DE LA RECHERCHE À L'INDUSTRIE

T2K : Latest Results and Near Detector Upgrade

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25/06/2019 - GDR Neutrino
LPNHE, Paris

OVERVIEW

- The T2K Experiment
- Latest Results
- The Upgrade of the Near Detector
- Time of Flight
- SuperFGD
- HA-TPC
- Simulation & Optimization Studies
- Summary & Outlook

NEUTRINO OSCILLATIONS PHYSICS

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric and accelerator
$\theta_{23} \sim 50°$
$|\Delta m_{32}^2| \sim 2.5\text{x}10^{-3}\ \text{eV}^2$

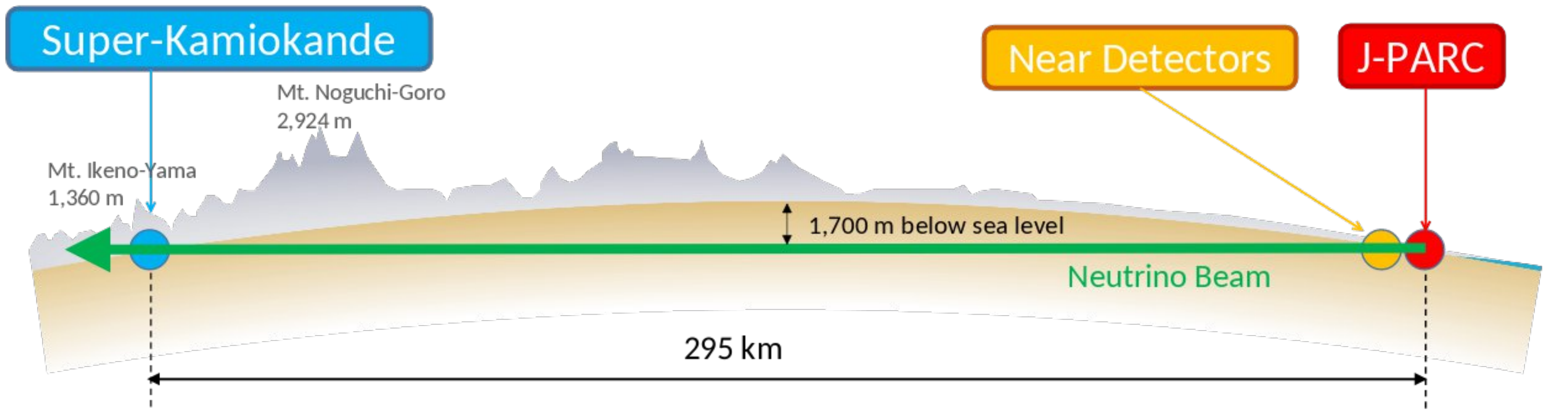
Reactor and accelerator
$\theta_{13} \sim 8°$
Accelerator only $\delta_{CP} = ??$

Solar and reactor
$\theta_{12} \sim 34°$
$\Delta m_{12}^2 \sim 7.5\text{x}10^{-5}\ \text{eV}^2$

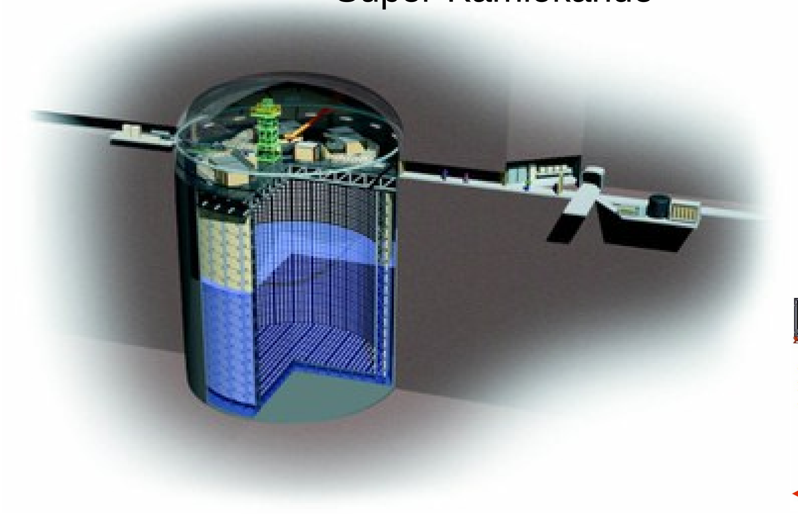
- What's keeping long-baseline neutrino oscillation physicists up at night:
  - CP VIOLATION PHASE δ_{CP}
  - θ_{23} OCTANT
  - MASS ORDERING
- Oscillation parameters inferred from event rates

$$P(\nu_\alpha \to \nu_\beta) = P(E,L,\Delta m,\theta,\delta_{CP})$$

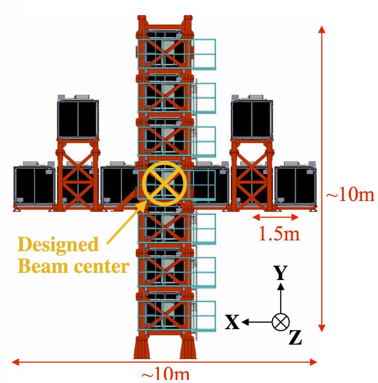
THE T2K EXPERIMENT



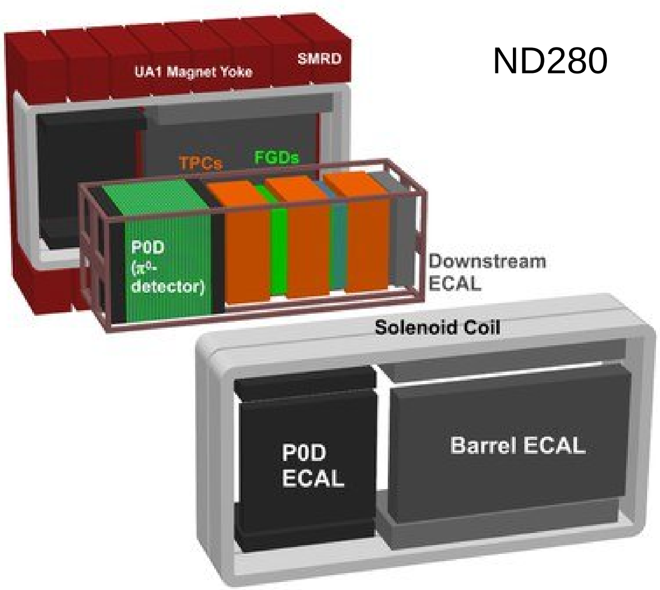
Super-Kamiokande



INGRID

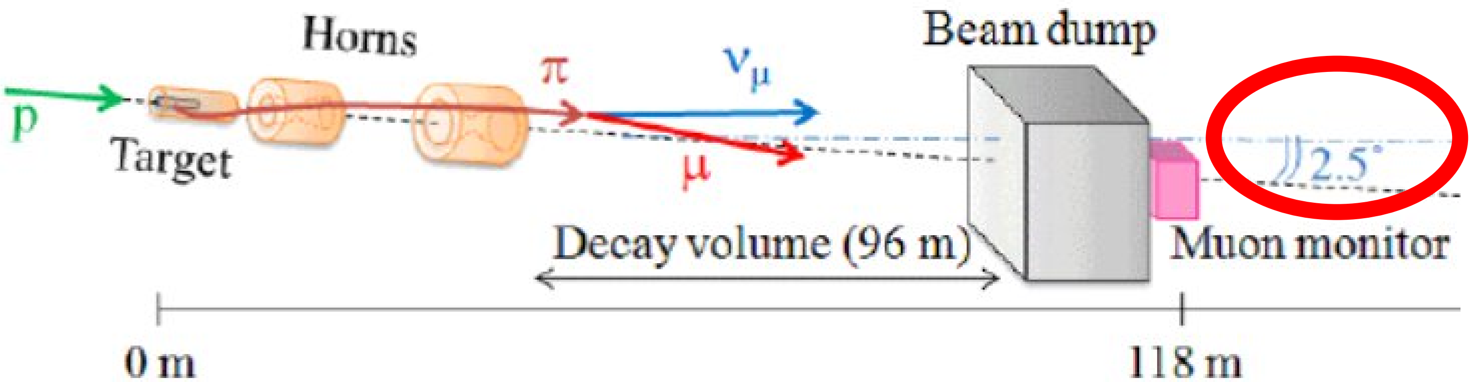


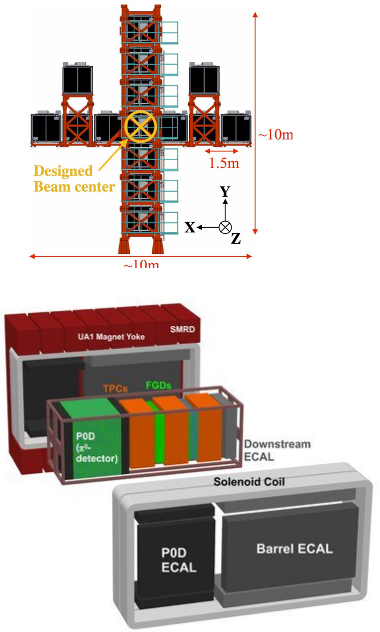
ND280

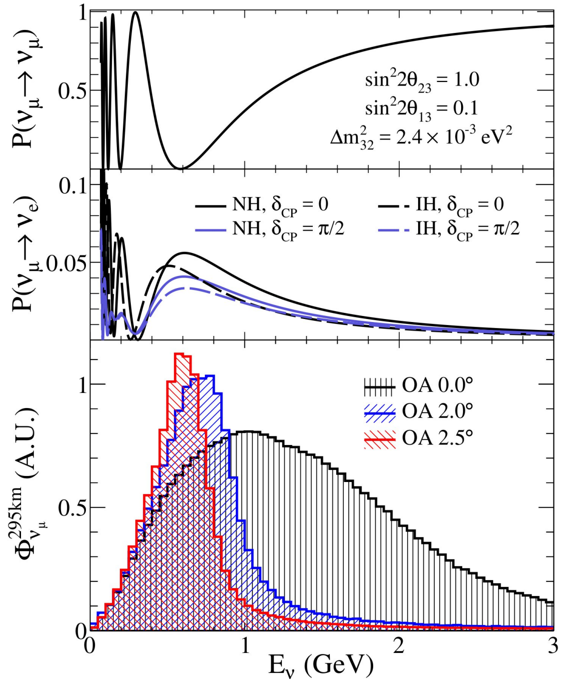


But what do we actually do?

JPARC

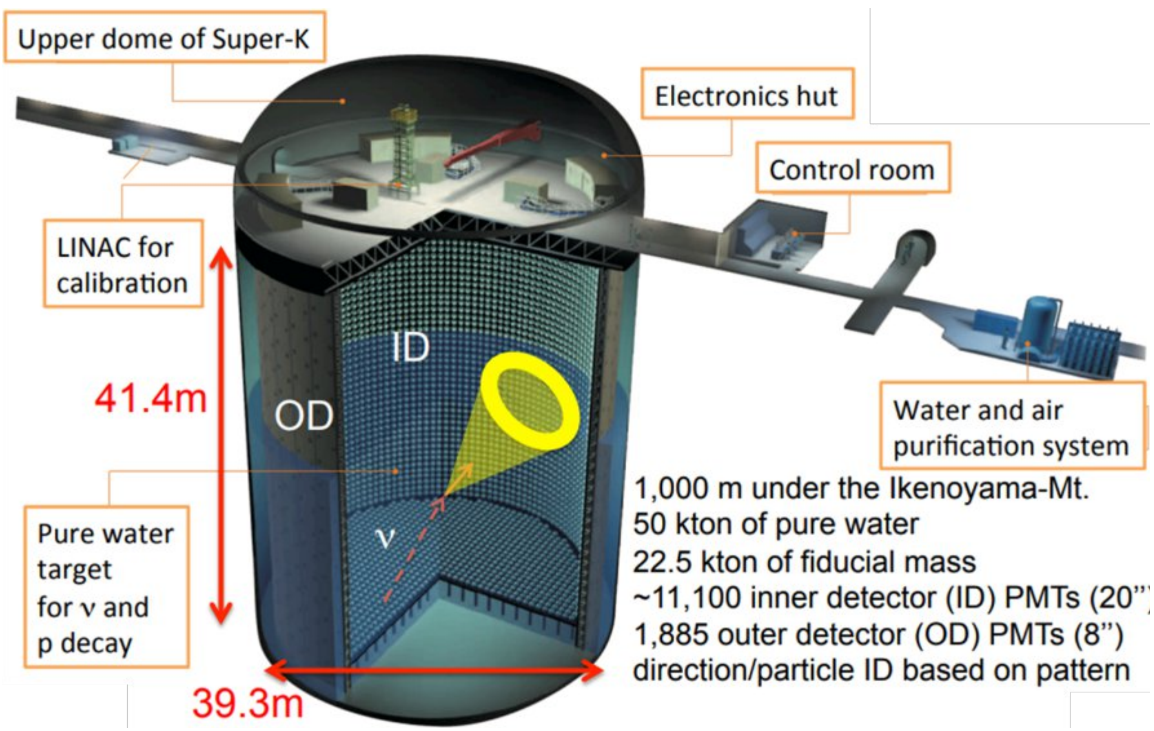




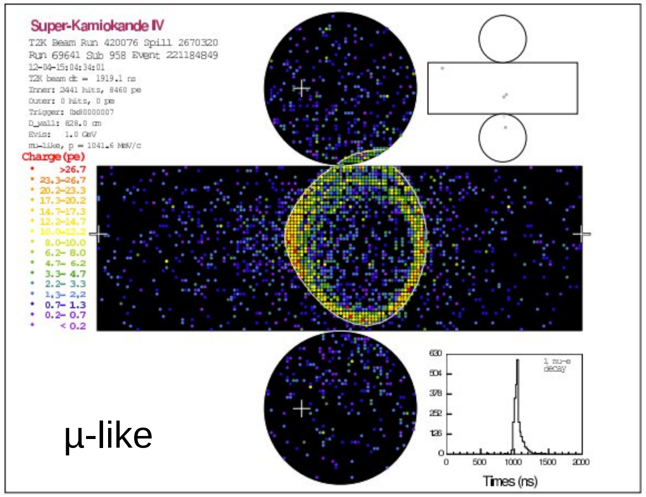


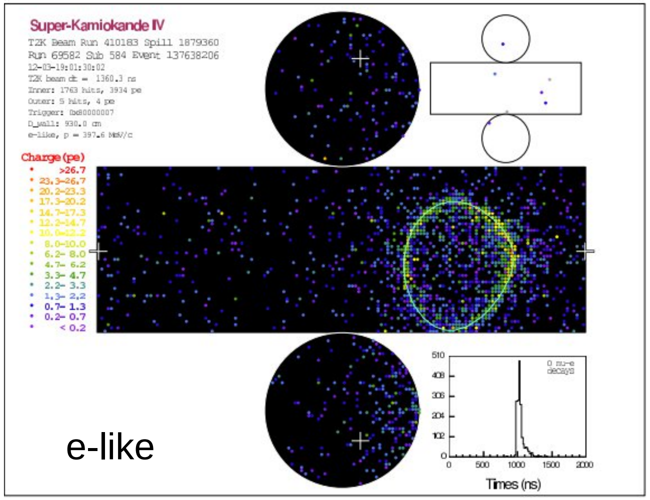
- Off-axis effect makes the flux peak at the energy for maximum muon neutrino disappearance and electron neutrino appearance probabilities at SK - also reduces electron neutrino contamination in the beam
- ND280 data used in combined ND-SK analysis to provide constraints on the oscillation parameters
- 14% to 5-7% with ND280 constraint
- ND280 also performs neutrino cross-section measurements

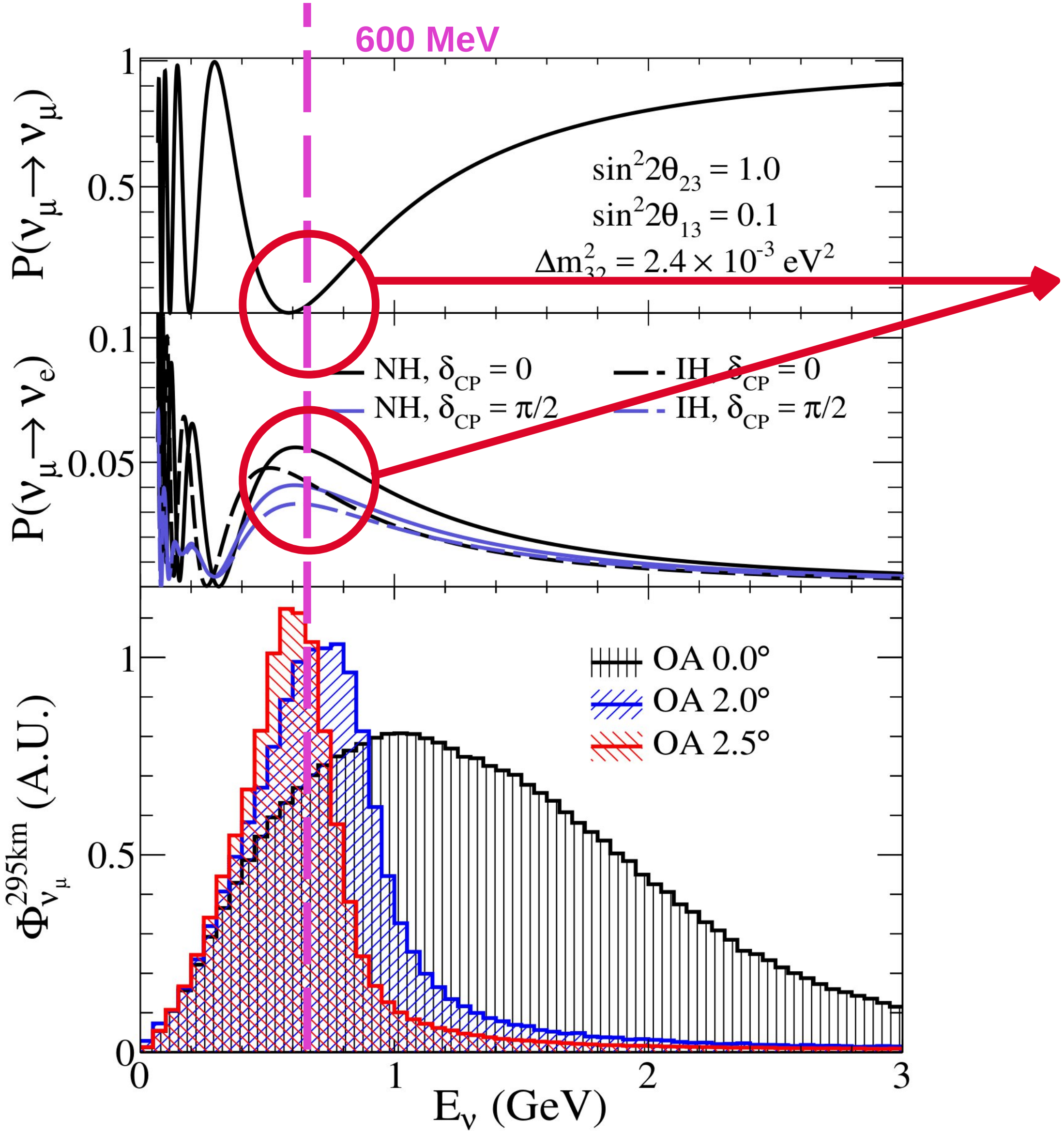
1 MILLISECOND LATER



1,000 m under the Ikenoyama-Mt.
50 kton of pure water
22.5 kton of fiducial mass
~11,100 inner detector (ID) PMTs (20")
1,885 outer detector (OD) PMTs (8")
direction/particle ID based on pattern

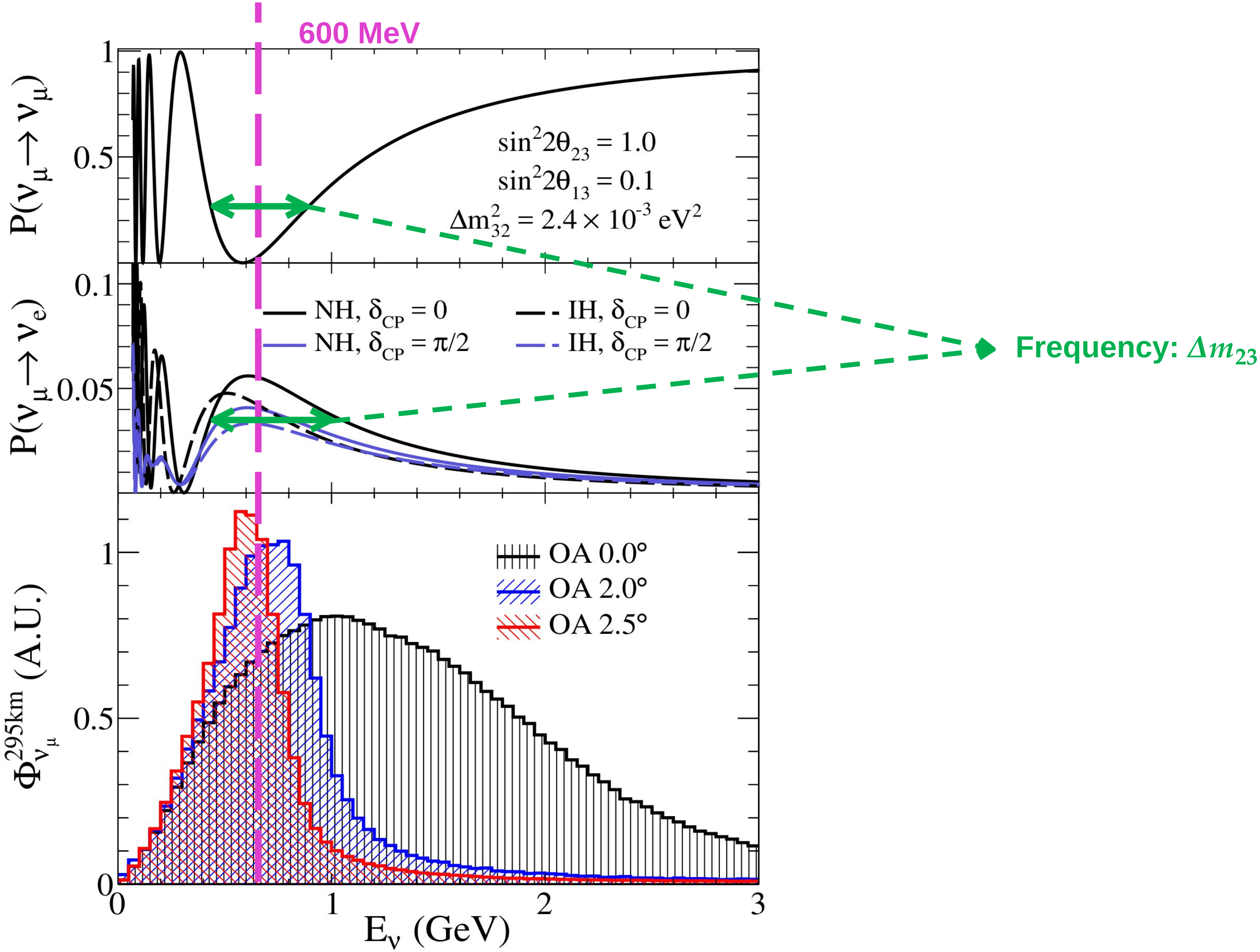




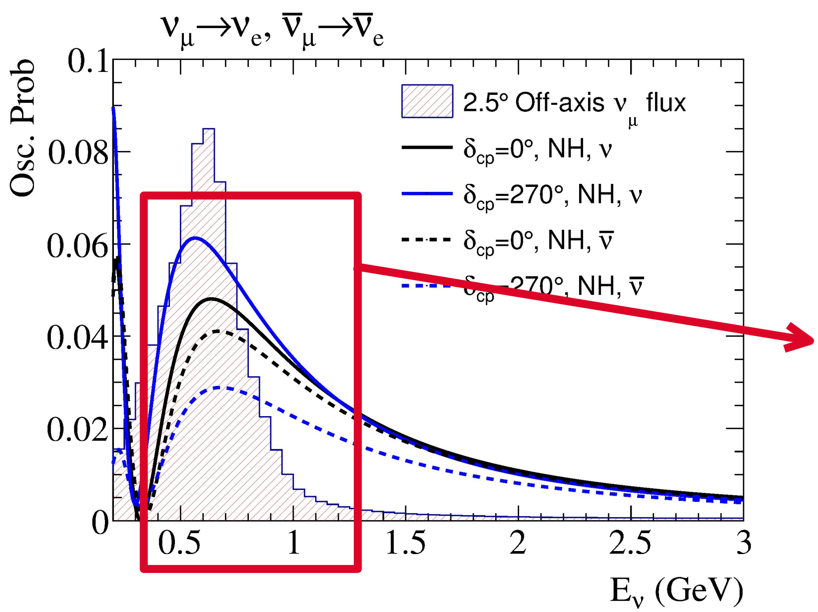


Amplitude of dip in numu and peak in nue : $\sin(\theta_{23})$

WHAT WE CAN MEASURE



WHAT WE CAN MEASURE

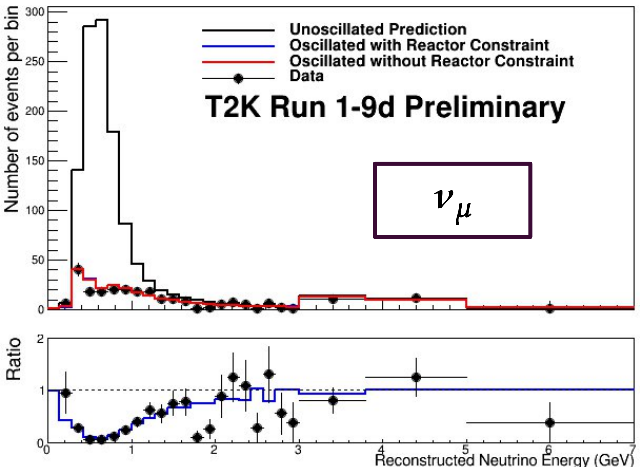


δ_{CP} value inferred from electron neutrino-antineutrino asymmetry $\frac{\nu_e - \overline{\nu_e}}{\nu_e + \overline{\nu_e}}$

Predicted and recorded event rates at Super-K for different values of δ_{CP} @ 3.13x10^{21} POT

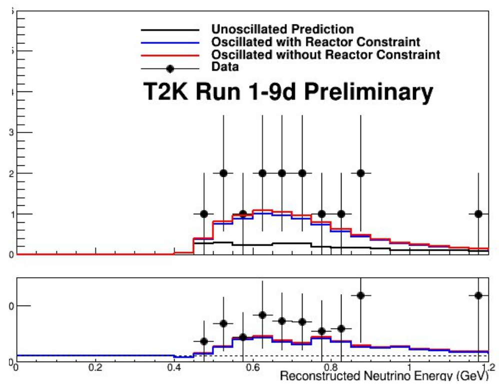
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	**Data**	**MC syst.err.**
1-Ring μ (ν)	272.34	271.97	272.30	272.74	243	5.5%
1-Ring μ ($\overline{\nu}$)	139.47	139.12	139.47	139.82	140	4.4%
1-Ring e (ν)	74.46	62.26	50.59	62.78	75	8.8%
1-Ring e ($\overline{\nu}$)	17.15	19.57	21.75	19.33	15	7.3%
1-Re (ν) CC1π	7.02	6.10	4.94	5.87	15	17.8%

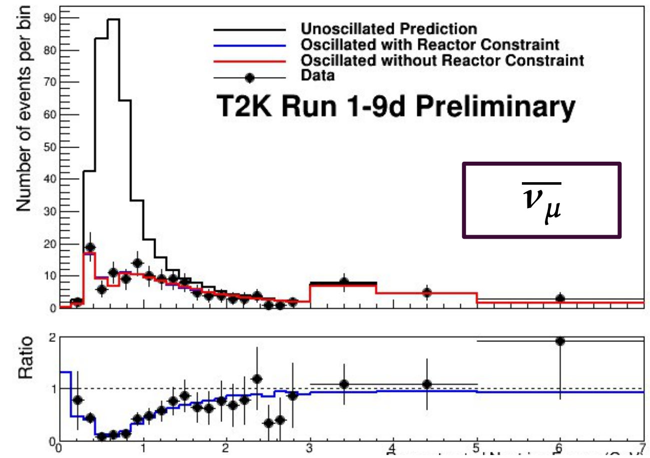
WHAT WE DO MEASURE

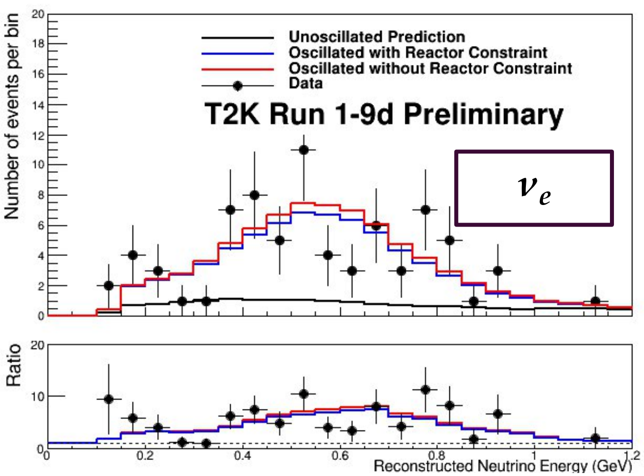


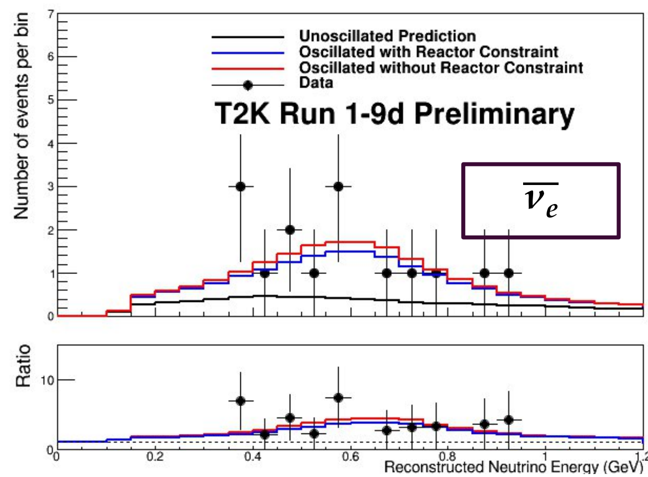
$3x10^{21}$ POT

New sample: 1Ring e $CC1\pi^+$ at SK





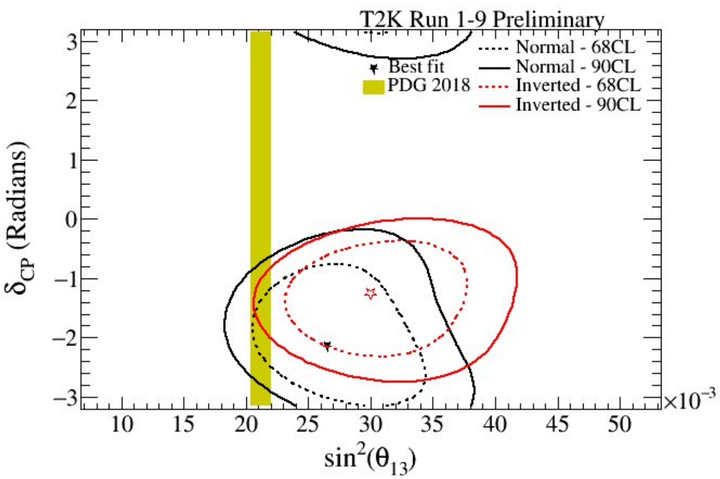




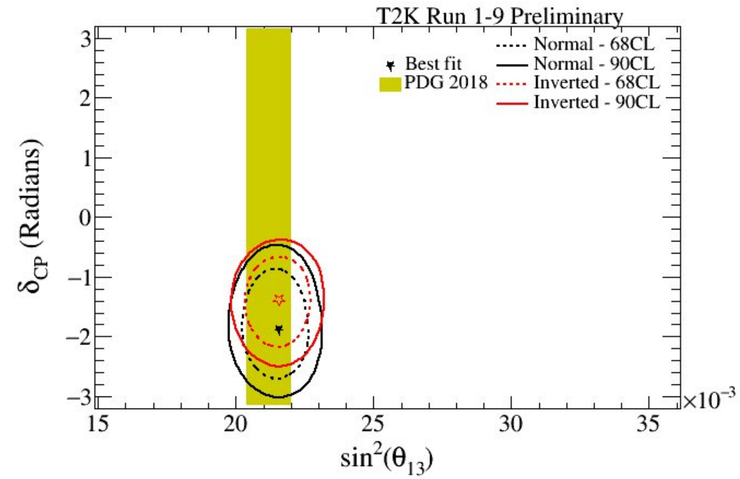
9 YEARS OF ANALYSIS LATER: CURRENT LATEST RESULTS

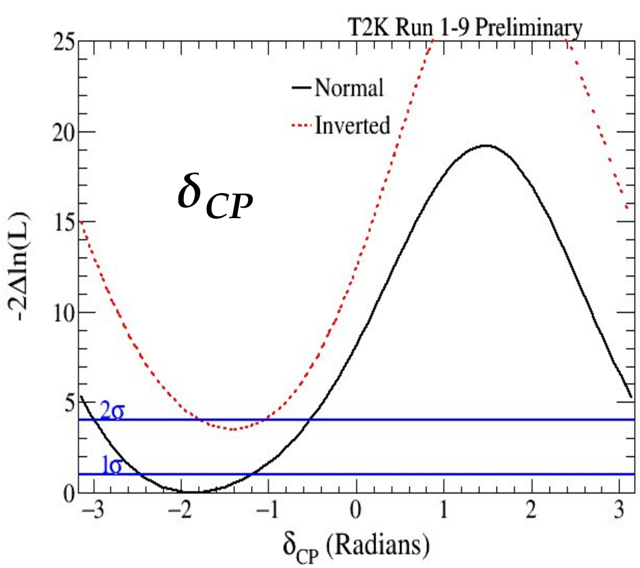
Without reactor constraint

With reactor constraint

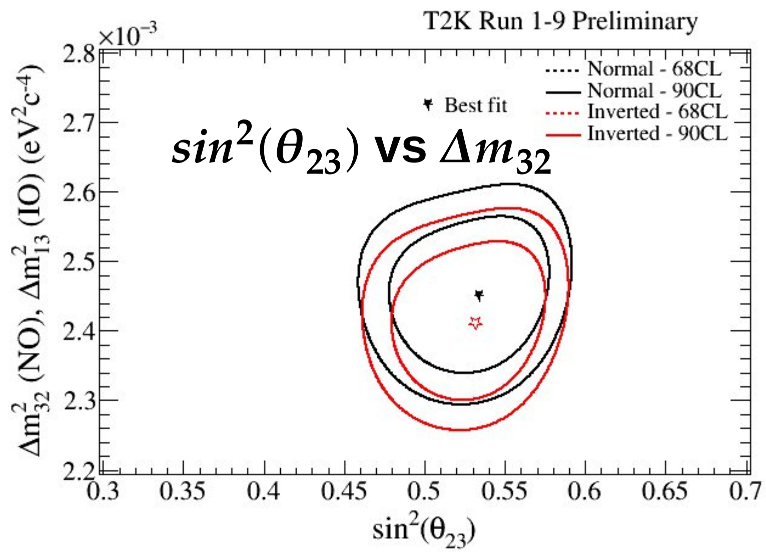


$sin(\theta_{13})$





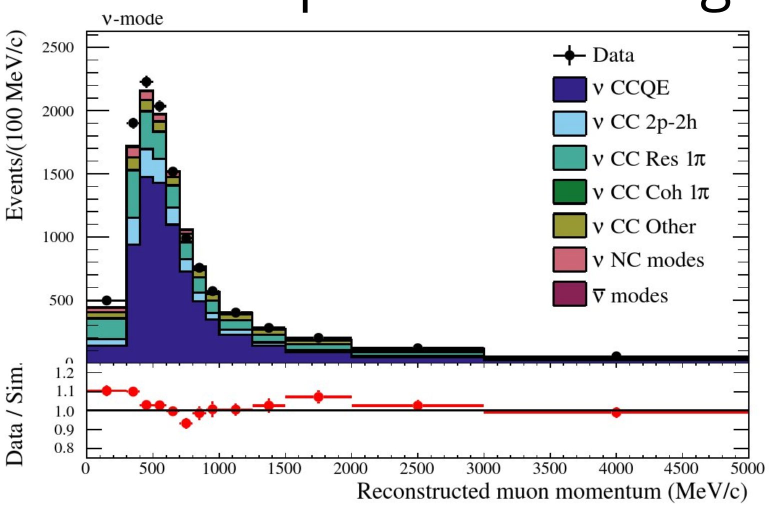
δ_{CP}



$sin^2(\theta_{23})$ vs Δm_{32}

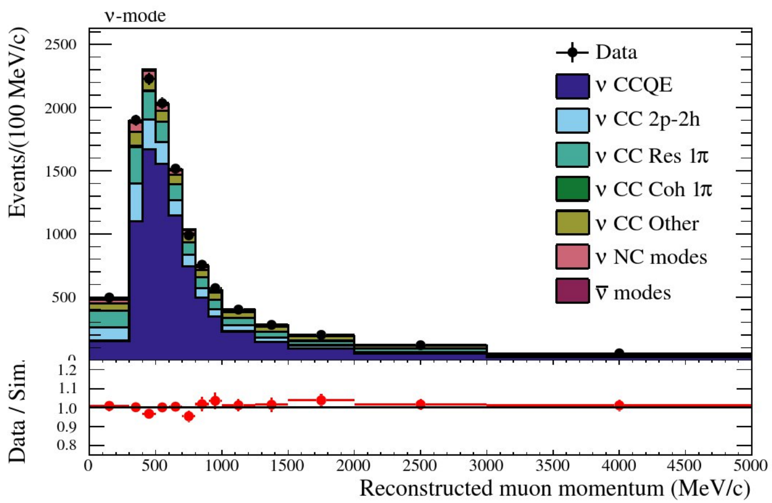
How do we reach such results?

- **Joint near-far detectors fit** -> ND280 has a large impact in lowering systematic uncertainties



PRELIMINARY

ND280 Prefit



PRELIMINARY

ND280 Postfit

Source	1-Ring μ (ν)	1-Ring μ ($\overline{\nu}$)	1-Ring e (ν)	1-Ring e ($\overline{\nu}$)	1-Re (ν) CC1π
Beam + x-sec (w/o ND280)	14.5%	12.6%	14.5%	13.0%	12.6%
Beam + x-sec (w ND280)	4.4%	2.9%	7.7%	5.7%	5.6%
Total (w ND280)	5.5%	4.4%	8.8%	7.3%	17.8%

What's keeping us

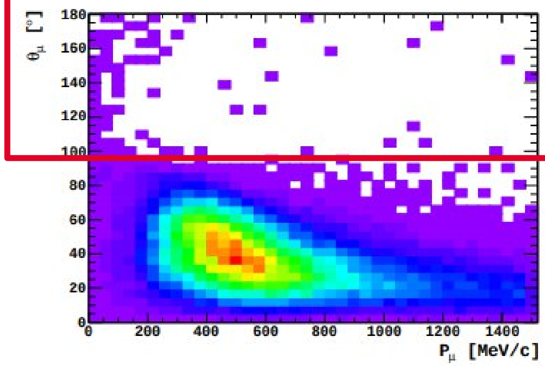
- Statistics
  - JPARC Beam Power -> Upgrade run 2024 (data taking ongoing)
- Systematics
  - Nuclear effects, Flux constraints and Neutrino interaction Cross-sections -> upgrade of ND280

Source	**1-Ring μ (ν)**	**1-Ring μ ($\overline{\nu}$)**	**1-Ring e (ν)**	**1-Ring μ ($\overline{\nu}$)**	**1-Re (ν) CC1π**
x-sec (with ND280)	5.6%	4.4%	8.4%	6.2%	5.6%
Total systematic	5.5%	4.4%	8.8%	7.3%	17.8%
Total statistics	6.42%	8.45%	11.55%	25.82%	25.82%

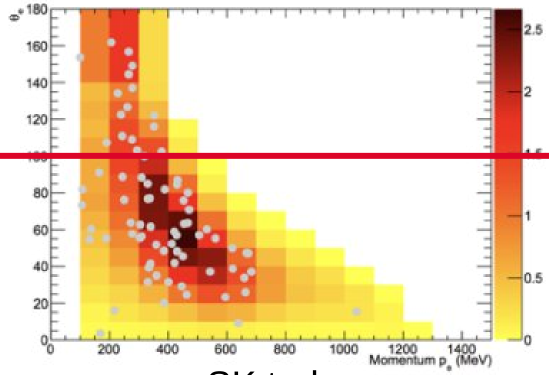
What can we do about it?

Requirements for the upgrade

- Increase phase space and statistics for both muons and protons



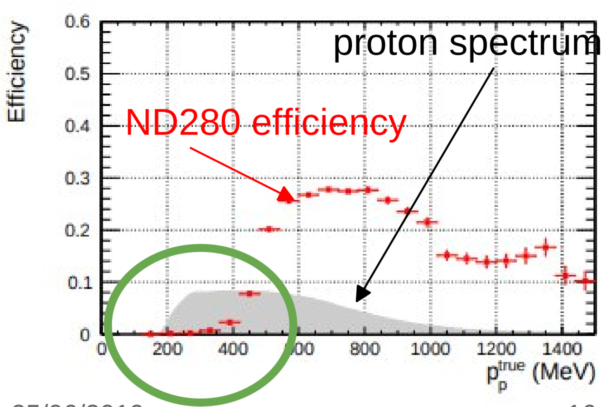
ND280 today

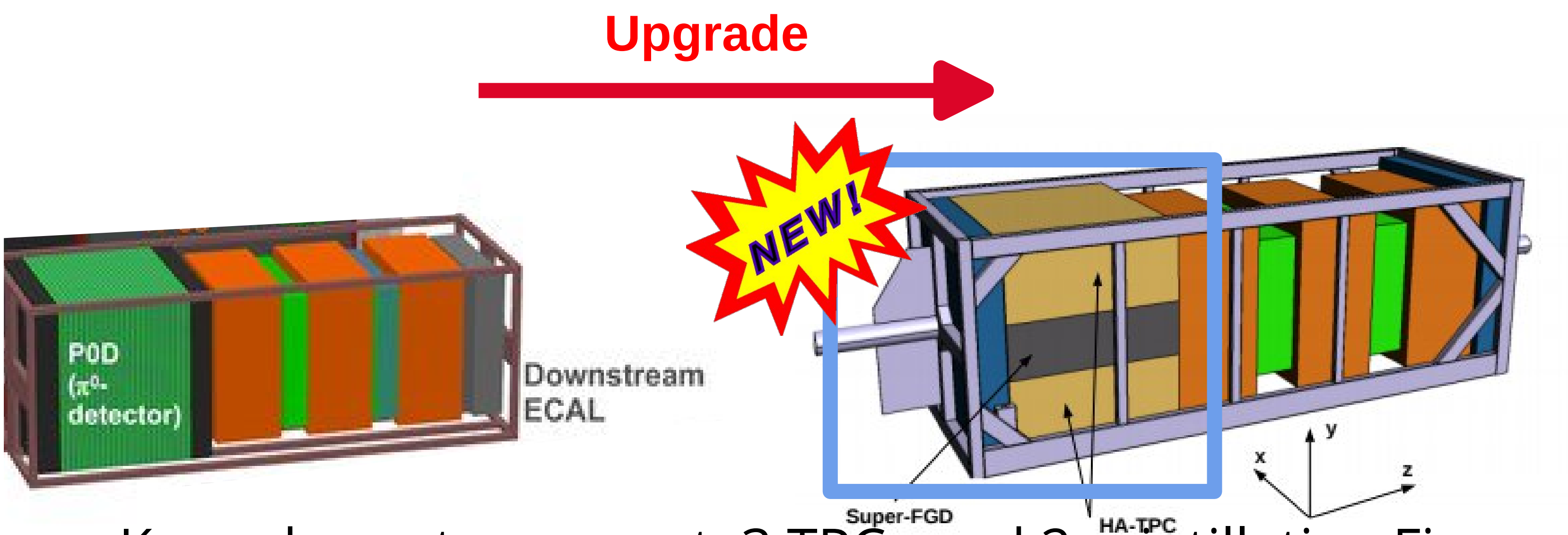


SK today

We're missing a lot of low momentum and backwards-angle muons

- Better phase space acceptance decreases neutrino-nucleus systematics and the model dependence of the analysis
- ND280 cannot detect low-momentum protons - lots of different physics lost
- Neutron tagging - may help with antineutrinos

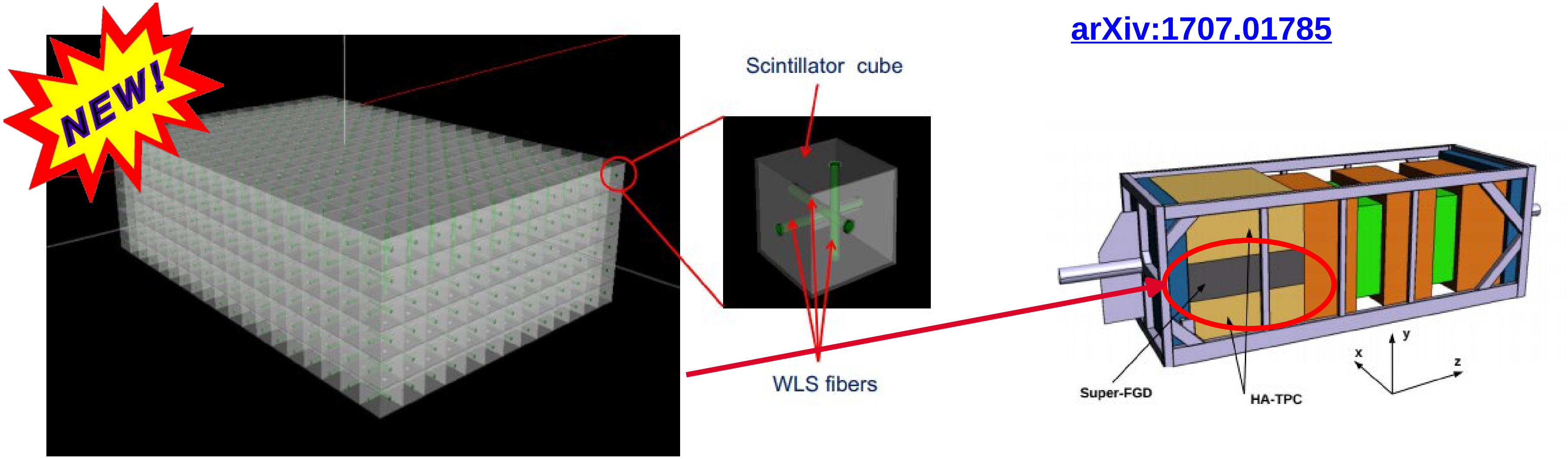




- Keep downstream part: 3 TPCs and 2 scintillating Fine Grained Detectors (FGD)
- Replace upstream part with 1 3D 2t Fine Grained Detector (SuperFGD) and 2 High-Angle TPCs (HA-TPC)
  - NEW GEOMETRY WILL ALLOW FULL POLAR ACCEPTANCE AND IMPROVED 3D TRACKING
- Target installation date : 2021
- Goal: collect 20×10^{21} POT in 2022-2026 to establish 3σ CPV

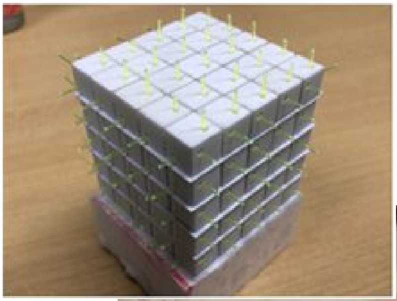
SUPER FINE-GRAINED DETECTOR (SUPERFGD)

arXiv:1707.01785



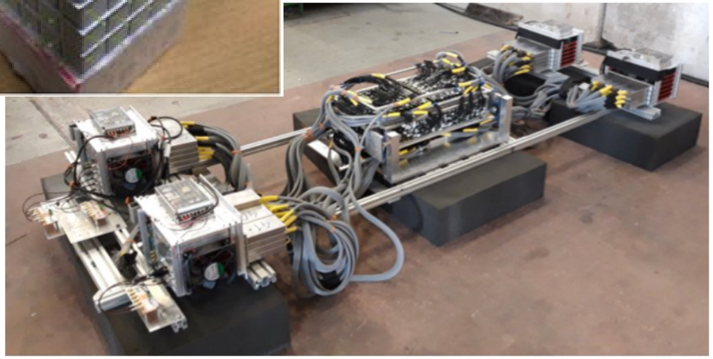
- Plastic scintillator cubes connected by optical fibers along (x,y,z)
- ~2m x 2m x 0.6m and 2t mass in 2 million 1 cm-wide cubes
- 3D Geometry - reconstruct tracks with less hits
  - ALSO REDUCES PROTON MOMENTUM THRESHOLD
  - BONUS: NEUTRON DETECTION POTENTIAL
- Test beam at CERN in 2018
- Ongoing assembly of larger prototype to define assembly method
- Performance: 40 p.e./cube/fiber for a MIP

SUPER FINE-GRAINED DETECTOR (SUPERFGD)

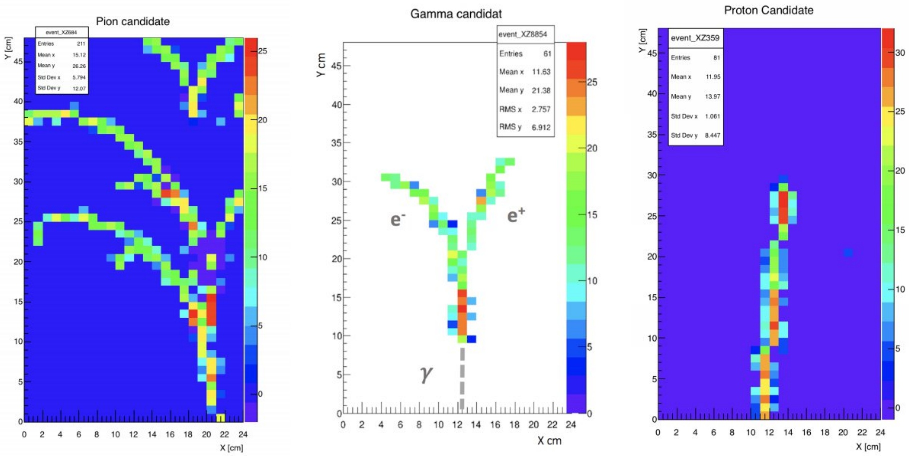


5x5x5 protype

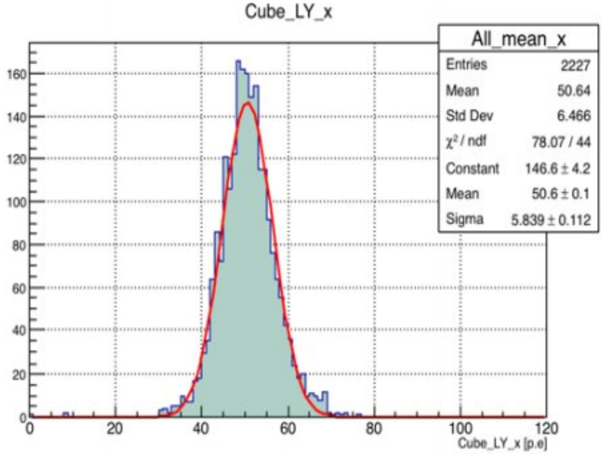
CERN Prototype
48x24x8



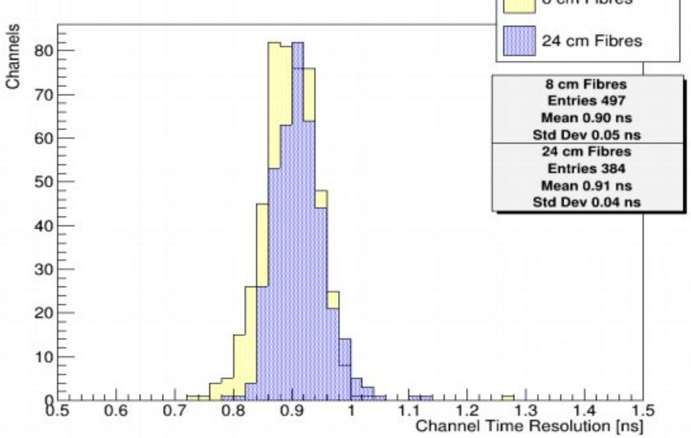
Prototype tested at CERN in 2018



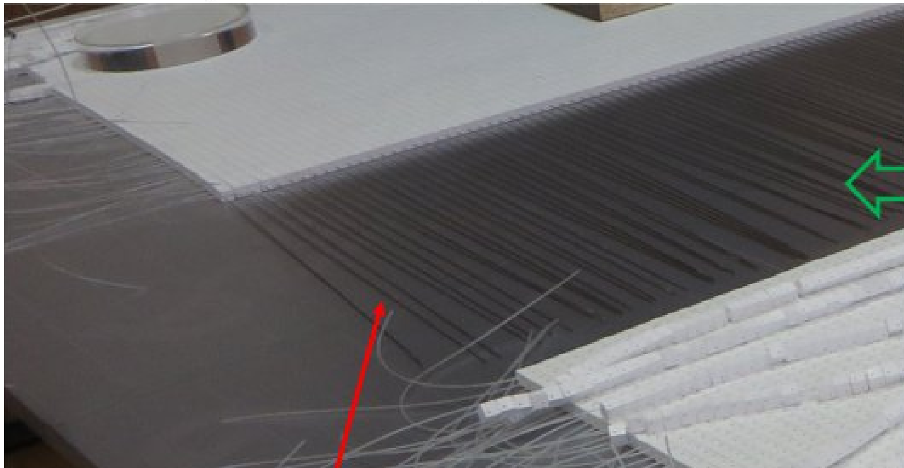
MIP LY: ~50 p.e. per fiber

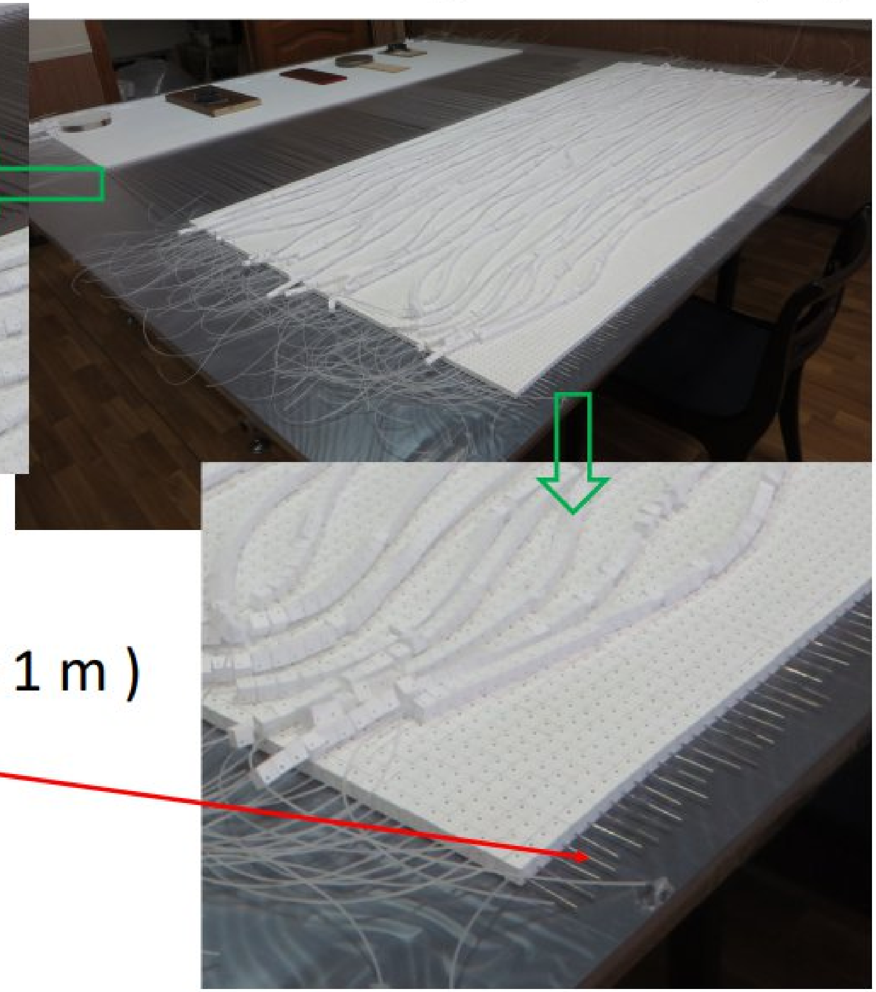


0.95 ns time resolution per fiber



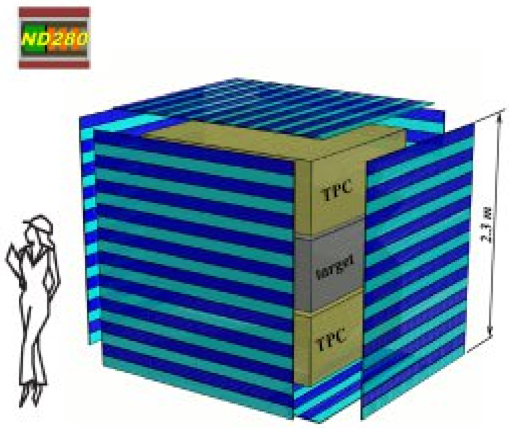
SUPER FINE-GRAINED DETECTOR (SUPERFGD)

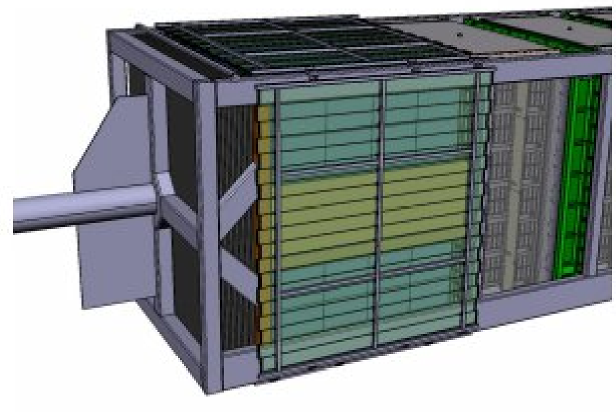




Welding rods (⃠1.2 mm, length = 1 m)
to be replaced
by a fishing line (⃠ ~1.4 mm)

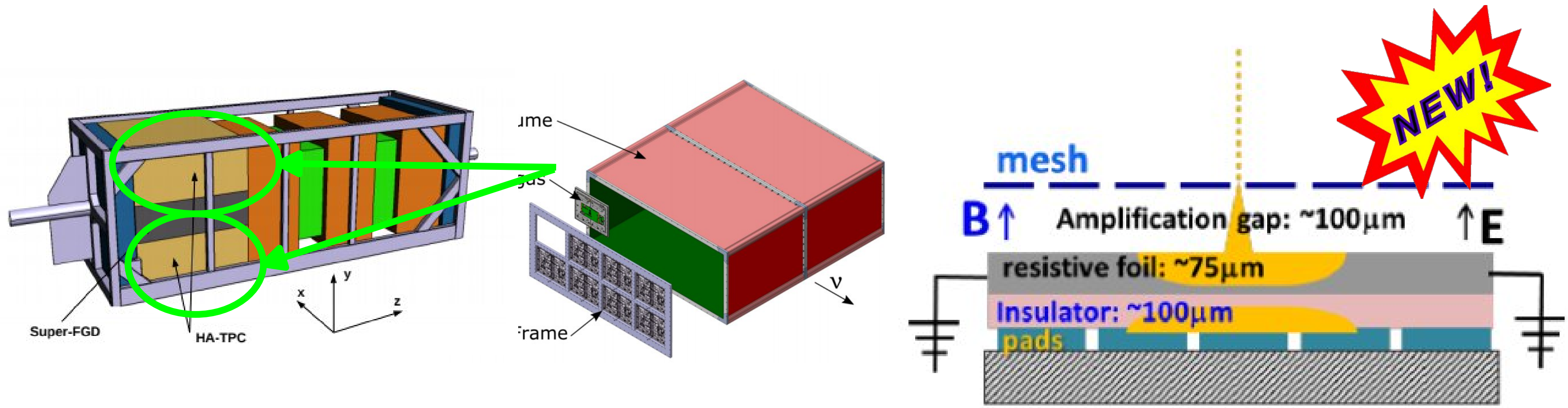
Now devising assembly method





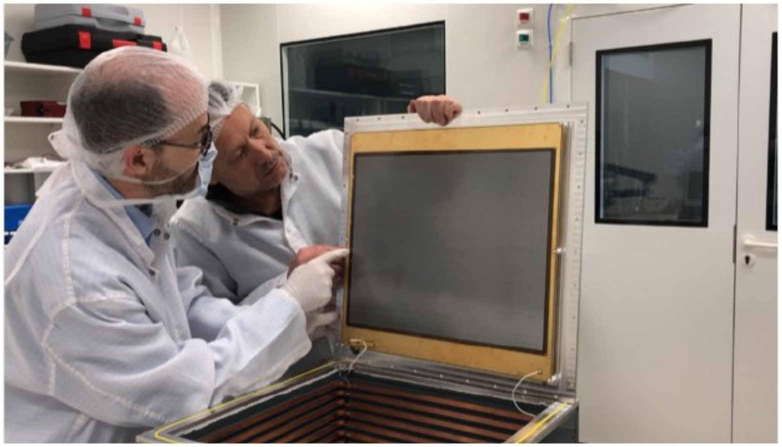
- Plastic scintillator based detector (MPPCs)
- Needed to achieve the timing resolution to distinguish between backward going positive particles and forward-going negative particles and high angle tracks
- 2018 CERN test beam results: timing resolution of the order of 150 ps

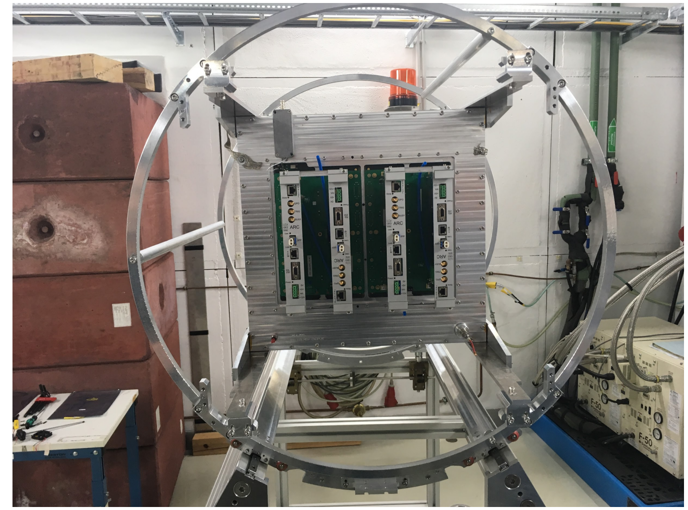
HIGH ANGLE TIME PROJECTION CHAMBER (HA-TPC)



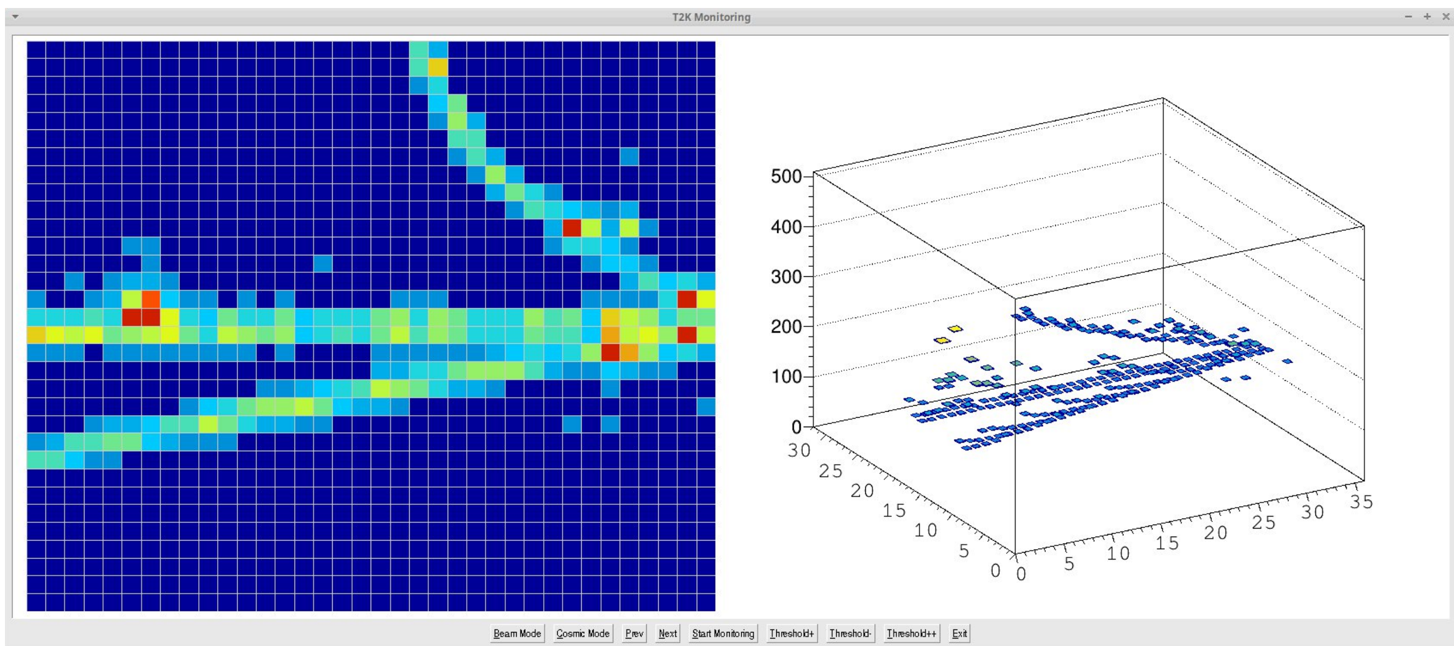
- 2 extra TPCs to track high angle tracks for nearly 4π acceptance
- Novelty: resistive MicroMegas technology - charge spreading improves spatial resolution with larger pads and less electronic channels (based on ILC R&D)
- Test beam summer 2018 at CERN (no magnetic field) - paper coming out soon
- Test beam (fresh out of the oven - last week) at DESY (0.2 T B field) - analysis ongoing

High Angle Time Projection Chamber (HA-TPC)

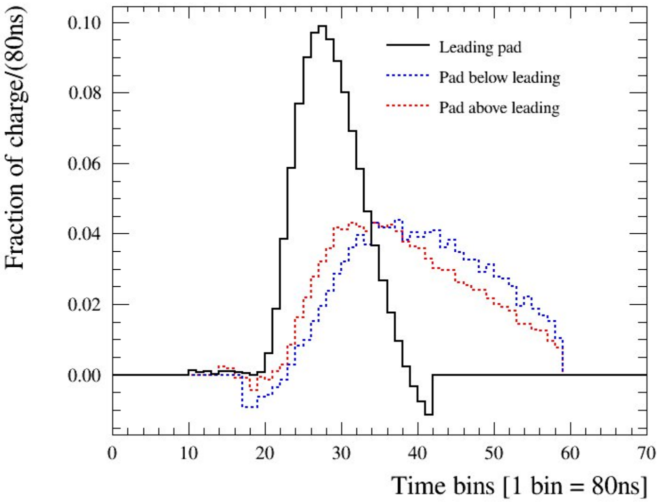


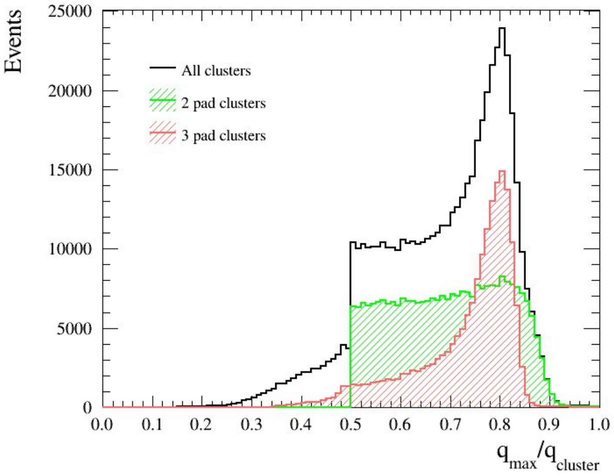


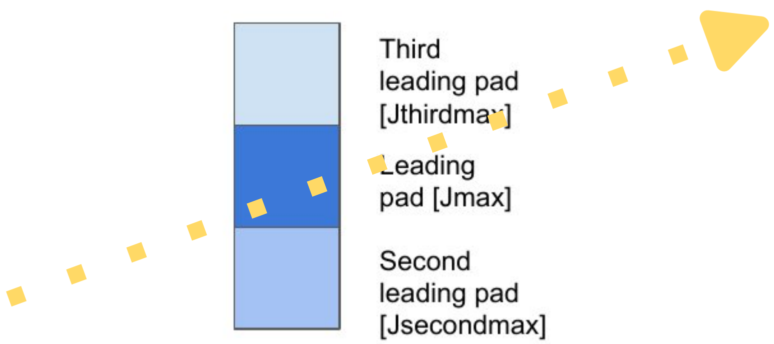
Last two weeks @ DESY

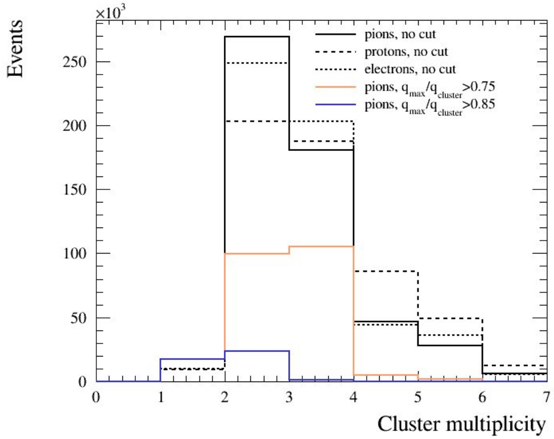


- First studies on the charge spreading phenomenon in this resistive micromegas detector



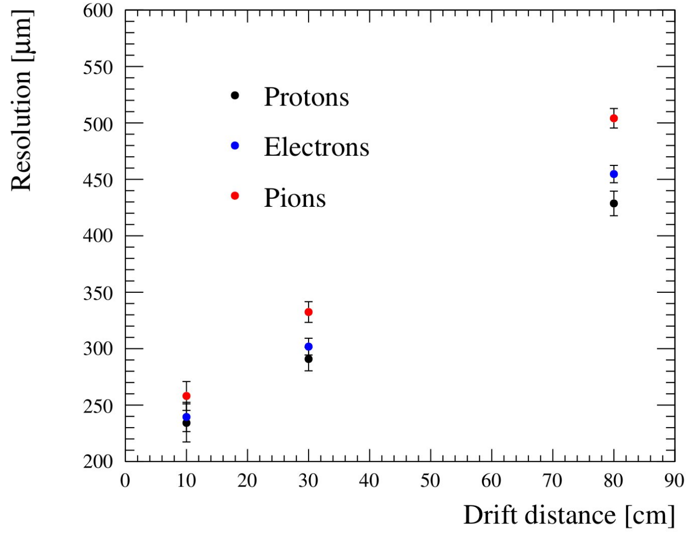




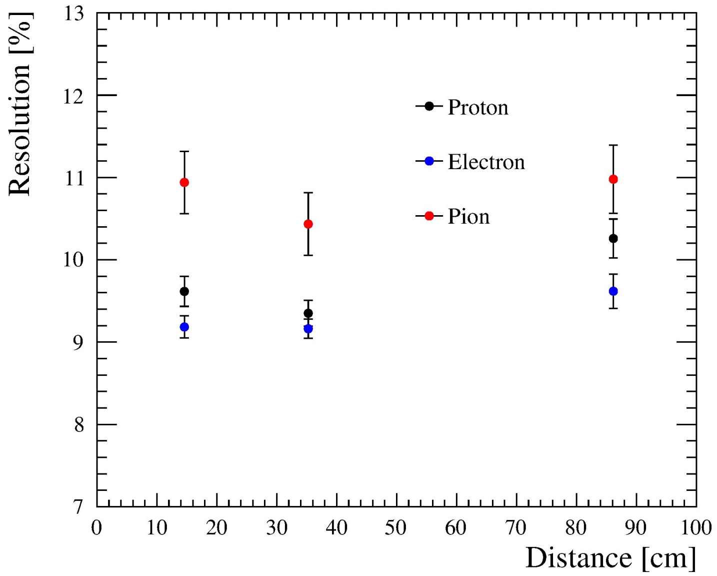


HA-TPC CERN 2018 Test Beam Results: Spatial Resolution

- Main advantage of resistive micromegas: improved spatial resolution - Spatial resolution of 300 μm @ 30 cm drift distance thanks to charge sharing between pads - almost a 1.5x improvement



- dE/dx resolution:

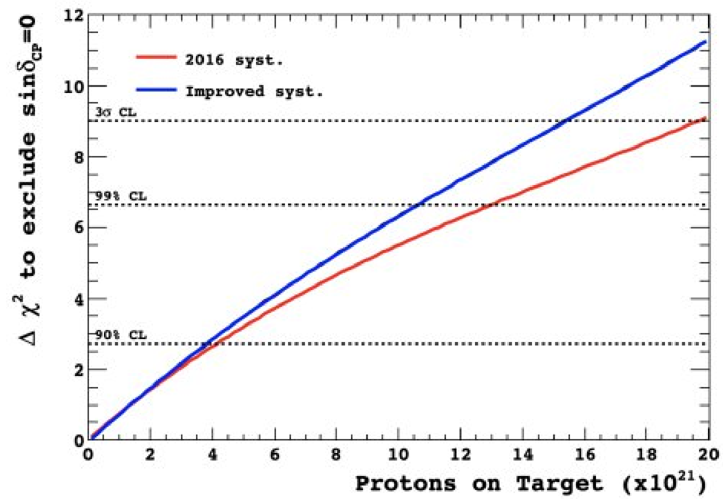


All of this looks nice and fancy, but what is it actually worth?

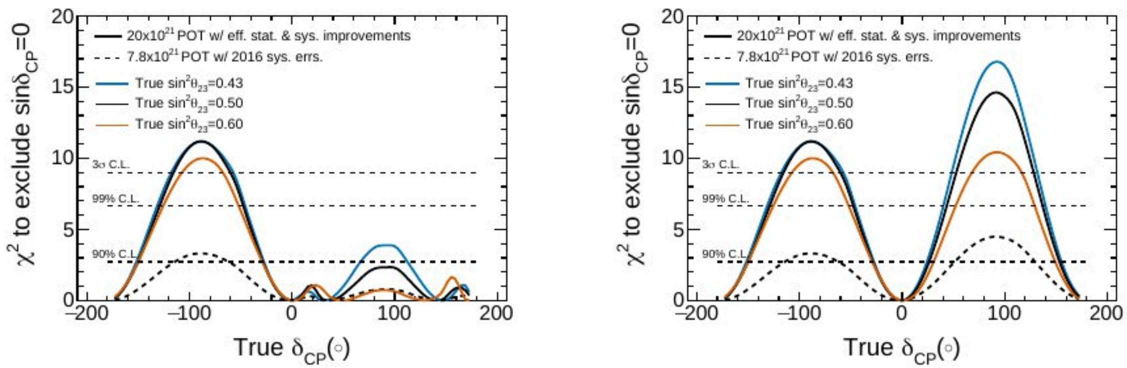
SYSTEMATICS-WISE

- 30% improvement in systematic constraints w.r.t ND280 for the same POT

Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation	3.1	2.4
$(0.6 < E_\nu < 0.7$ GeV)		
MA_{QE} (GeV/c^2)	2.6	1.8
ν_μ 2p2h normalisation	9.5	5.9
2p2h shape on Carbon	15.6	9.4
MA_{RES} (GeV/c^2)	1.8	1.2
Final State Interaction (π absorption)	6.5	3.4



- 3σ sensitivity on δ_{CP} !!!



(a) Assuming the MH is unknown.

(b) Assuming the MH is known – measured by an outside experiment.

- 30% improvement in systematic constraints w.r.t ND280 for the same POT

SK

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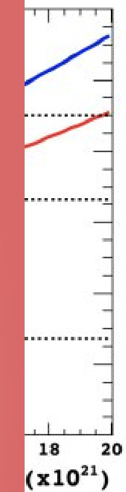
2p2

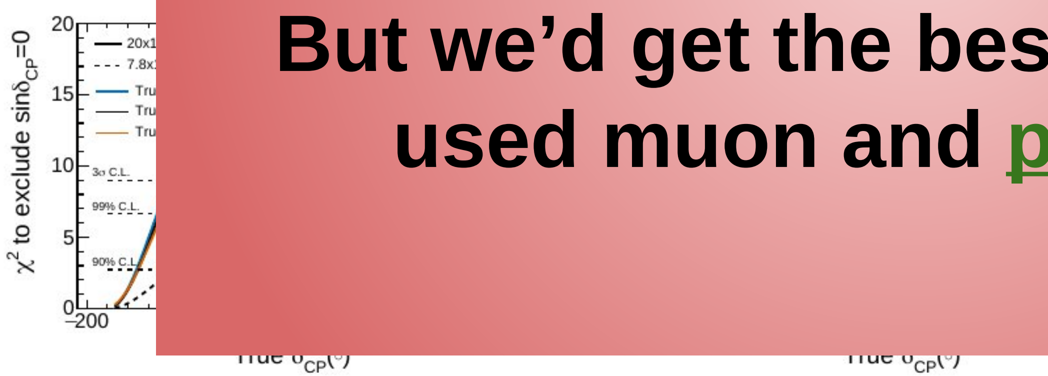
Final State



This is only using muon information to reconstruct the neutrino energy kinematically.

But we'd get the best results if we used muon and proton data

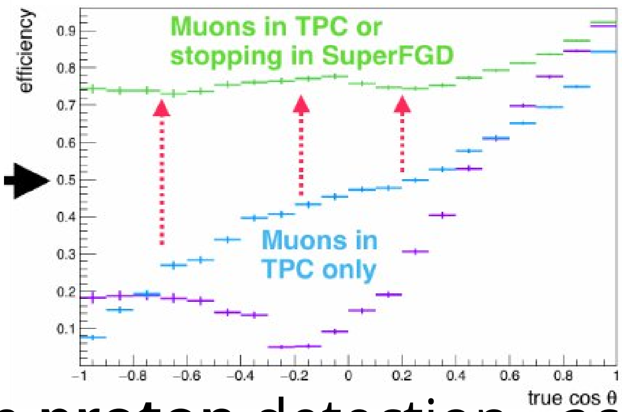
- 3σ



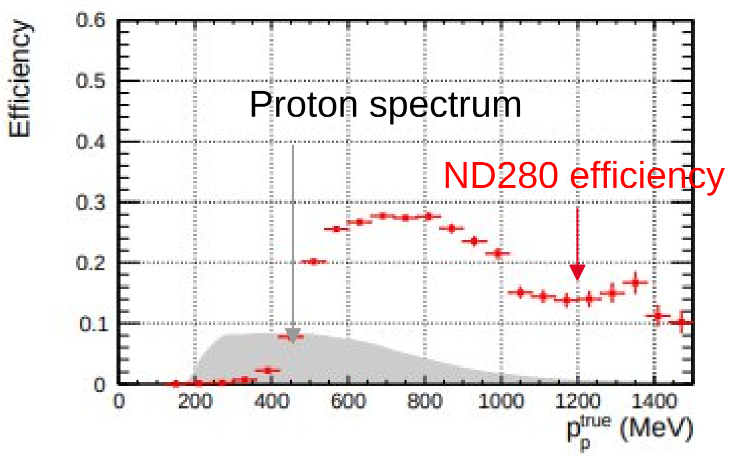
(a) Assuming the MH is unknown.

(b) Assuming the MH is known – measured by an outside experiment.

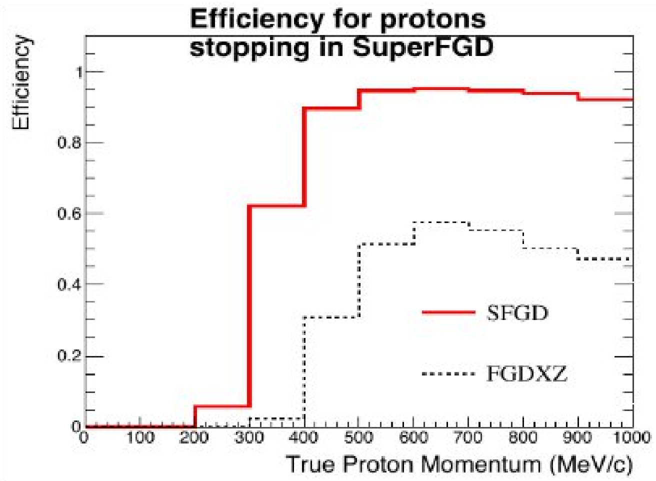
- Increase **muon** detection efficiency - lower threshold and 4π acceptance



- Allow low momentum **proton** detection - access to valuable new physics relevant for the oscillation analysis



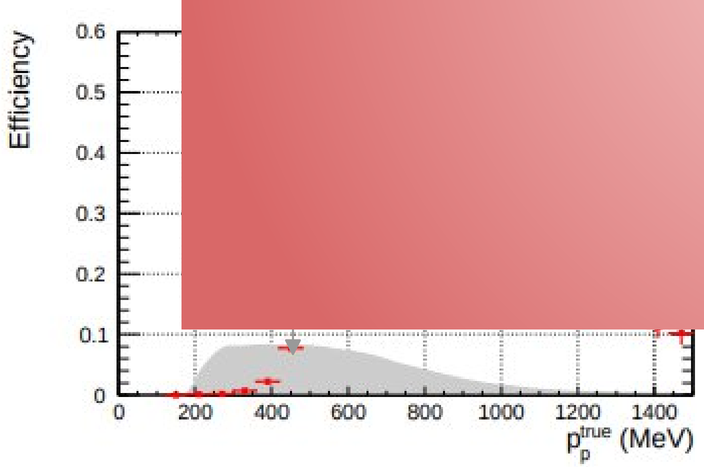
Upgrade

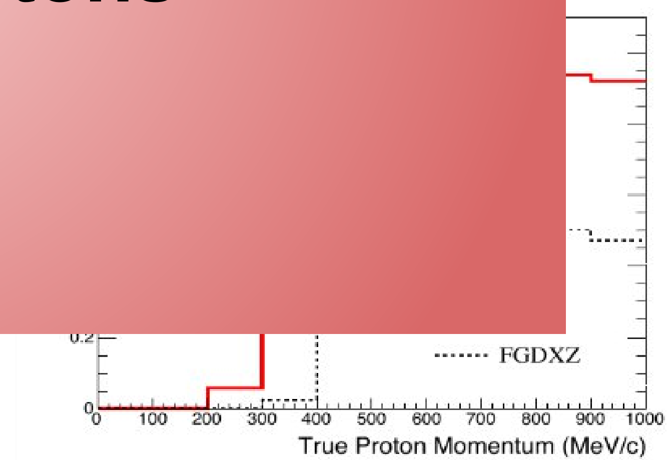


PARTICLE DETECTION-WISE

- Increase **muon** detection efficiency - lower threshold
- able

In the following slides I'll show you how we can make use of these low-momentum protons

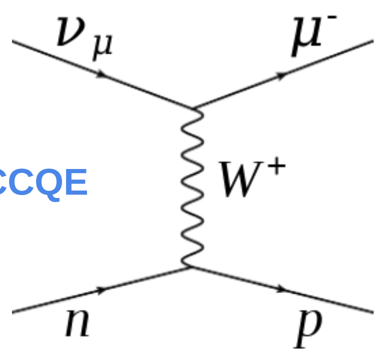


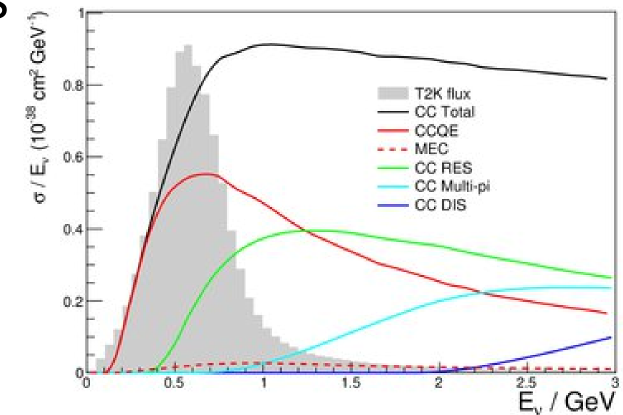


Neutrino energy reconstruction is done by assuming CCQE (Charged-Current Quasi-Elastic) Interactions

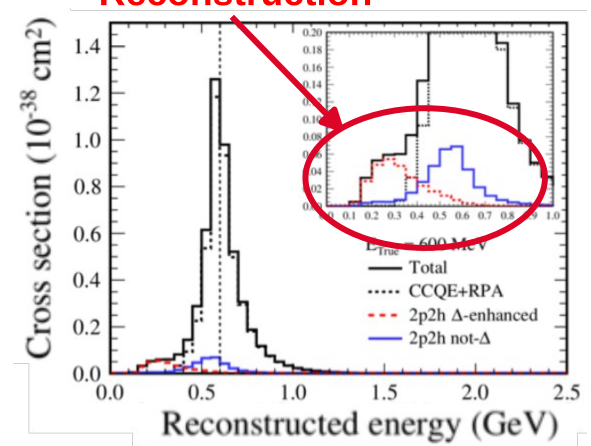
$$E_\nu^{\rm rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l\cos\theta_l)}$$

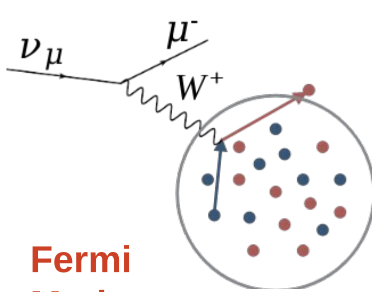
CCQE



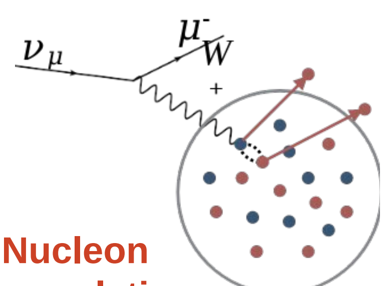


Bias in Neutrino Energy Reconstruction

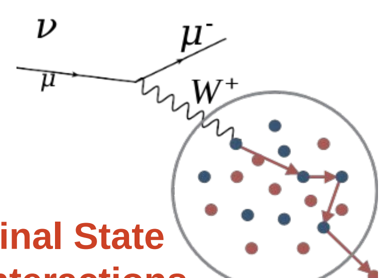




Fermi Motion

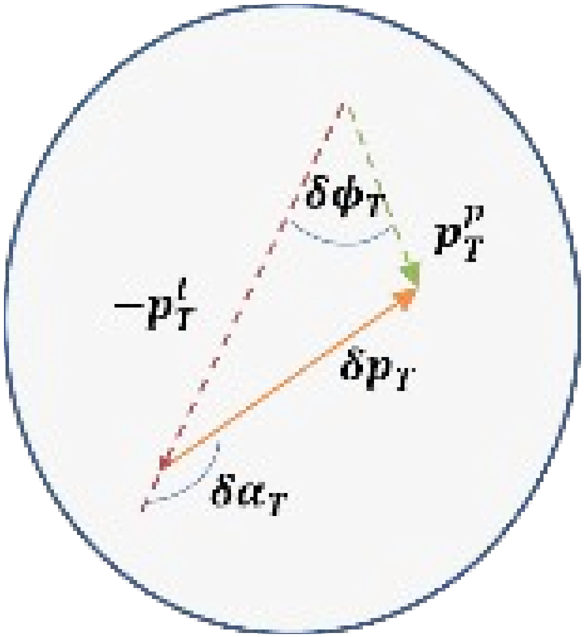


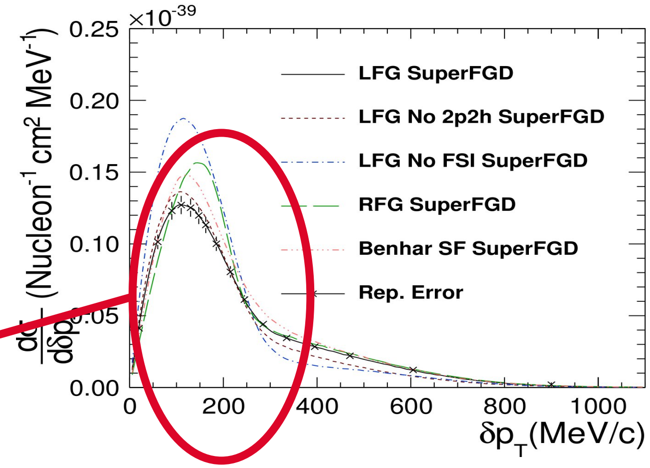
Nucleon correlations (2p2h)

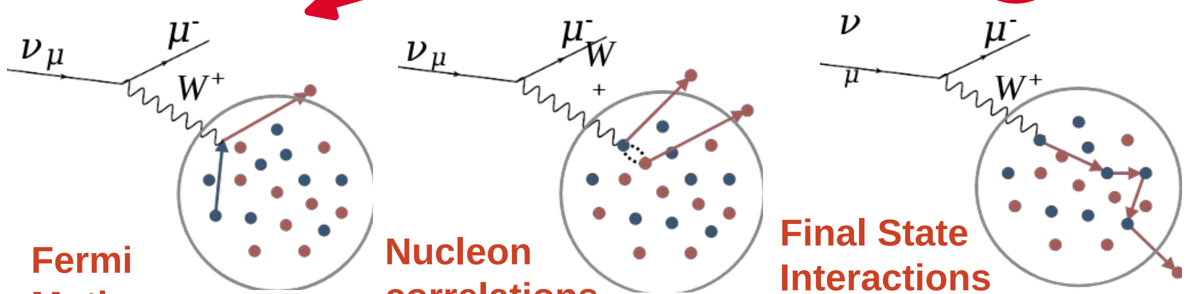


Final State Interactions (FSI)

- δp_T directly translates to the Fermi motion of the nucleons inside the nucleus





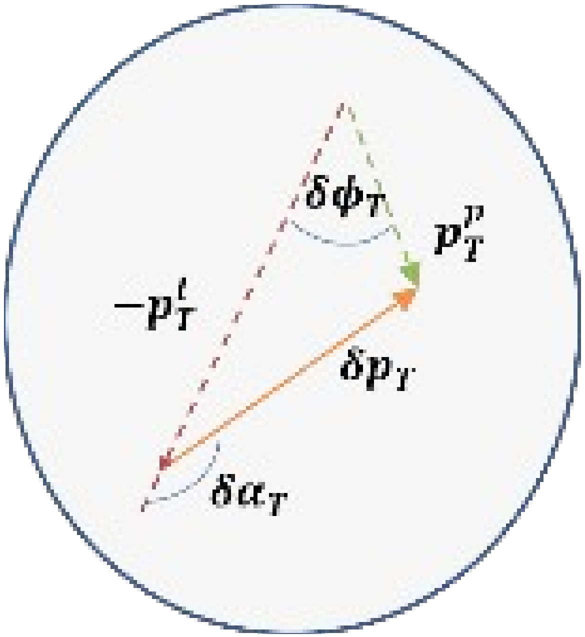


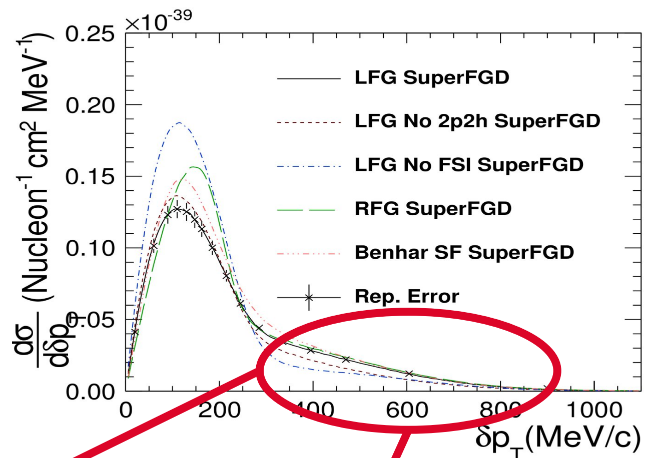
Fermi Motion

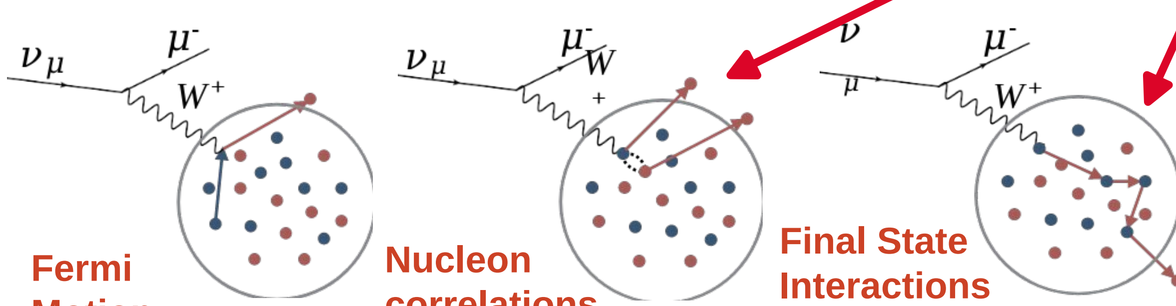
Nucleon correlations (2p2h)

Final State Interactions (FSI)

- 2p2h and FSI events decelerate particles - they populate the tail of the distribution of δp_T





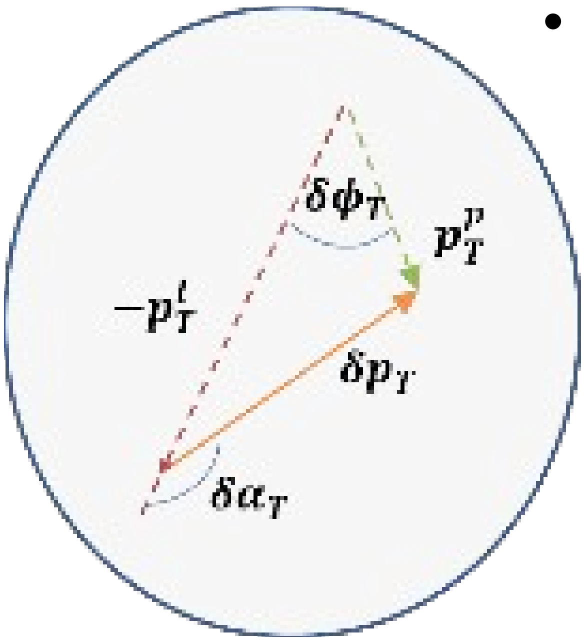


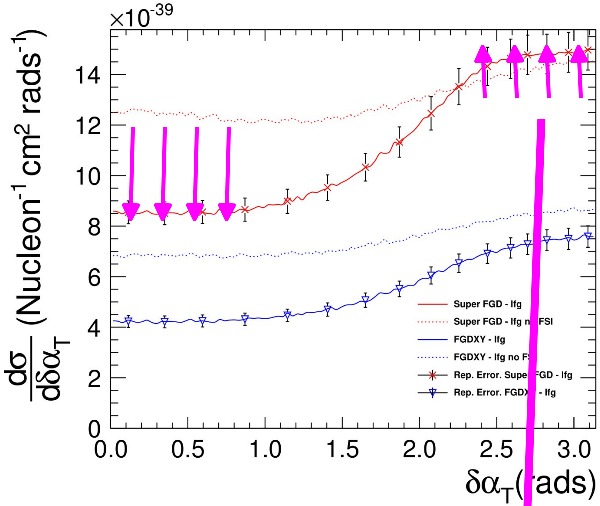
Fermi Motion

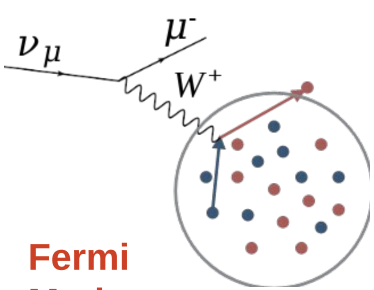
Nucleon correlations (2p2h)

Final State Interactions (FSI)

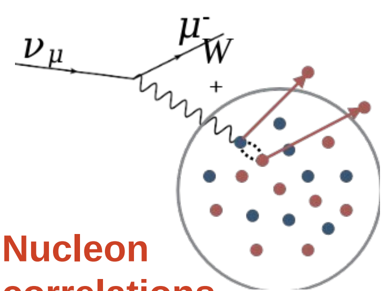
- The deceleration due to FSI also alters the direction of the tranverse momentum - shifts $\delta\alpha_T$ towards π



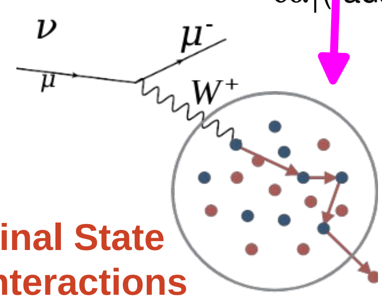




Fermi Motion



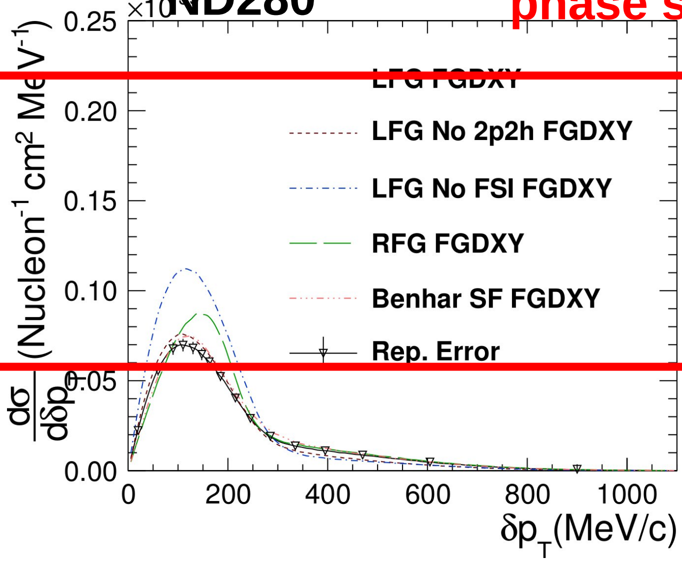
Nucleon correlations (2p2h)

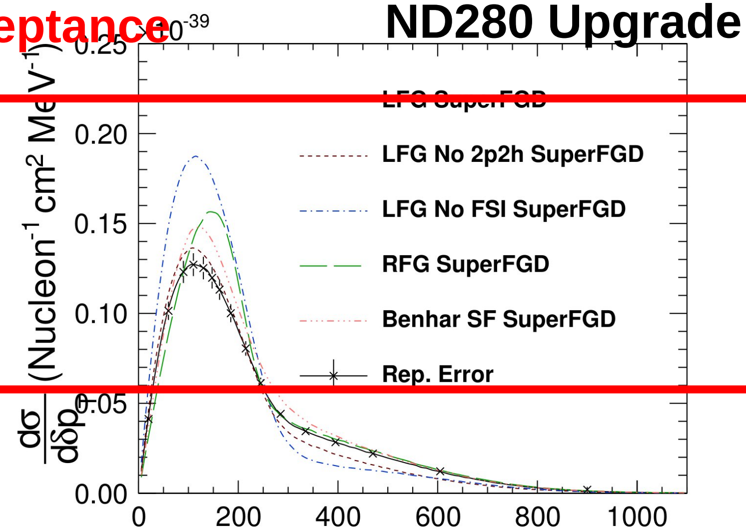


Final State Interactions (FSI)

EXAMPLES OF HOW ND280 UPGRADE CAN IMPROVE STV MEASUREMENTS

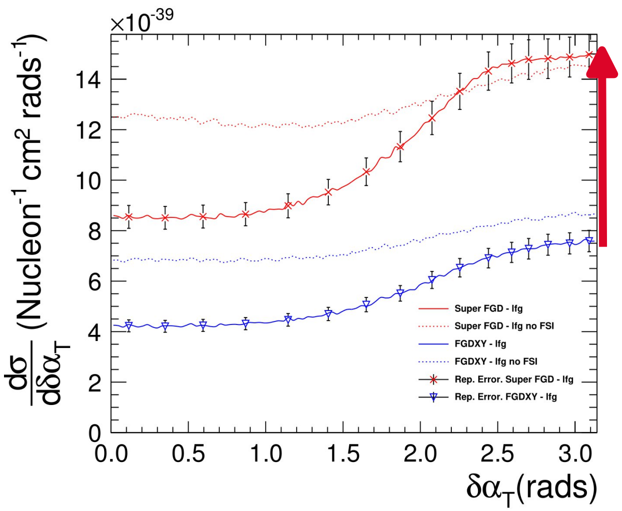
Clear increase in statistics and phase space acceptance





Increase in statistics

- **Clear shape - helps distinguish FSI from 2p2h**
- **Impact on 2p2h normalization**

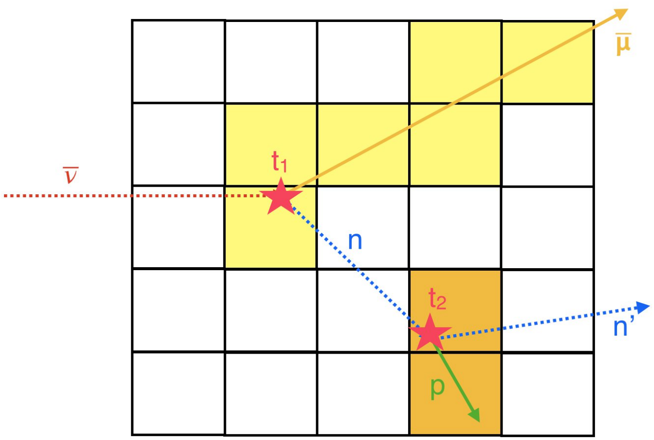


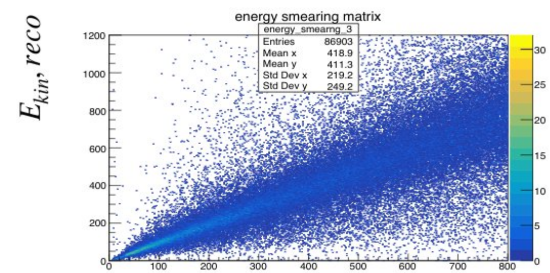
ND280 today	ND280 w 8×10^{21} POT	ND280 Upgrade 8×10^{21} POT (muons only)	ND280 Upgrade 8×10^{21} POT (muons+protons)
20%	10%	6%	3%

Reco. Eν precision - 10MeV (today) -> 1Mev (ND280 Upgrade w 8×10^{21} POT, muons and protons)

NEUTRON DETECTION CAPABILITIES

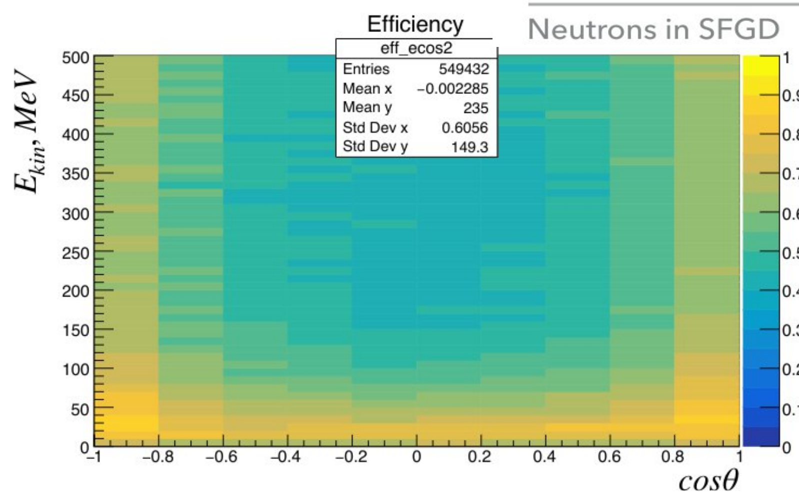
- SuperFGD has a promising potential to detect **neutrons**
  - LOOK FOR NEUTRON SCATTERING IN THE FIRST HIT IN TIME IN A SUPERFGD CUBE THAT PRODUCES AT LEAST ONE DETECTABLE PHOTOELECTRON
  - SELECT PARTICLES THAT PRODUCE AT LEAST 40 P.E. (L.Y OF A MIP)
  - POSSIBLE THANKS TO BETTER ELECTRONICS WHICH WILL ALLOW US TO GO TO 0.95 NS OF TIME RESOLUTION PER OPTICAL FIBER - FURTHER IMPROVED BY NUMBER OF FIBERS AND NUMBER OF PHOTOELECTRONS
  - PARTICLE GUN SIMULATION:





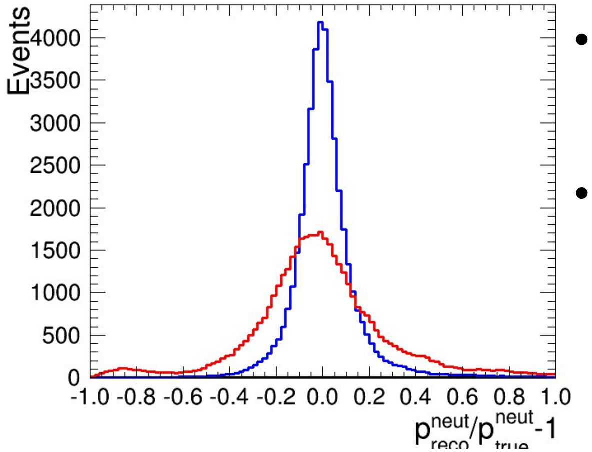
Neutrons in SFGD

E_{kin}, true

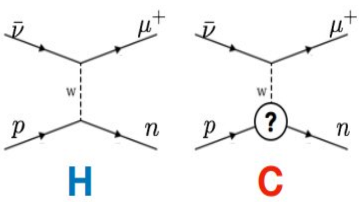


NEUTRON DETECTION CAPABILITIES

nominal - 0.95 ns/sqrt(#fibers)
light yield correction - 0.95/sqrt(3)/sqrt(l.y/40 p.e.)

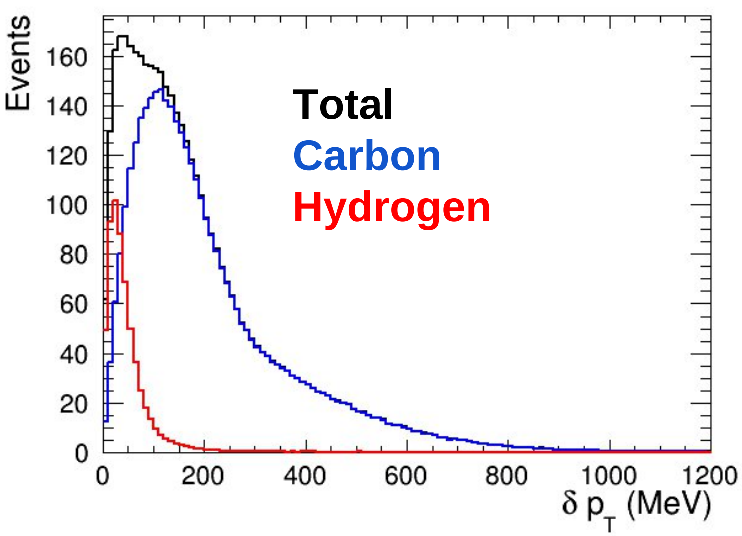


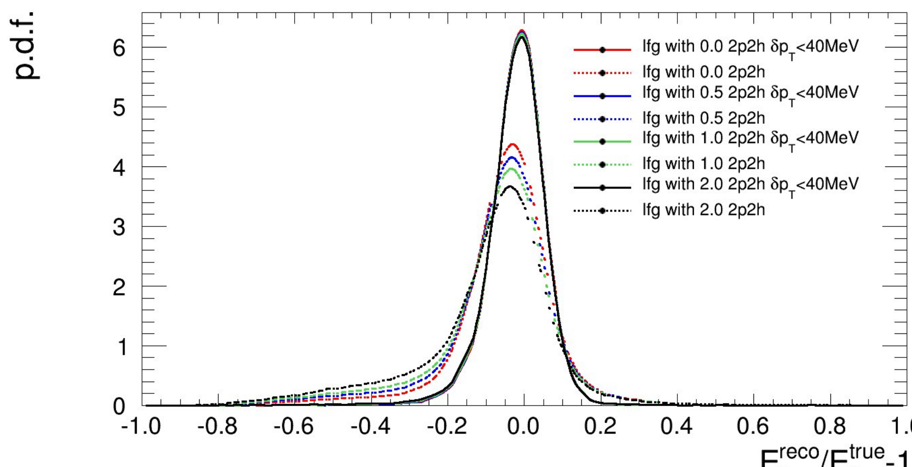
- The neutron momentum resolution we expect with SuperFGD is between 20-30%
- Detecting neutrons in antineutrino mode allows us to reduce nuclear effects by identifying hydrogen events - no nuclear effects!



STV expectations

$\delta\phi_T = \delta p_T = 0$ $\quad$ $\delta\phi_T \neq \delta p_T \neq 0$
$\delta\alpha_T$ is undefined $\quad$ $\delta\alpha_T \to \pi$ for high F





Highly decreased dependence on 2p2h and neutrino energy resolution improved!!

Neutron Detection Capabilities

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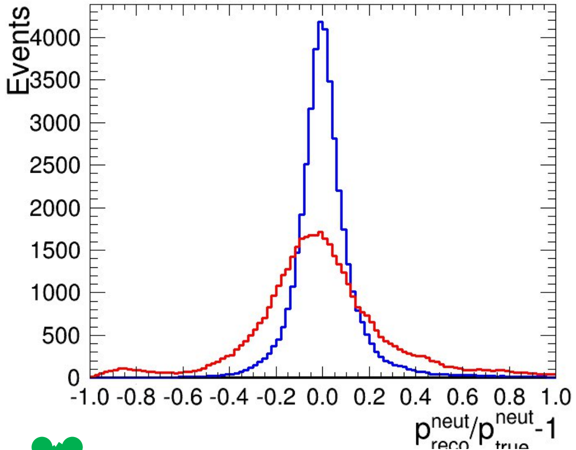

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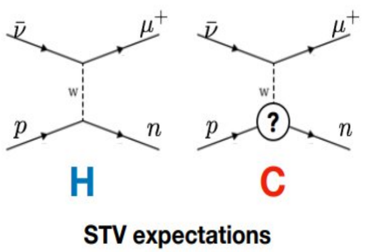
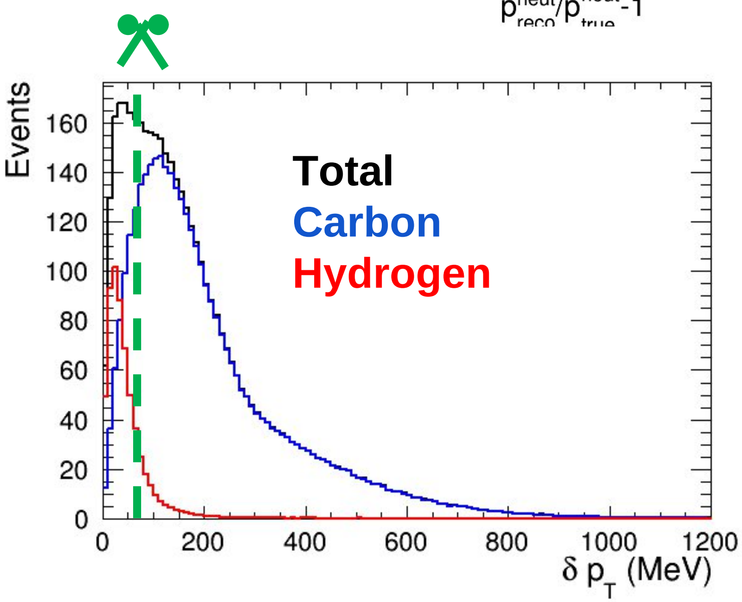
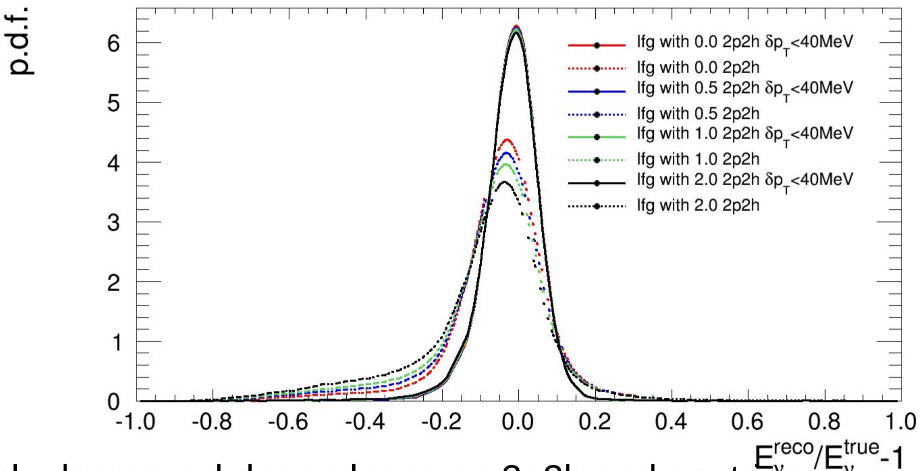


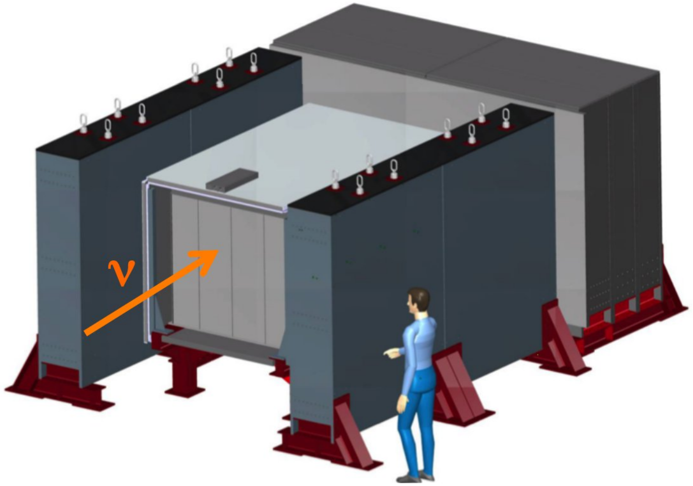




Highly decreased dependence on 2p2h and neutrino energy resolution improved!!

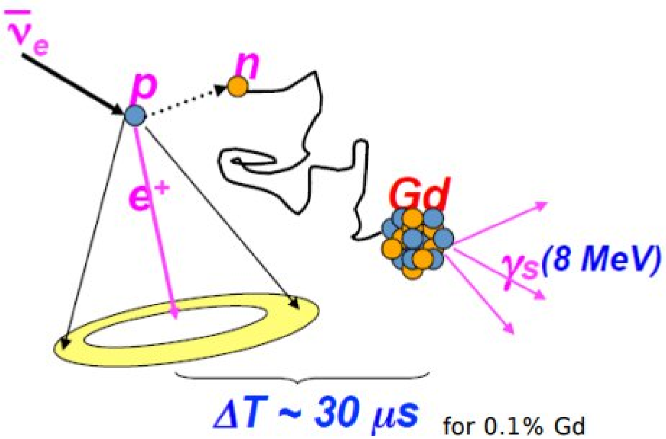
More about the future of T2K

WAGASCI



- Water filled scintillator grid at 1.5 ° off axis
- Make precise water-carbon ratio neutrino cross-section measurements
- In place @ JPARC since January 2019, ready to take data

Super-K Gadolinium (SK-Gd)



$Gd_2(SO_4)_3$

- Load SK water tank with Gd for neutron tagging
- Determine neutron multiplicity - discriminate non CCQE events

Exciting times to come!

So why is the upgrade important?

CONCLUSIONS AND OUTLOOK

- T2K running steadily: 90% CL on δ_{CP} -> beam upgrade to 1MW will allow 3 sigma measurement
- ND280 Upgrade is crucial to establish 3σ CP violation - currently limited by statistics but will be limited by systematics if we do not improve our understanding of neutrino-nucleus interactions
- Will provide a lot of data to improve our knowledge on neutrino interactions before the beginning of HK -> possible further update in HK era can be envisaged
- DUNE prospects : 3DST detector uses a similar detector design to ND280 upgrade - also neutron test beam foreseen with US and Japan collaboration
- Novel R&D : SuperFGD & Resistive Micromegas for the HA-TPC
- T2K-NOvA joint fit being discussed

Many thanks to all the people who let me use their slide materials in my talk: Sara Bolognesi, Stephen Dolan, Ciro Riccio.

And many thanks to all the hard-working people working to make the ND280 Upgrade possible!

Thank you for your attention!

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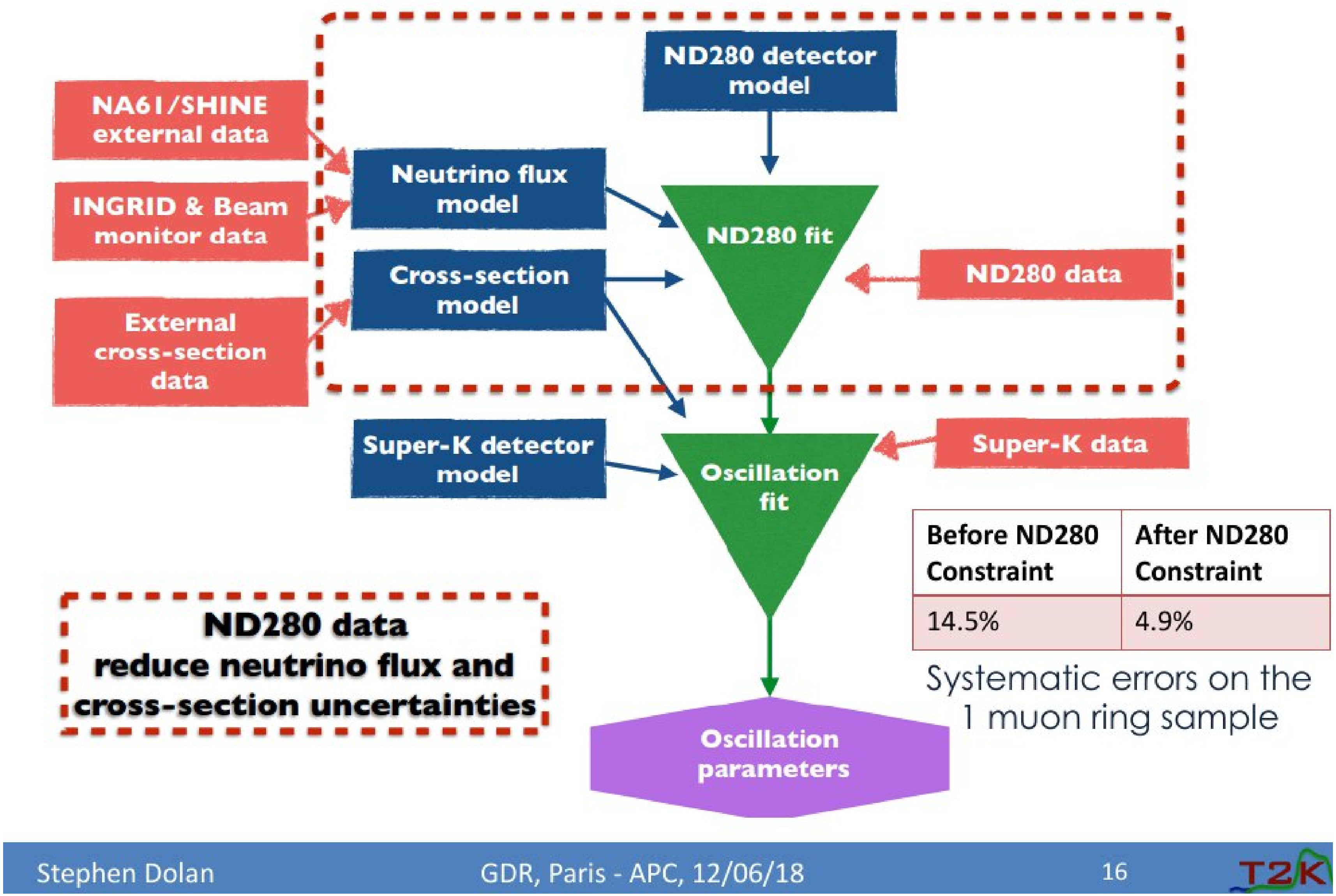
Direction de la Recherche Fondamentale
Institut de recherche
sur les lois fondamentales de l'Univers
Service

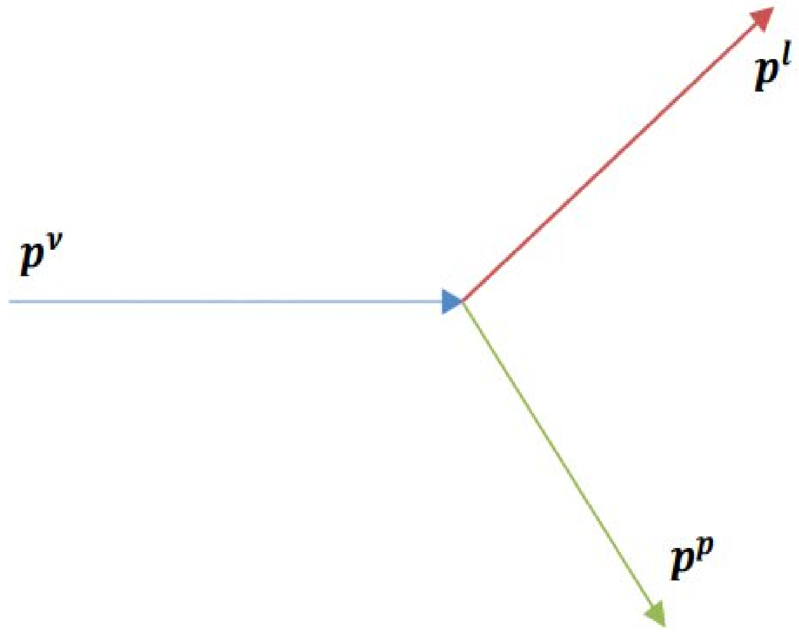
BACK-UPS

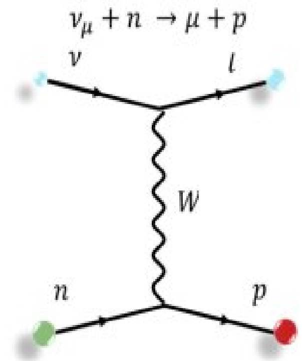
OSCILLLATION ANALYSIS (OA) STRATEGY



Before ND280 Constraint	After ND280 Constraint
14.5%	4.9%

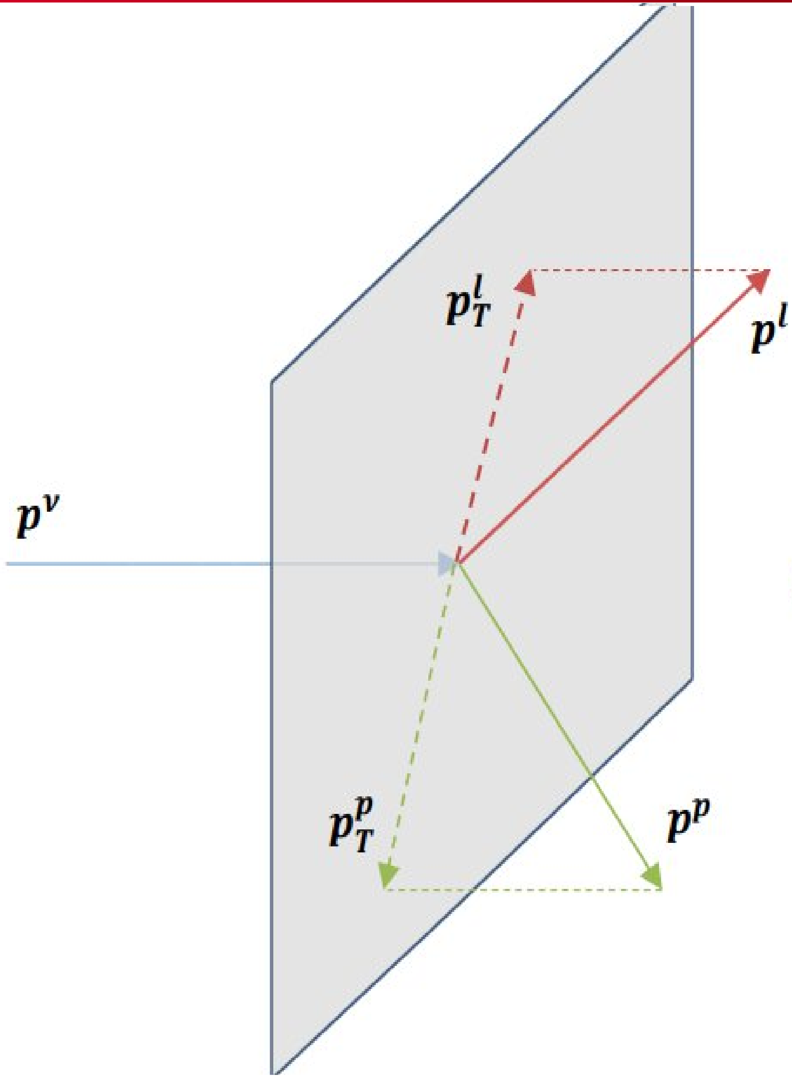
SINGLE TRANSVERSE VARIABLES

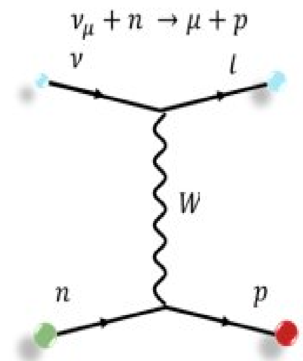




No nuclear Effects

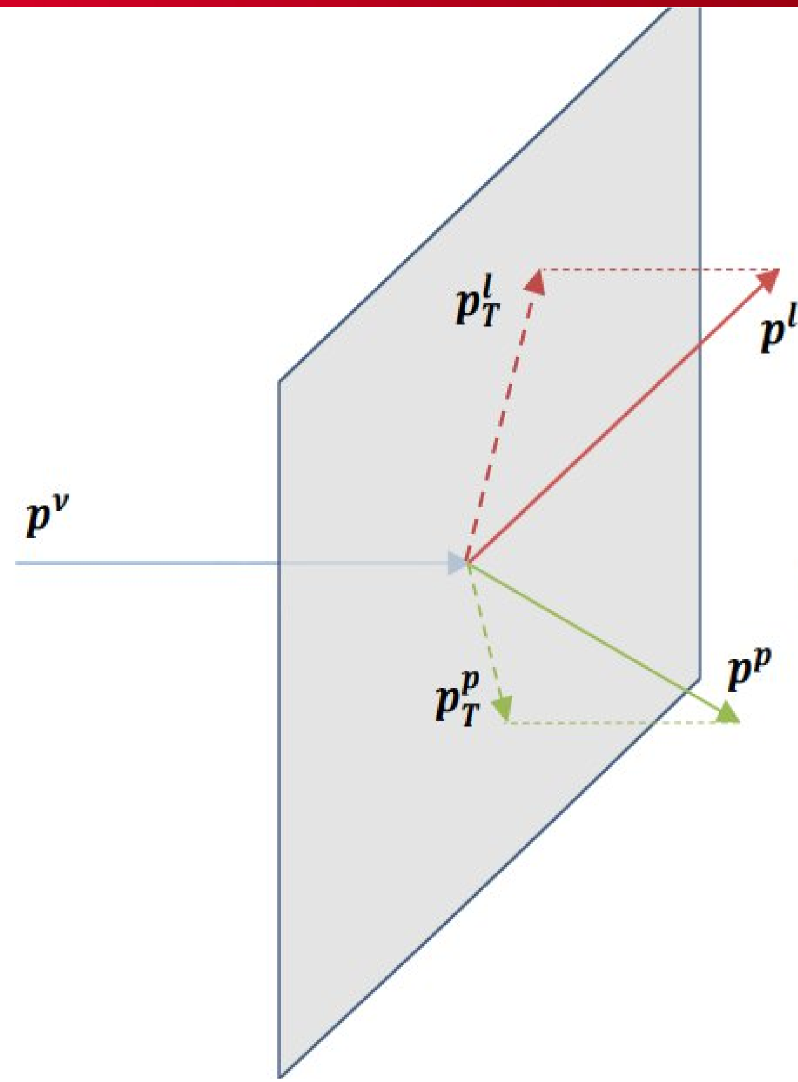
SINGLE TRANSVERSE VARIABLES

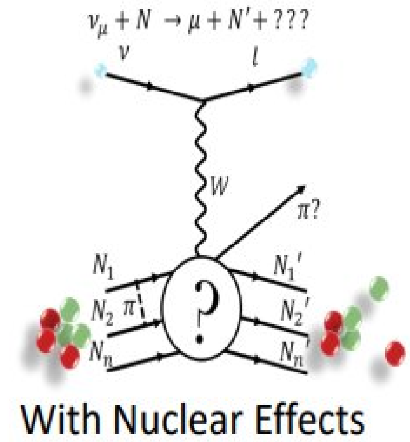




No nuclear Effects

$$p_T^l = -p_T^p$$

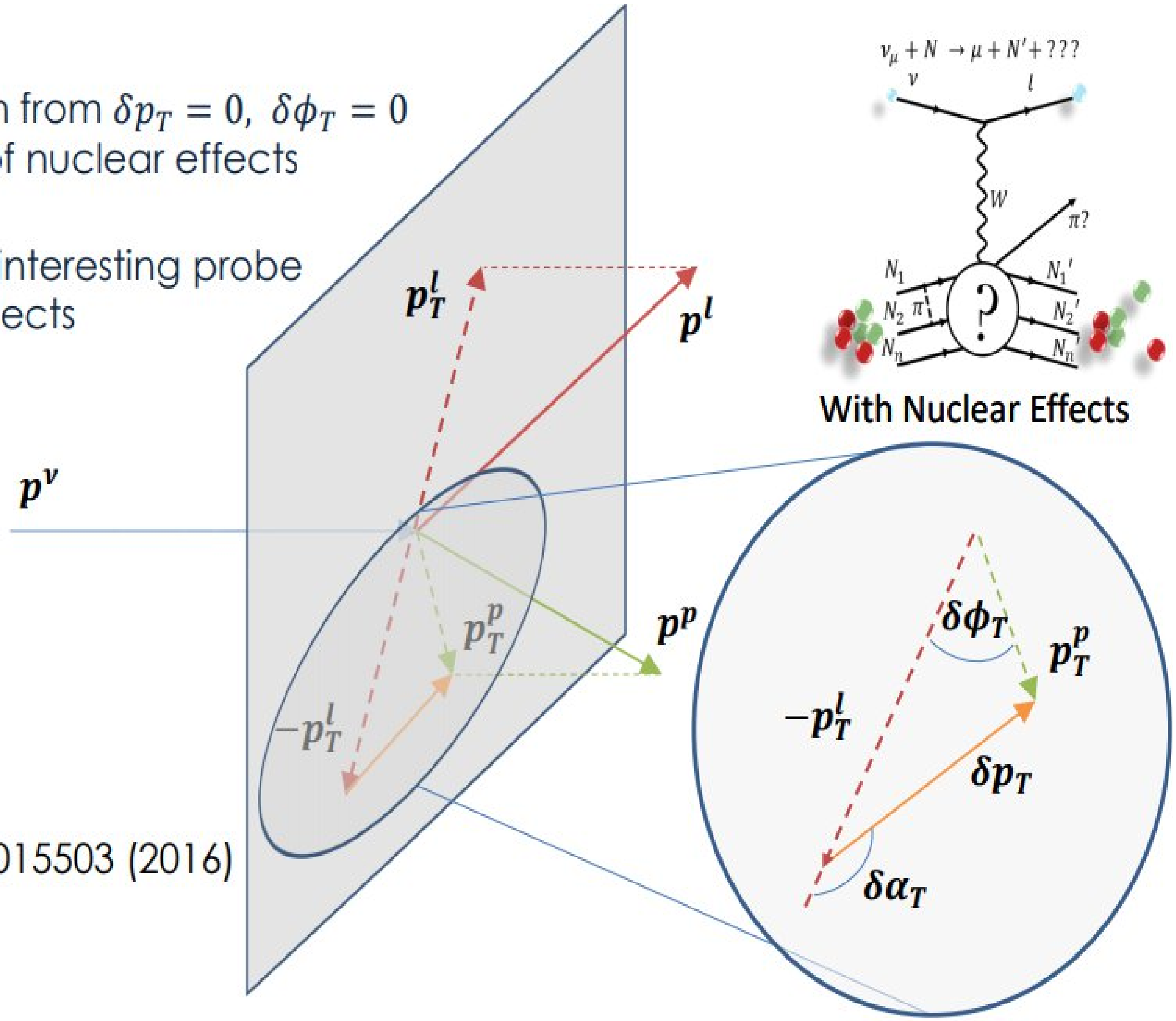

p^ν
p_T^l
p^l
p_T^p
p^p


$\nu_\mu + N \rightarrow \mu + N' + ???$
ν
l
W
$\pi?$
N_1
N_2
π
N_n
N_1'
N_2'
N_n'
?
With Nuclear Effects

$$p_T^l \neq -p_T^p$$

Single Transverse Variables

- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects
- STVs offer an interesting probe of nuclear effects



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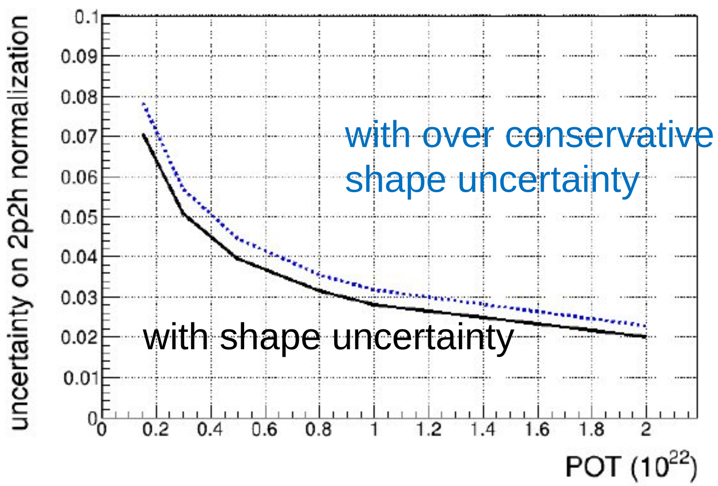
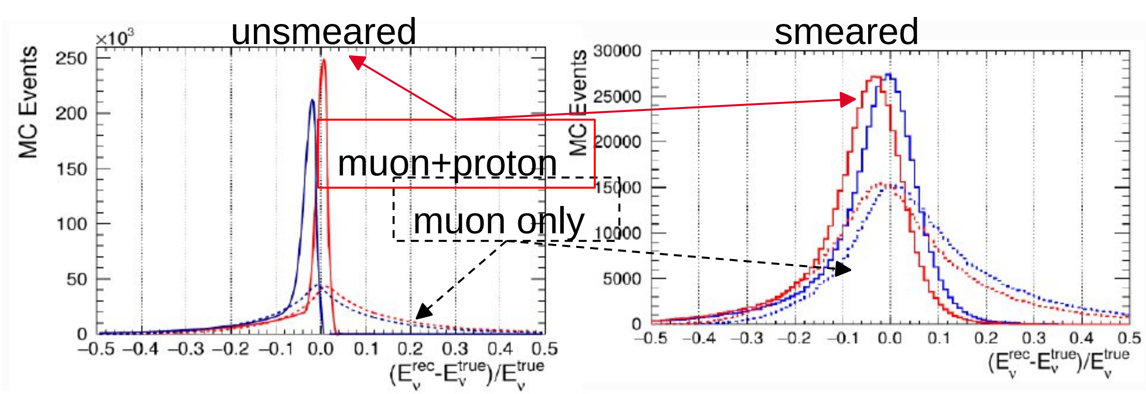
Sensitivity study of upgrade potential

- Better constraints on systematics, which will become dominant once we are no longer limited by statistics



- Precision on 2p2h with muons only today **~ 20 %**
- Precision after ND280 Upgrade **- 6%** with 8×10^{21} POT muons only and **3%** with muons and protons



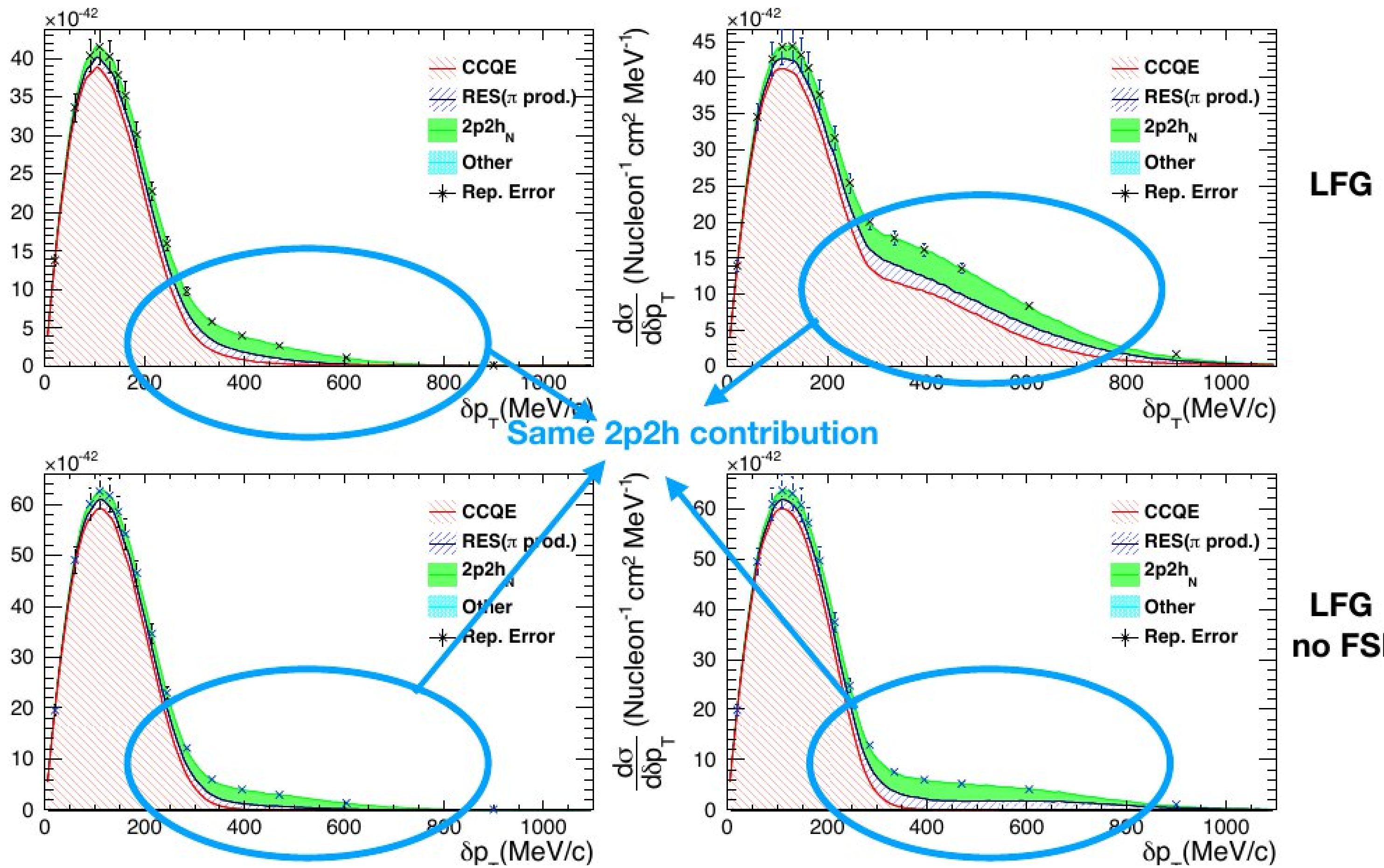
Neutrino energy reconstruction:

- now using muon only
- **better** to use muon+proton information to gain sensitivity to binding energy (Eb) (energy lost to extract nucleon)
- Today : 15 MeV error
- ND280 Upgrade ~1MeV with 8×10^{21} POT

Single Transverse Variables

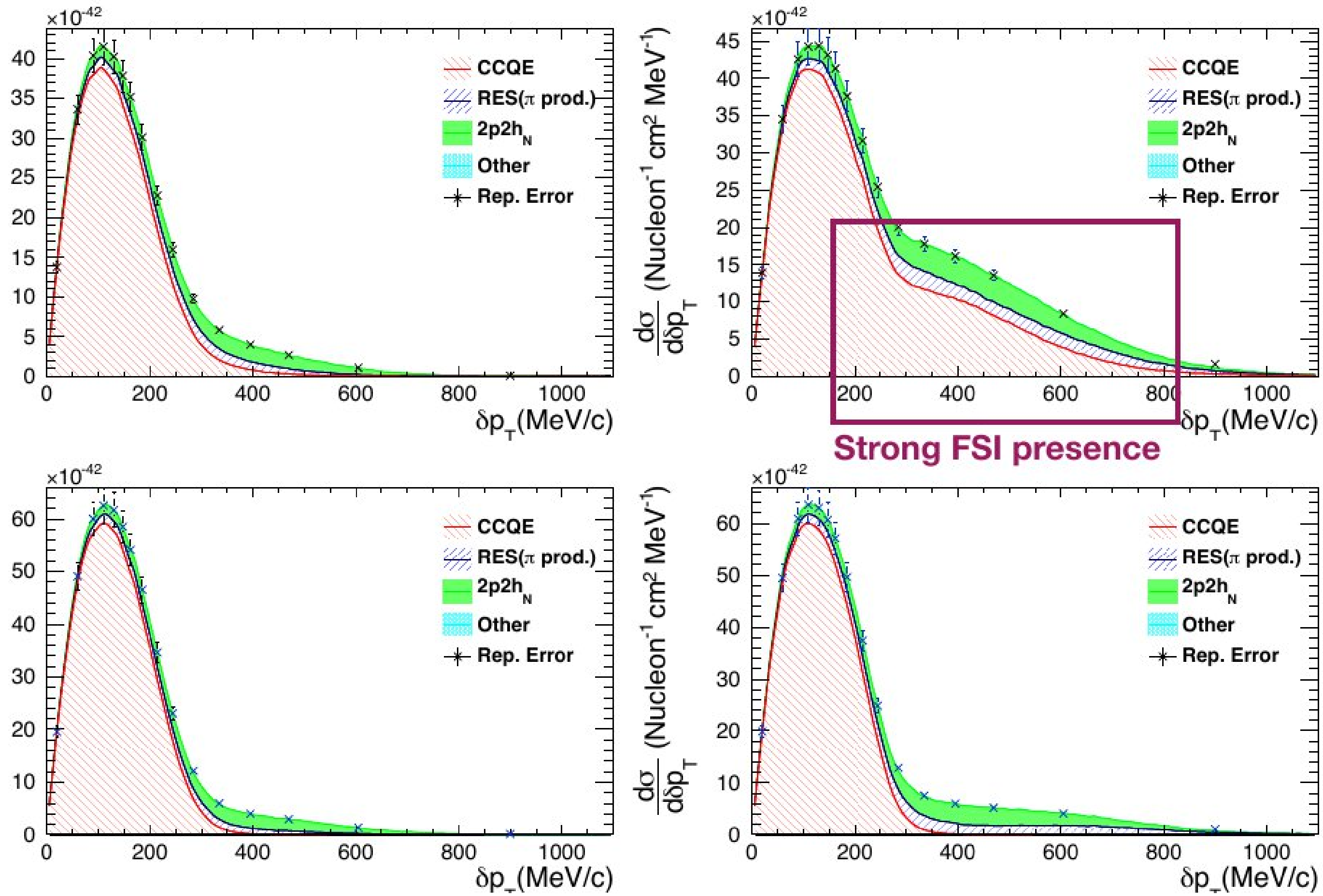
Exploiting daT (SuperFGD)

- Low daT
- High daT



Exploiting daT (SuperFGD)

- Low daT
- High daT



LFG

LFG no FSI

Source of uncertainty	ν_e CCQE-like $\delta N/N$	ν_μ $\delta N/N$
ND280 unconstrained cross-section	3%	1%
Flux + cross-section (constrained by ND280 upgrade)	1.8%	1.9%
SuperKamiokande detector systematics	1%	1%
Hadronic re-interactions	1%	1%
Total	3.8	2.6