Latest cross-section results from the T2K experiment

Laura Munteanu (CERN)

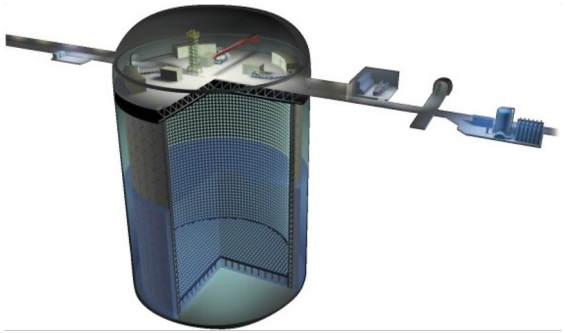
On behalf of the T2K Collaboration

NuFACT 2024, Argonne National Laboratory

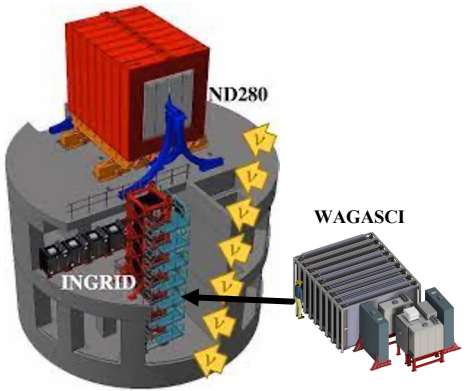
18 September 2024

The T2K Experiment

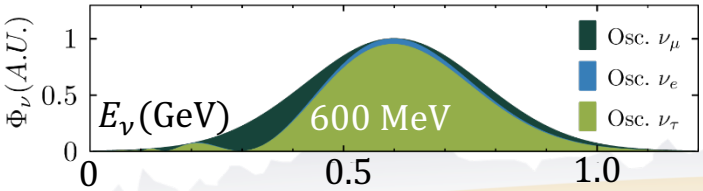
Far detector: Super-Kamiokande



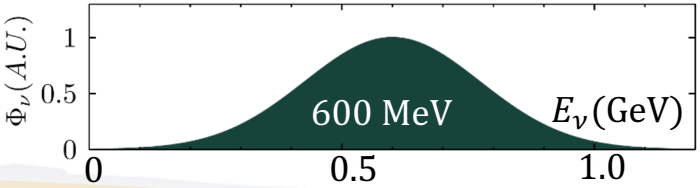
Near detector complex

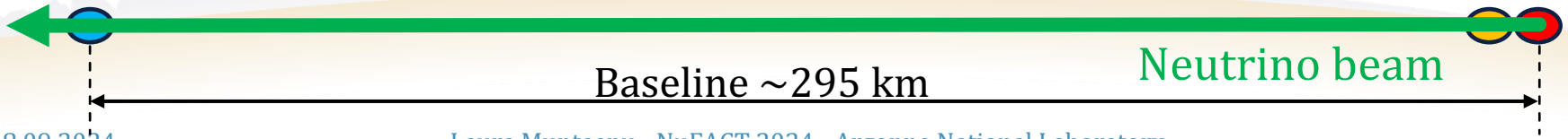


$$N_{\nu_{\mu/e}}(E_\nu) = P_{\nu_\mu \to \nu_{\mu/e}}(E_\nu)\Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)$$



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





The T2K Experiment

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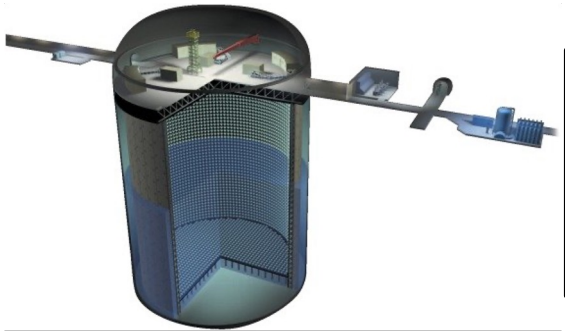
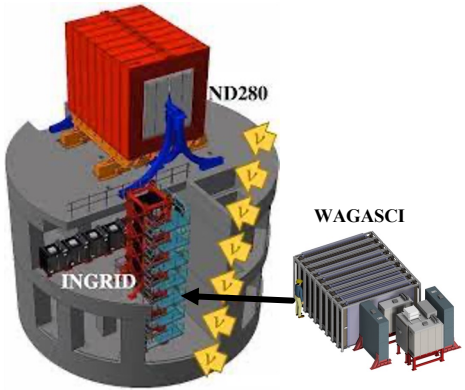


See T2K talks at NuFACT 2024:
SK detector uncertainties – *M. Reh, Monday*
3-flavor Oscillations – *E. Atkin, Monday*
Near detector fit – *E. Miller, Tuesday*
T2K plenary – *T. Doyle, Thursday*

Near detector complex



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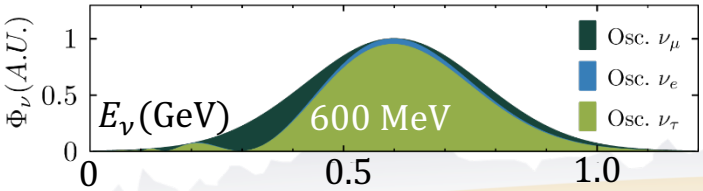

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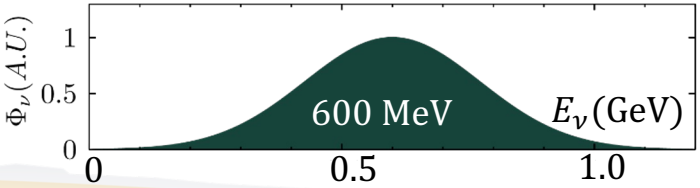
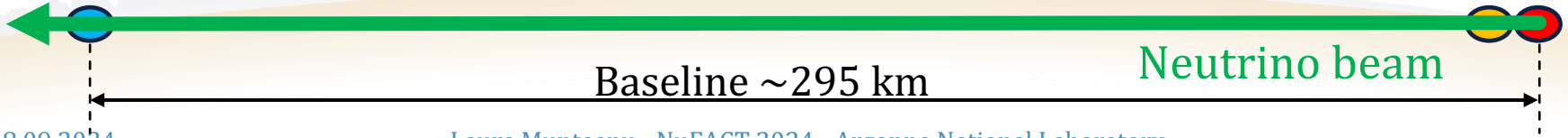
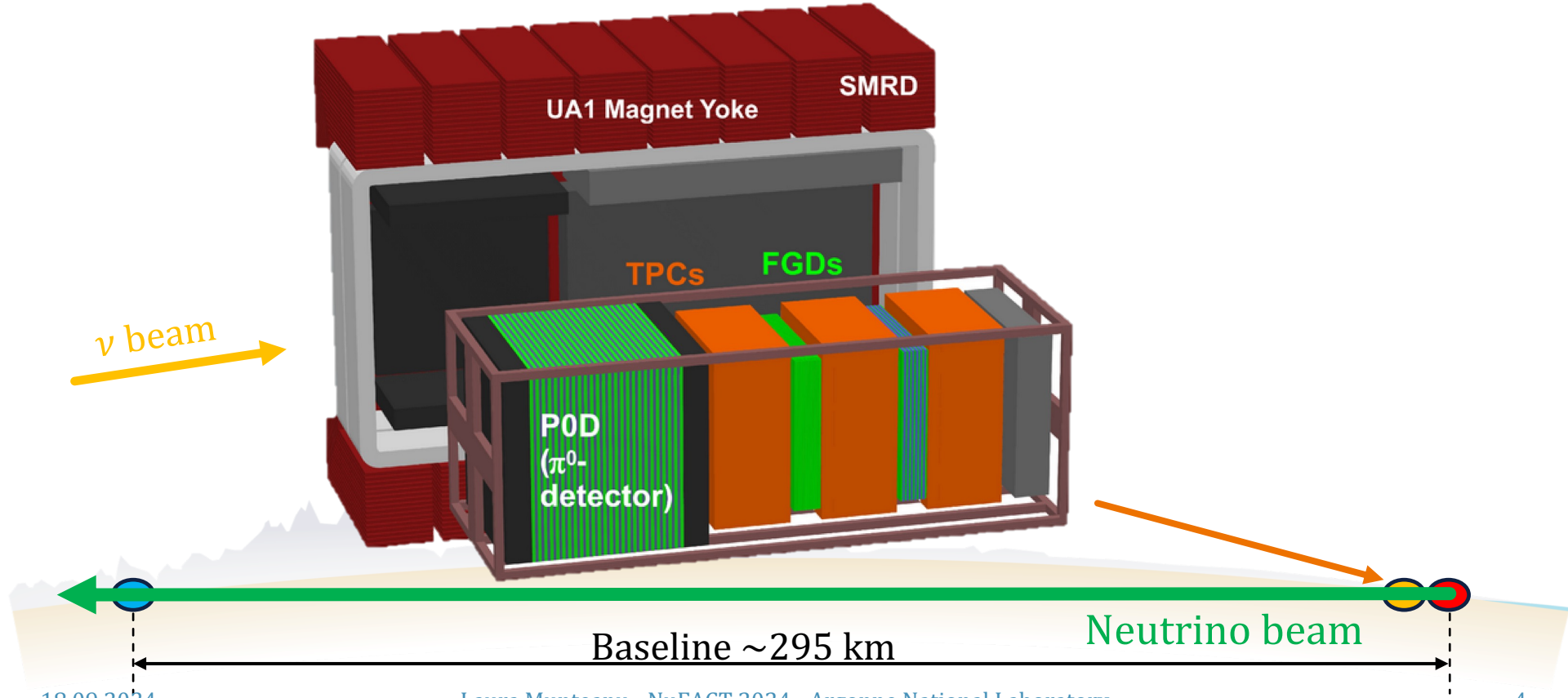




The T2K near detector at 280 m: ND280



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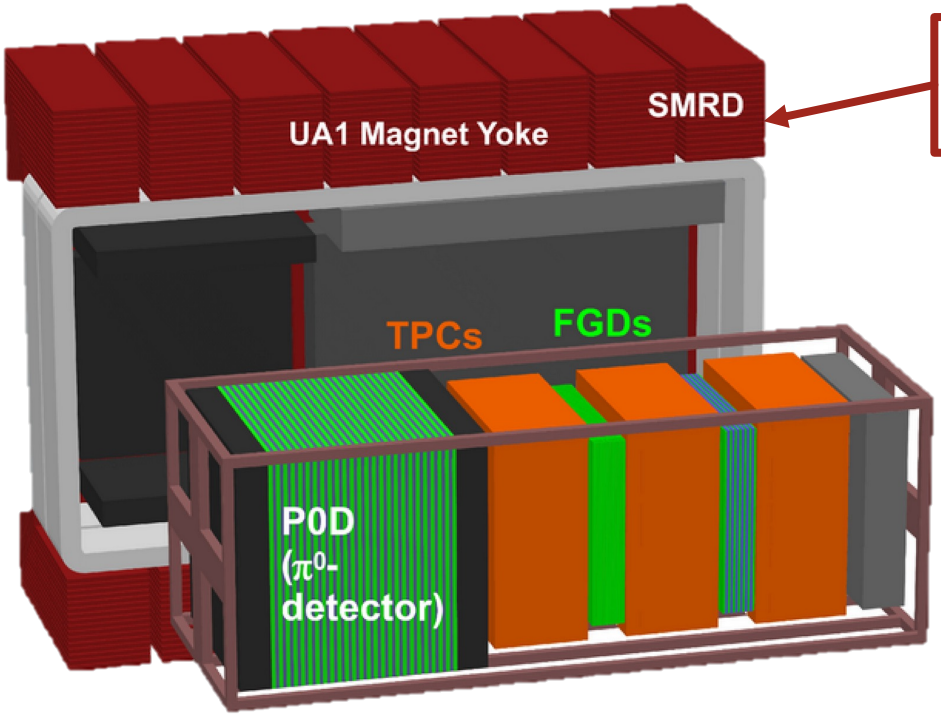
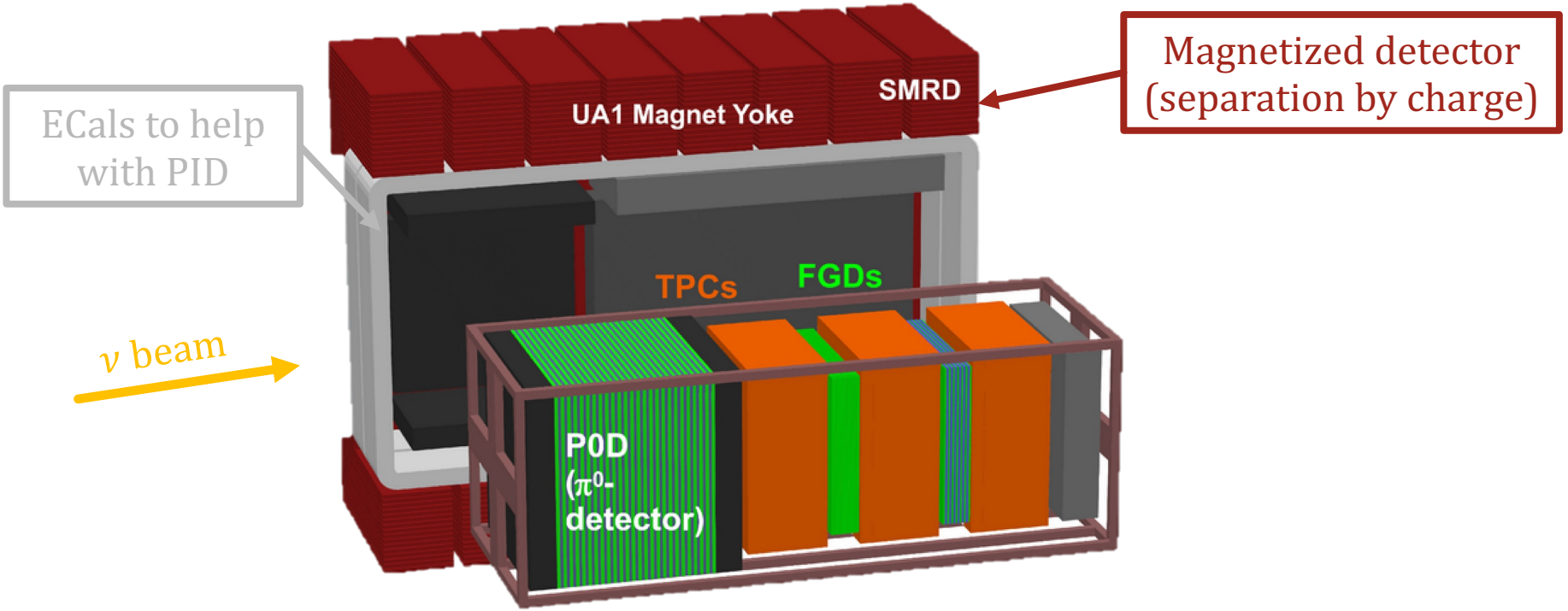


Magnetized detector
(separation by charge)

ν beam

The T2K near detector at 280 m: ND280



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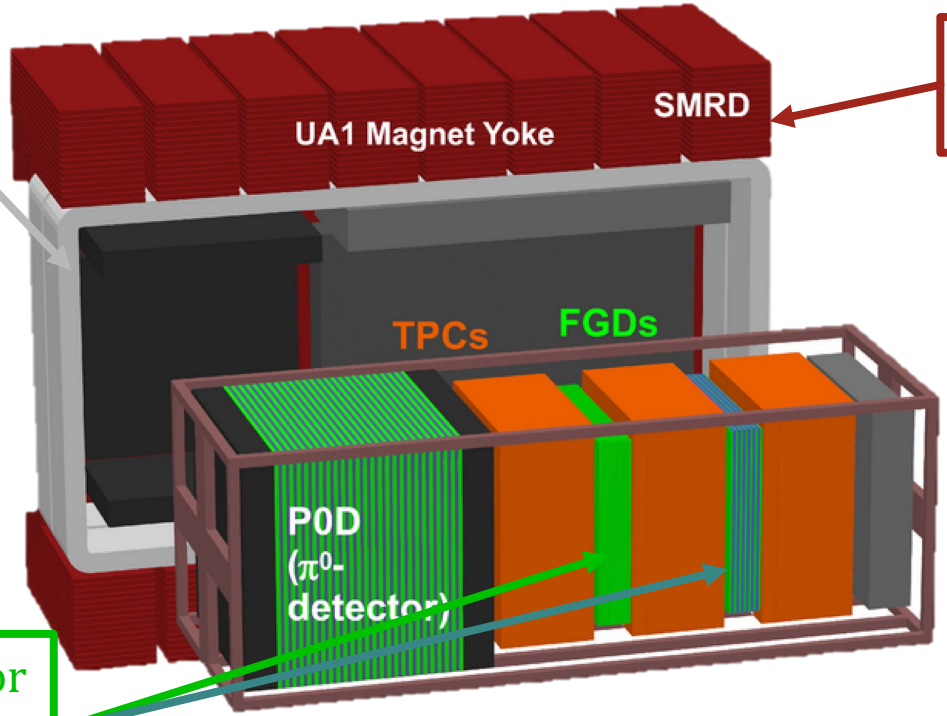

ECals to help with PID

Magnetized detector (separation by charge)

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Plastic scintillator targets (+water bags in FGD2)

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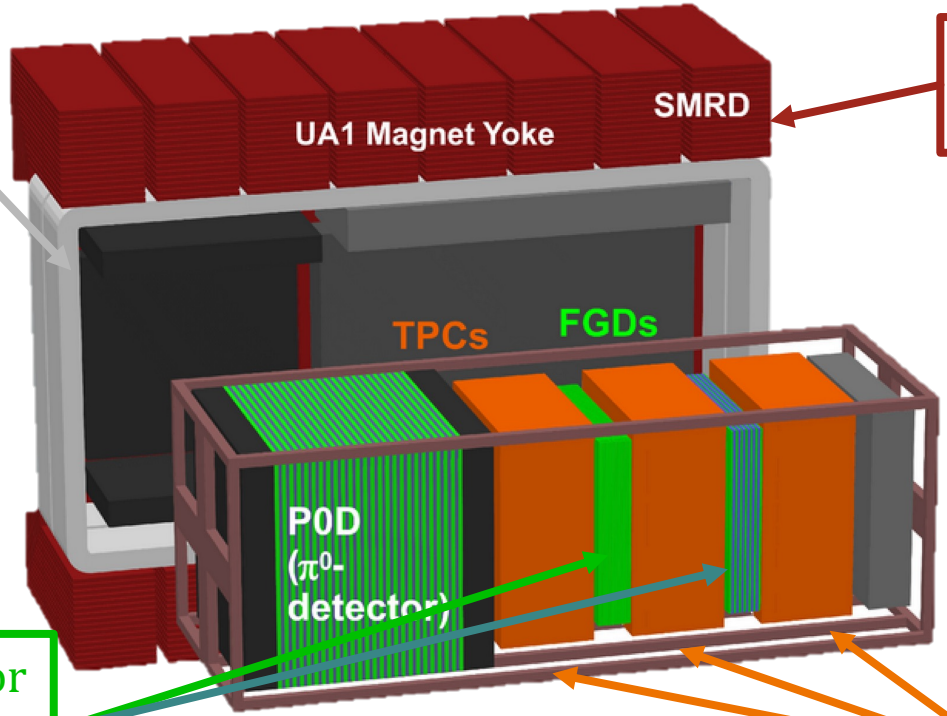

ECals to help with PID

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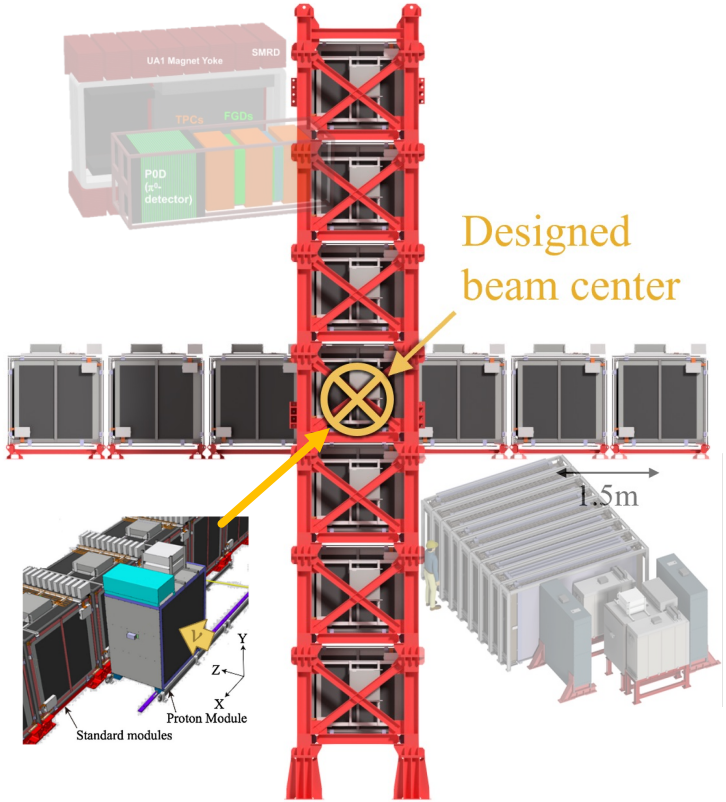
Time projection chambers for tracking and PID

INGRID and WAGASCI-BabyMIND

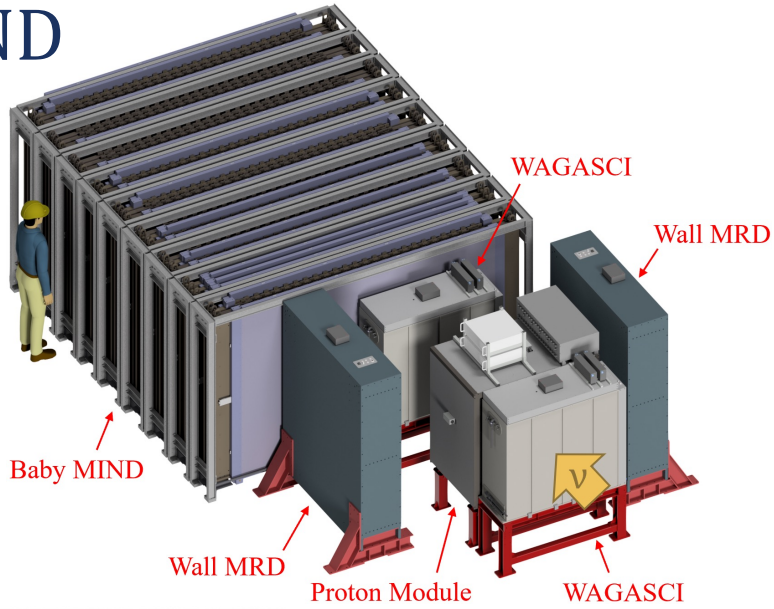


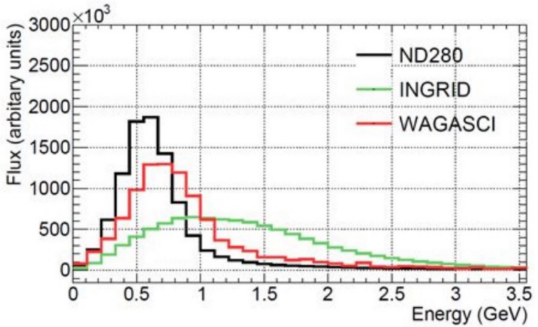
2.5°

Off-axis angle

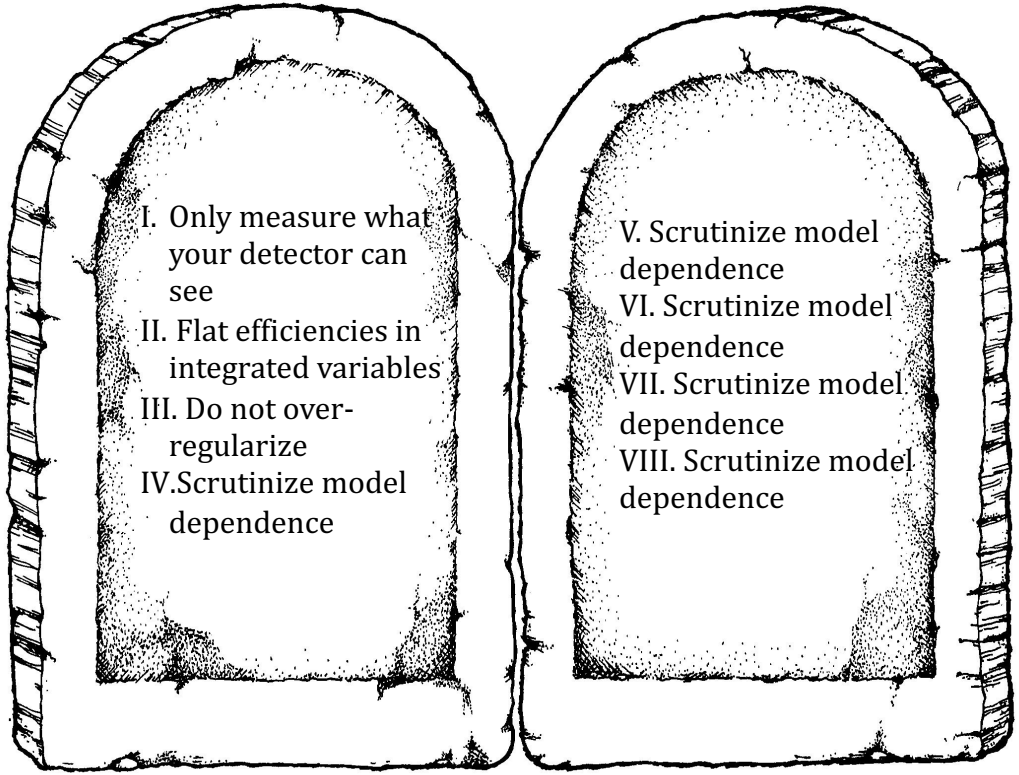
0°

1.5°



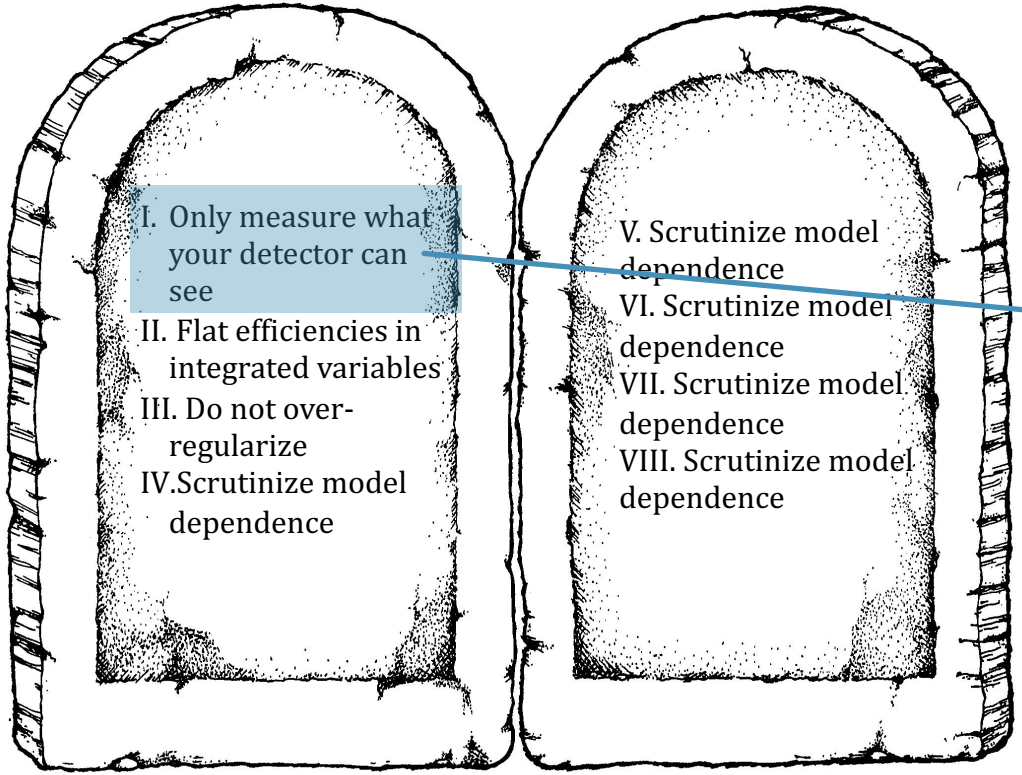


Cross-section extraction philosophy



$$\frac{d\sigma}{dx_i dy_j} = \frac{N_{ij}^{signal}}{\epsilon_{ij} \Phi N_{nucleons}^{FV}} \times \frac{1}{\Delta x_i \Delta y_j}$$

Cross-section extraction philosophy



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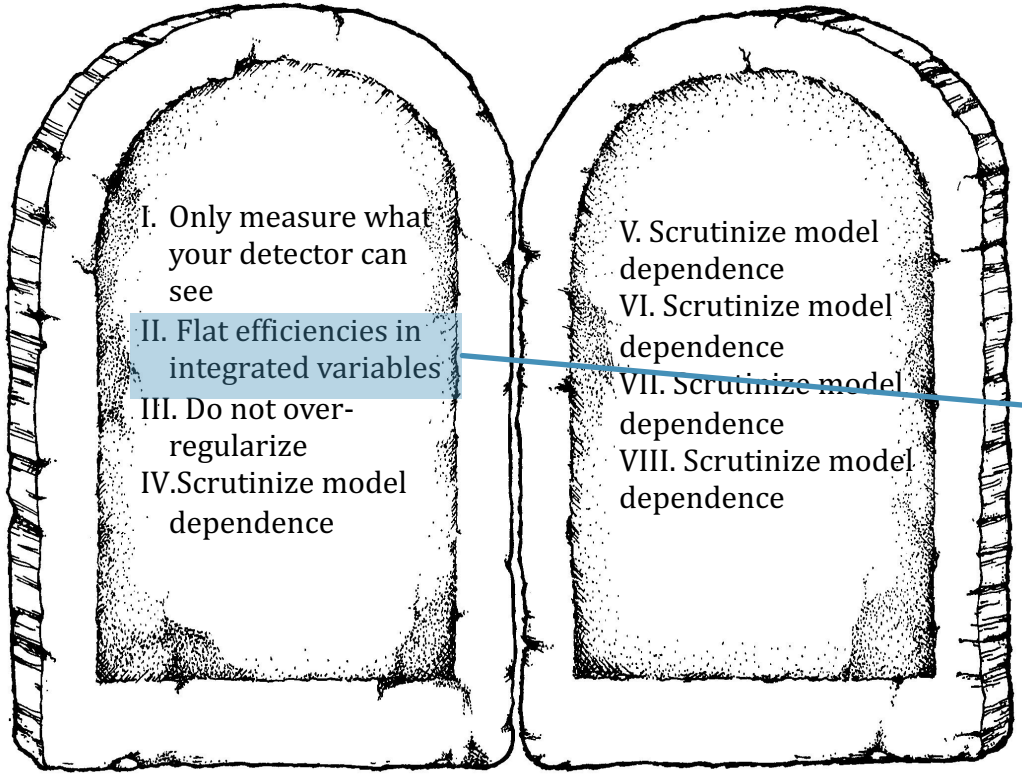

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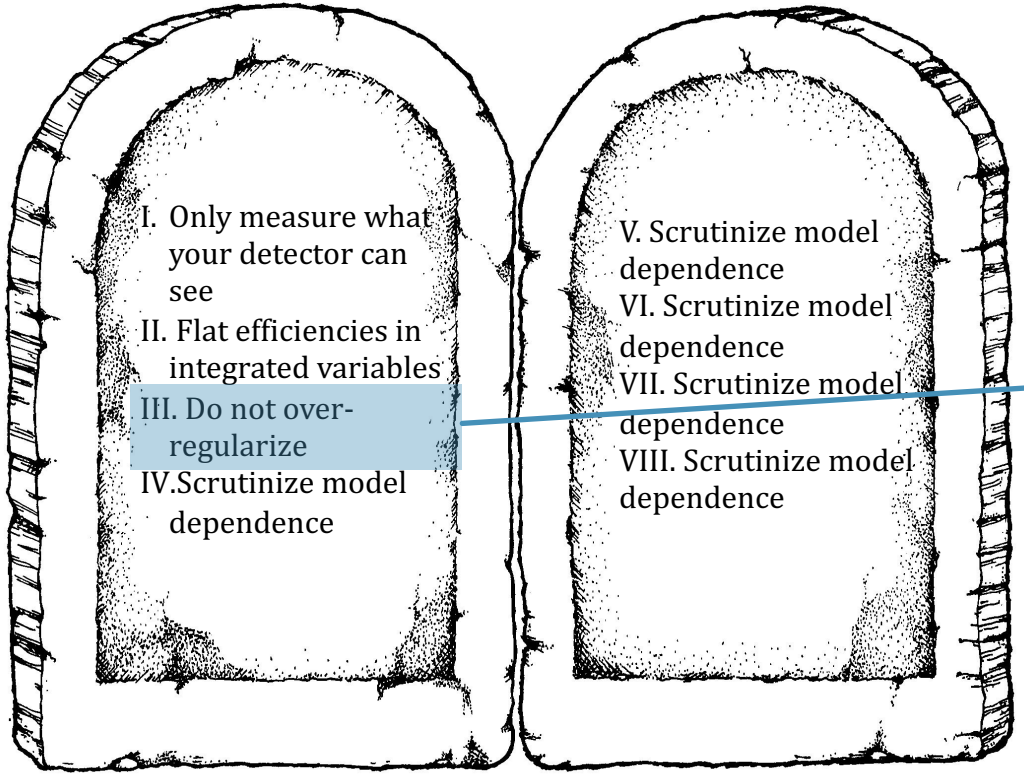

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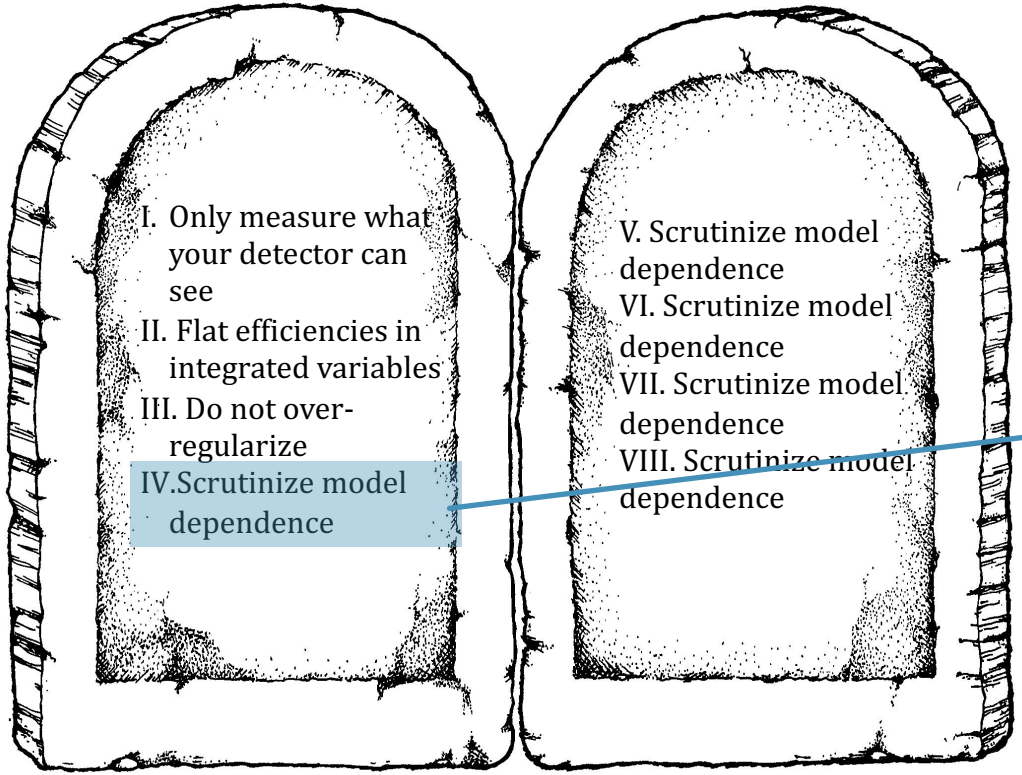

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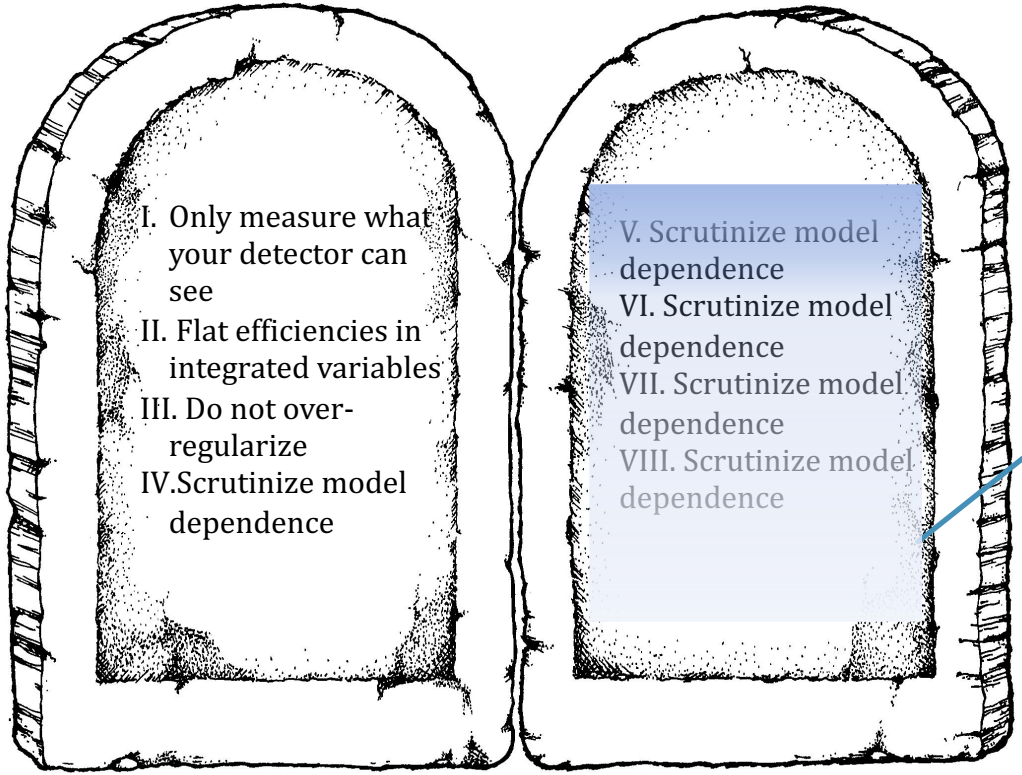

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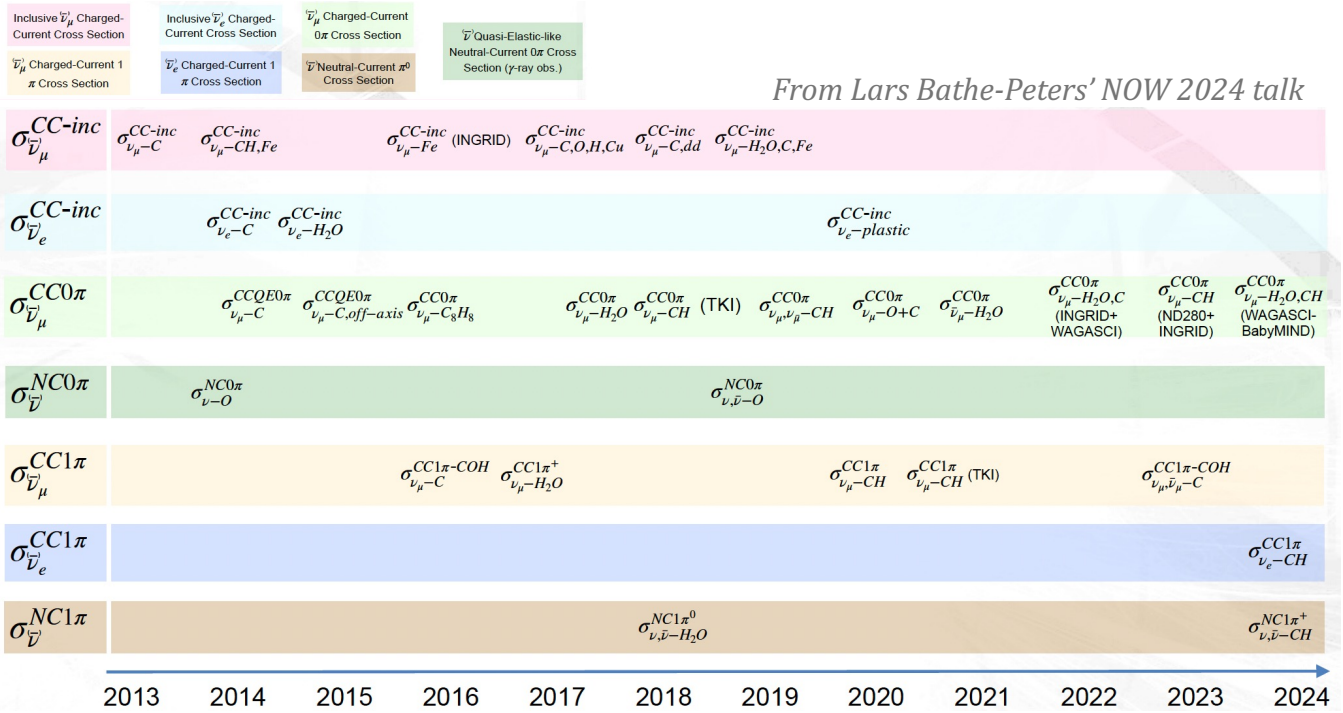
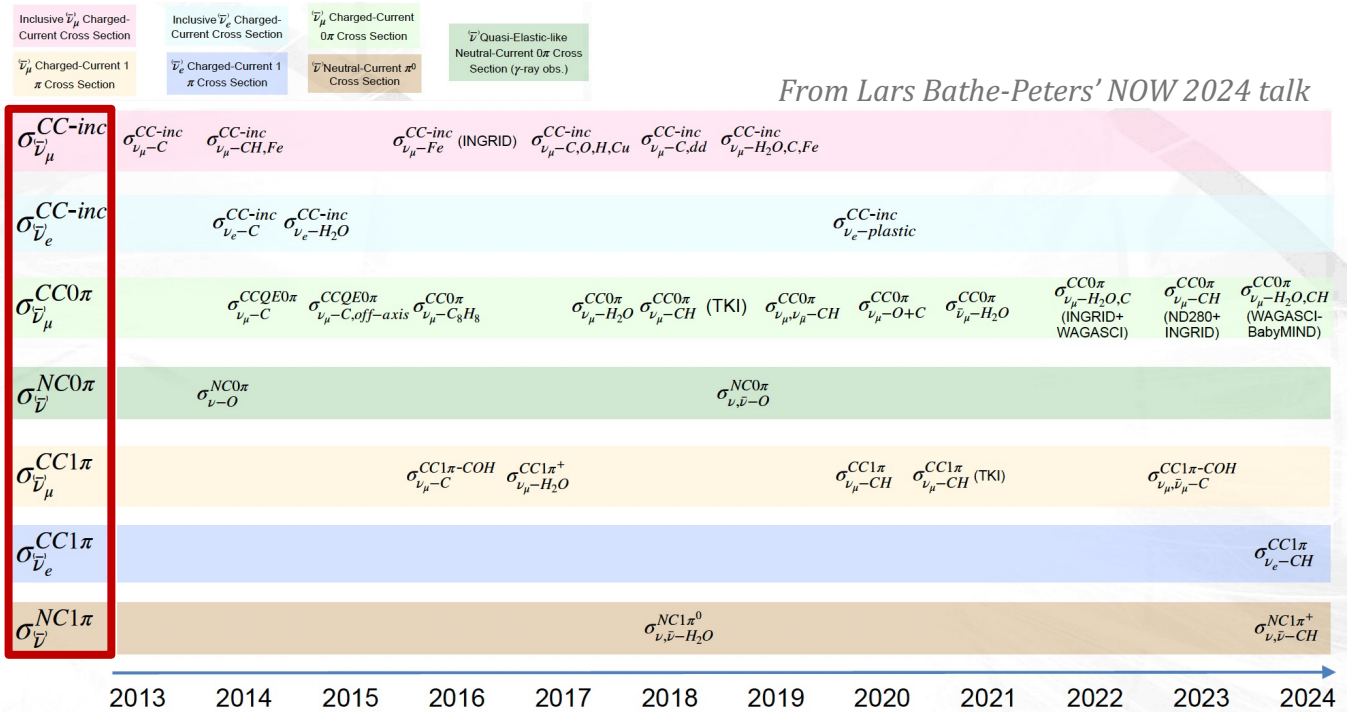
The T2K cross-section program



From Lars Bathe-Peters' NOW 2024 talk

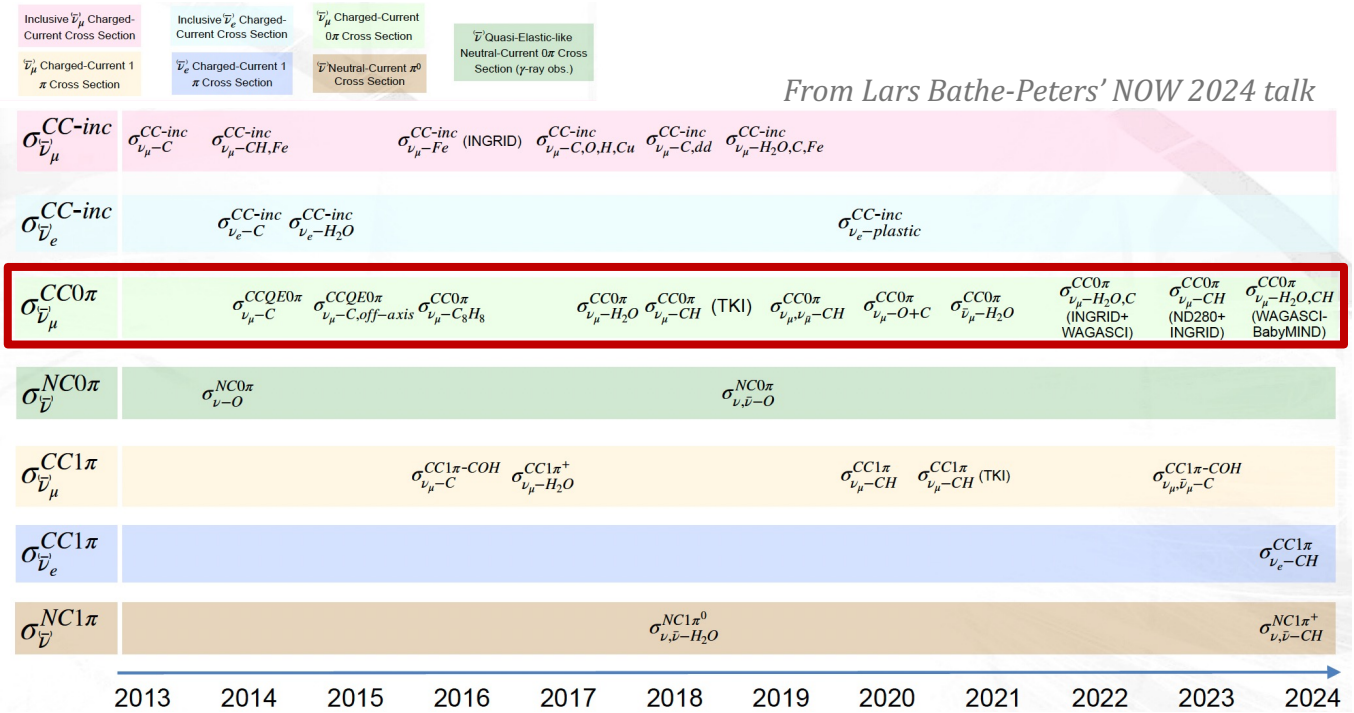
The T2K cross-section program



From Lars Bathe-Peters' NOW 2024 talk

- Covered many different channels

The T2K cross-section program



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- Particular focus on **CC0π processes** (main signal for oscillations)

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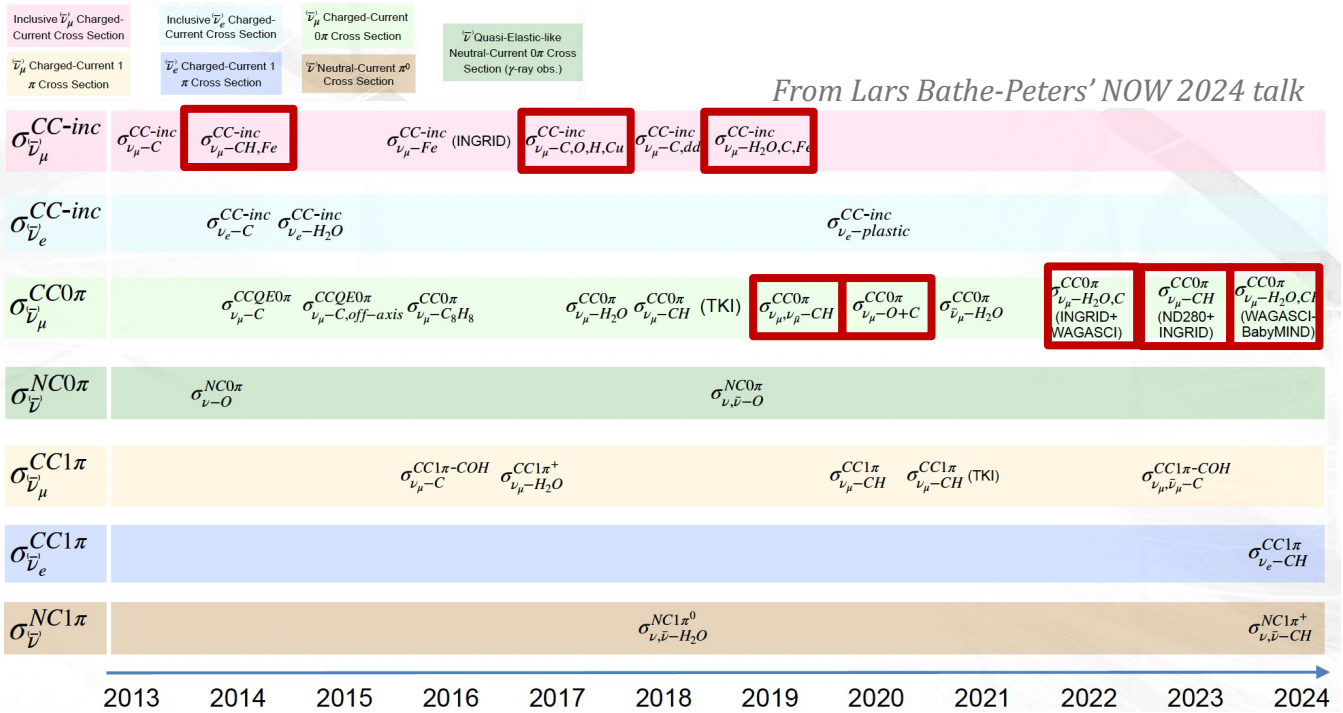

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- Many **joint measurements**

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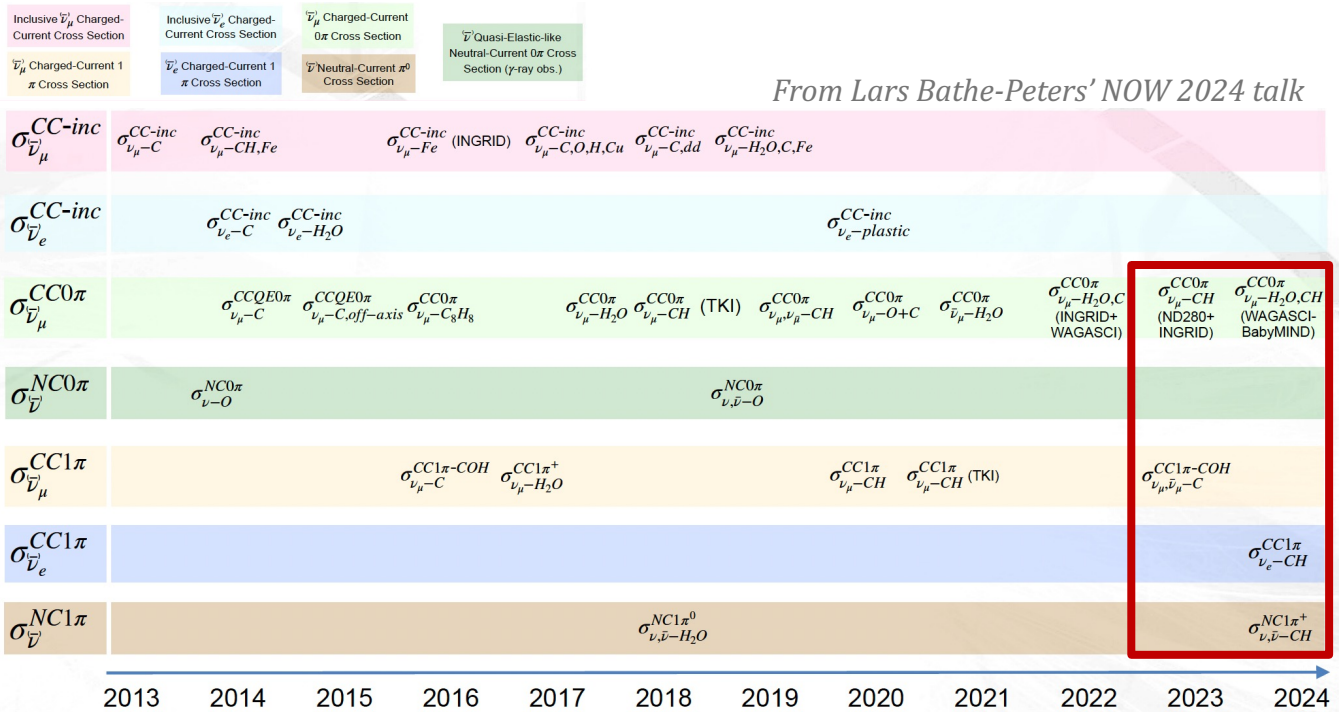


- Covered many different channels
- Particular focus on **CC0π processes** (main signal for oscillations)
- Many **joint measurements**

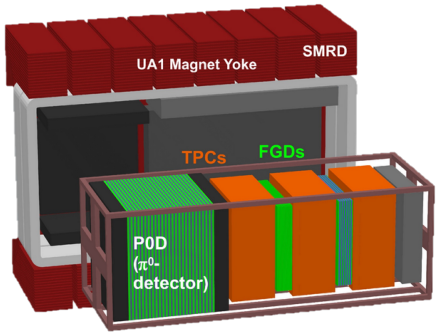
Latest results: focus of this talk

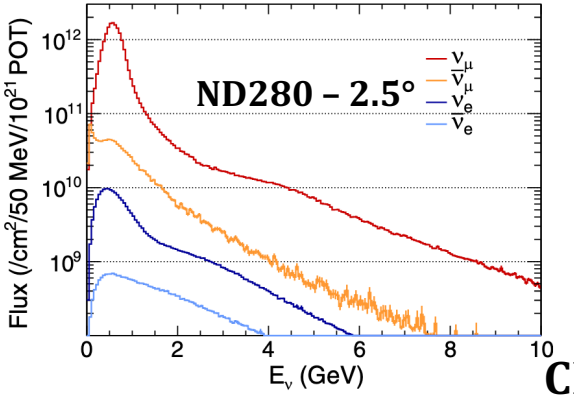
Latest results

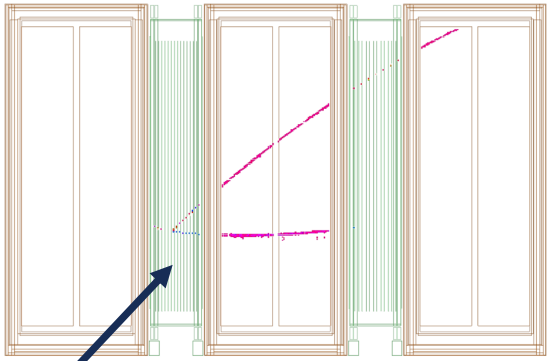
- Joint on-/off-axis ν_μ CC0π measurement (*Phys. Rev. D 108, 112009*)
- Measurement of CC coherent pion production (*Phys. Rev. D 108, 092009*)
- CC0π on CH & water using WAGASCI-BabyMIND
- Measurement of NC1π^+ cross section
- First measurement of ν_e CC1π^+ cross section on C

} Approved results, publication coming soon

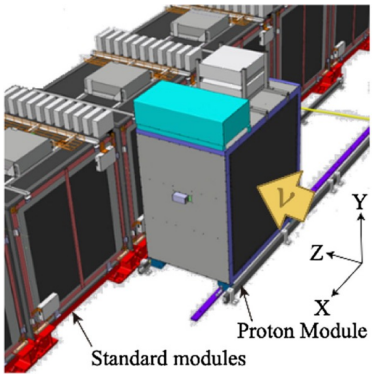
Joint on-/off-axis ν_μ CC0π measurement

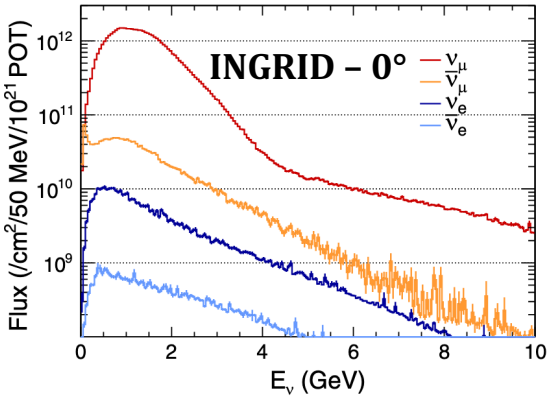


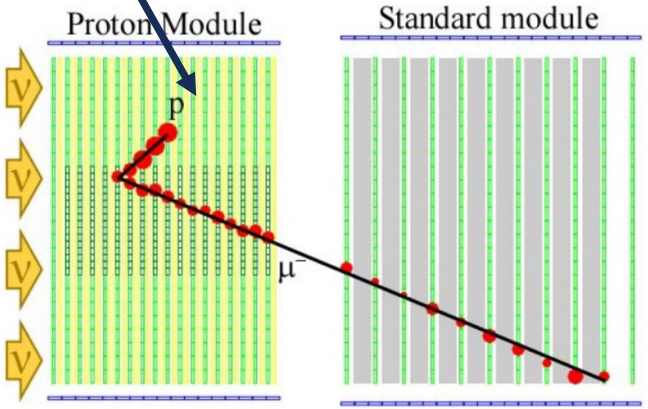




CH target





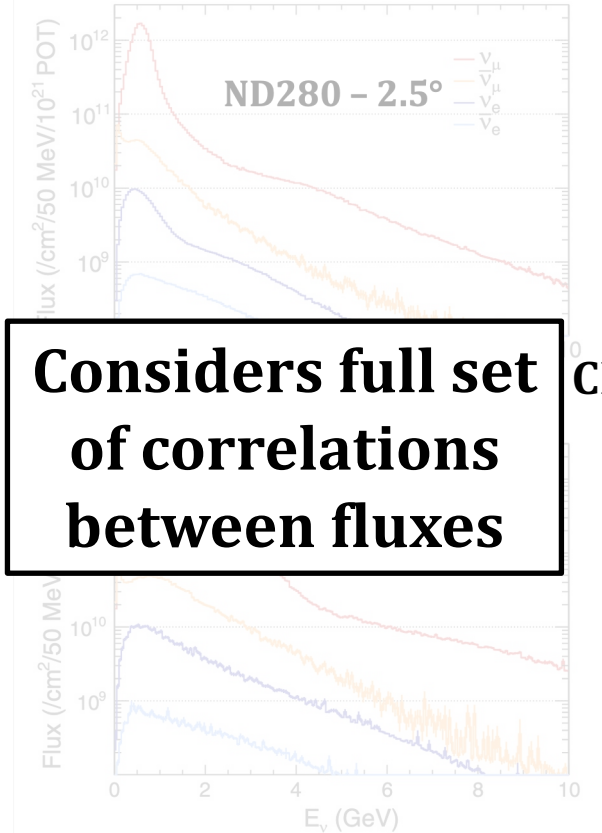


Joint on-/off-axis ν_μ CC0π measurement

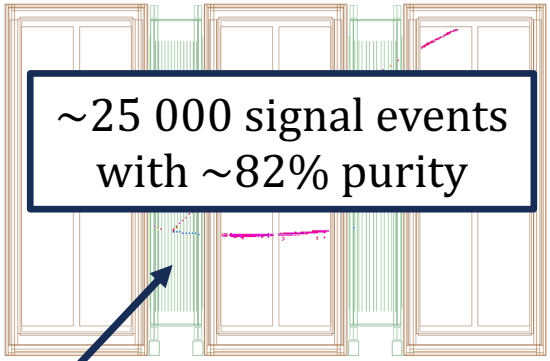
Signal definition:
1 μ^- track with 0 pions in final state

ND280:
- Any number of hadrons
- Any values of p_μ and $\cos\theta_\mu$ (but low efficiency for $\cos\theta_\mu < 0.2$)

INGRID:
- Either 0 or exactly 1 proton-like track
- $p_\mu > 0.35$ GeV
- $\cos\theta_\mu > 0.5$

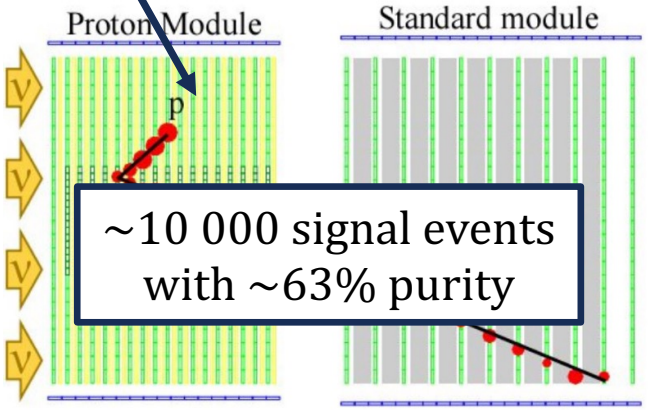


Considers full set of correlations between fluxes



~25 000 signal events with ~82% purity

CH target



~10 000 signal events with ~63% purity

Joint on-/off-axis ν_μ CC0π measurement

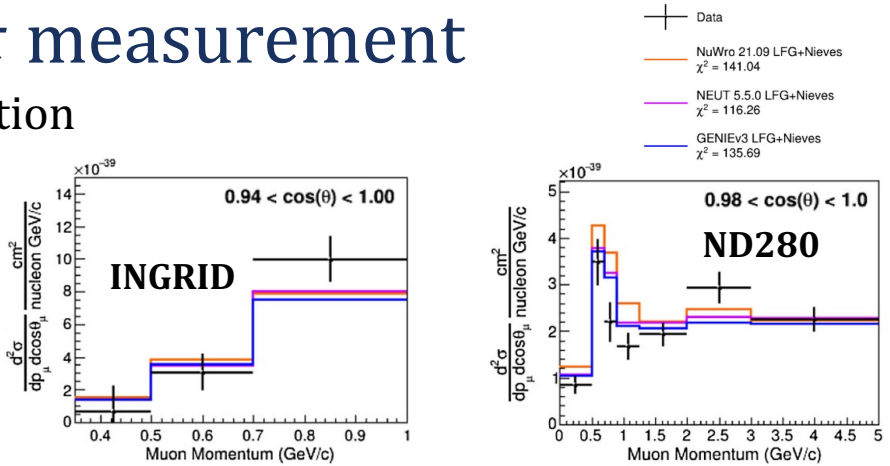
Results reported as 2D differential cross section in **70 bins** in muon kinematics $(p_\mu, \cos\theta_\mu)$

- ND280: 58 bins
- INGRID: 12 bins

χ^2 values

Model	ND280	INGRID	Joint
Nominal MC (NEUT)	136.34	18.21	158.71
NEUT LFG + Nieves	106.46	11.46	116.26
NEUT SF + Nieves $M_A = 1.03$	194.88	14.36	209.18
NEUT SF + Nieves $M_A = 1.21$	158.71	9.98	170.93
NuWRO SF + Nieves	122.74	15.68	137.02
NuWRO LFG + Nieves	125.88	12.75	141.04
NuWRO LFG + SuSAv2	121.57	11.13	135.38
NuWRO LFG + Martini	138.86	12.46	155.68
GENIE BRRFG + EmpMEC	141.40	12.80	156.05
GENIE LFG + Nieves	125.50	14.45	135.69

All tested models are insufficient to describe the joint measurement



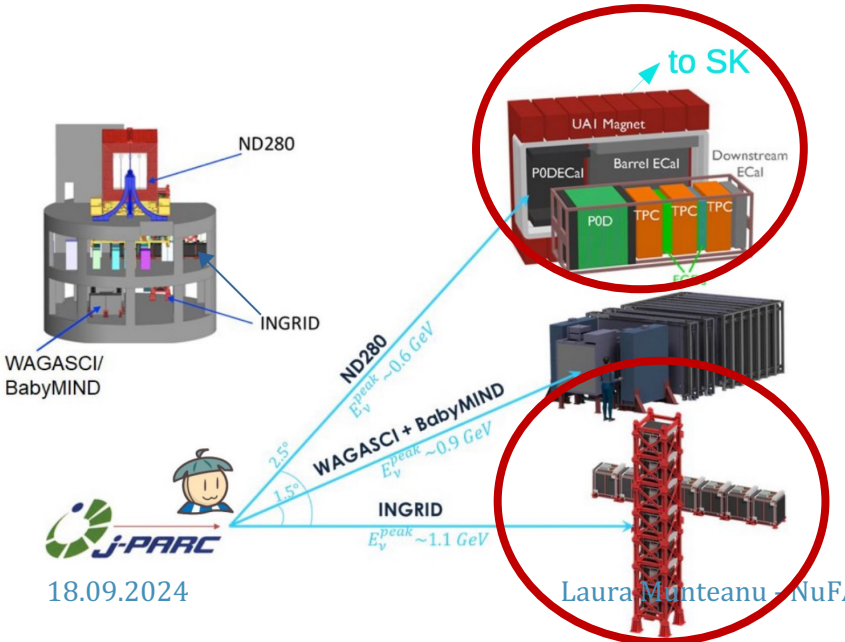
Results consistent with previous T2K measurements

- Generators struggle to describe forward-going, mid- to low-momentum muons
- Struggle to describe ND280 measurements but not INGRID

Issues with RPA/energy dependence?

A PRISM-like analysis?

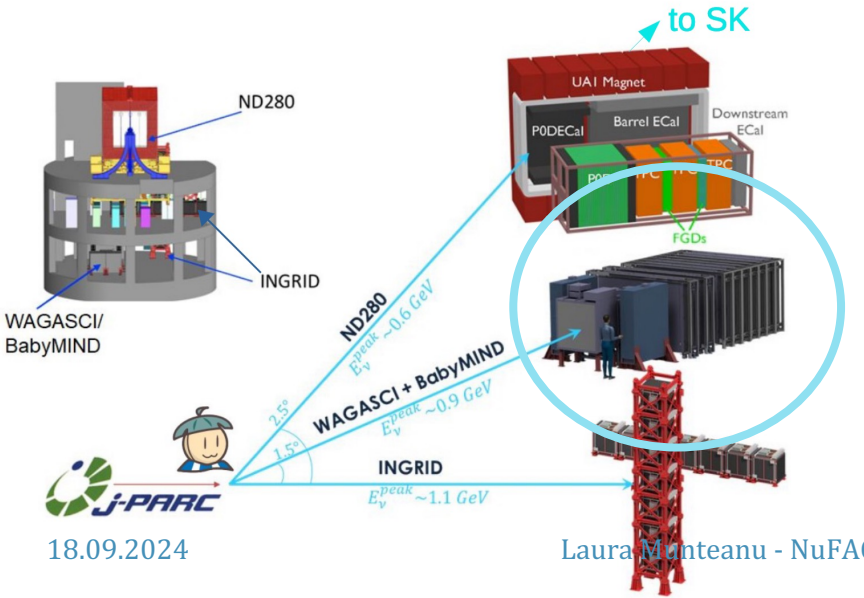
The joint INGRID+ND280 analysis is a PRISM-like analysis but using only two fluxes



Towards a PRISM-like analysis – WAGASCI-BabyMIND

The joint INGRID+ND280 analysis is a PRISM-like analysis but using only two fluxes

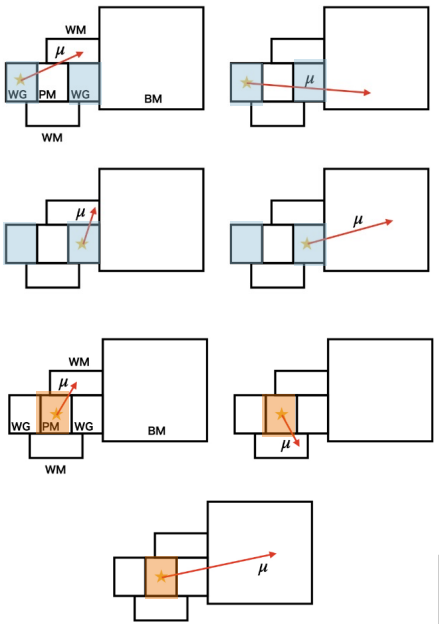
Goal: add a third point – WAGASCI



CC0π measurement on CH & H_2O with WAGASCI

~few thousands of events

H_2O target



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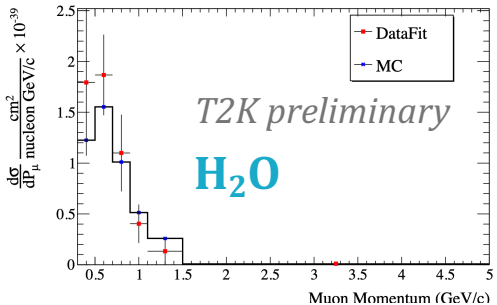
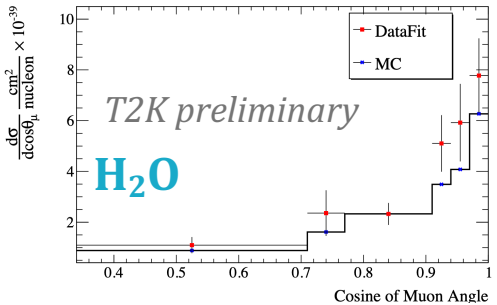
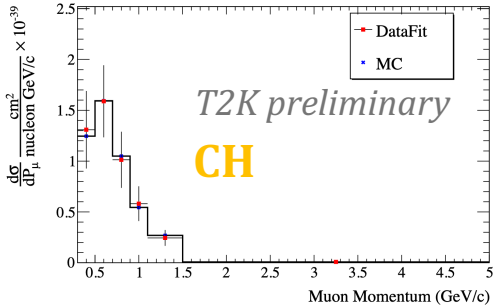
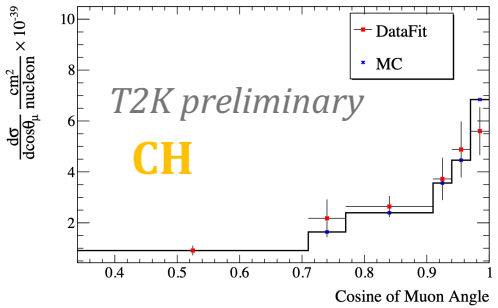




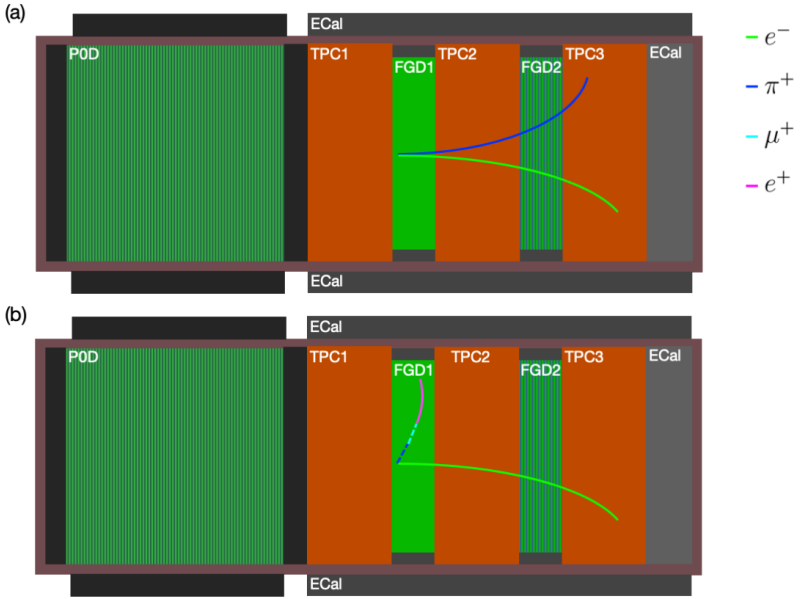




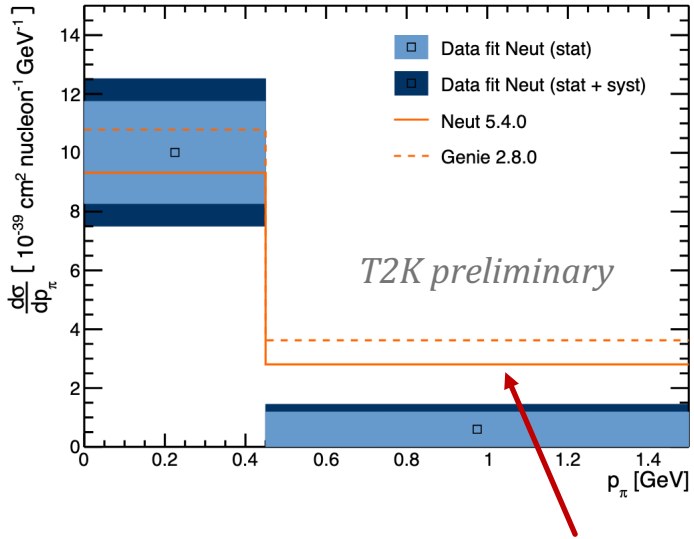
Model	χ^2 in momentum binning			χ^2 in angle binning		
	CH	H_2O	total	CH	H_2O	total
NEUT nominal	0.493	5.619	6.673	4.040	5.082	9.005
NEUT alternative version	1.827	5.550	7.611	4.279	6.615	11.29
GENIE	1.086	6.030	7.667	2.199	4.783	6.955
Post fit by the ND fit	1.318	5.547	7.424	3.217	5.169	8.208

12 bins

First measurement of ν_e CC1π^+ cross section on C



3D measurement in $(p_e, cos\theta_e, p_{\pi^+})$ projected into 1D p_{π^+}



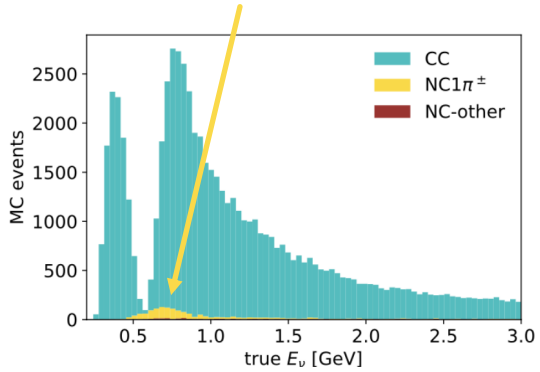
$p_e > 350$ MeV
$\cos\theta_e > 0.7$
$p_{\pi^+} < 1.5$ GeV

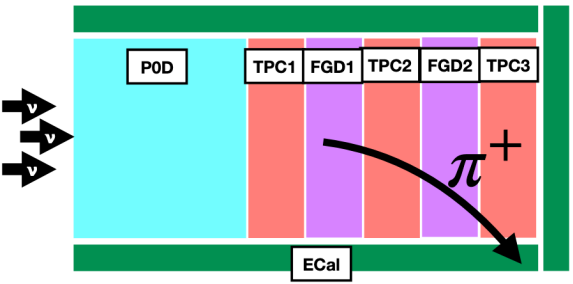
$O(150)$ events
~60% purity
~20% efficiency

Predictions overestimate the measurement by ~2σ but very statistically limited

Measurement of NC1π^+ cross section

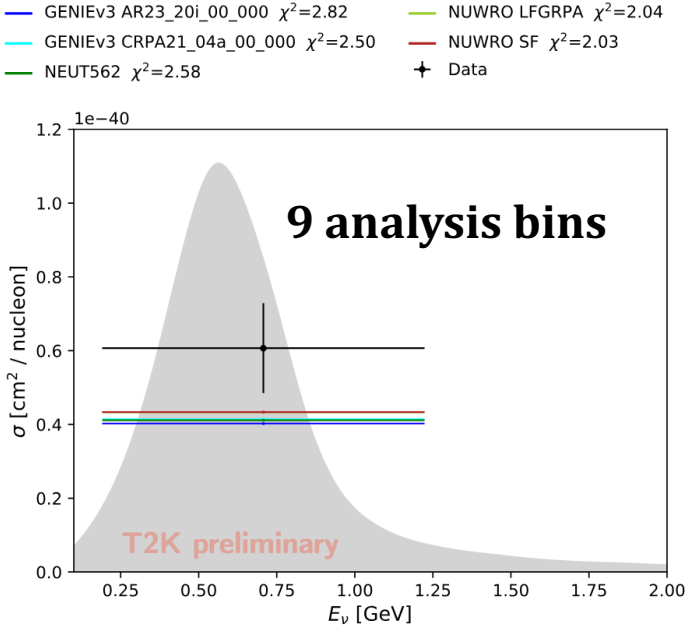
First dedicated measurement in >40 years
Background process at oscillation maximum





Challenging topology due to OOFV backgrounds and mis-PID (~40% purity and ~15% efficiency)
Less than 1% of events at ND280 → **~500 selected events**

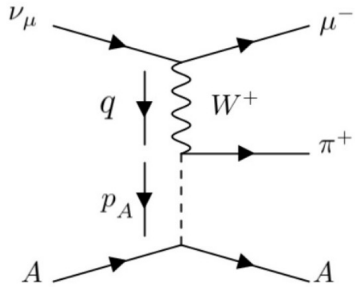
$$1\ \text{GeV} > p_{\pi^+} > 0.2\ \text{MeV}$$
$$\cos\theta_{\pi^+} > 0.5$$



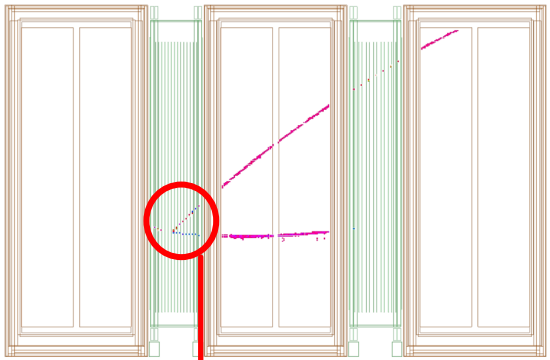
None of the tested models are excluded

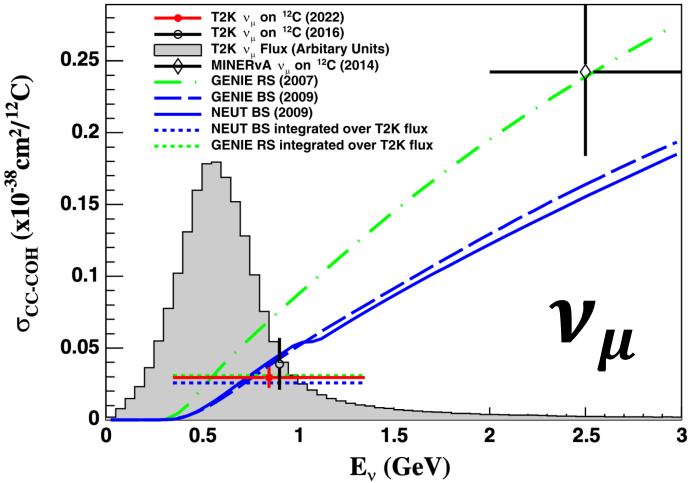
Measurement of ν_μ and $\bar{\nu}_\mu$ CC coherent pion production

Poorly understood process which can be a background for oscillation analyses in Cherenkov detectors or exotic searches



$$|p_A|^2 = |q - p_\pi|^2 = |t|$$



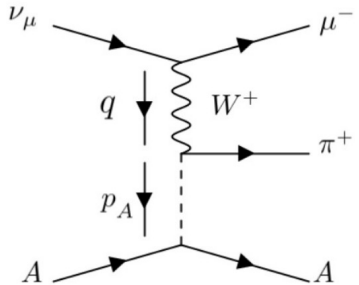


No nuclear fragmentation
- Require low $|t|$
- And low energy deposition around vertex

- Improvement of uncertainty w.r.t. previous ν_μ result (Phys. Rev. Lett. 117, 192501) **by a factor of 2**
- Compatible with Rein-Sehgal and Berger Sehgal models

Measurement of ν_μ and $\bar{\nu}_\mu$ CC coherent pion production

Poorly understood process which can be a background for oscillation analyses in Cherenkov detectors or exotic searches



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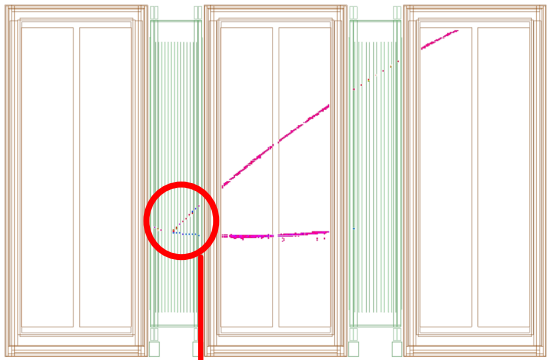
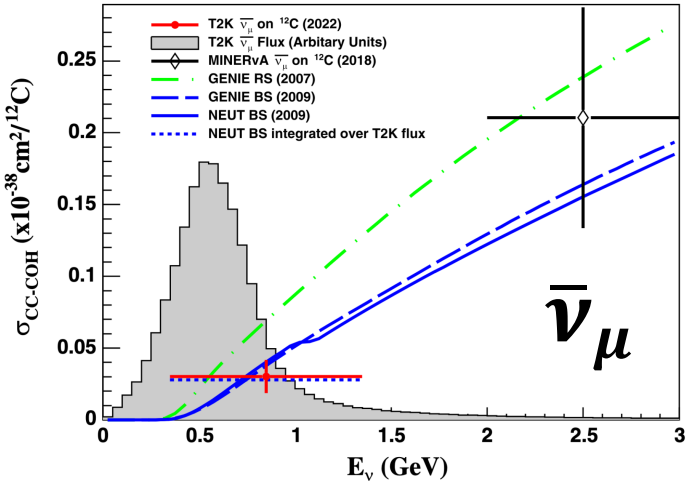




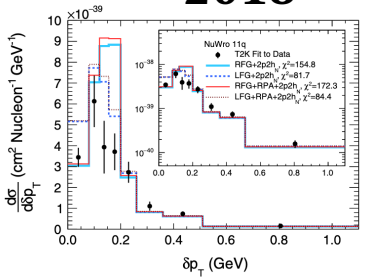
No nuclear fragmentation
- Require low $|t|$
- And low energy deposition around vertex

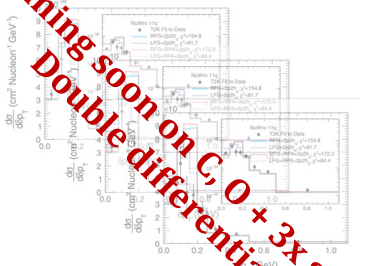
- First T2K $\bar{\nu}_\mu$ **measurement**
- Compatible with Rein-Sehgal and Berger Sehgal models

Coming soon

TKI with increased stat. on C & O

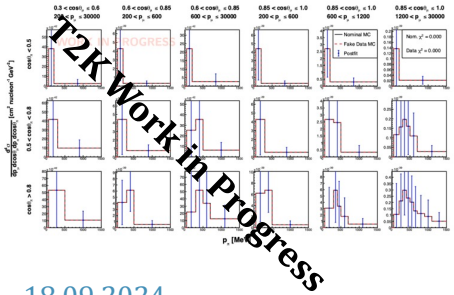
~2018





Phys. Rev. D 98, 032003

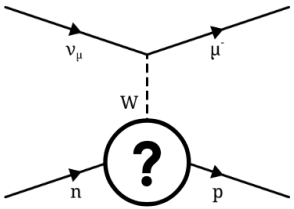
CC1π^+ as a function of pion kinematics



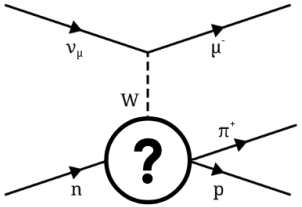
$p_\mu, cos\theta_\mu,$
$p_\pi, cos\theta_\pi$
Including Michel electrons

Joint CC0π+CC1π measurement on CH

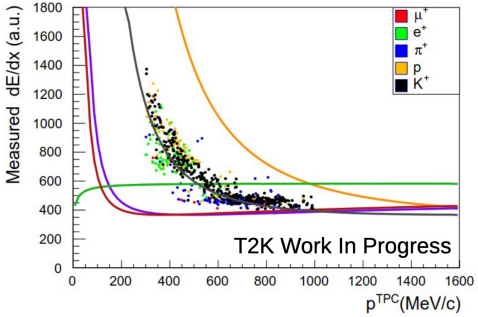
CC-0π



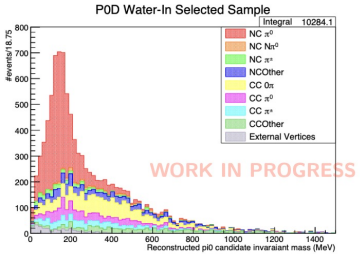
CC-1$\pi^{+/-}$



CC1K^+ measurement



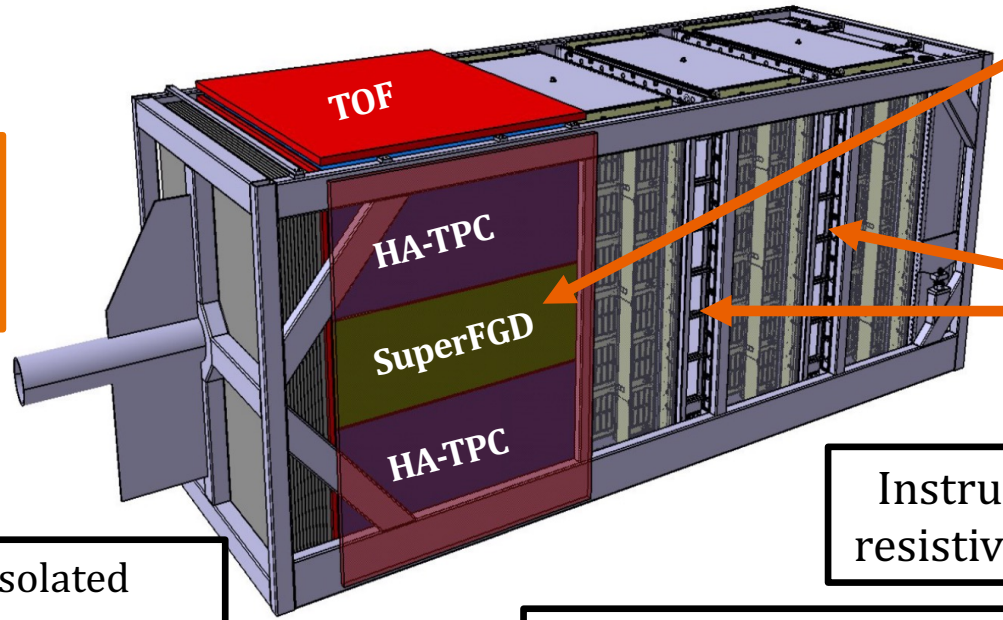
NCπ^0 measurement

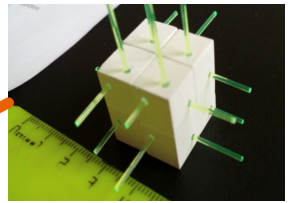


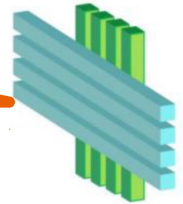
The T2K ND280 Upgrade project

ND280 Upgrade TDR

Replace P0D by new suite of detectors







>100 researchers
22 institutes
7 countries

ν beam
750+ kW

Instrumented with resistive Micromegas

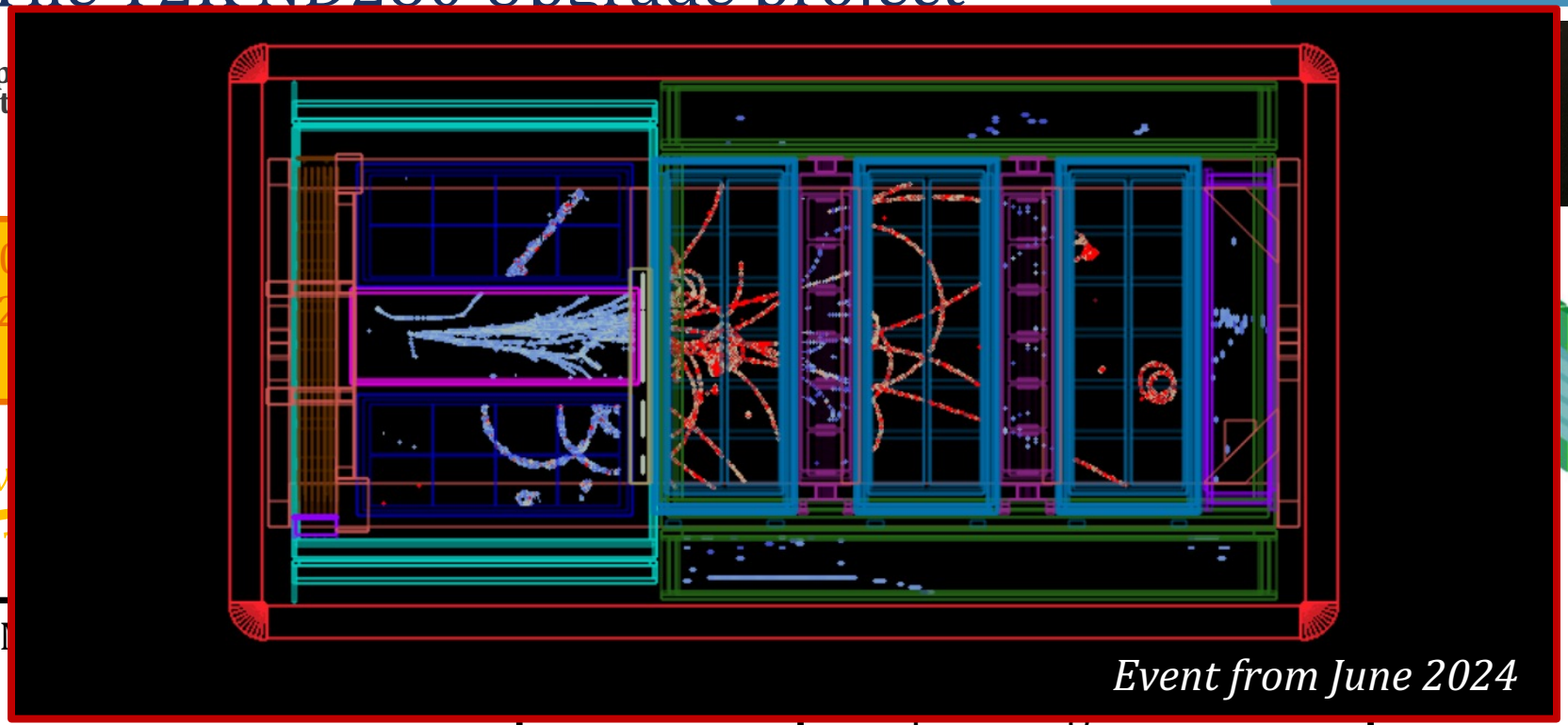
2M 1cm^3 optically isolated scintillator cubes

2x fiducial mass of current FGDs

150 ps timing resolution to veto backgrounds

The T2K ND280 Upgrade project

ND280 Upgrade TDR



2x fiducial mass of current FGDs

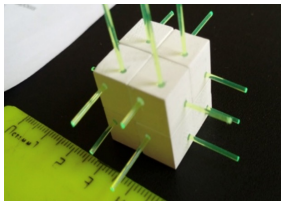
veto backgrounds

The T2K ND280 Upgr

See talk at NuFACT 2024:
HA-TPC Challenges – *S. Hassani, Thursday*

See talk at NuFACT 2024:
SuperFGD – *T. Doyle, Thursday*

ND280 Upgrade TDR



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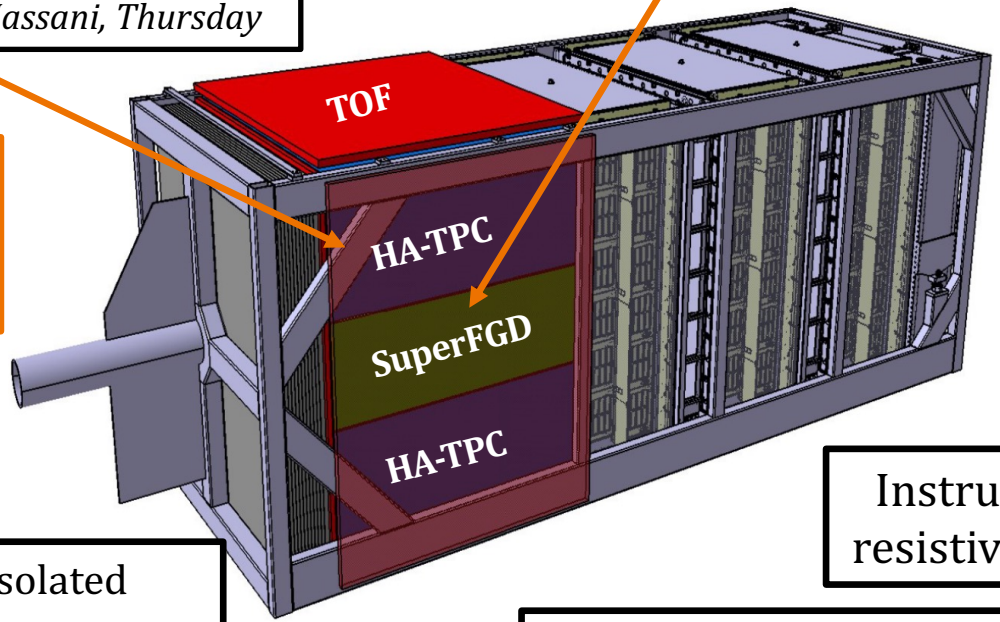

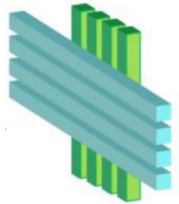

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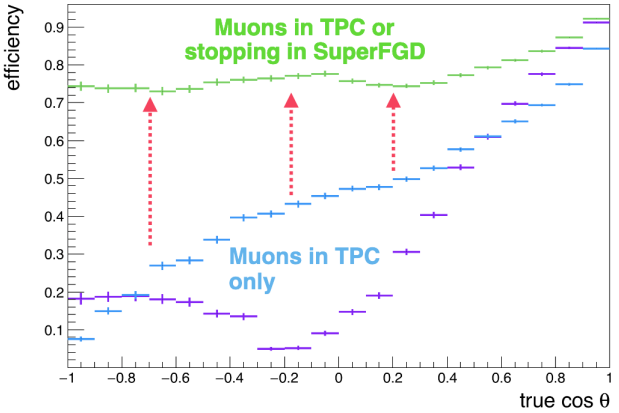
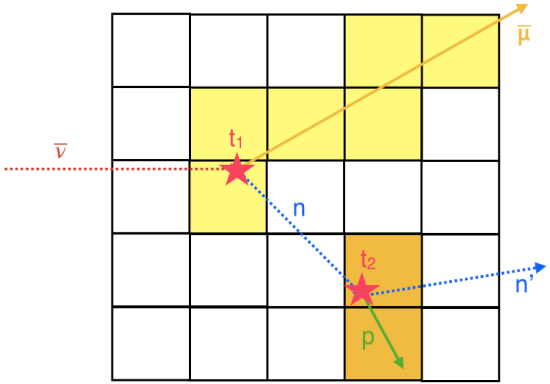
150 ps timing resolution to veto backgrounds

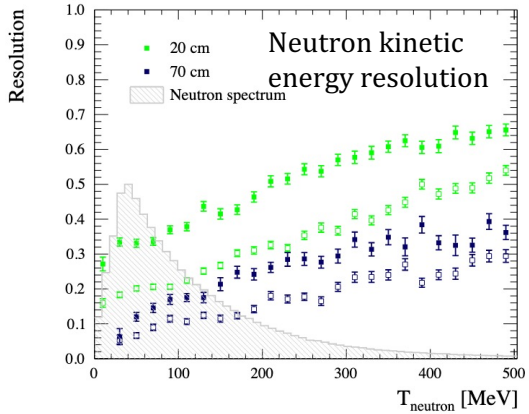
Capabilities of the ND280 Upgrade

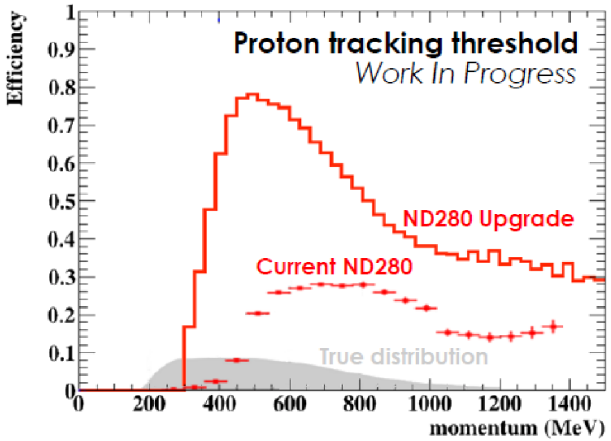
- Full 4π angular coverage (same as SK)
- Low momentum thresholds for detecting **protons**
  - Can realiably measure full final state in neutrino interactions!
- Capability to measure (not just tag!) **neutrons**
  - Unique capability of scintillator technology





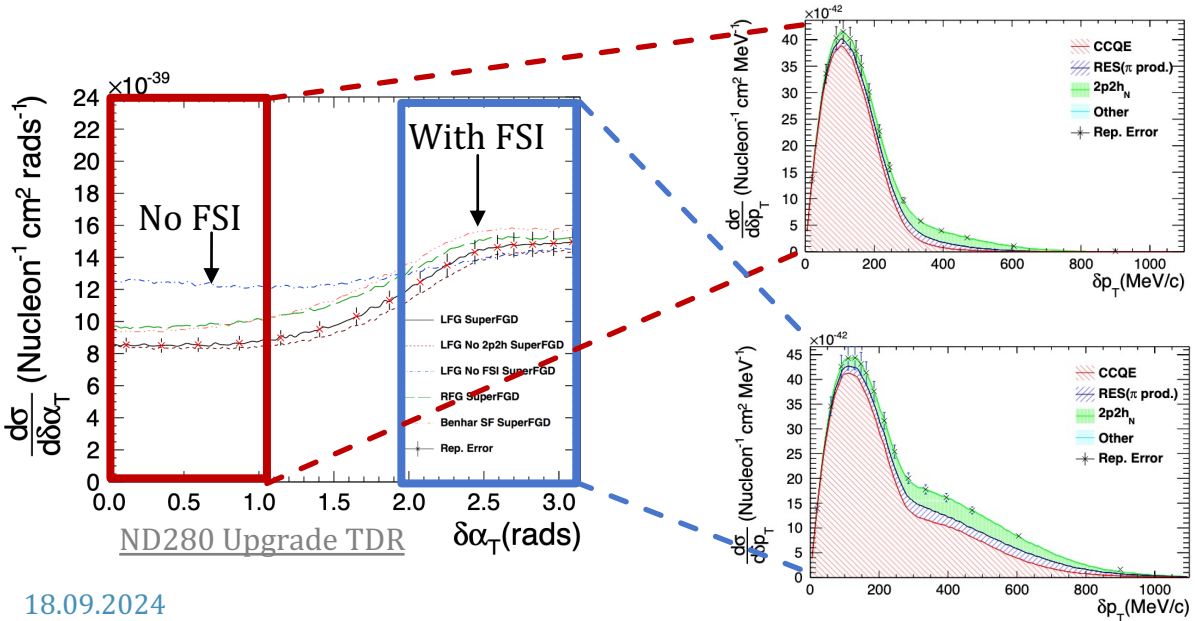
Phys. Rev. D 101, 092003



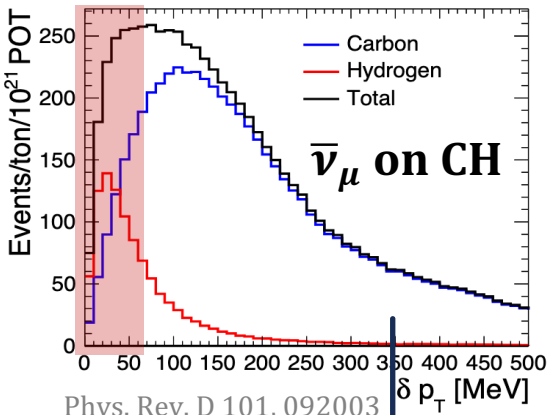


The next generation of T2K cross section measurements

- Finer measurements (esp. at high muon angles)
- More exclusive measurements (e.g. TKI & beyond)
- Expoiting calorimetry in the SuperFGD
- Measuring neutrons (& interactions off free protons!)



ND280 Upgrade TDR



Phys. Rev. D 101, 092003
Phys. Rev. D 110, 032019

Expect purities of >60% (>80% if using also longitudinal information)

Summary

- T2K has a prolific cross-section program (>30 publications)
- Focus is on providing robust measurements of processes important for oscillation analyses
- Latest results include joint measurements and new channels
- Last generation of pre-upgrade measurements will benefit from 10+ years of cross-section extraction experience
- Newly installed ND280 Upgrade detector will provide some of the most precise measurements to date

Thank you for your attention!

Back-Up

Measuring neutrino oscillation Parameters

- The observed event rate at the FD is the result of the convolution of multiple effects

$$N_{obs}^{FD} = \Phi^{\mathrm{FD}}(E_\nu) \otimes \sigma(E_\nu) \otimes \epsilon^{FD} \otimes P_{\nu_{\alpha \to \nu_\beta}}(E_\nu)$$

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Neutrino flux
"What was sent"

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Interaction cross-section
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Detector efficiency
"What was actually *seen*"

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…for each flavor

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Neutrino flux
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Sources of systematic uncertainties

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- The observed rate at the ND is identical in form, up to the last term

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- The near detector(s) play a key role in constraining systematic uncertainties for oscillation parameter measurements
  - But it's not a trivial task due to experiment resolution

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- Detector efficiency needs to be well understood
- $\sigma(E_\nu)$ has an intrinsic dependence on E_ν
  - …and we do not know enough about neutrino interactions with matter in general!