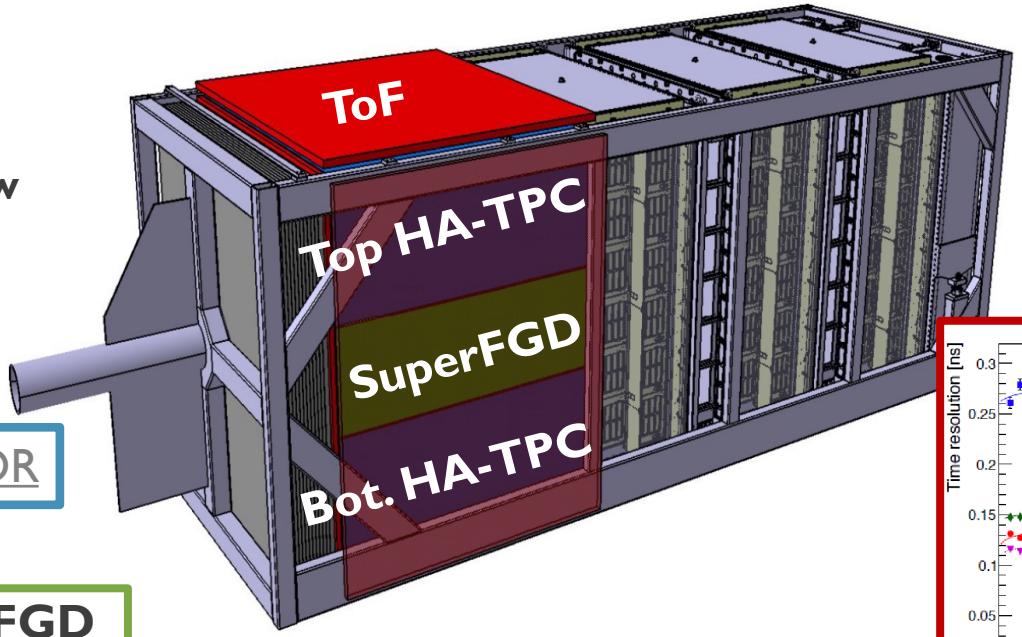
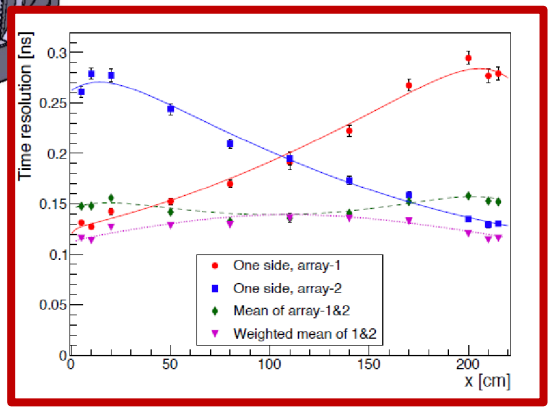


ND280 Upgrade TDR



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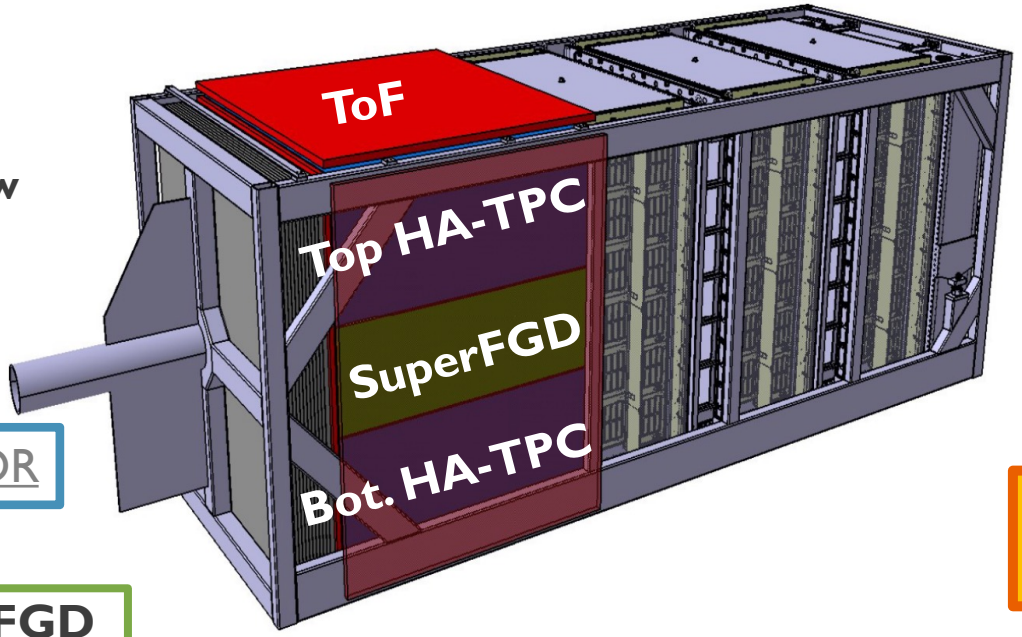

>100 researchers from 22 institutes and 7 countries

ND280 Upgrade TDR

Installation foreseen in 2023

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INSTALLATION STATUS

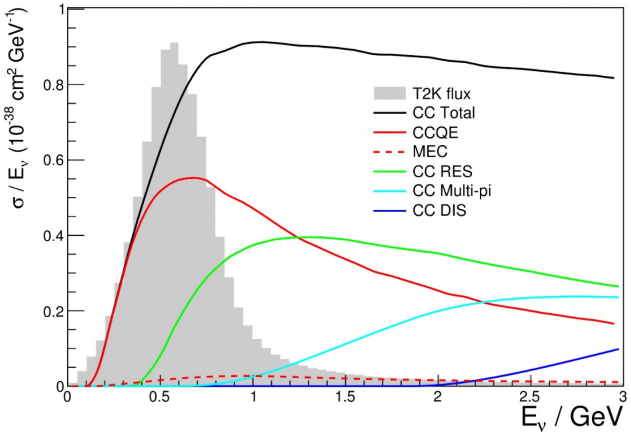
- SuperFGD assembly has started in Japan!
- Removal of previous ND280 elements ongoing – P0D already removed
- ToF detector will soon be shipped
- HA-TPC production ongoing with testing and assembly at CERN before shipment
  - To be shipped mid-2023
- Data taking will resume in autumn 2023

So what can we do with the ND280 Upgrade?

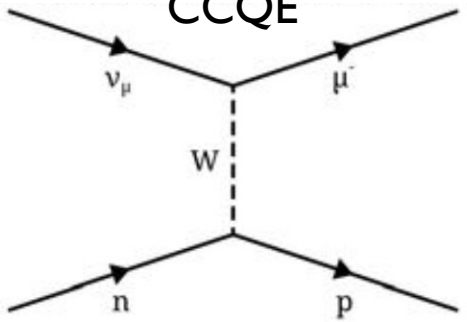
A BETTER PICTURE OF THE FINAL STATE

- CCQE events dominate T2K spectrum
- Only lepton kinematics are used in energy reconstruction

$$E_{QE} = \frac{m_p^2 - m_\mu^2 - (m_n - E_B)^2 + 2E_\mu(m_n - E_B)}{2(m_n - E_B - E_\mu + p_\mu^z)}$$



True process
CCQE



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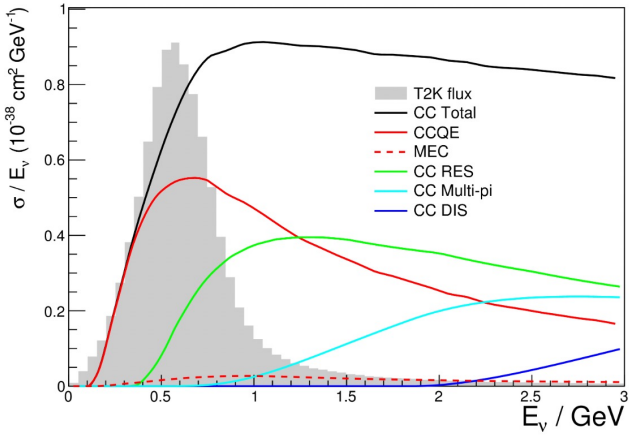
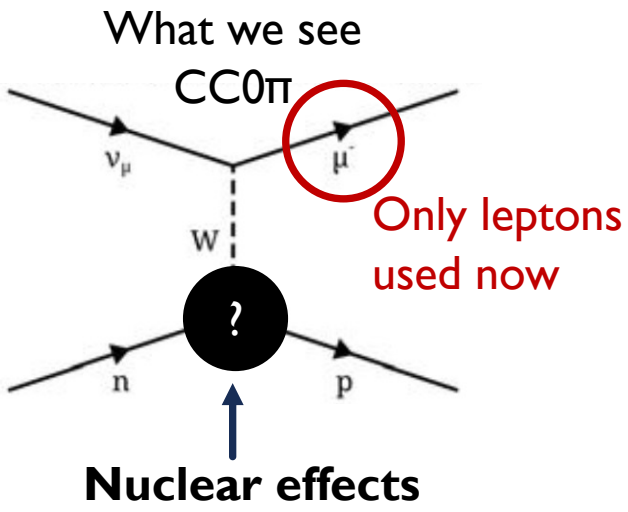
- Control of nuclear effects relies on **inclusive model predictions**





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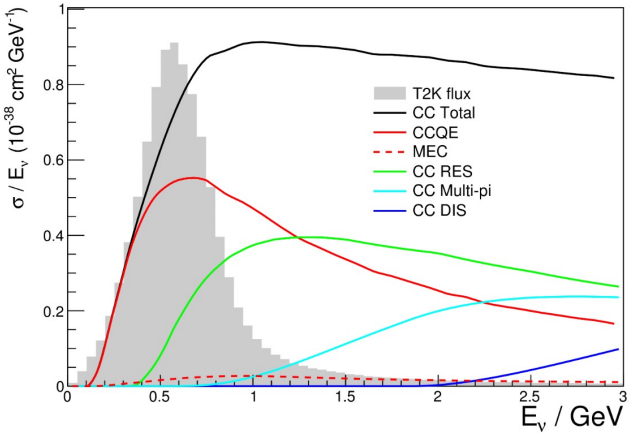
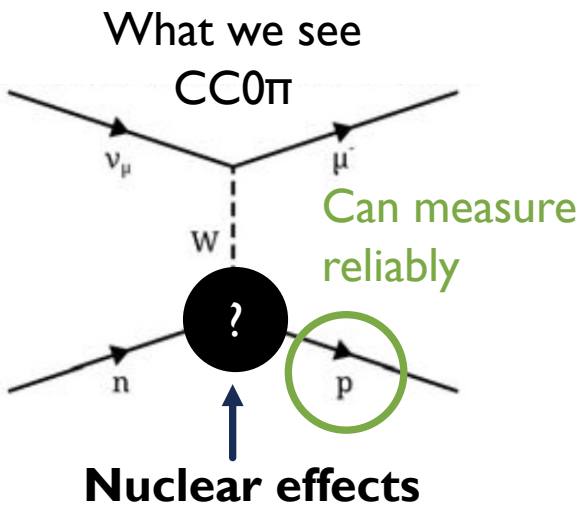
- CCQE events dominate T2K spectrum
- Only lepton kinematics are used in energy reconstruction

$$E_{QE} = \frac{m_p^2 - m_\mu^2 - (m_n - E_B)^2 + 2E_\mu(m_n - E_B)}{2(m_n - E_B - E_\mu + p_\mu^z)}$$

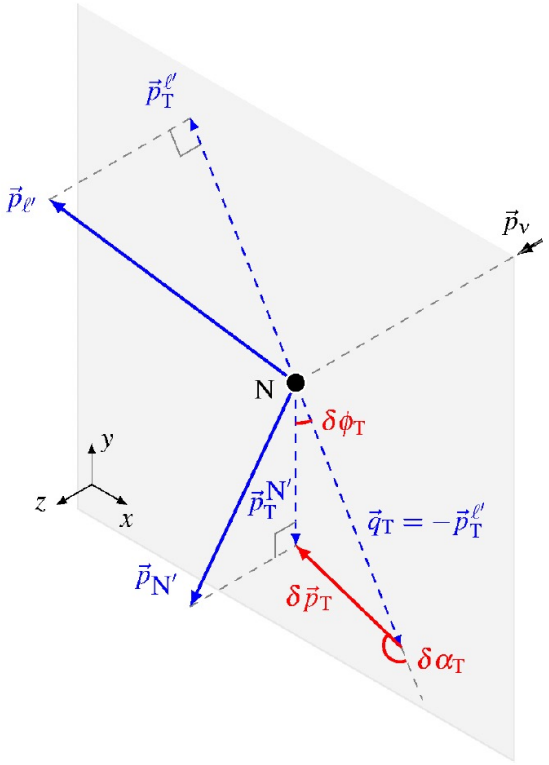
- Control of nuclear effects relies on **inclusive model predictions**
- Thanks to ND280 Upgrade, we can measure **all final state particles** in neutrino interactions
  - With low enough thresholds
  - Opens the door to more robust sets of systematic uncertainties!





EXCLUSIVE VARIABLES

Transverse Kinematic Imbalance Variables



Phys. Rev. D 105, 032010

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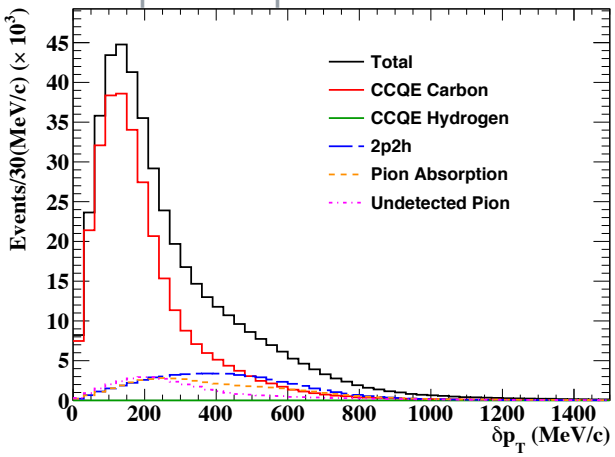
SuperFGD pseudo-reconstruction



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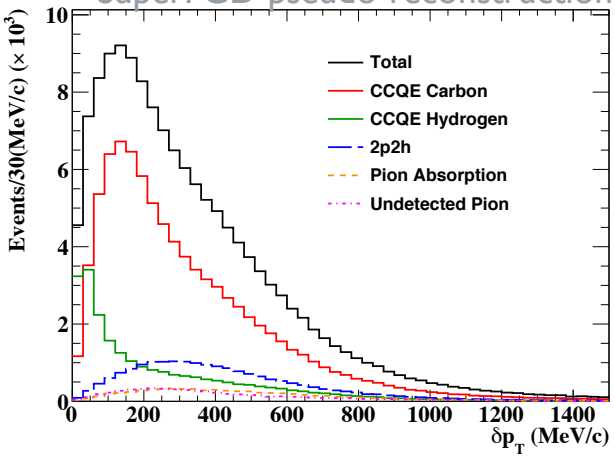

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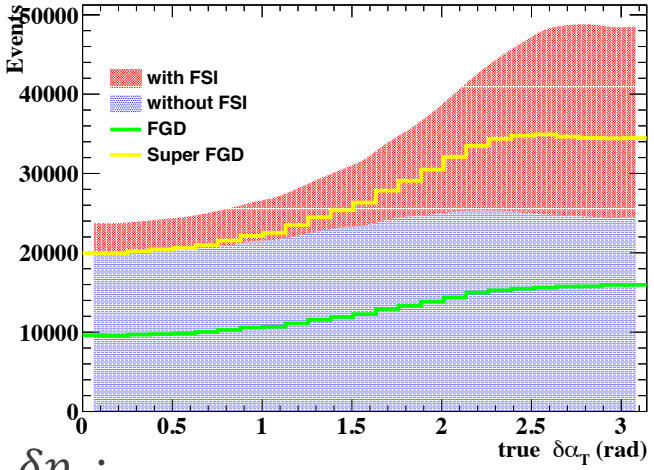

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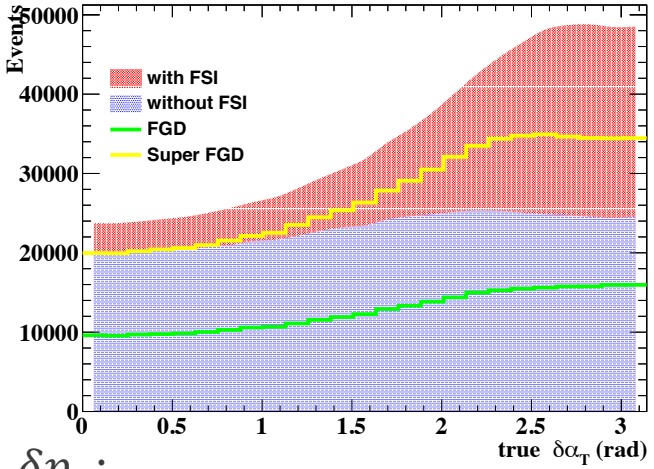

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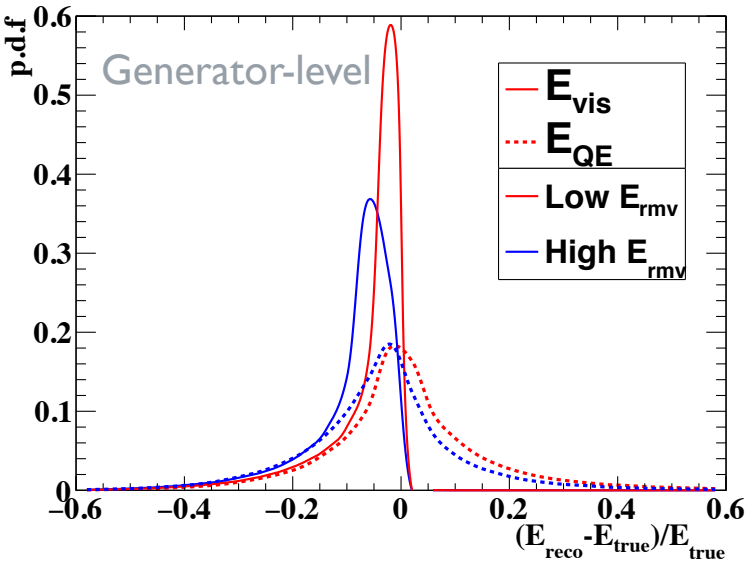
Hadronic variables

$$E_{vis} = E_\mu + T_N$$

E^{ν}_{QE} dominated by **nuclear** effects

E_{vis} dominated by **detector** effects

- Sensitive to E_{rmv}



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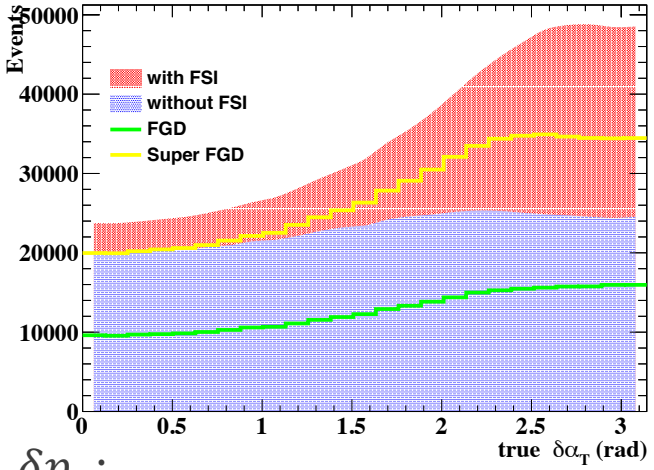

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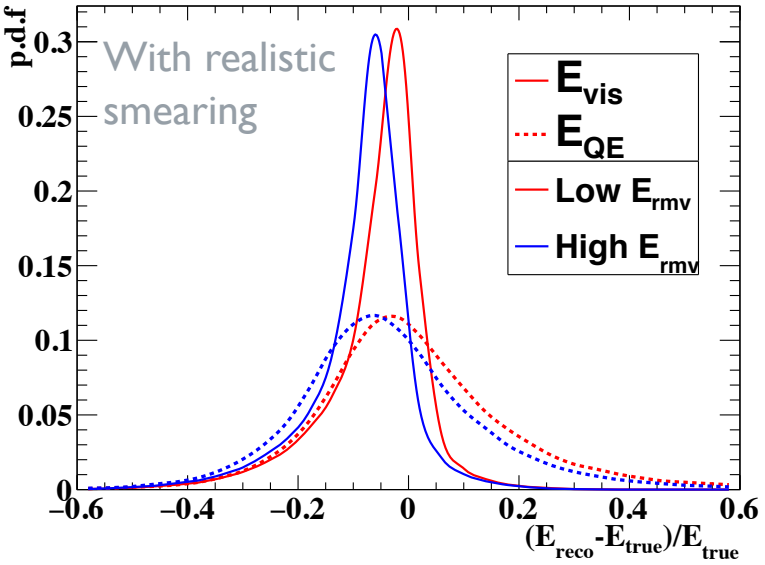
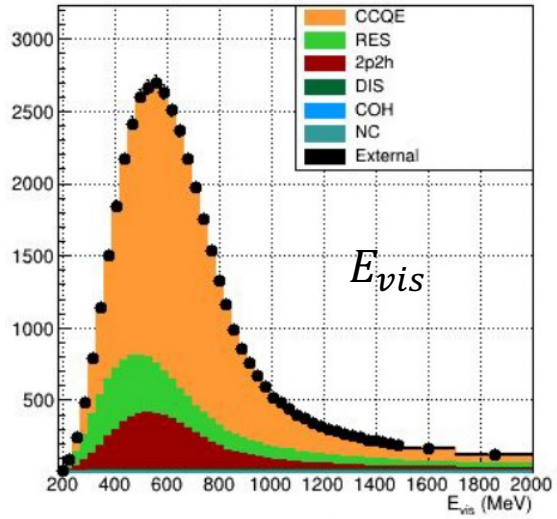
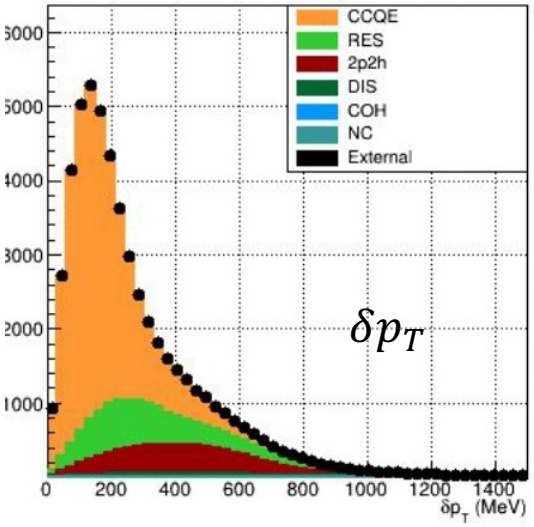


SUPERFGD SAMPLES

CC0π + Np

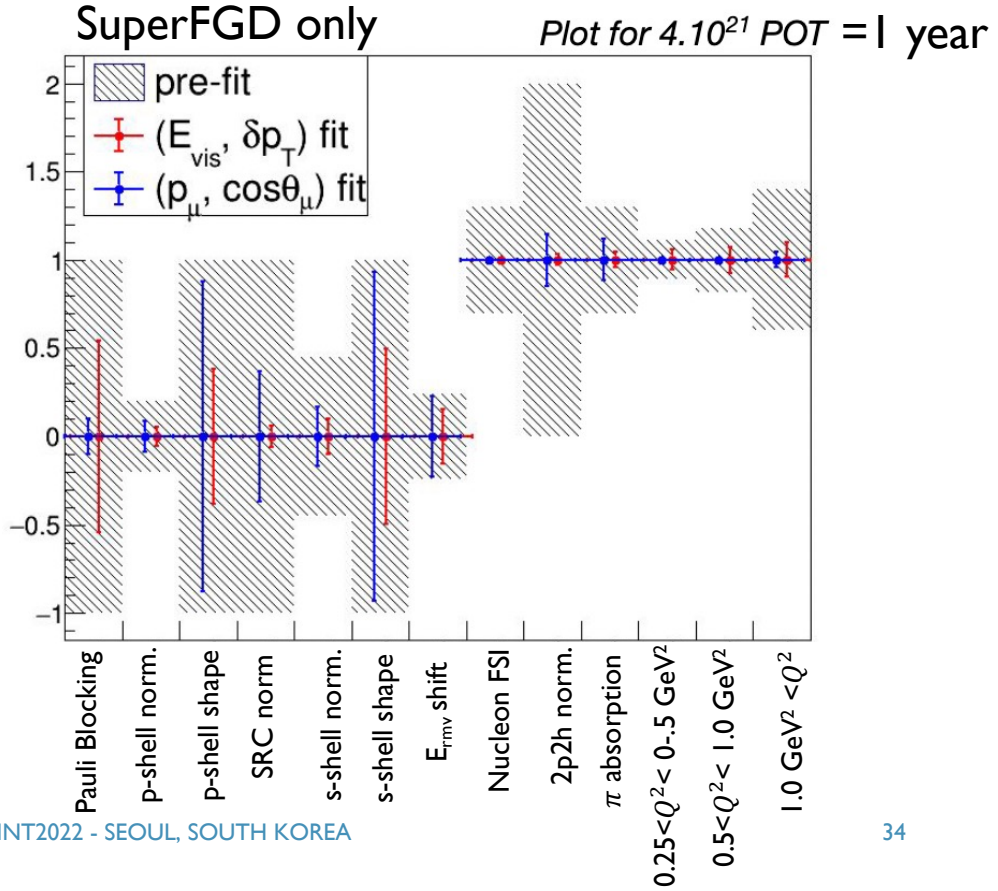




- T2K has been building an increasingly sophisticated interaction model to prepare for Upgrade-era analyses [*See talk by S.Dolan*]
- Preliminary sensitivity studies using pseudo-SuperFGD samples + existing ND280 samples [*See talk by C.Wret for the latter*]

SYSTEMATIC PARAMETER CONSTRAINTS

- Fit variables:
  - E_{vis}; δp_T
  - p_μ; $\cos\theta_\mu$ (current binning)



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- Fit variables:
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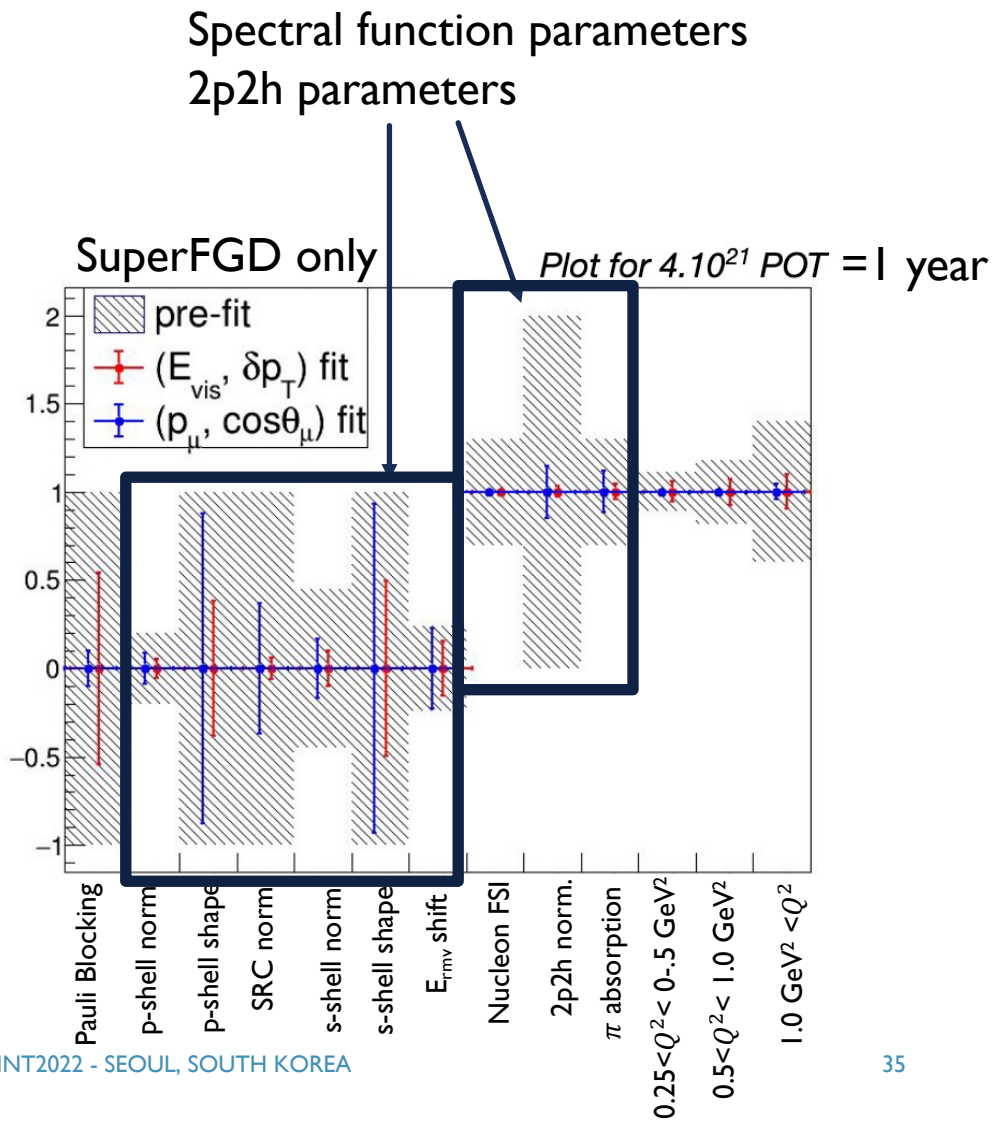
- Hadronic variables improve constraint on SF & 2p2h parameters (direct physical correspondence)



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  - $E_{vis}; \delta p_T$
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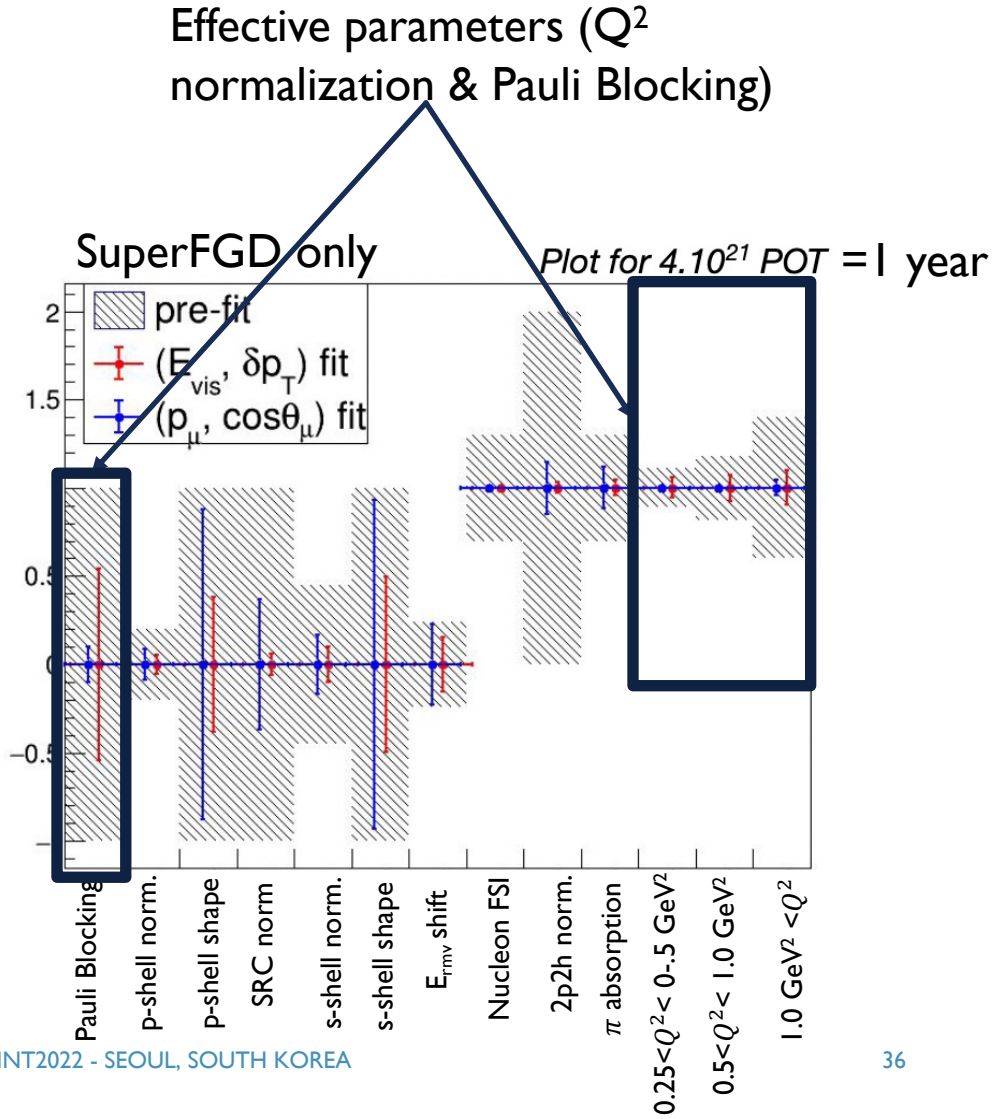
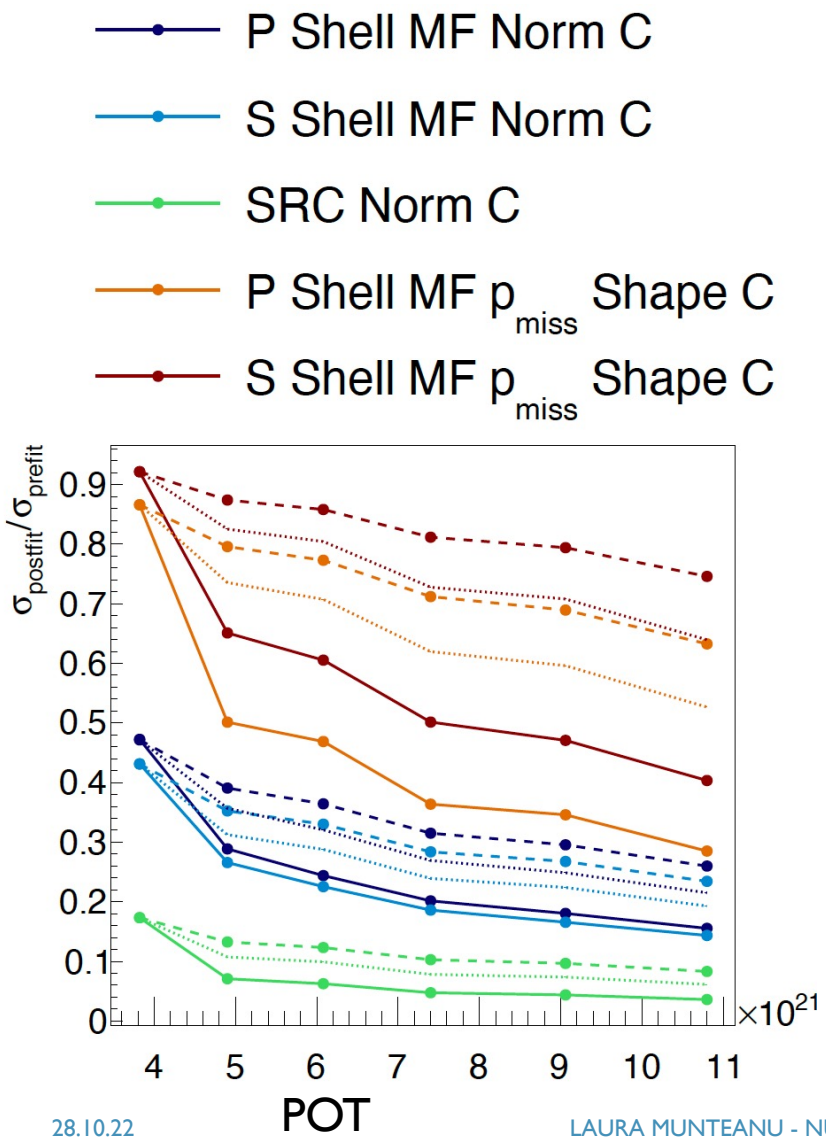
- Hadronic variables improve constraint on SF parameters (direct physical correspondence)
- Lepton variables are better at constraining effective parameters designed for current binning



EVOLUTION OF CONSTRAINT AS A FUNCTION OF POT



- Assume T2K data taking scenario where ν and $\bar{\nu}$ beam modes are alternated every year for 10 years
- SF uncertainties on carbon see a significant improvement **from first year of data taking**

Next steps: estimating impact on oscillation parameter measurements

SUMMARY

- T2K has an ambitious physics program, as neutrino physics enters the precision measurement era
- Significant beamline upgrade will drive huge increase in statistics
- ND280 Upgrade project aims to mitigate systematic effects in the next years
- Extensive R&D program to design and commission a powerful set of detectors for the upgrade era
- ND280 Upgrade low detection thresholds and full polar angle coverage will allow T2K to probe the entire final state of neutrino-nucleus interactions
- Preliminary sensitivity studies show immediate improvement in systematic errors
- Iterative process between neutrino interaction measurements + theoretical developments is essential to achieve goals of current and future neutrino oscillation experiments

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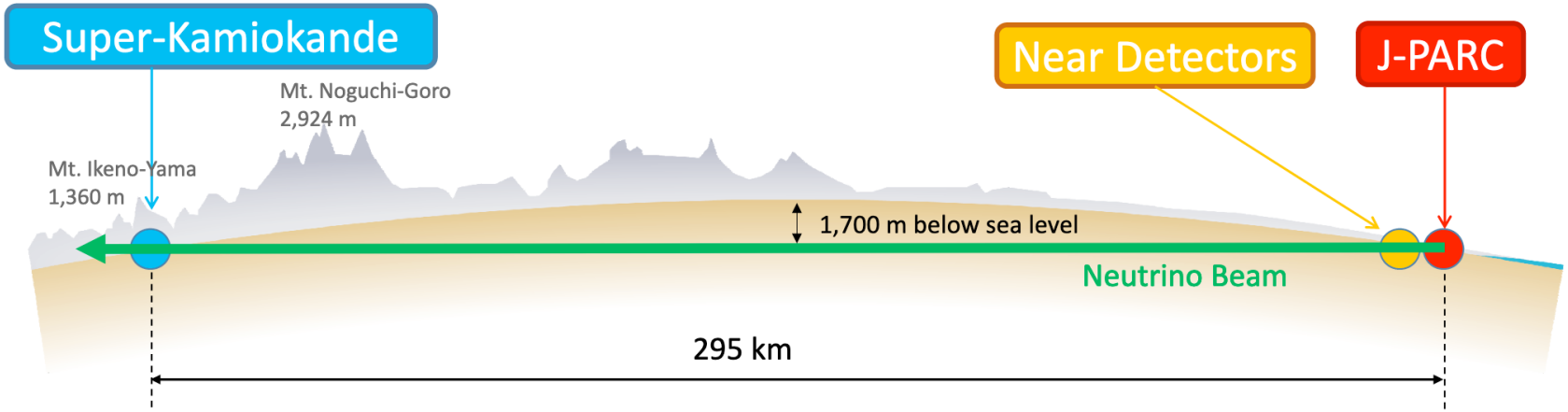
Thank you for your attention!

Back-Up

THE T2K EXPERIMENT



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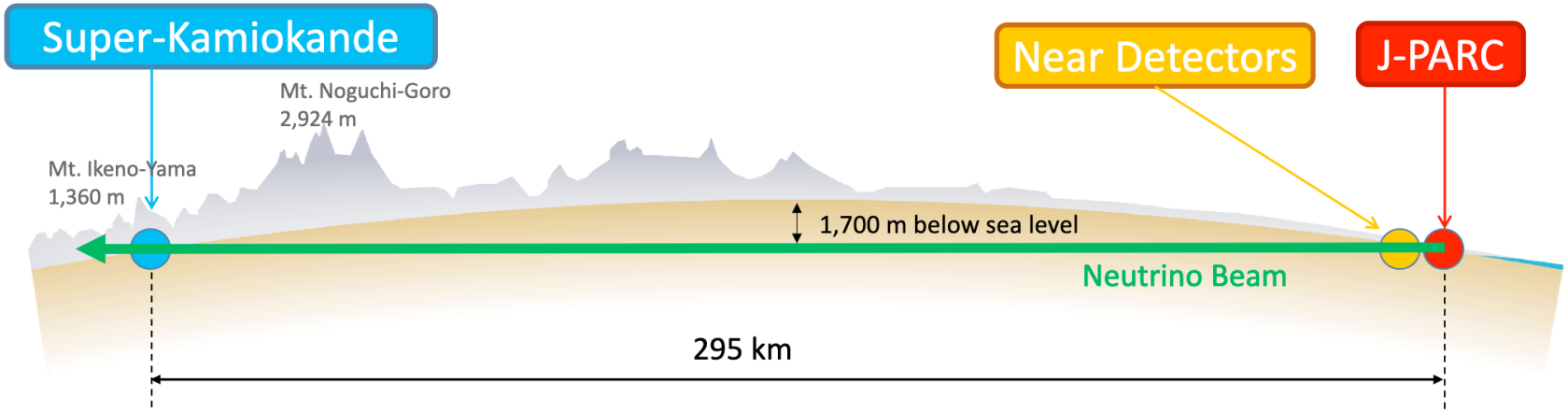

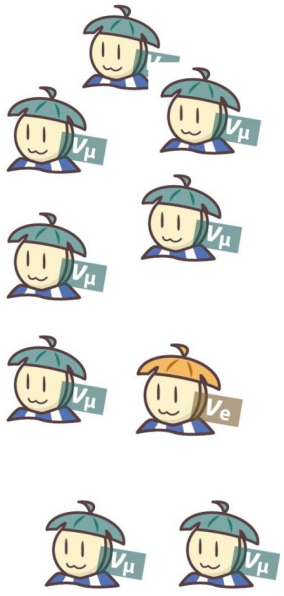

Neutrino cartoons by Yuki Akimoto

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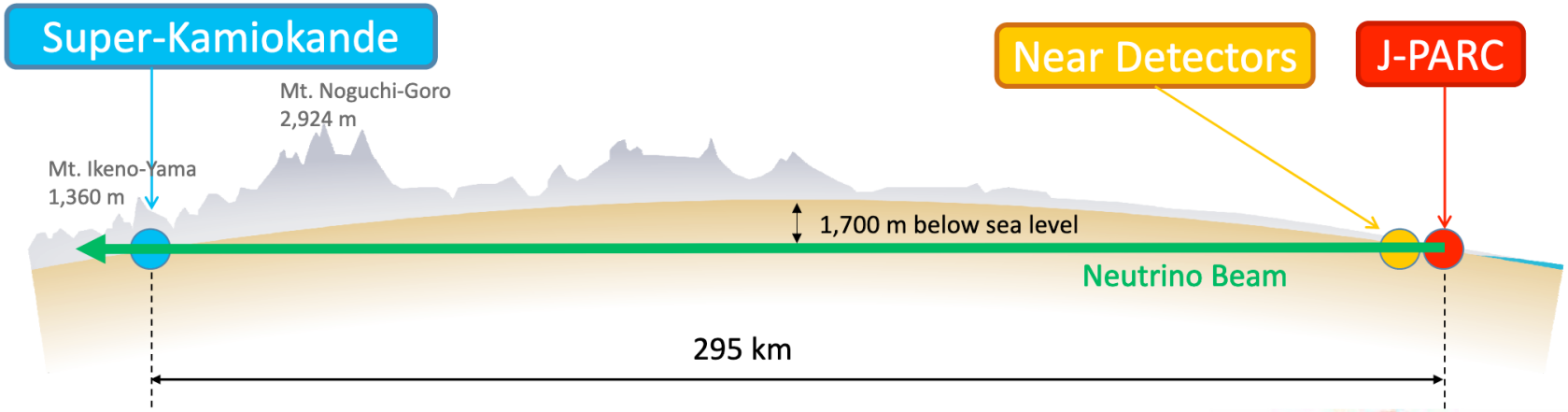

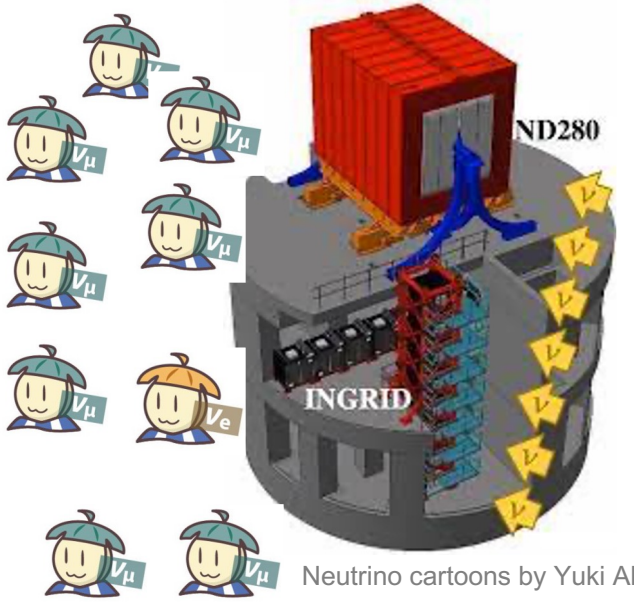

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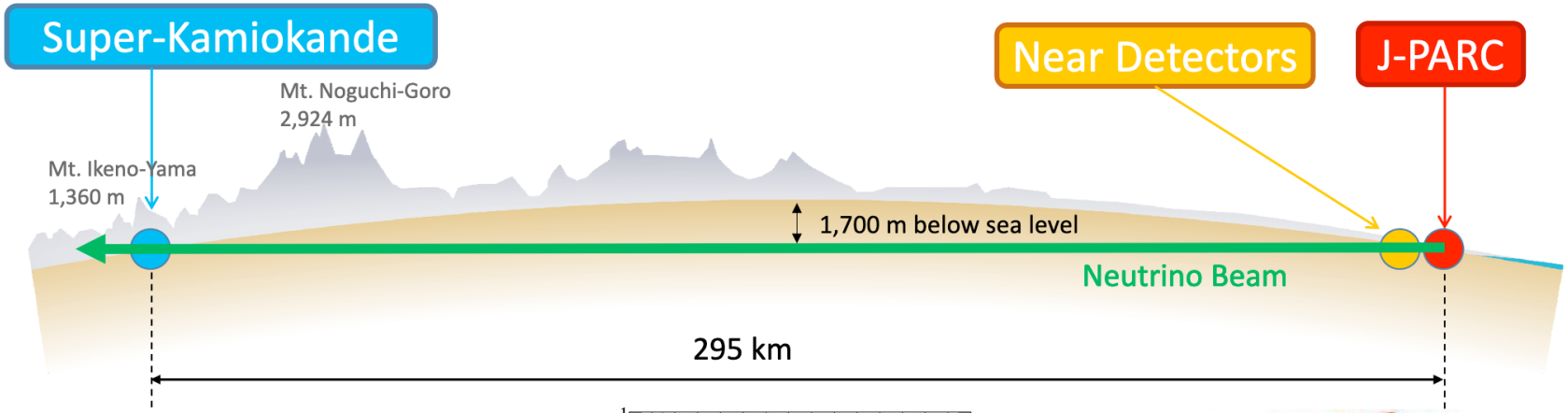
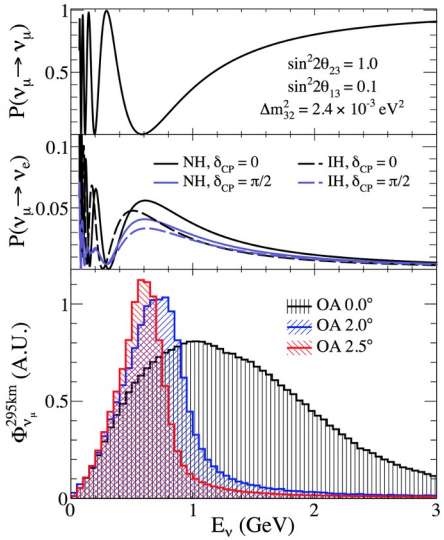
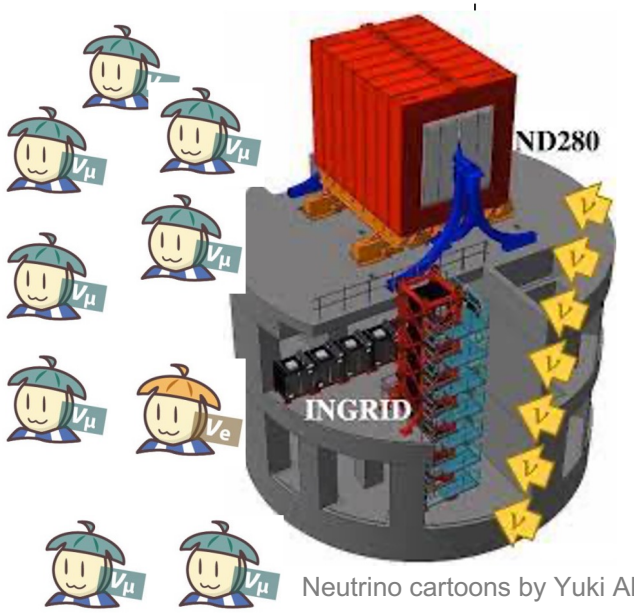




2.5° off-axis



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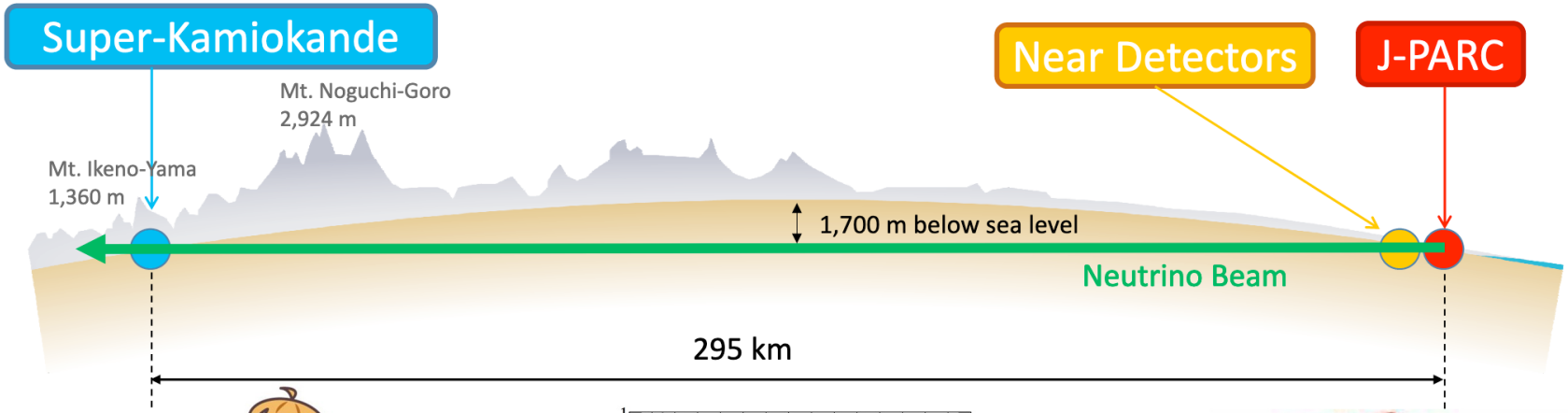

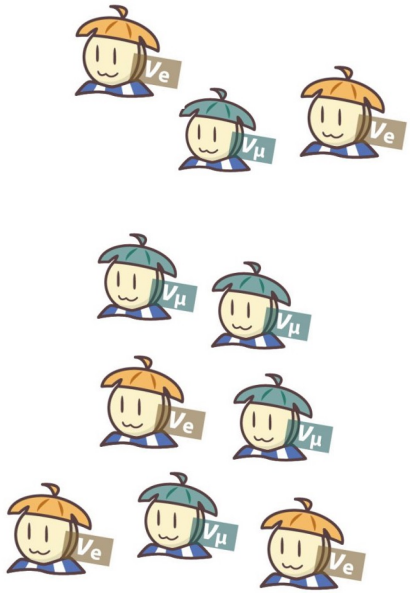

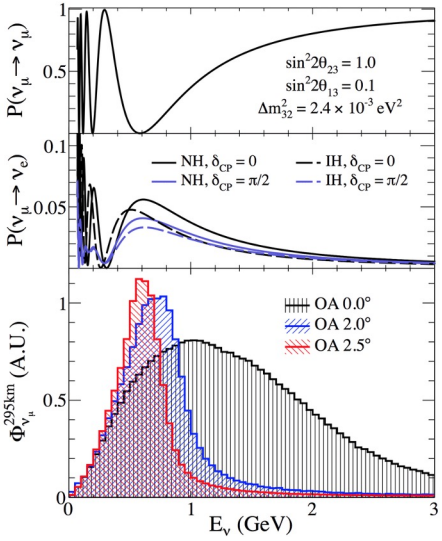

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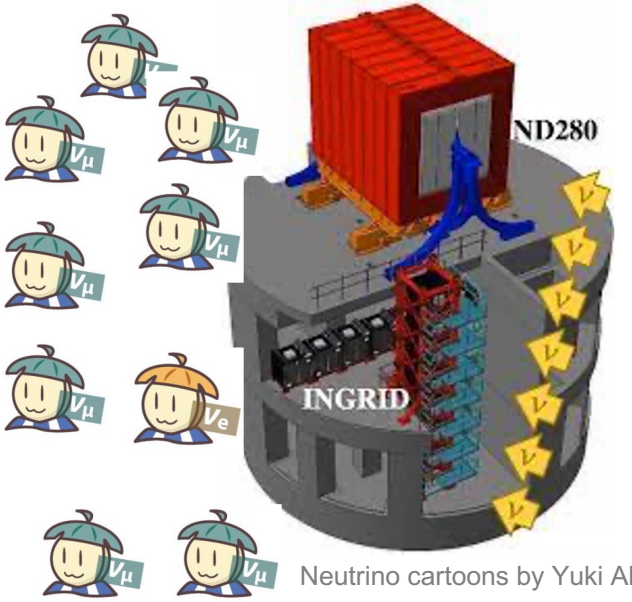

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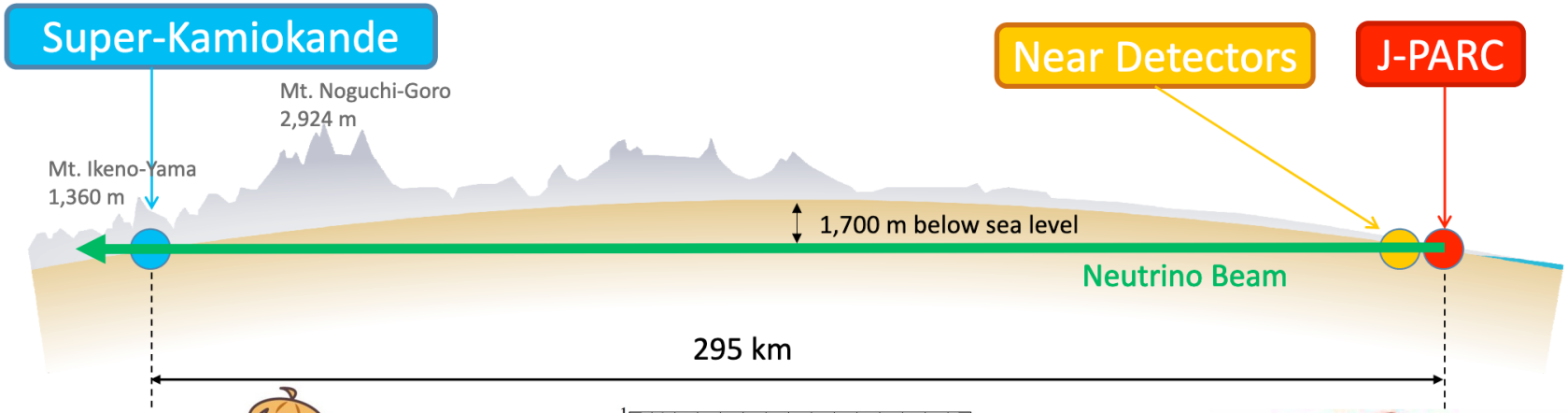

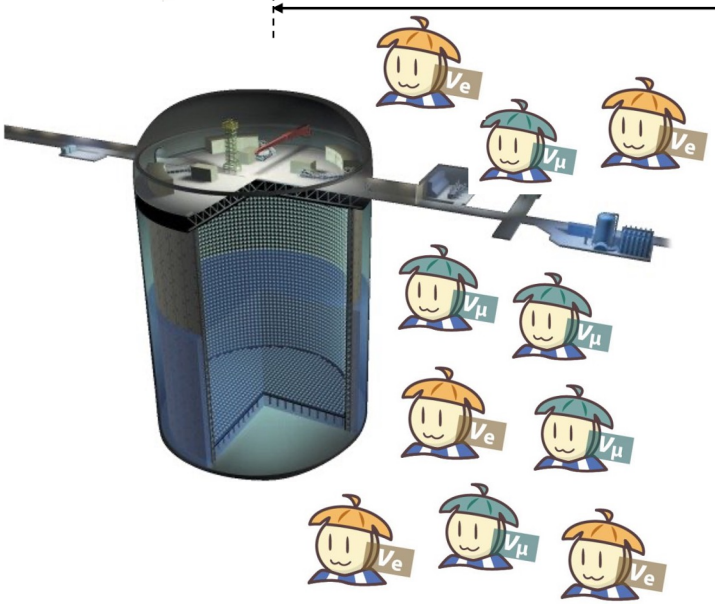

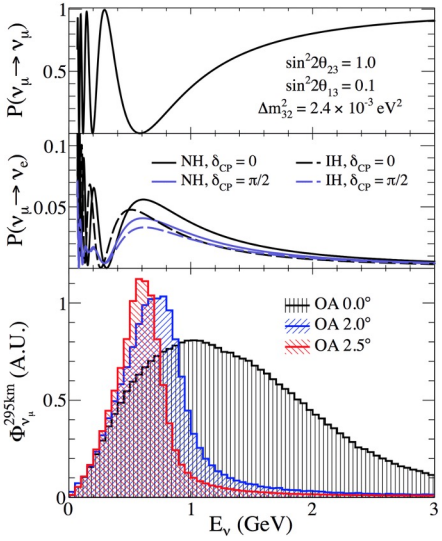

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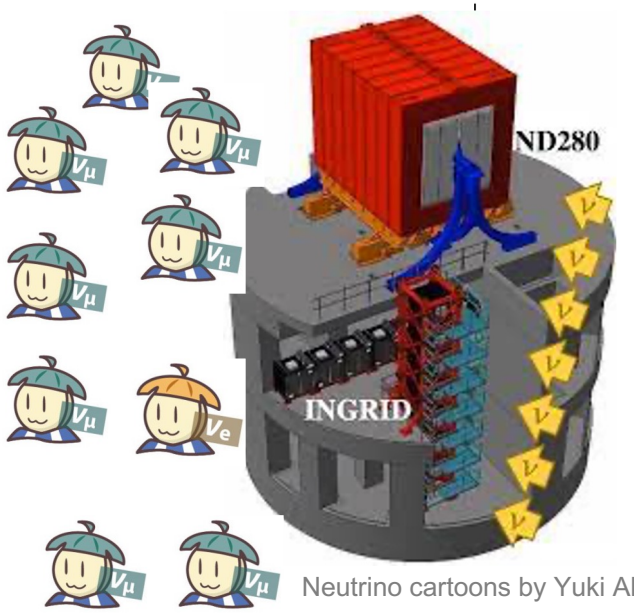

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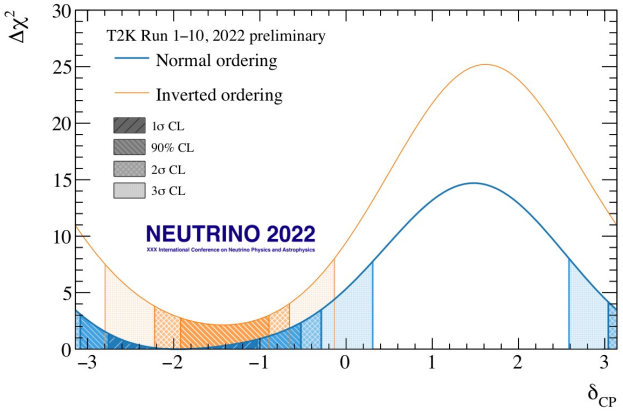

Nature 580, 339–344 (2020)

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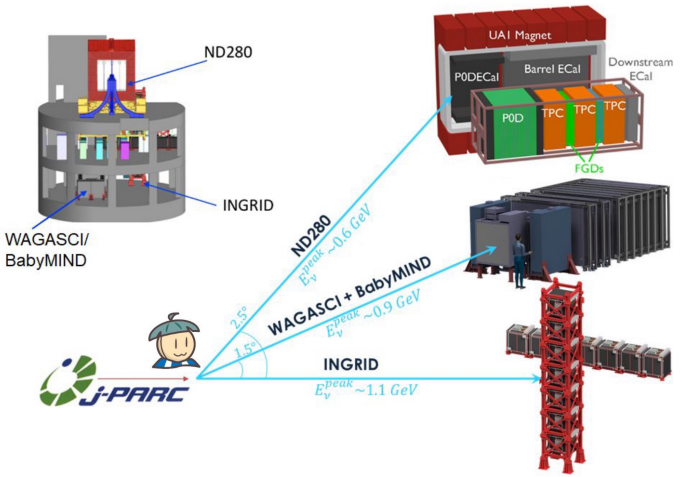

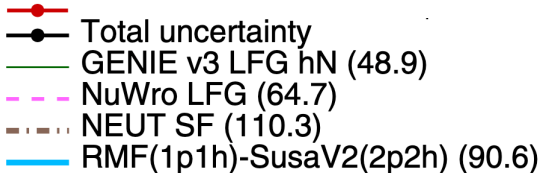

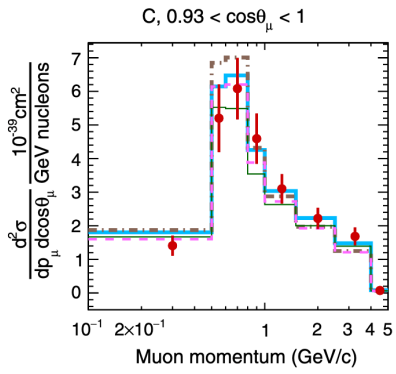

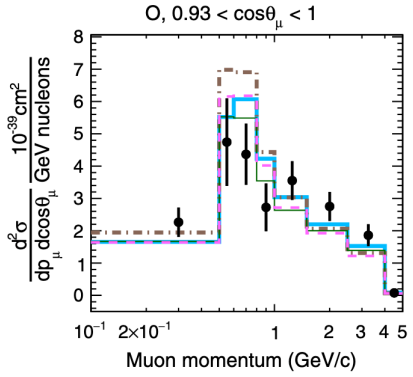

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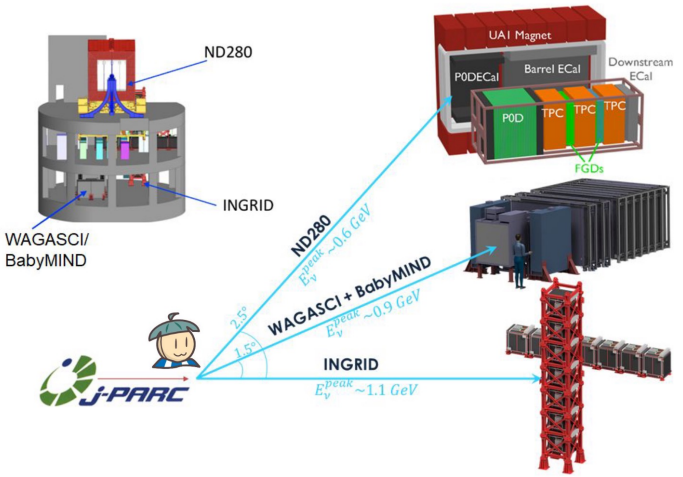
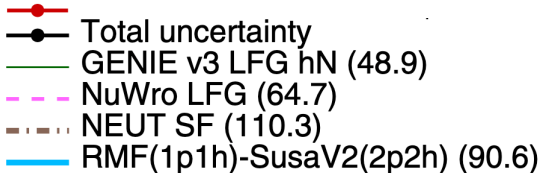
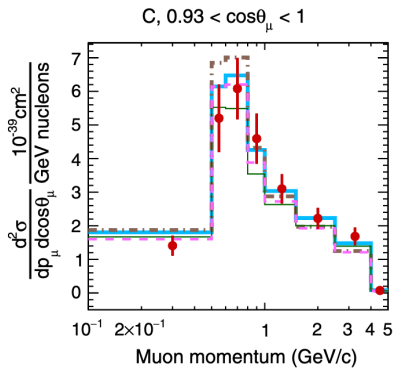
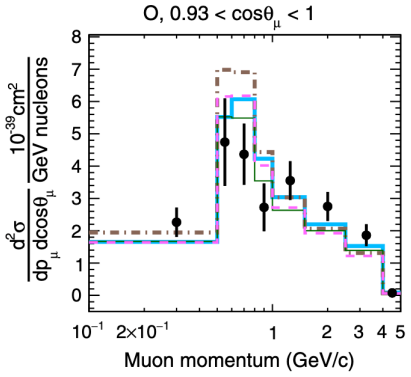
Sterile searches









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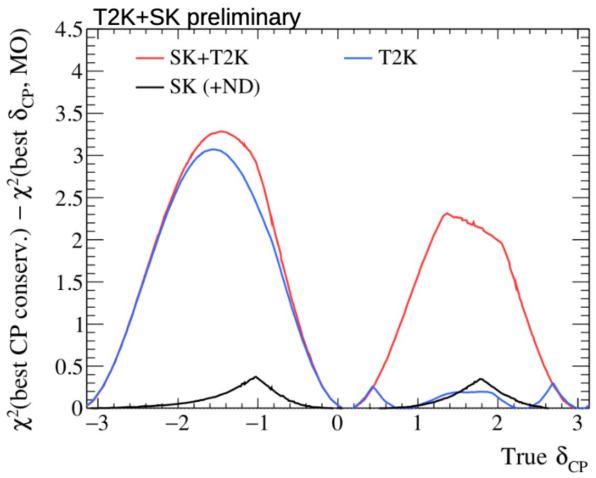
Sterile searches

Joint fits

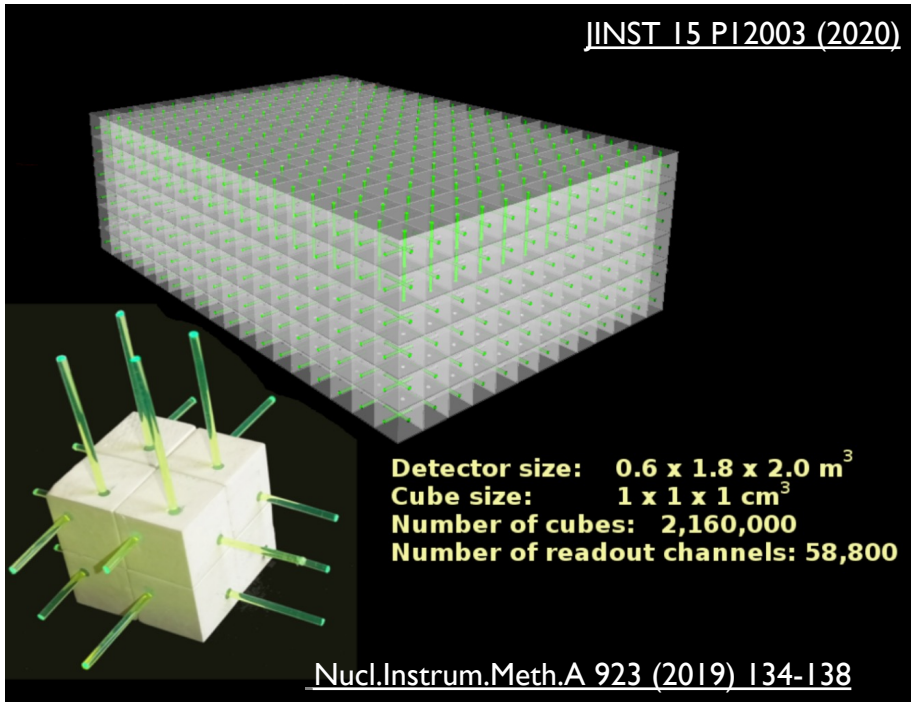
- T2K + SK atmospherics joint fit
- T2K-NOvA joint fit



Experimental Property	T2K	NOvA
Proton Beam Energy	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection Technology	Water Cherenkov	Segmented liquid sintillator bars
CP Effect*	32%	22%
Matter Effect	9%	29%

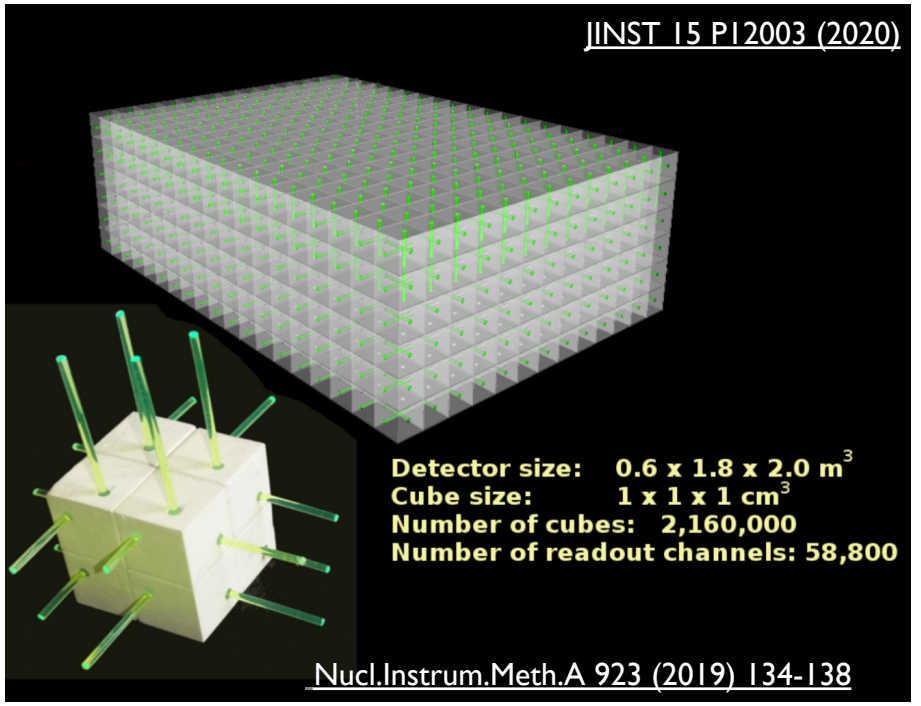
THE SUPERFGD DETECTOR

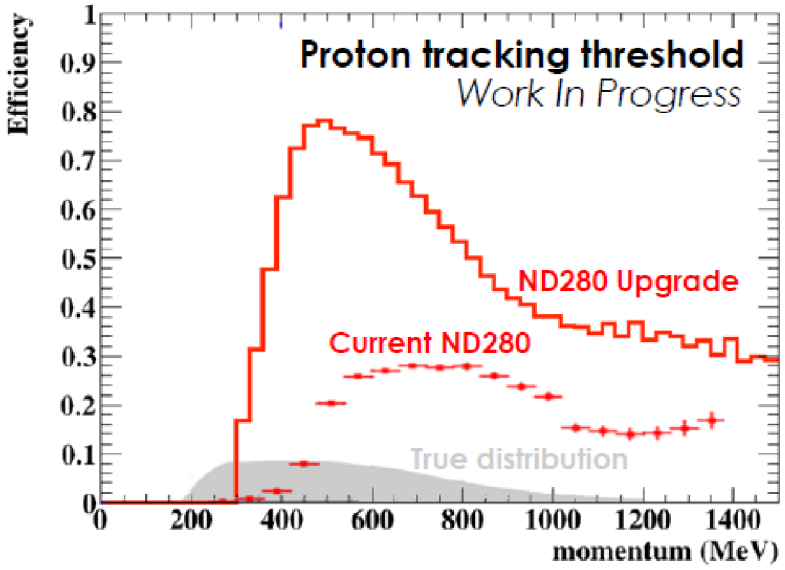
- **Double the mass** of FGD 1+2
- Light collected by WLS fibers



THE SUPERFGD DETECTOR

- **Double the mass** of FGD 1+2
- Light collected by WLS fibers
- **High granularity**: 2 mil. 1cm^3 polystyrene scintillator cubes
  - Makes it possible to detect **short tracks**
  - **Proton det. threshold ~300 MeV/c!**





THE SUPERFGD DETECTOR

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- Light collected by WLS fibers
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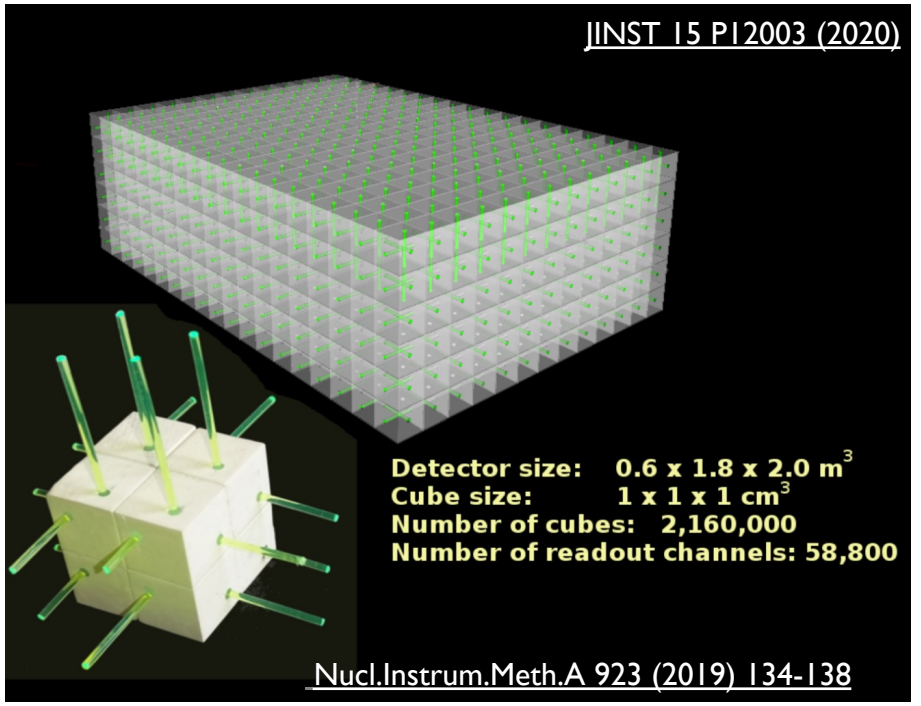
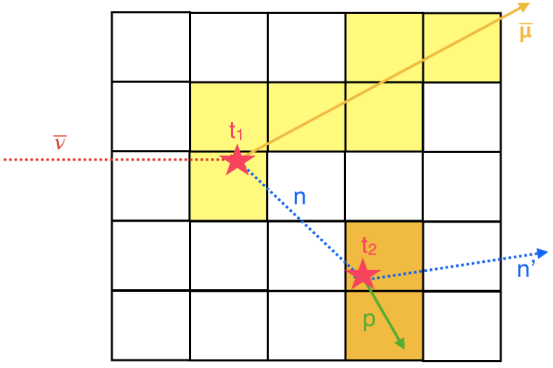
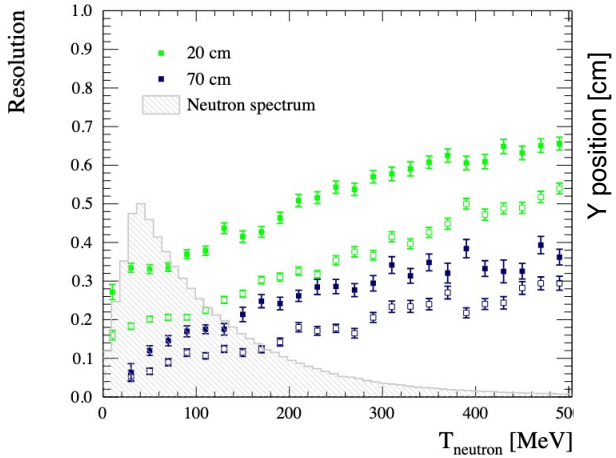
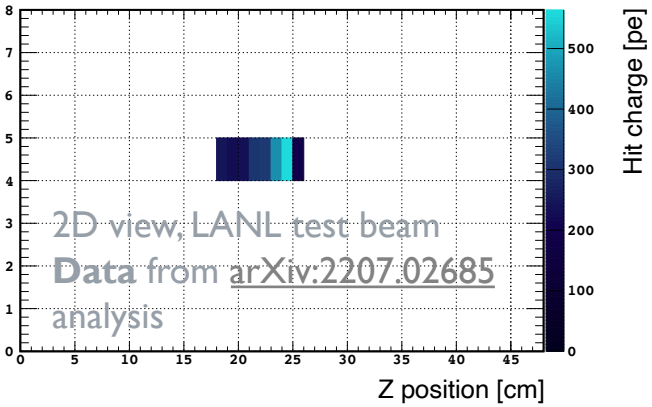


Phys. Rev. D 101, 092003





173 MeV Neutron candidate



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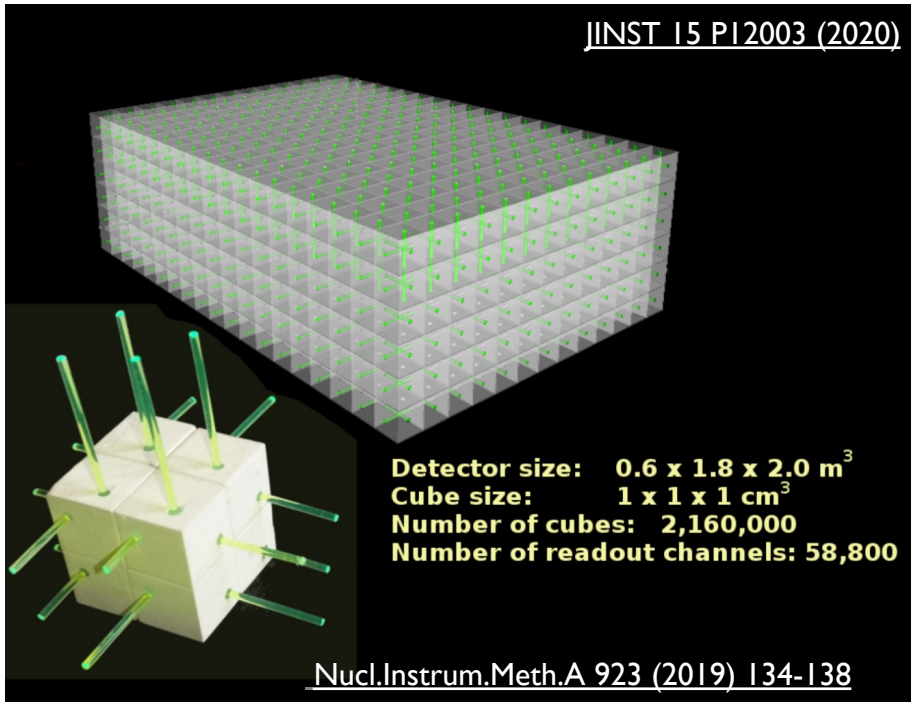

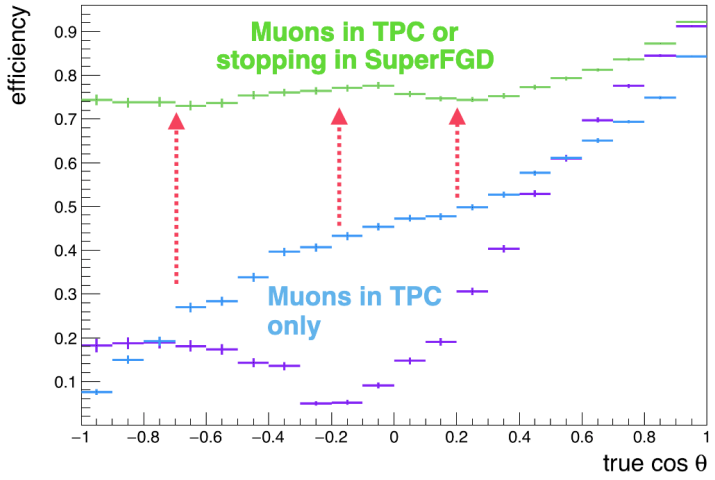

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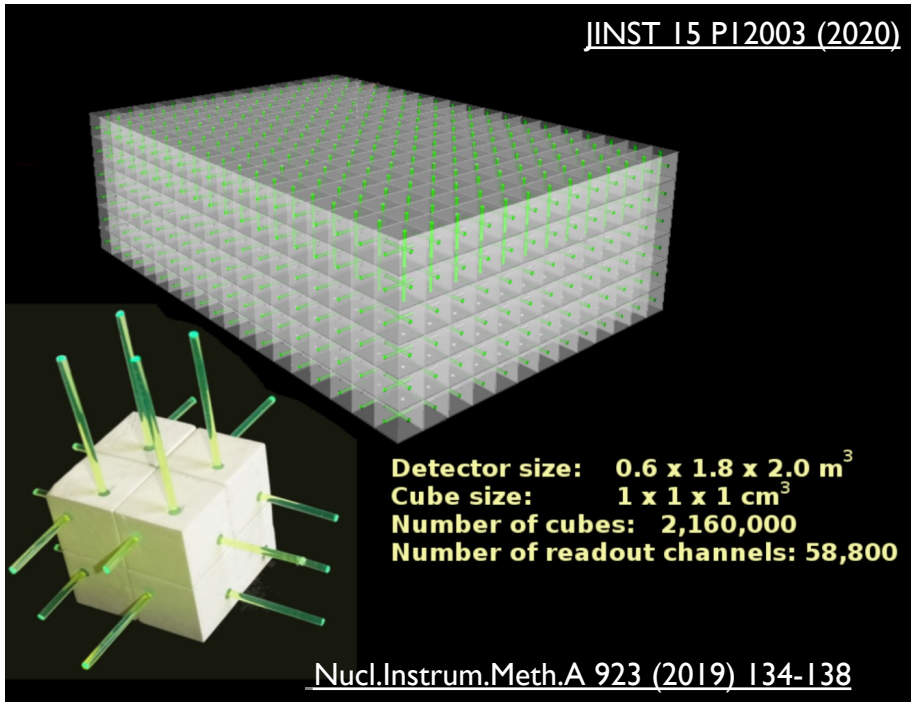
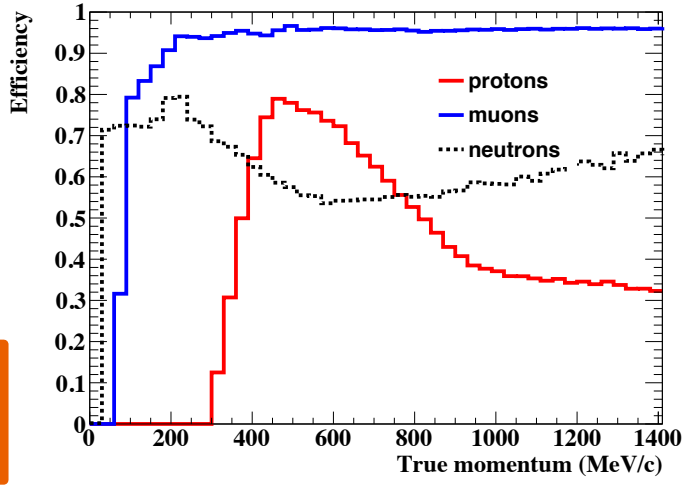
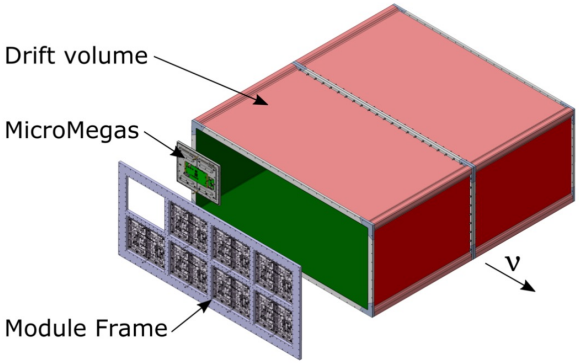




SuperFGD opens a whole new chapter for particle detection @T2K

THE HIGH-ANGLE TPCS (HA-TPC)



- New and improved field cage design

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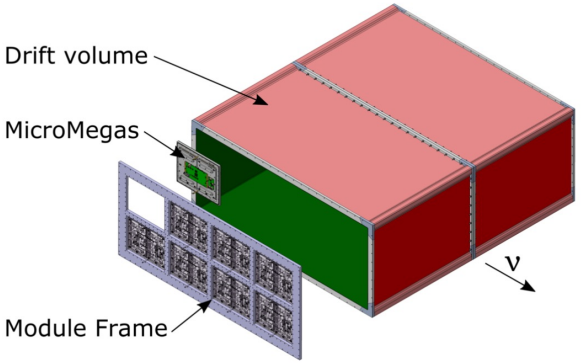

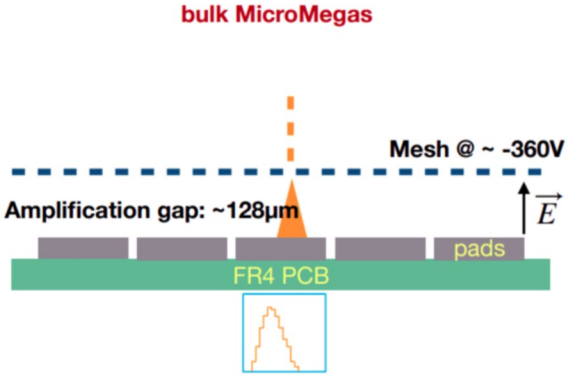

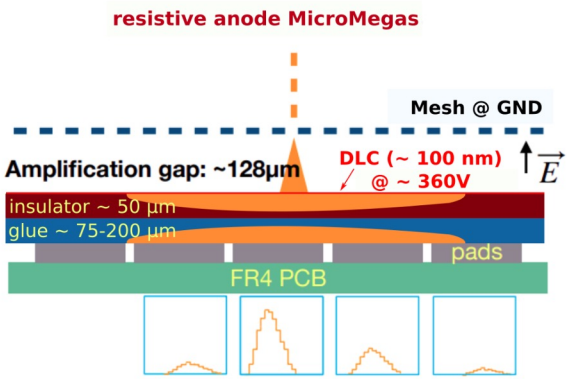

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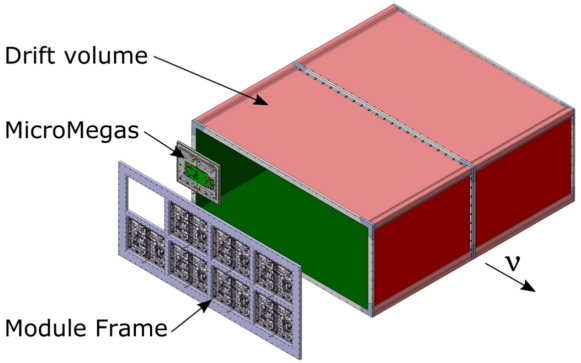

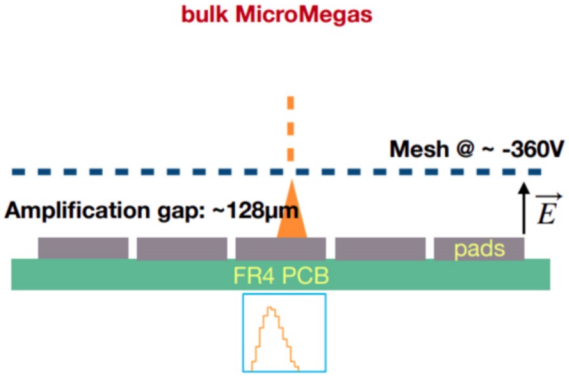

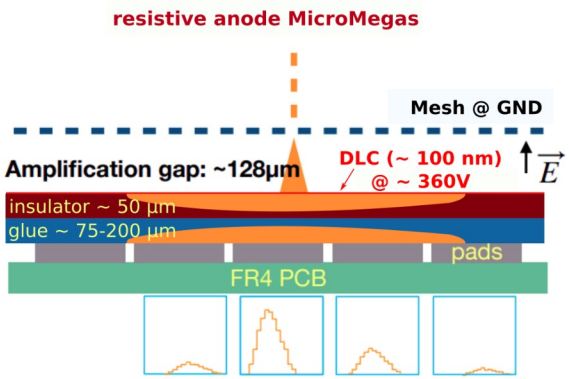

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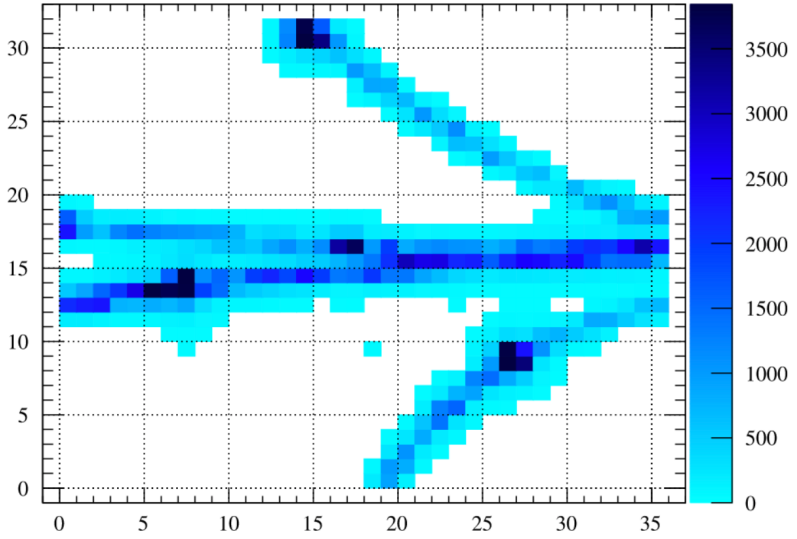
- Clear track separation



Nucl.Instrum.Meth.A 1025 (2022) 166109

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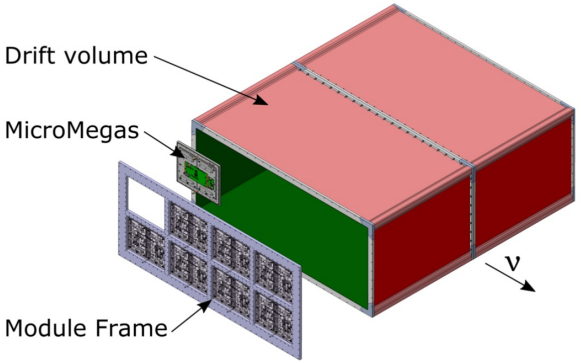

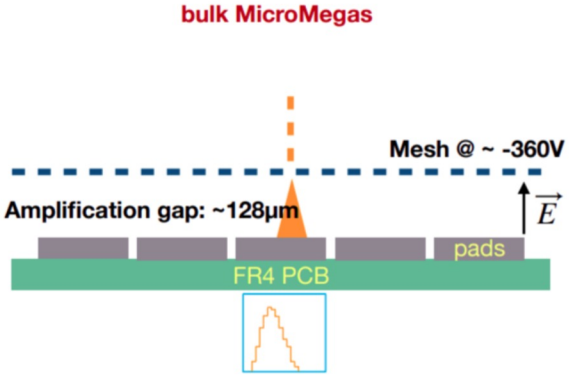

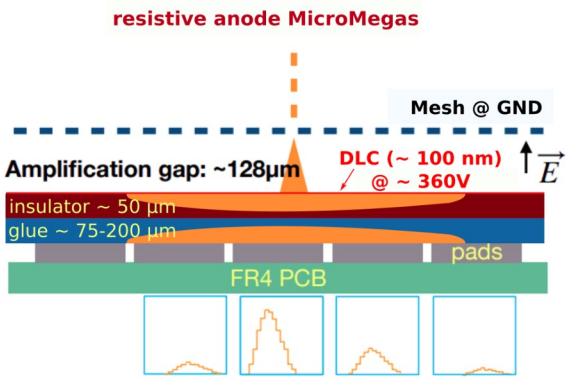

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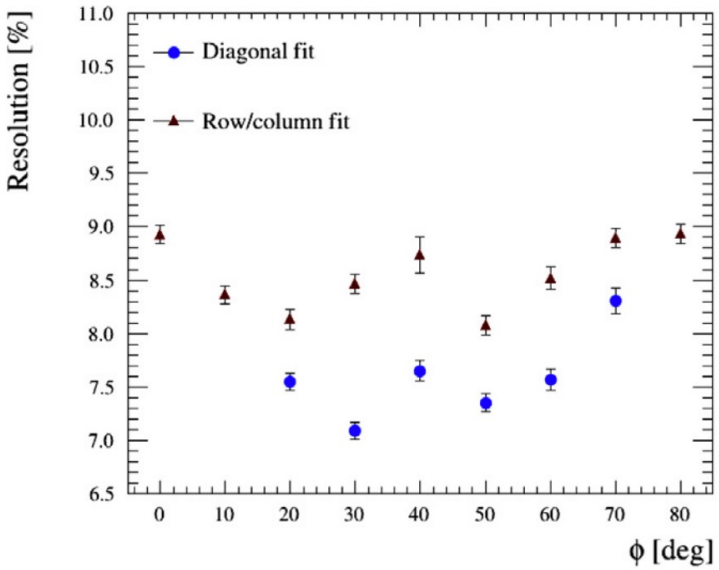

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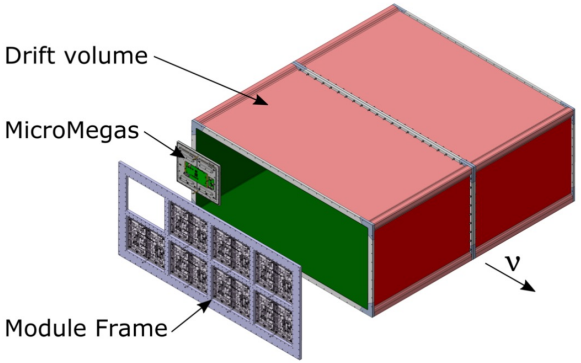

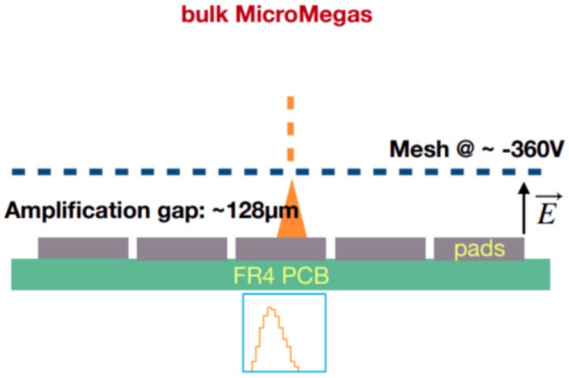

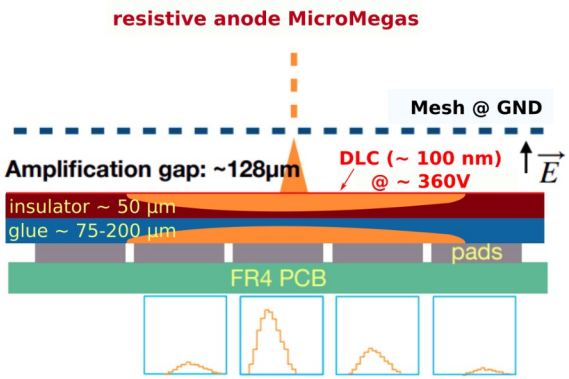

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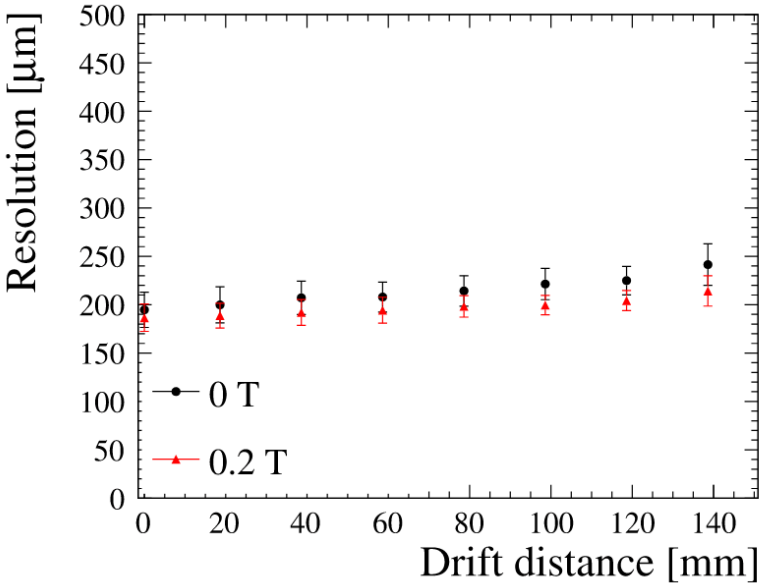

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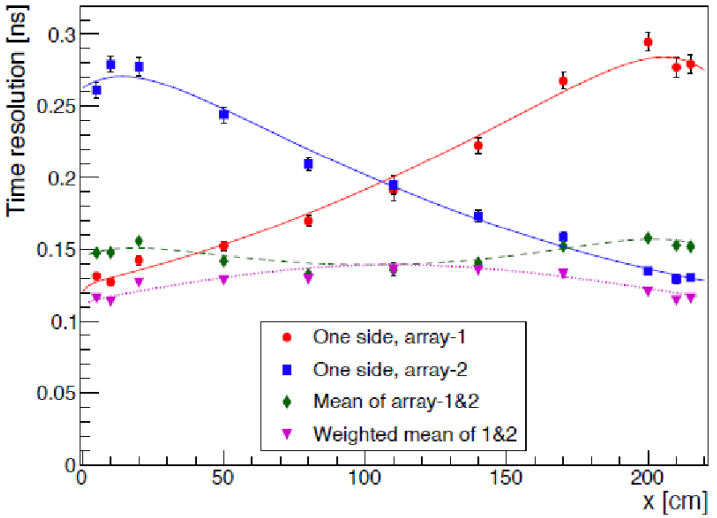
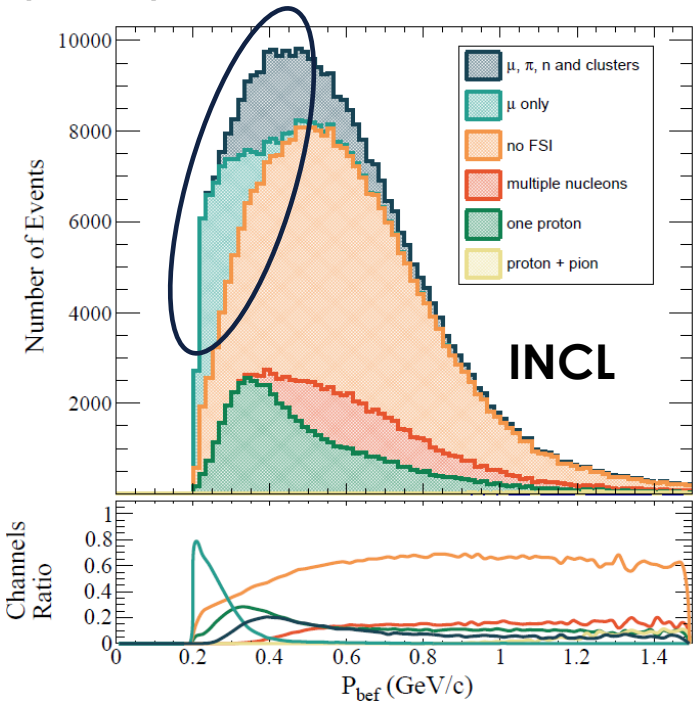
THE TIME-OF-FLIGHT (TOF) DETECTOR

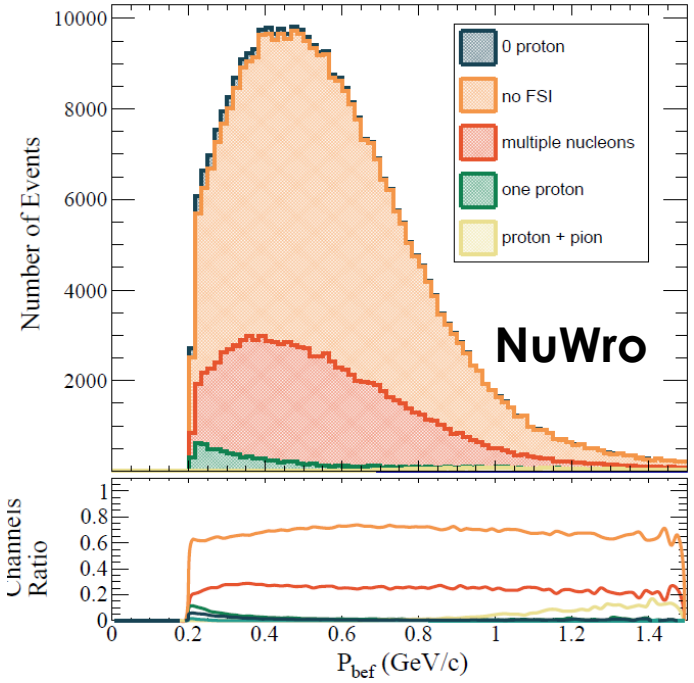
- 6 planes with 20 scintillator bars each
- Double readout
- Excellent timing resolution (<150 ps)
- Essential to identify track direction (backward or forward)
- Important for vertex timing information



BEYOND OSCILLATION MEASUREMENTS

- ND280 Upgrade sensitivity was estimated using current uncertainty model
  - But that may not be enough!
- ND280 Upgrade can help us further our knowledge about neutrino interactions and help us build an even better uncertainty model
- Example: improved models for final state interactions (INCL) Phys. Rev. D 106, 032009

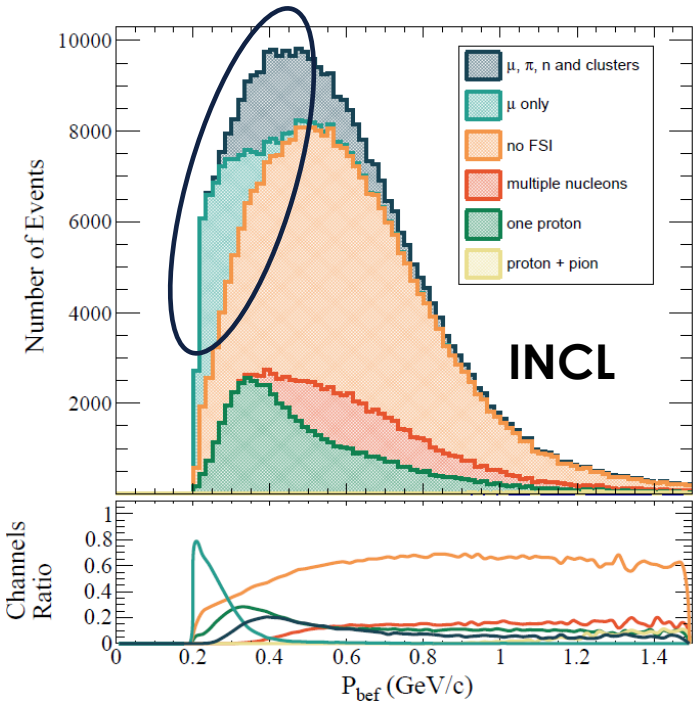


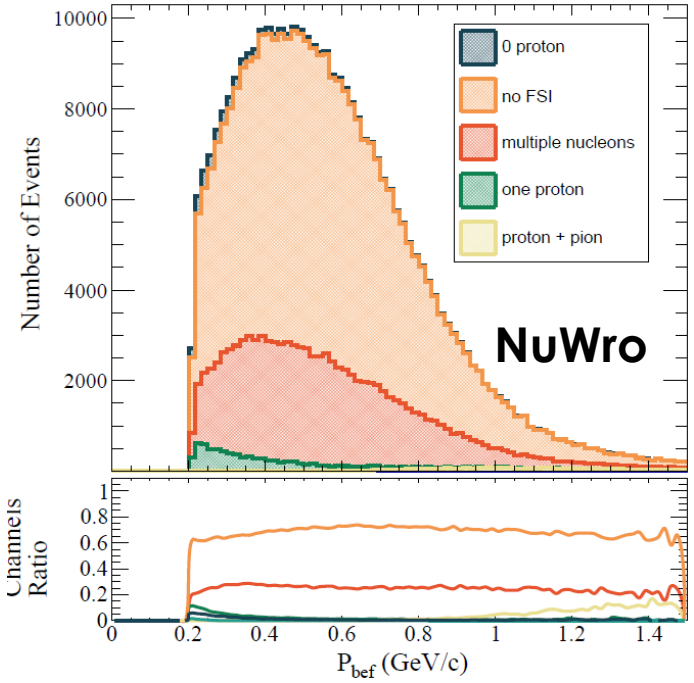


BEYOND OSCILLATION MEASUREMENTS

- INCL predicts significant proton absorption and multi-nucleon final states (cluster production)
- This has a **non-negligible impact** at the level of SuperFGD statistics
- Next steps: use INCL to build better uncertainties for our analyses

Phys. Rev. D 106, 032009





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2009