Opportunities with upgraded T2K near/intermediate detectors: cross sections and beyond

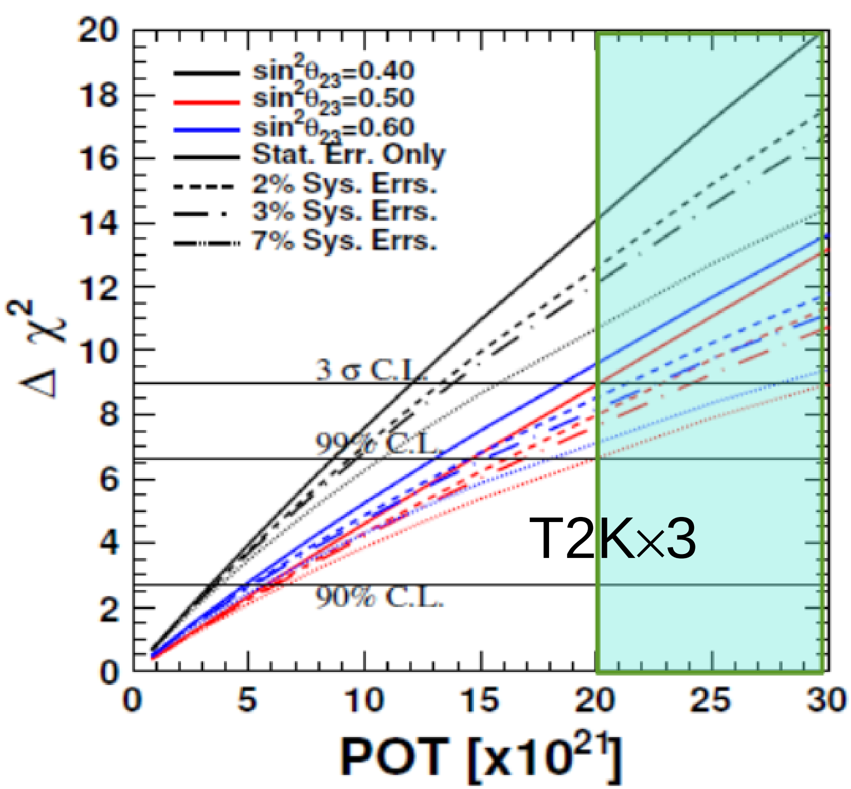
Neutrino cross sections
Bologna 9-10 Novembre 2015

A. Longhin (INFN-LNF) for T2K Italia

The upgrade

- JPARC Main Ring upgrade approved: 7.8×10^{21} POT (=T2K design), 0.9 MW by 2020
- "T2K×3" (2020-25) phase (2×10^{22} POT). Before Hyper-Kamiokande (~2025).
- If **sys. < 2-3 %** "T2K×3" could give > 3σ CPV for **any value of θ_{23}**
- Upgrade of near/intermediate detectors **necessary** already from 2020 !

Effect of Reduction of Systematic Errors



50% ν- + 50% $\bar{\nu}$-mode

True $\delta_{CP} = -90°$, true MH = NH

- $\Delta\chi^2$ for resolving non-zero δ_{CP} vs. POT
- Systematic error size matters!
  $\rightarrow$T2K measurement of δ_{CP} is systematics limited at high statistics
- Sensitivity depends on true value of $\sin^2\theta_{23}$ (and δ_{CP}, of course)
  - If errors can be reduced to 2%, T2K can make a $>3\sigma$ measurement of non-zero δ_{CP} for any value of $\sin^2\theta_{23}$ (at $\delta_{CP} = -90°$, NH)

Importance of cross sections for oscillation physics

Ideally ... in a near-far double detector oscillation experiment neutrino cross sections are **NOT** important:

$$N_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)$$

$$N^{far}_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)P_{osc}(E_\nu)$$

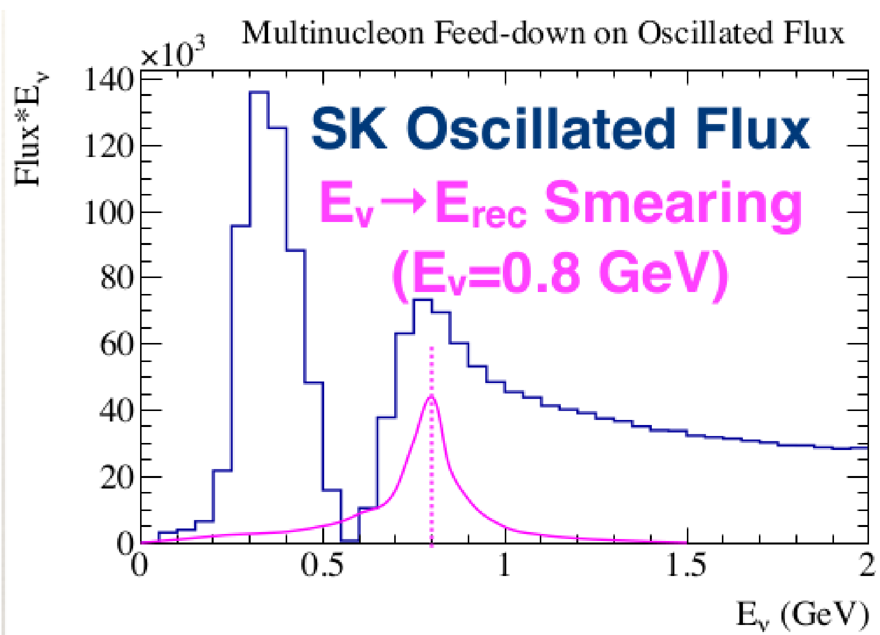
$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = P_{osc}(E_\nu)$$

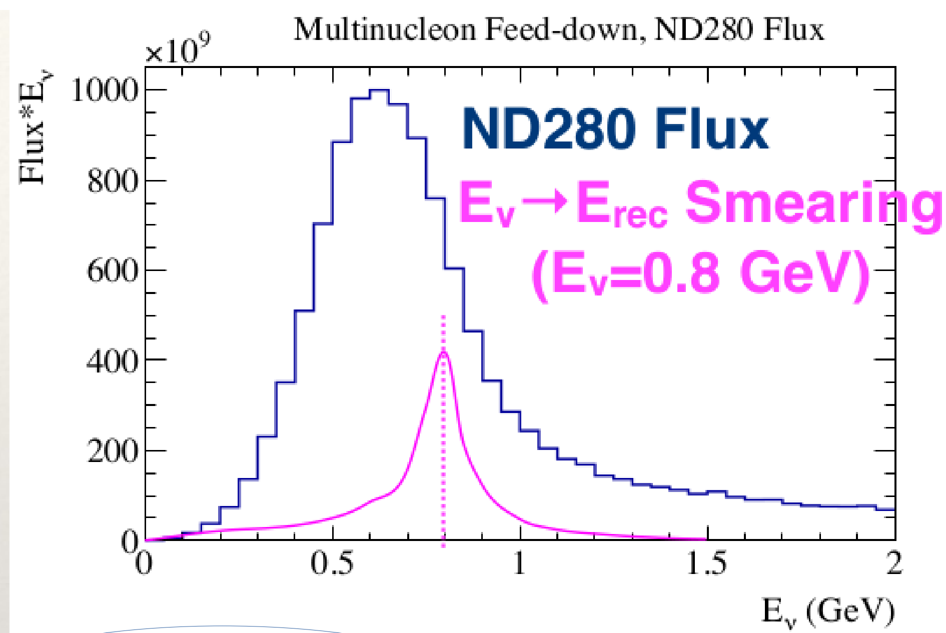
Importance of cross sections

But beams are not monochromatic → we need to determine E_ν event by event

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

Oscillations introduce differences in the flux spectrum:
the ratio does not cancel out cross-sections





We need: $\phi(E_\nu)$, $\sigma(E_\nu)$, $P(E_\nu|E'_\nu)$

"Cross section" related

Current issues and possible mitigations for T2K

$\phi(E_\nu) \times \sigma(E_\nu)$

- **Different target** at N&F (C,H vs O,H) → ("well-defined") H_2O target @ NEAR
- **Different acceptance** at N&F
  - model dependency in the not common p-θ phase space → 4π also @ NEAR
- **Different flux** at N&F due to 1) oscillations (dominant) and 2) finite-distance effects → 1) a tunable shape beam at NEAR ! 2) a "not too near" NEAR
- **Differences in $\sigma(\nu_e) \leftrightarrow \sigma(\nu_\mu)$**: ν_e at near is subdominant → not easy just with detector upgrades (but … refer to the talk by Ludovici)

Energy reconstruction $P(E_\nu | E'_\nu)$

- **Bias, broadening** when the **reconstruction formula is applied to CC-QE like** (non genuine CCQE) events due to π absorption in nuclei (FSI), multi-nucleon interactions → 1) high granularity, low threshold detector 2) neutron tagging (for multi-nucleon processes)
- **Different detector** technique at N&F: → water Cherenkov (WC) also @ NEAR

Where we stand: systematics and cross sections

Events prediction at Super-K with ~ 7% accuracy for neutrinos (10% in anti-ν mode).
Large contribution from difference in nuclear targets between far and near
+ the effect of the poorly known multi-nucleon cross section

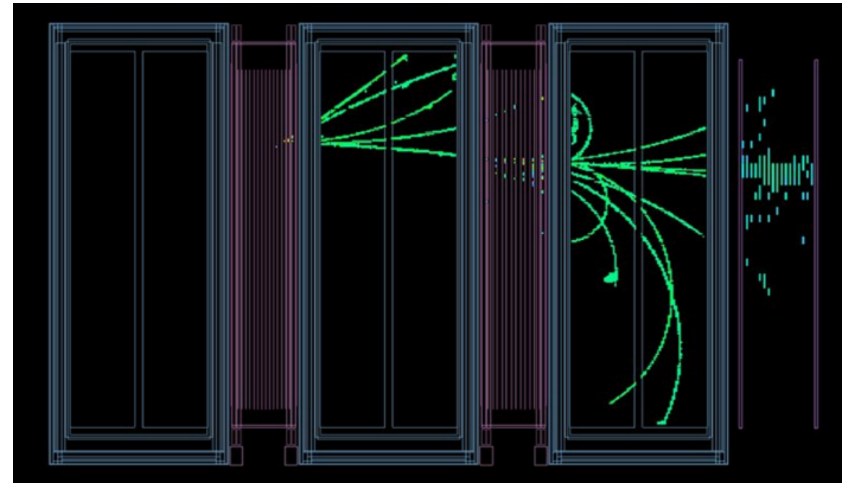
2014 → 2015

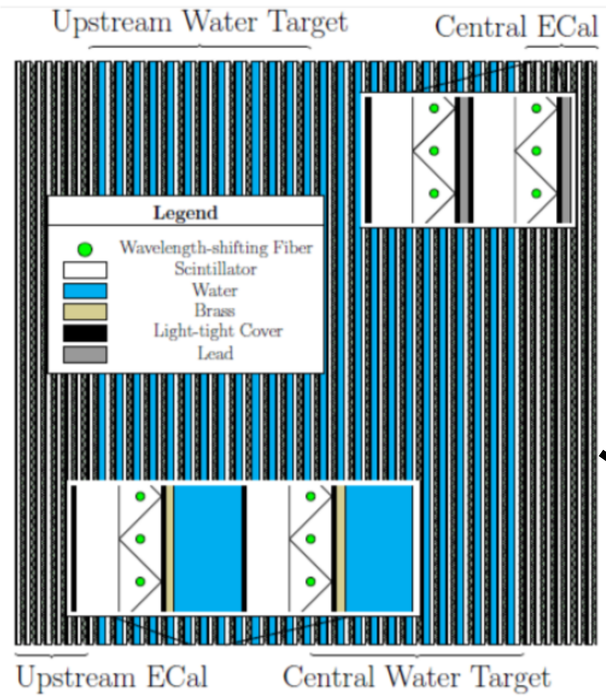
		ν_μ sample	ν_e sample	$\bar{\nu}_\mu$ sample	$\bar{\nu}_e$ sample
ν flux		16%	11%	7.1%	8%
ν flux and cross section	w/o ND measurement	21.8%	26.0%	9.2%	9.4%
	w/ ND measurement	2.7%	3.1%	3.4%	3.0%
ν cross section due to difference of nuclear target btw. near and far		5.0%	4.7%	10%	9.8%
Final or Secondary Hadronic Interaction		3.0%	2.4%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%
total	w/o ND measurement	23.5%	26.8%	14.4%	13.5%
	w/ ND measurement	7.7%	6.8%	11.6%	11.0%

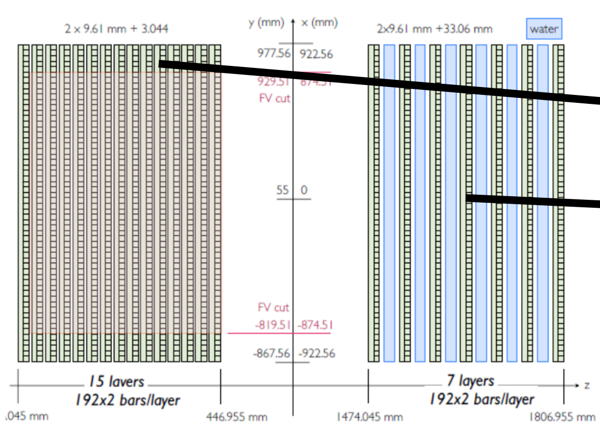
Many improvements
* 2014 error does not include the effect of multi-nucleon at the neutrino-nucleus interaction.

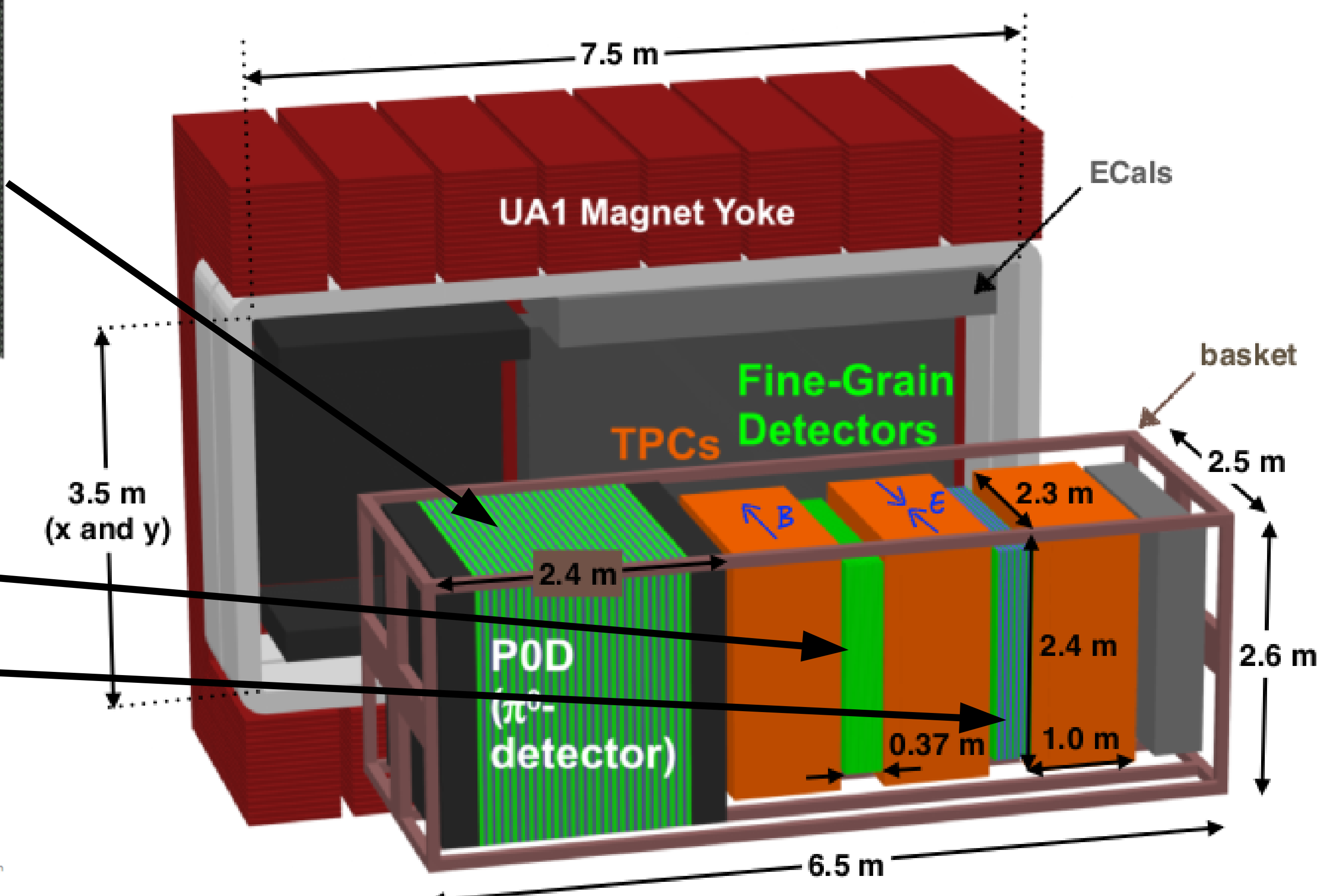
The T2K near detector

ND280



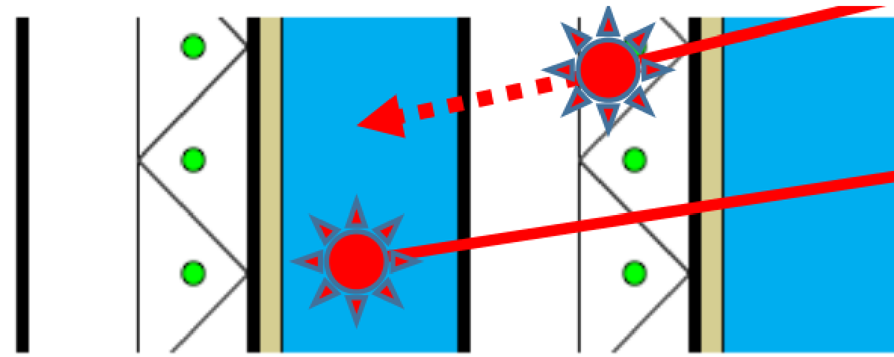


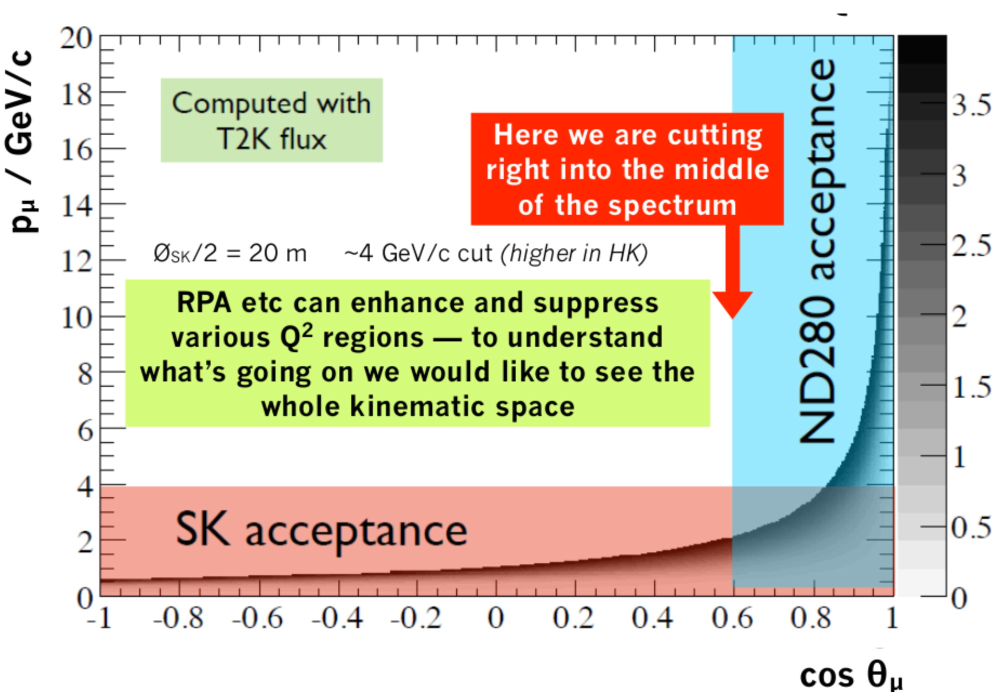


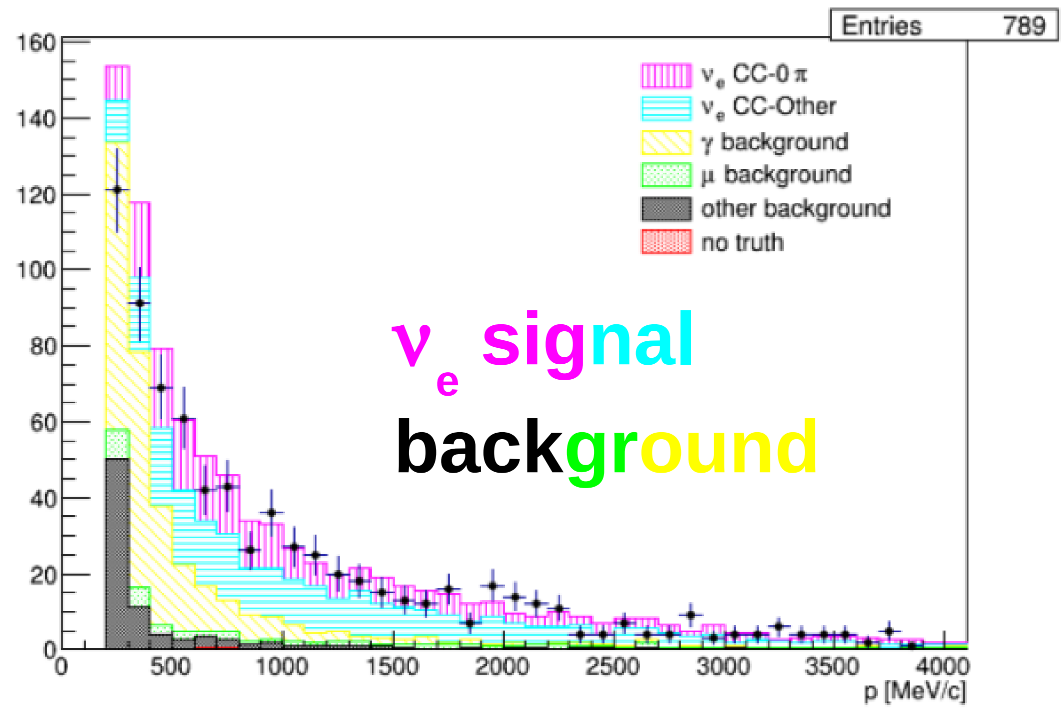


Limitations of ND280

- Different target
  - large migrations between scintillator and water layers. Ambiguity on the target nucleus
- Different Acceptance
- External backgrounds (especially for ν_e!)



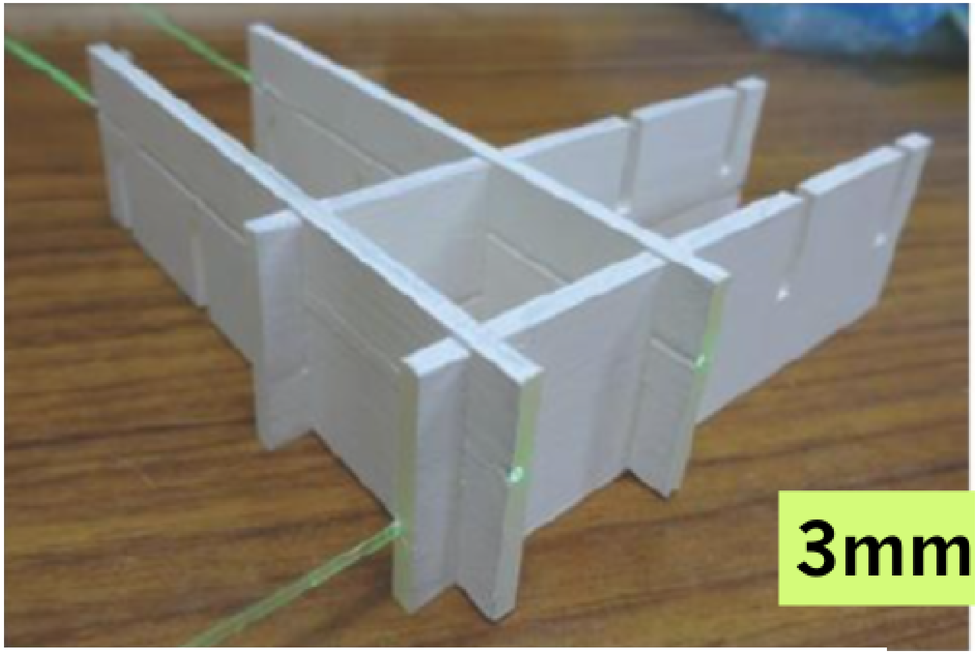




Specific proposals synopsis

Improvements/ name	High granularity, final state precision	Water target	Acceptance, purity	same flux shape at N&F	Same detector at NEAR and FAR	Status, notes
WAGASCI	N	Y	Y	N	N	In construction
High pressure TPC	Y	N	Y	N	N	discussion
TITUS	N	Y	Y/N	Y	Y	proposal
νPRISM	N	Y	Y/N	Y the oscillated one (!)	Y	LoI

WAGASCI

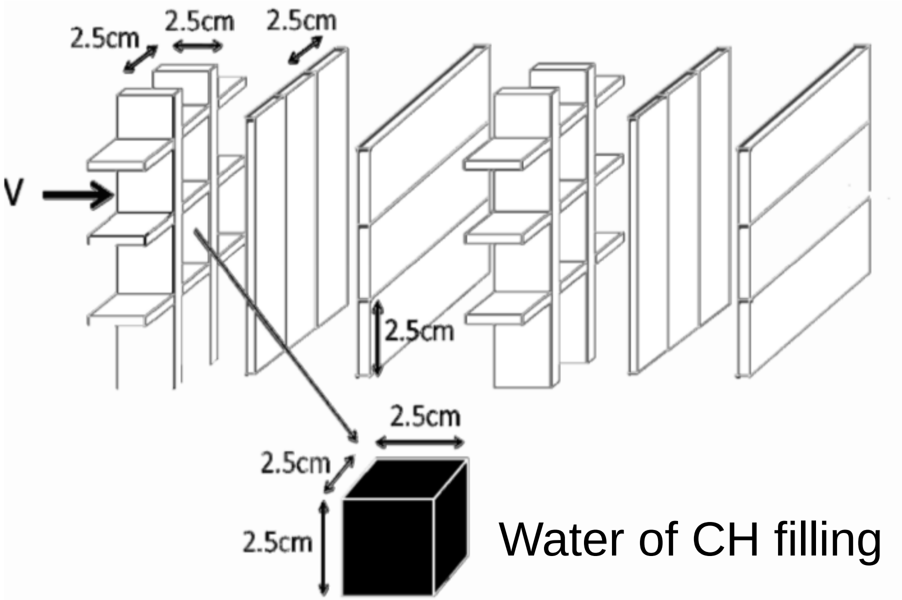


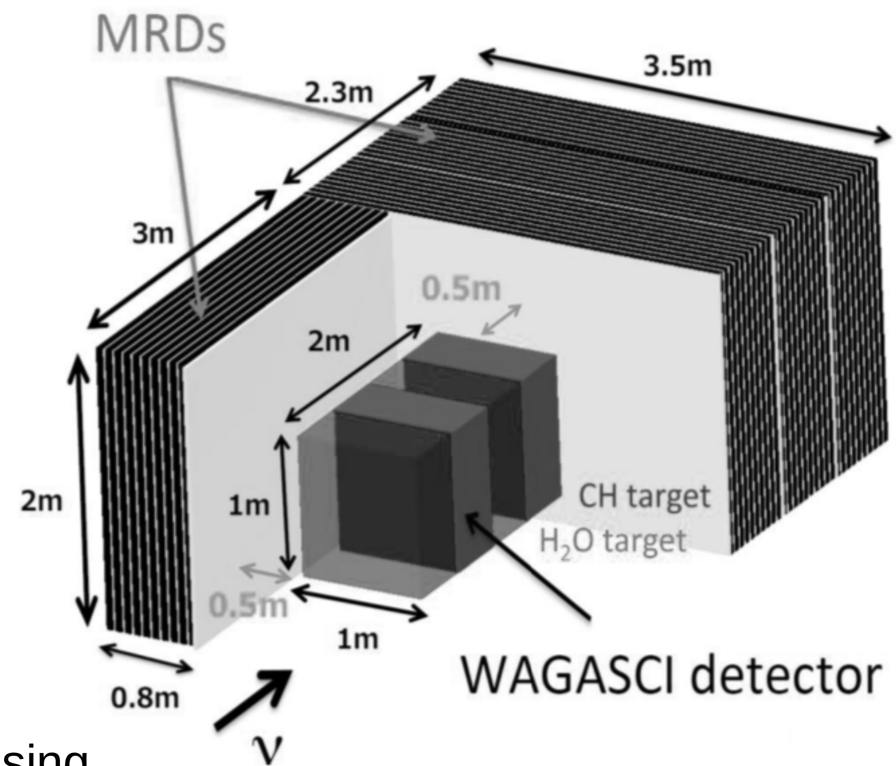
Addresses the issues of: **acceptance, target definition, external backgrounds.**

Goal: 3 % error on cross section ratio (water/CH)

Plastic scintillators + WLS fibers in arrays (water/plastic) filled. Hamamatsu MPPC (SiPM) readout.

Being constructed close to ND280, INGRID

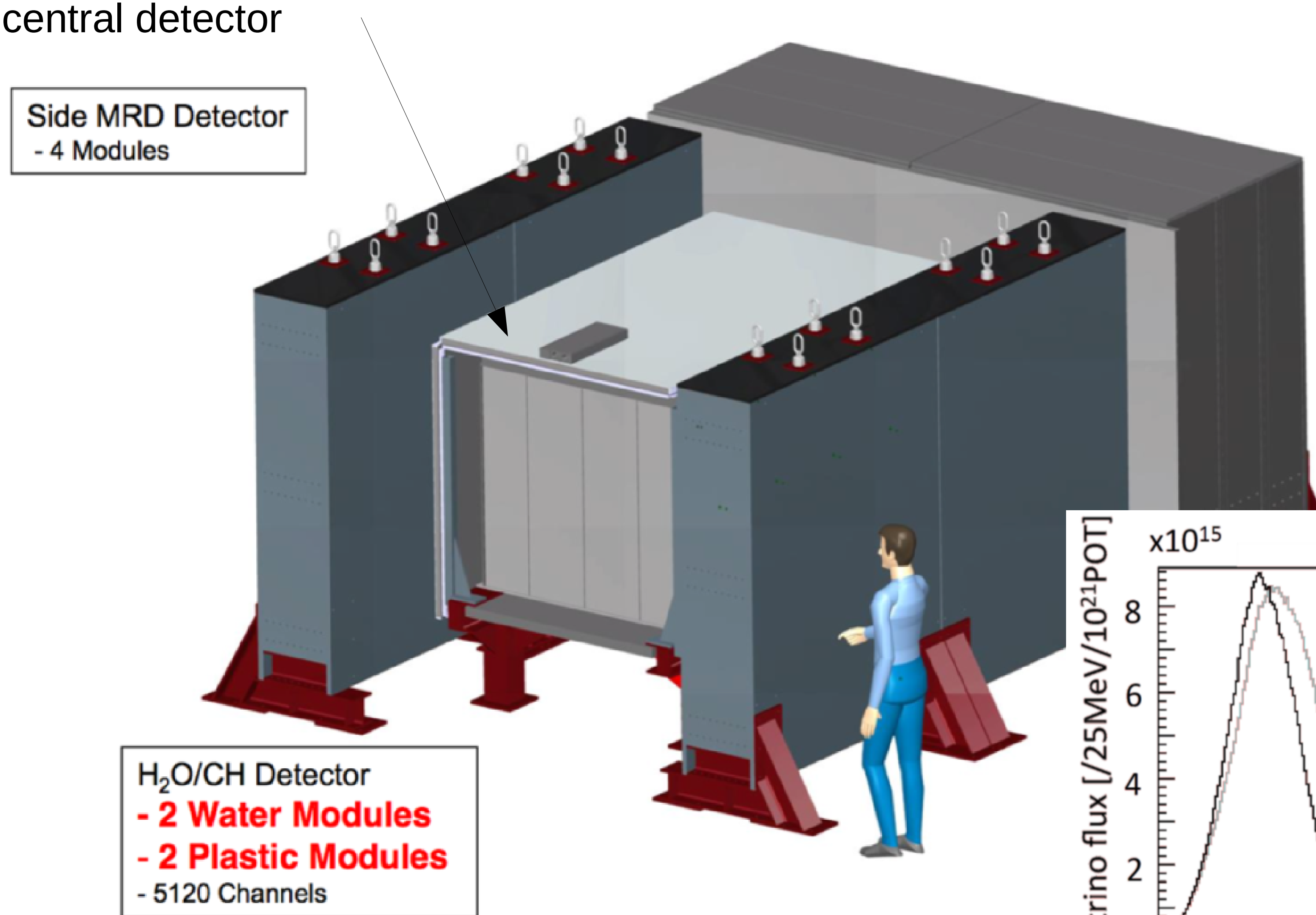


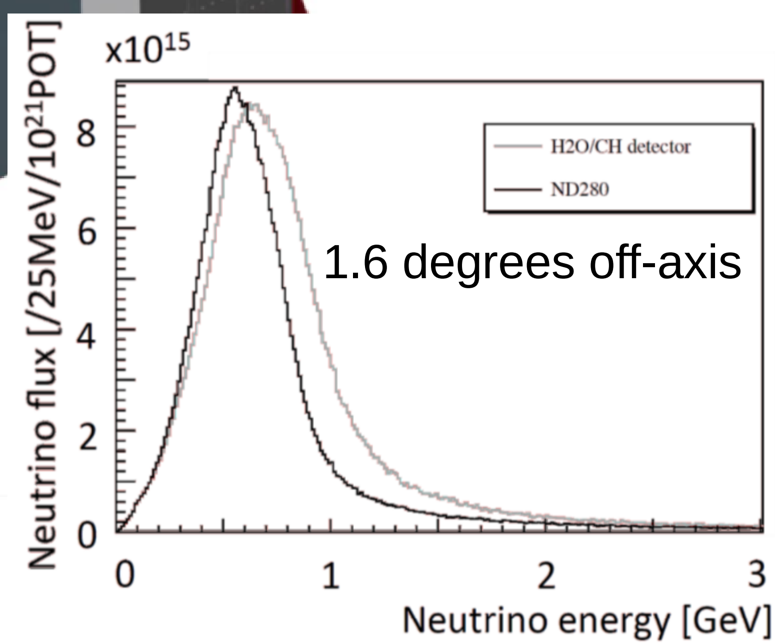


Grooves to mechanically connect orthogonal scintillator bars. Shallow enough to allow fiber housing.

WAGASCI

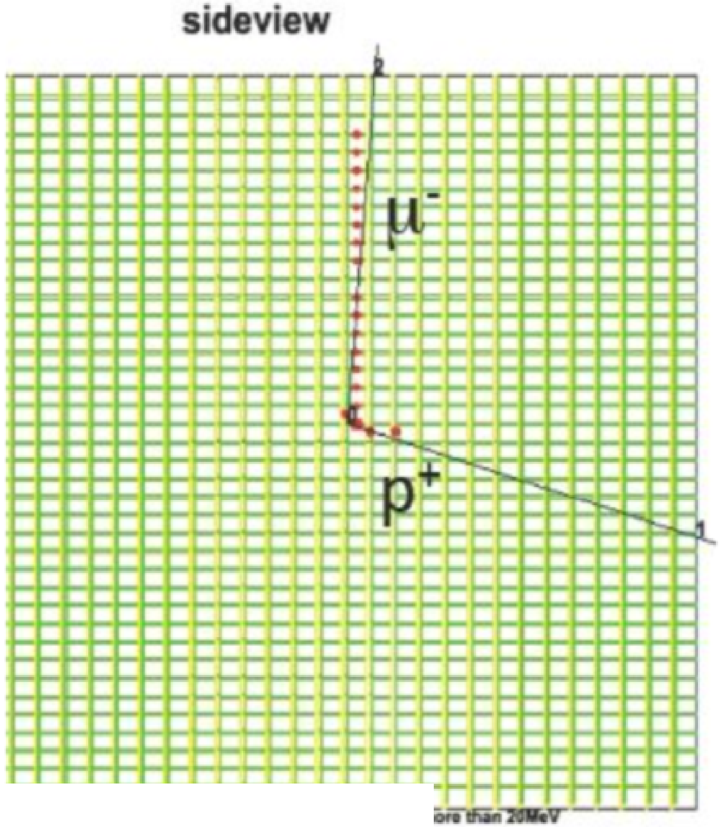
External background: neutrino interactions in the MRD and building walls → Time-Of-Flight system (3 1cm thick scintillator layers). Profits of 50 cm gaps surrounding the central detector

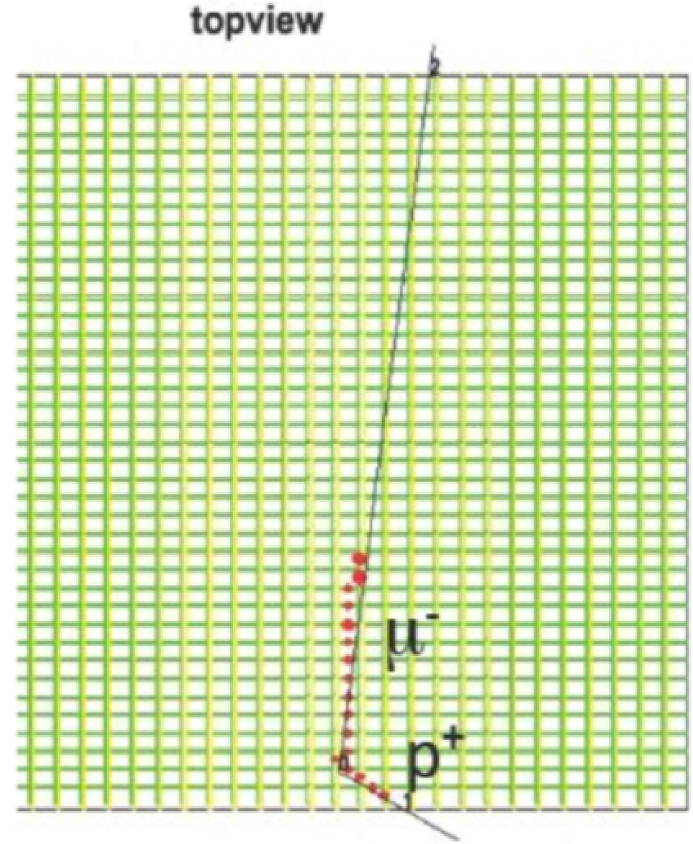


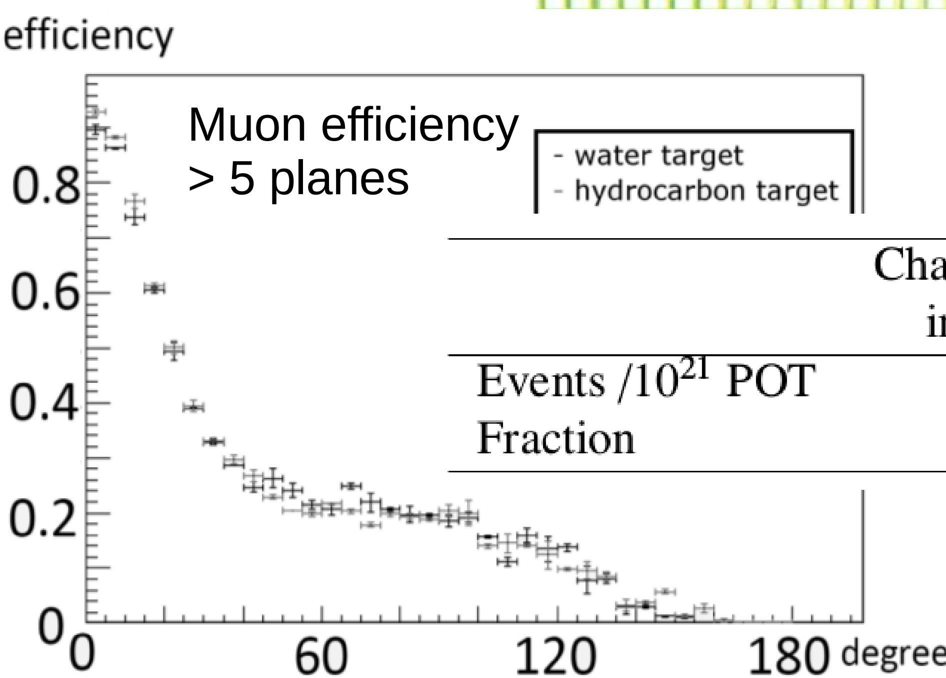


WAGASCI acceptance, purity

Very good acceptance also at high angles thanks to 3D structure.





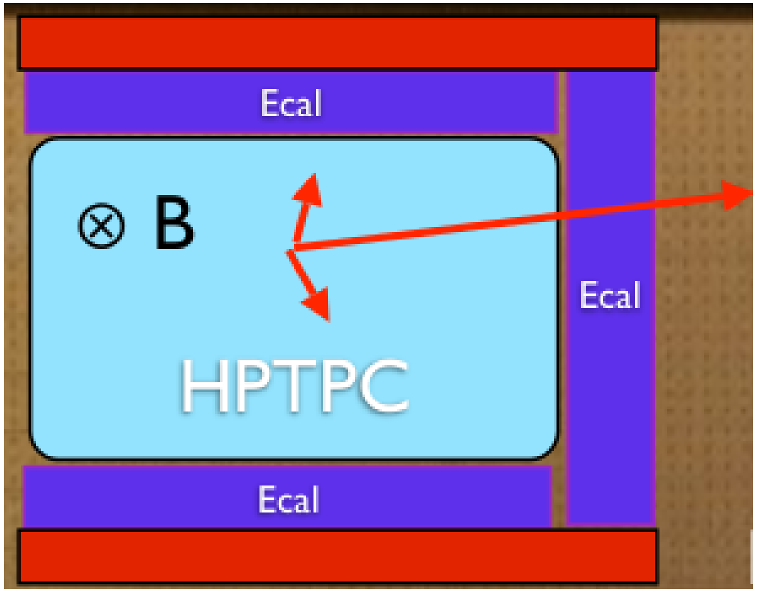


Muon efficiency > 5 planes

	Charged current interaction	Neutral current interaction	Background from outside	All
Events /10^{21} POT	39580	2560	1300	43440
Fraction	91.1%	5.9%	3.0%	100%

Decrease of efficiency at large angles due to minimal plane cut (backward tracks are "soft"!), not geometry.

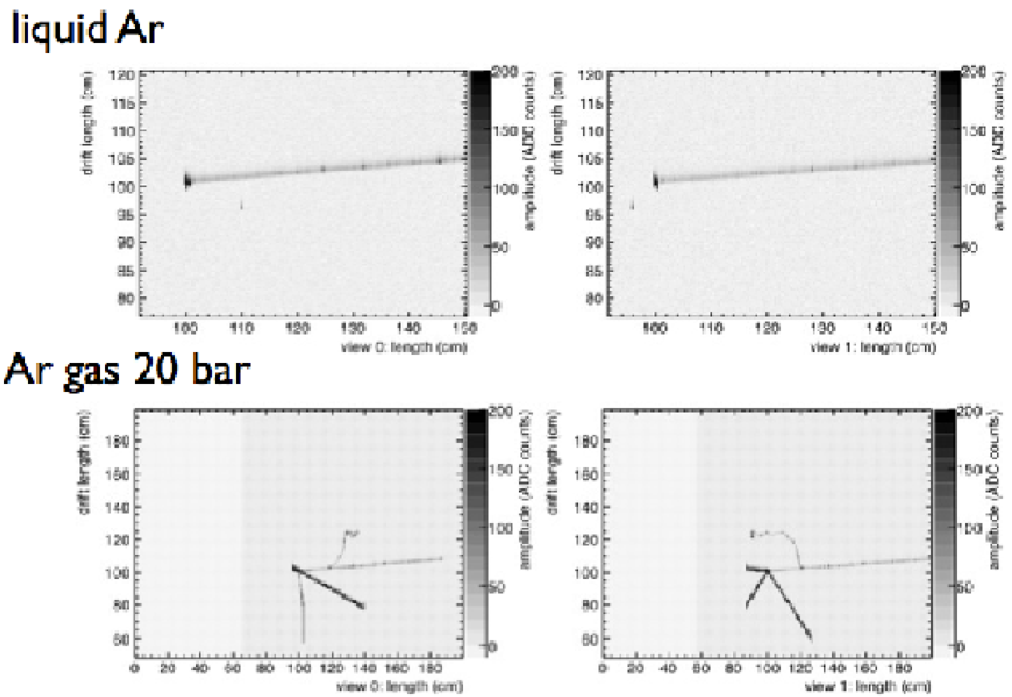
High pressure TPC



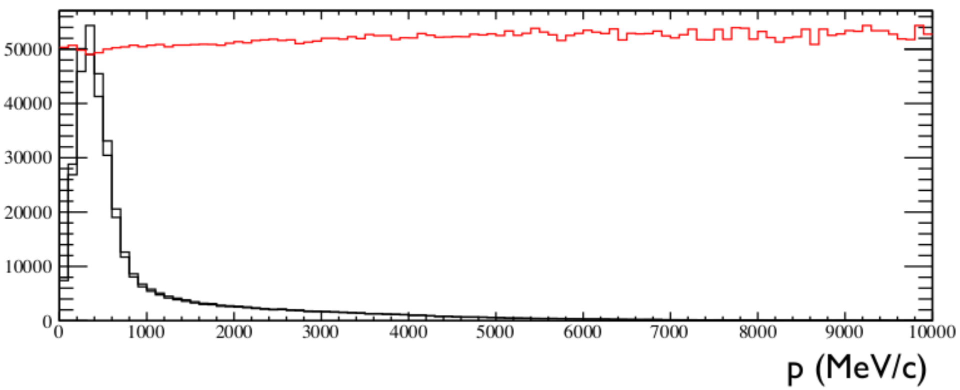
- No passive material (interactions in the gas)
- Low thresholds (5-10 bar pressure)
  disentangle multi-nucleon processes from CCQE
- Realistic gases:
  He, Ne, Ar, CF_4
- H and D would "by-pass" nuclear physics … not realistic

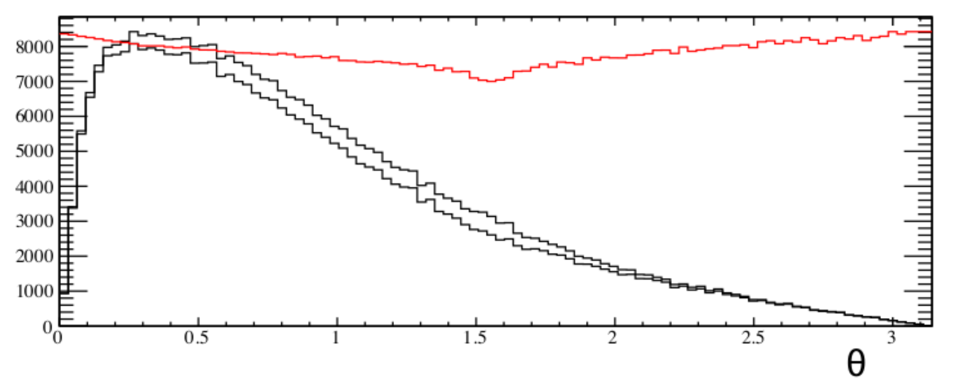
- In principle more appealing for the US program (Argon). Difficult to use CO_2, H_2O (for water)

Taken from
F. Sanchez



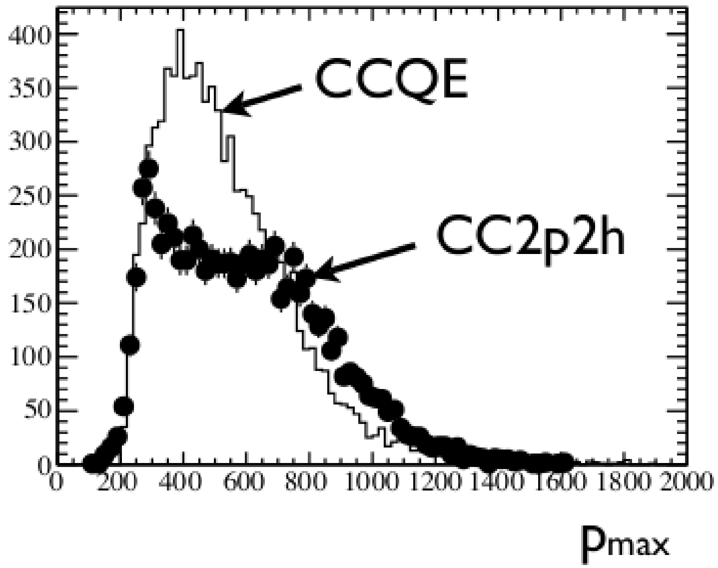
A. Curioni

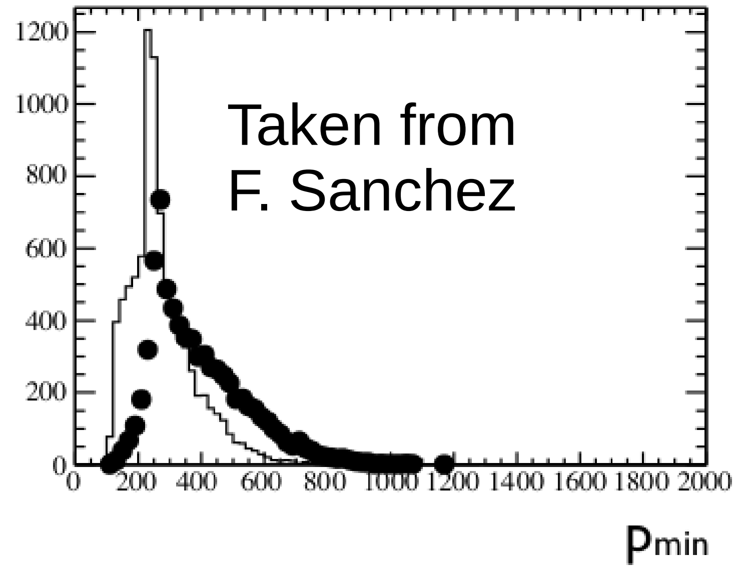


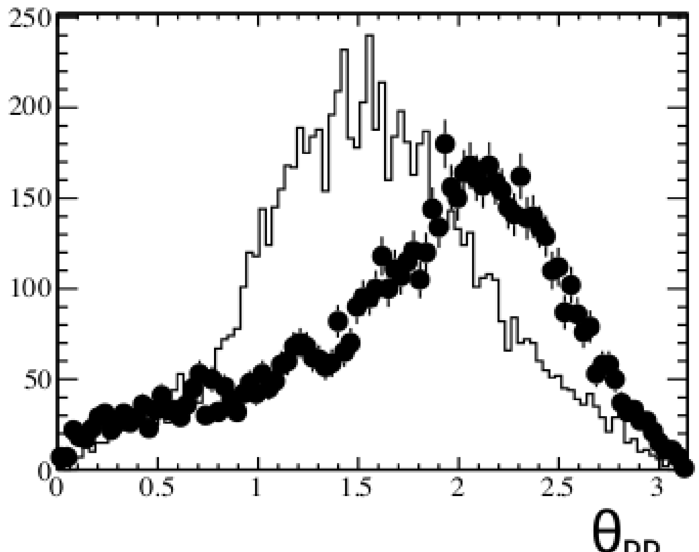


High pressure TPC

2 proton final states: observables can discriminate CCQE + Final State Interactions from multi-nucleon interactions (“MEC” or “2p-2h”)







High pressure TPC

Taken from
F. Sanchez

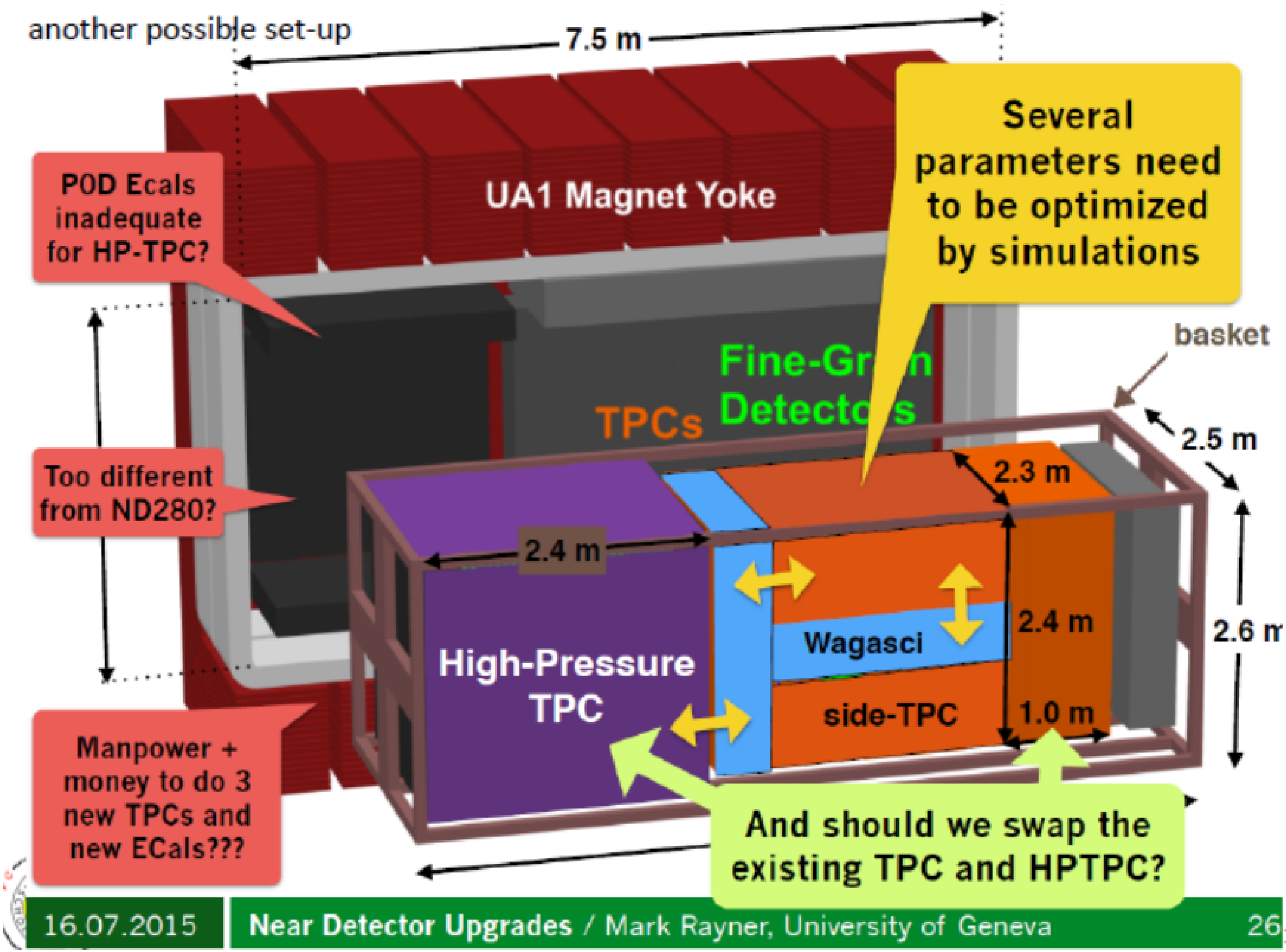
CC events assuming a 8m^3 detector & full FV.

Acceptance ~45% for a 2x2x2 m^3

2x2x2 m^3 20°C		5 bars	10 bars
He	mass	6.65 kg	13.3 kg
	events	520 evt/10^{21}pot	1040 evt/10^{21}pot
Ne	mass	32.5 kg	67.1 kg
	events	2543 evt/10^{21}pot	5086 evt/10^{21}pot
Ar	mass	66.5 kg	133 kg
	events	5203 evt/10^{21}pot	10406 evt/10^{21}pot
CF_4	mass	146.3 kg	293 kg
	events	11450 evt/10^{21}pot	22893 evt/10^{21}pot

Expected ~1.6 10^{21} pot/year for ~4 years

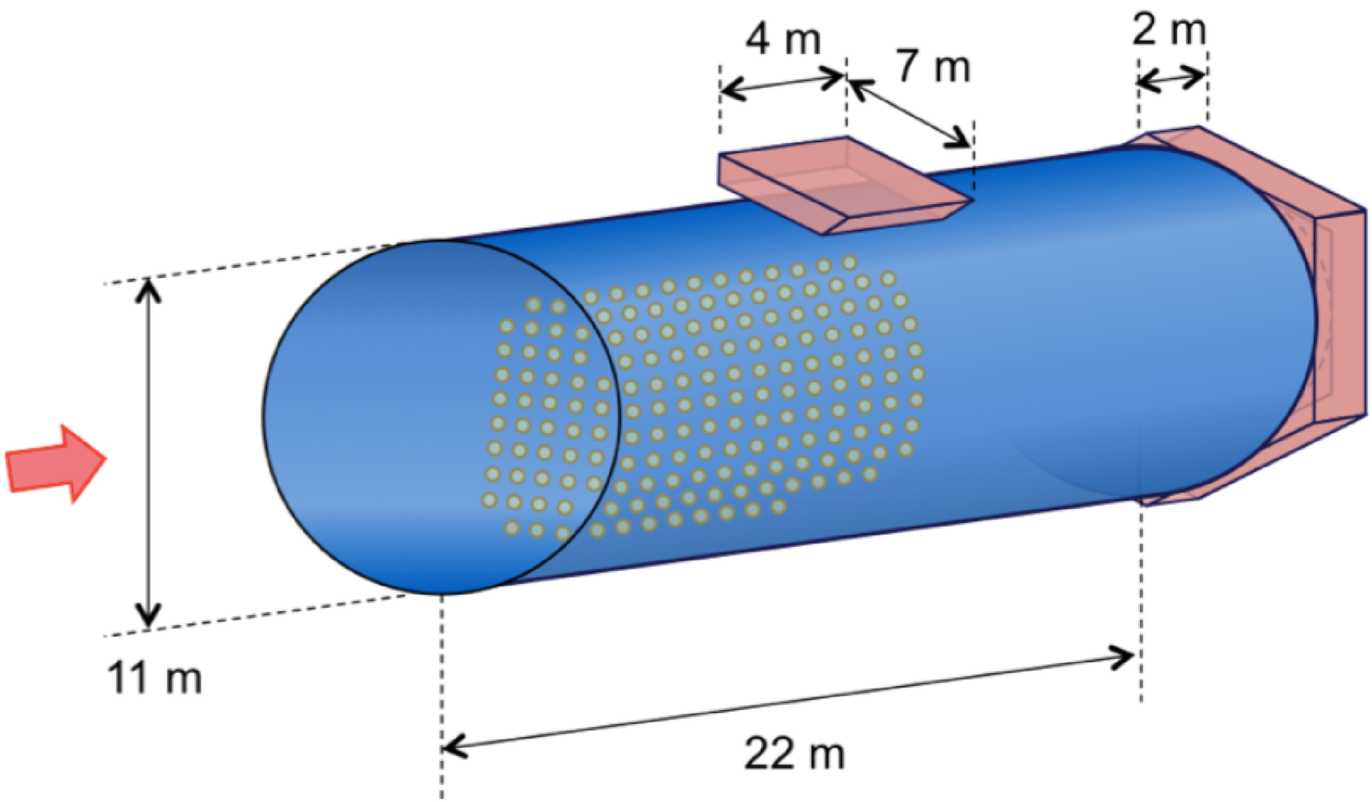
Hybrid schemes:
WAGASCI + TPC rearrangement + HP-TPC

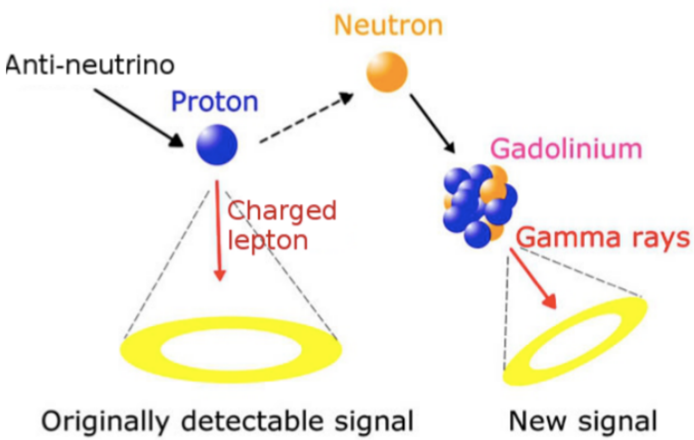


TITUS

Tokai Intermediate Tank with Unoscillated Spectrum

- 2kt Gd doped (0.1%) water Cherenkov
- ~2 km from J-PARC, 2.5° off-axis
- Magnetized downstream Muon Range Detector (MRD)
- Small side MRD





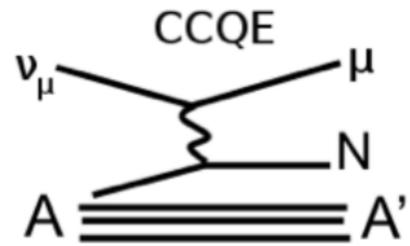
0.1% Gd doping:

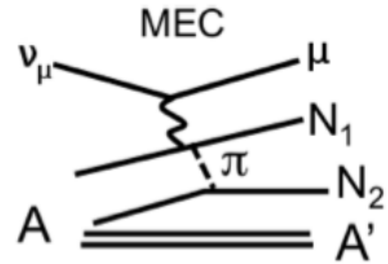
- 49000 b vs 0.3 b (H)
- 8 MeV γ (4-5 MeV visible)
- 90% capture efficiency

NB. **> 2018 also SuperKamiokande planned to become Gd-doped** (EGADS demonstrator)

Same target, similar acceptance, same flux, sensitivity to multi-nucleon with n-tagging

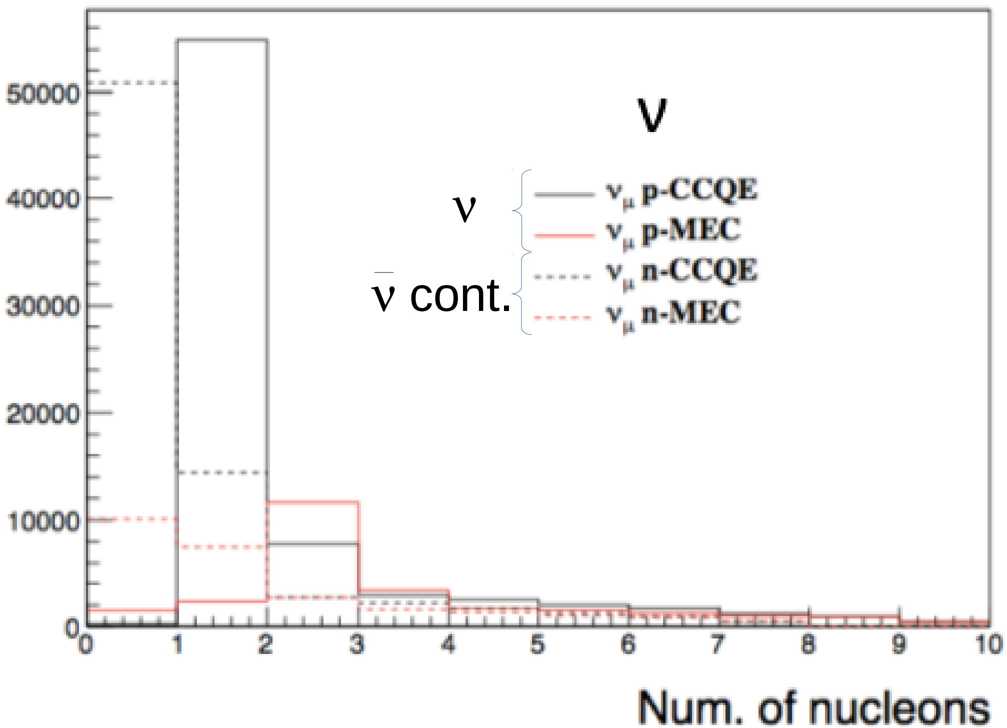
TITUS: MEC with neutron tagging

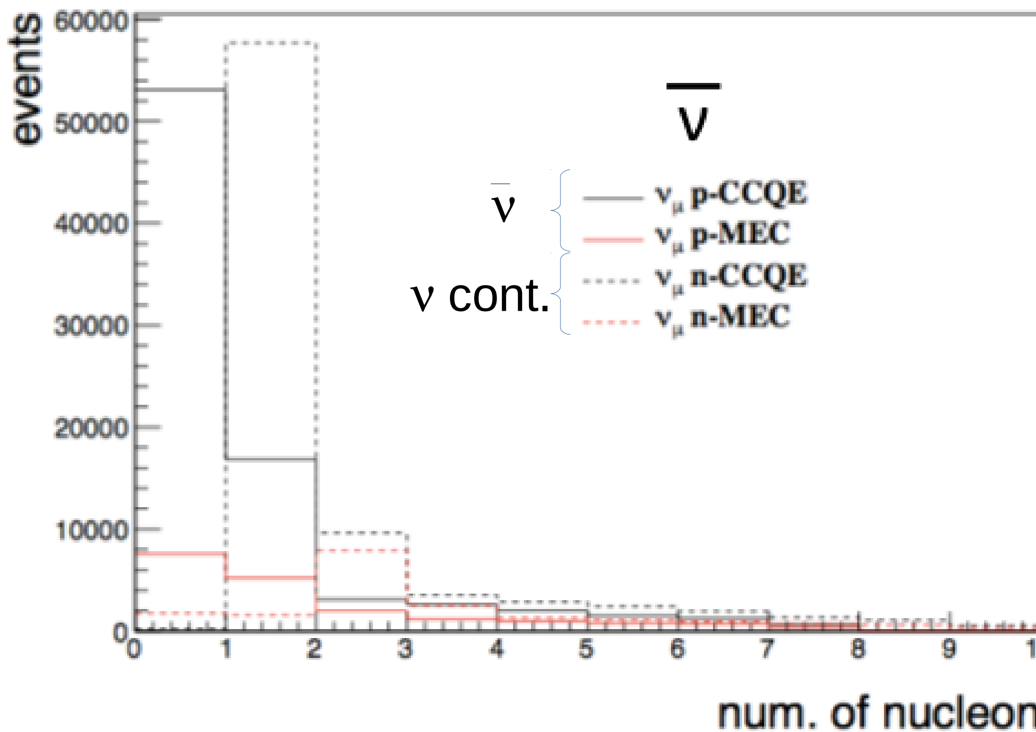




		<neutrons>
ν_μ CCQE:	$\nu_\mu + n \rightarrow \mu^- + p$	0
$\bar{\nu}_\mu$ CCQE:	$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$	1
ν_μ MEC:	$\nu_\mu + (n+n) \rightarrow \mu^- + p + n$	0.2
$\bar{\nu}_\mu$ MEC:	$\bar{\nu}_\mu + (p + p/n) \rightarrow \mu^+ + n + p/n$	1.8

Clear n signals can be modified by nuclear effects: re-scattering, charge exchange and absorption in the nuclear medium



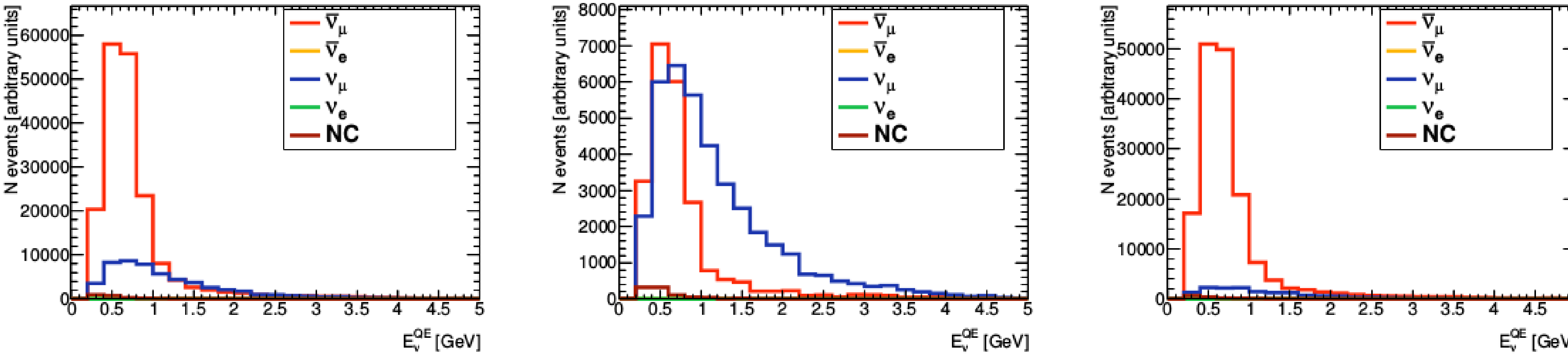


Neutron tagging offers a powerful extra-handle for discrimination

TITUS

anti-nu mode

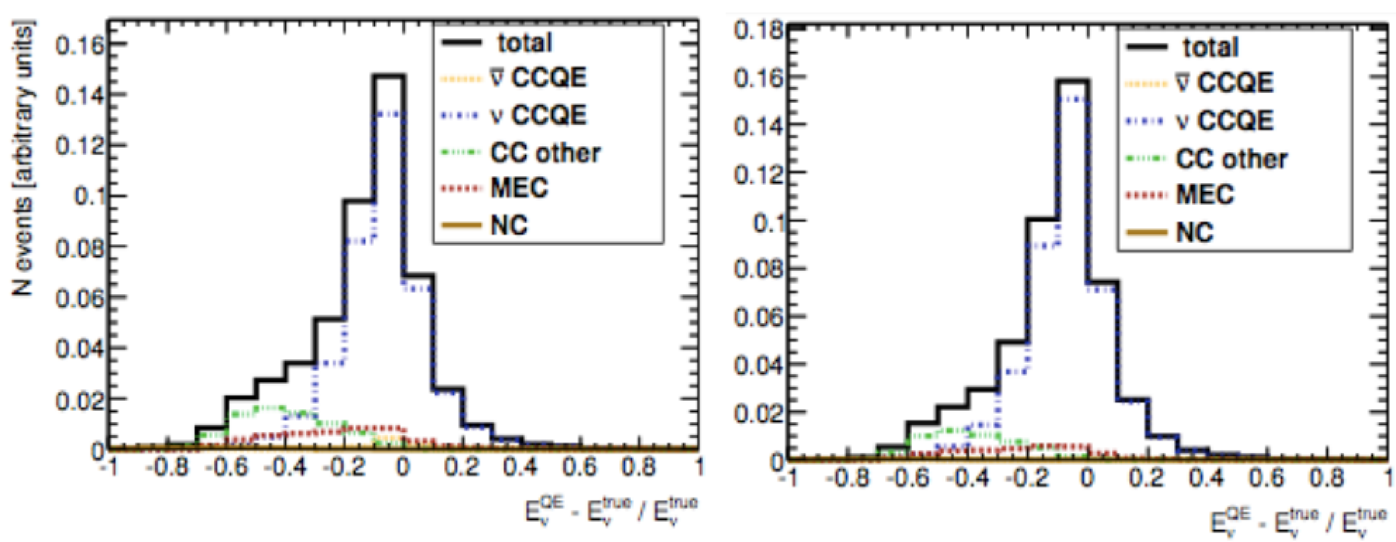
1 ring μ selection: neutrino contamination 23 → 8% with neutron tagging



(a) Before neutron tagging (b) No tagged neutron (c) Tagged neutron

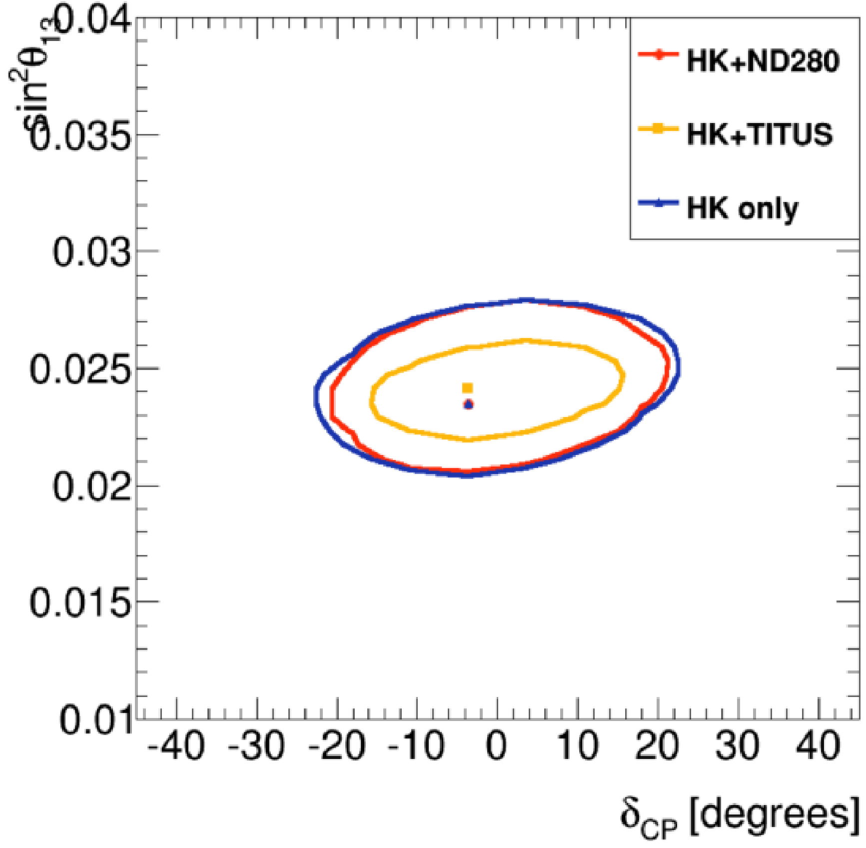
nu mode

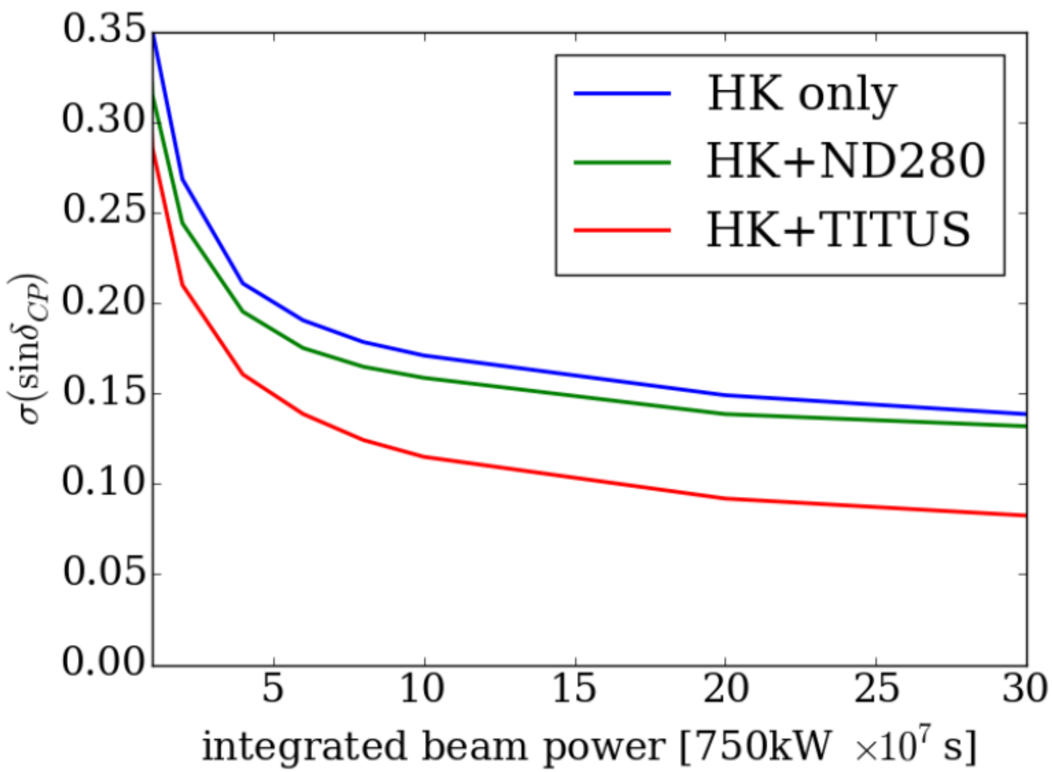
Improvement of CCQE purity with n-tagging → better energy reconstruction



(a) Any N_{neutrons} (b) $N_{\mathrm{neutrons}} = 0$

TITUS + HyperK: impact on δ_{CP}





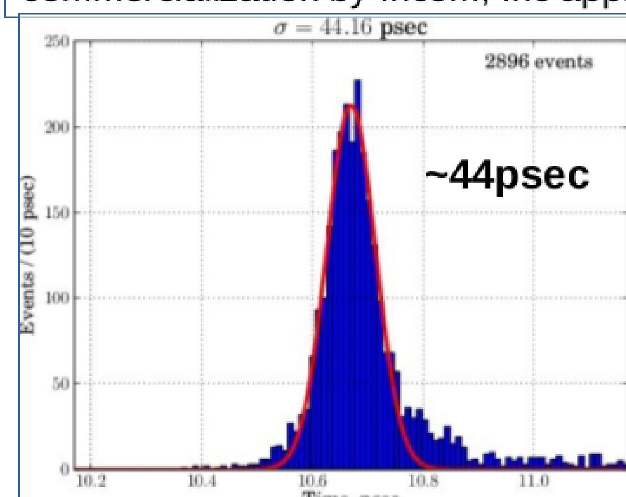
R&D for innovative photosensors (LAPPD) within ANNIE at FNAL

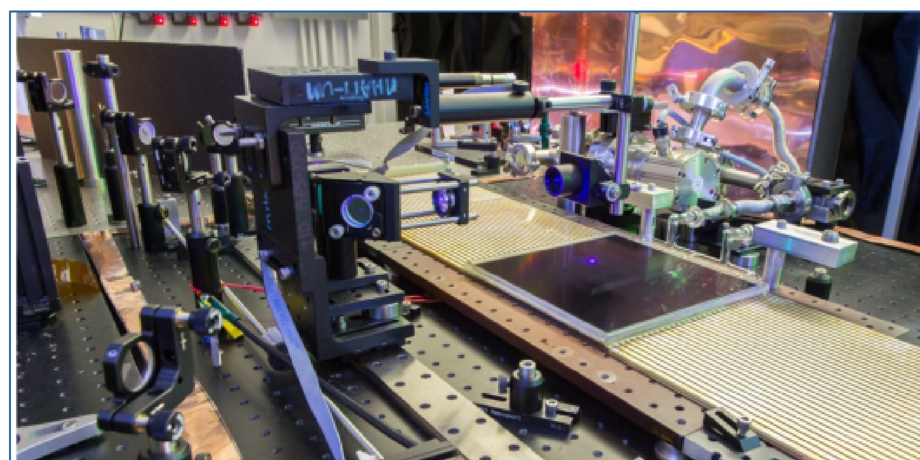
Accelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment (1504.01480)

LAPPDs

http://psec.uchicago.edu

The Large Area Picosecond Photodetectors (LAPPD):
- Large, flat panel, (multi-channel plate) MCP-based photosensors. Use Atomic Layer Deposition.
- <50 psec time resolutions and < 1cm spatial resolutions
- Based on new, potentially economical industrial processes
- LAPPD design includes a working readout system
- Phase II request for $3M for commercialization by Incom, Inc approved

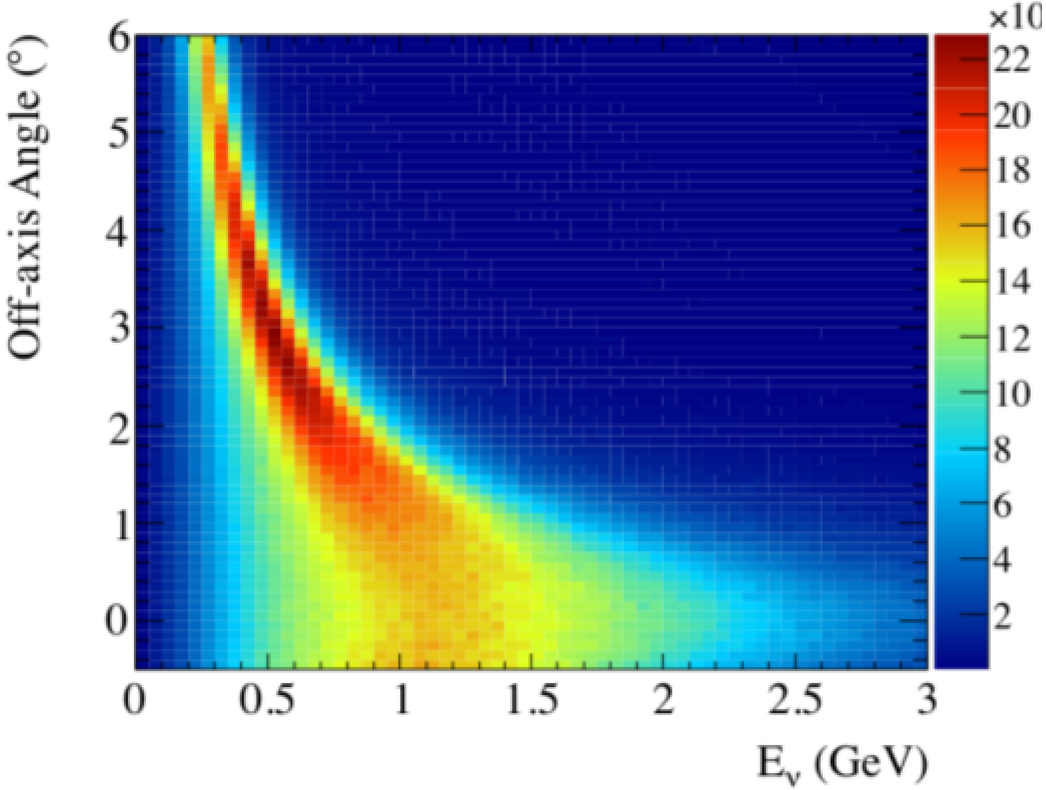


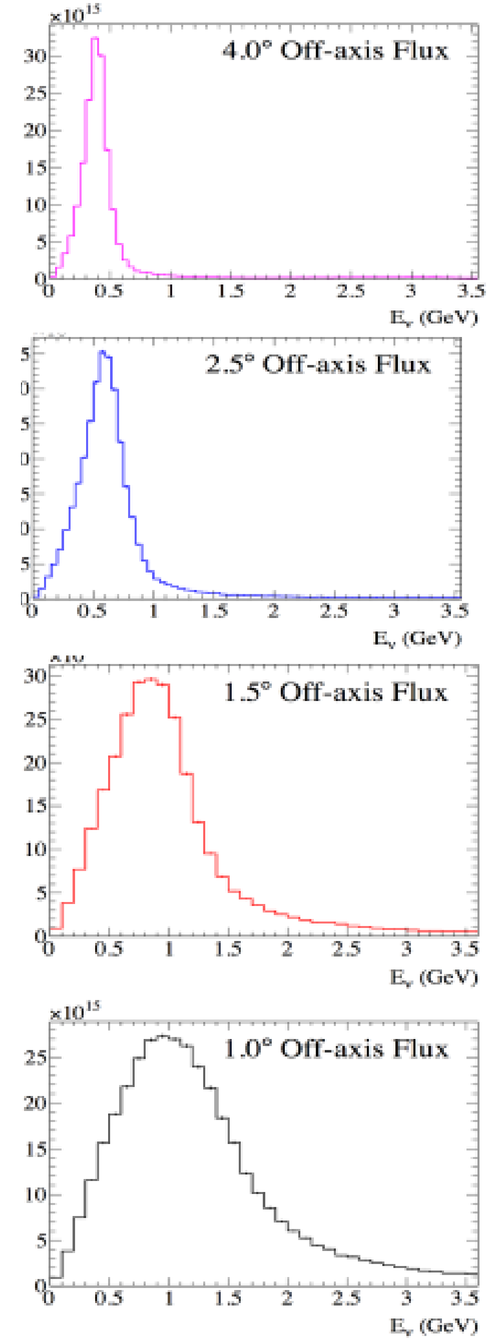


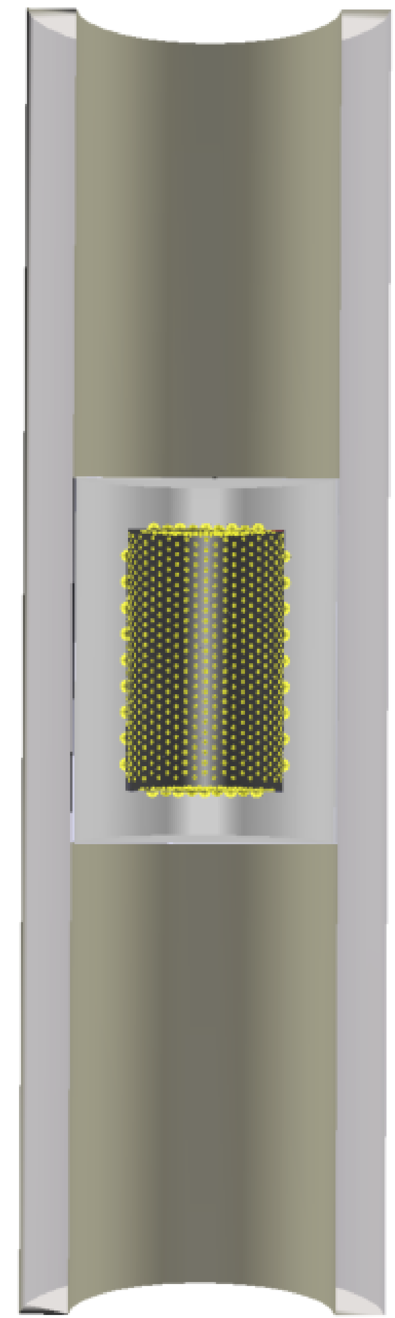
QMUL, 18-19 Dec 2014 Francesca Di Lodovico (QMUL) 5

νPRISM

Extract the energy dependence by measuring the rates and final state kinematics over a range of off-axis angles







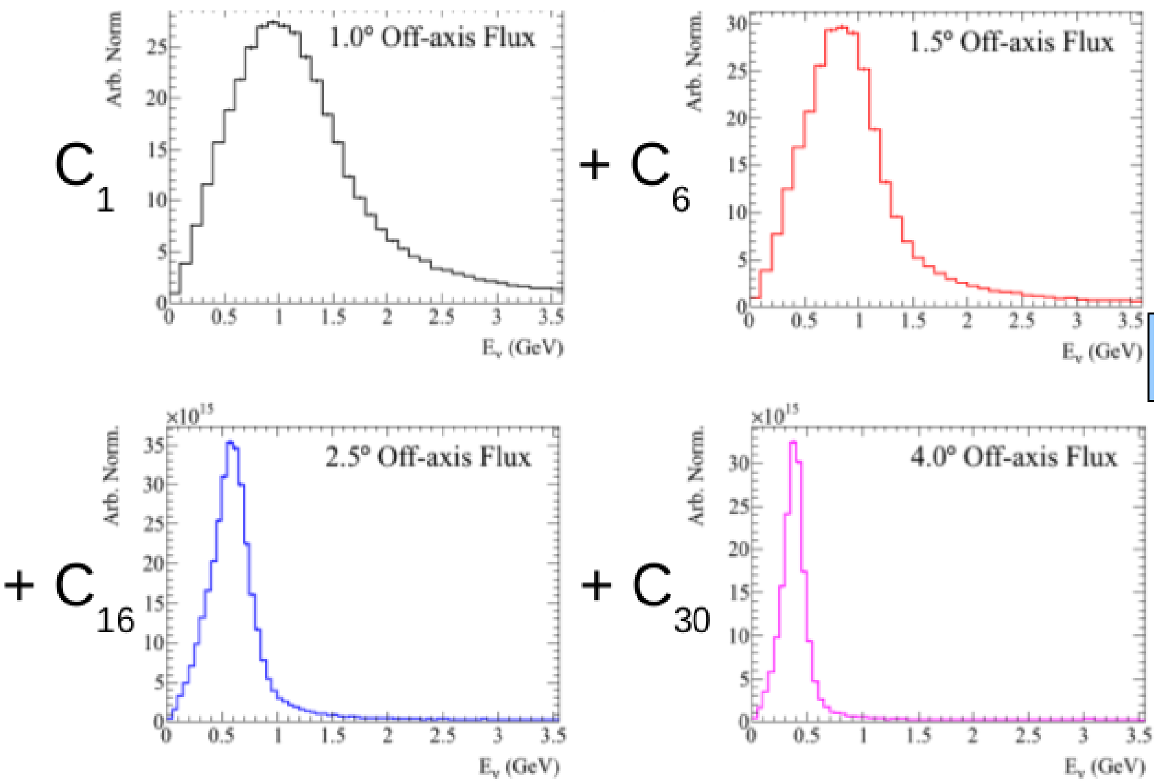
Detector moved up and down a shaft
~ 1 km baseline: span: 1-4 degrees

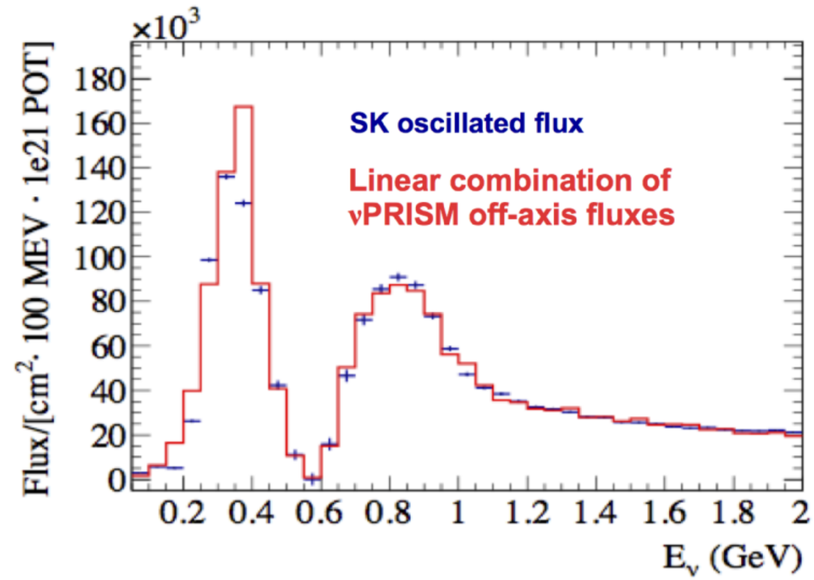
WC detector: 6 m diameter x 10 m height
40 % photo-coverage: 3120 8” PMT or 7385 5” PMT

νPRISM

Derive linear combinations of the fluxes at different off-axis angles to produce a flux that closely matches the predicted oscillated flux at Super-K

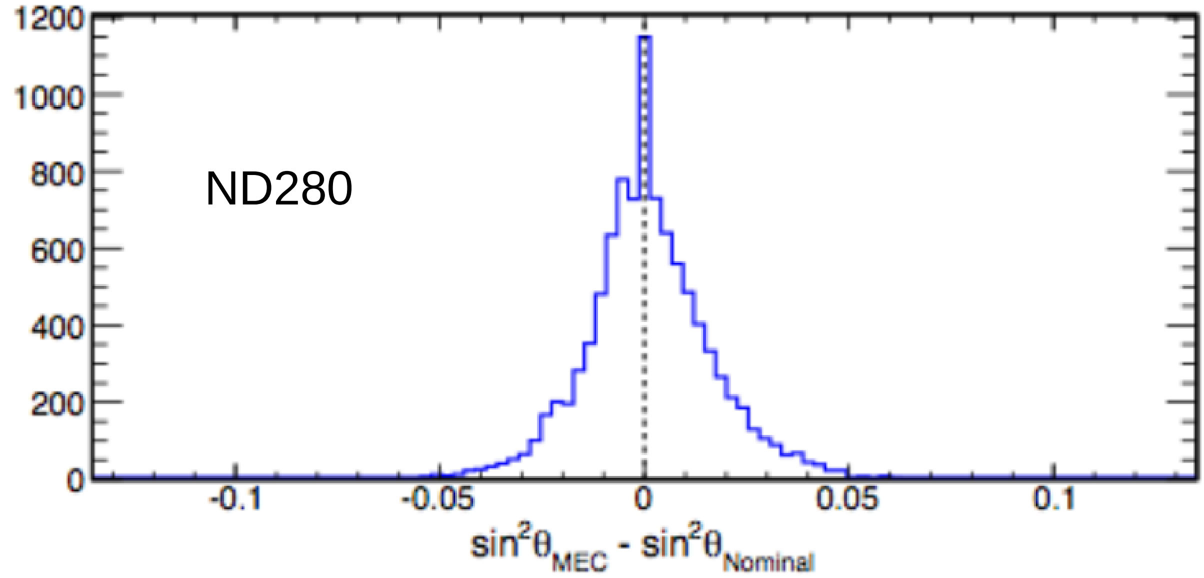
$$\Phi^{SK}\left(E_\nu;\theta_{23},\Delta m^2_{32}\right)E_\nu=\sum_{i=1}^{30}c_i\left(\theta_{23},\Delta m^2_{32}\right)E_\nu\Phi_i^{\nu P}(E_\nu)$$

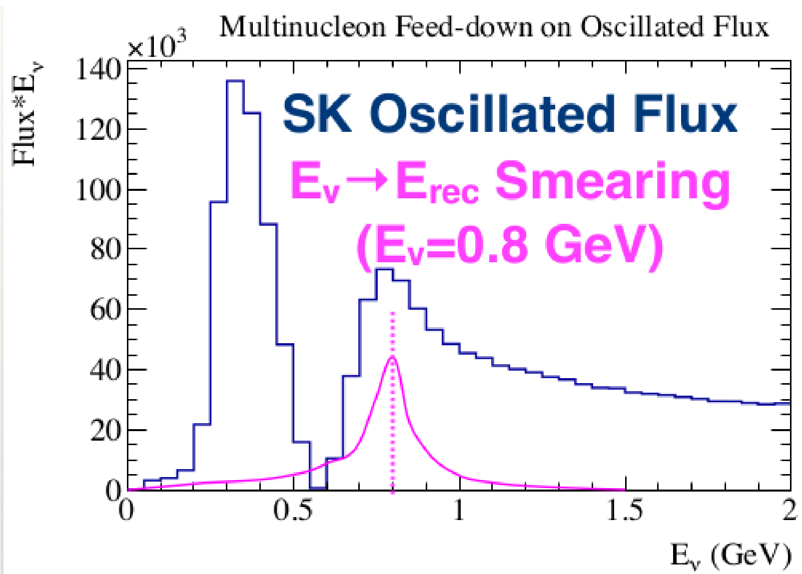


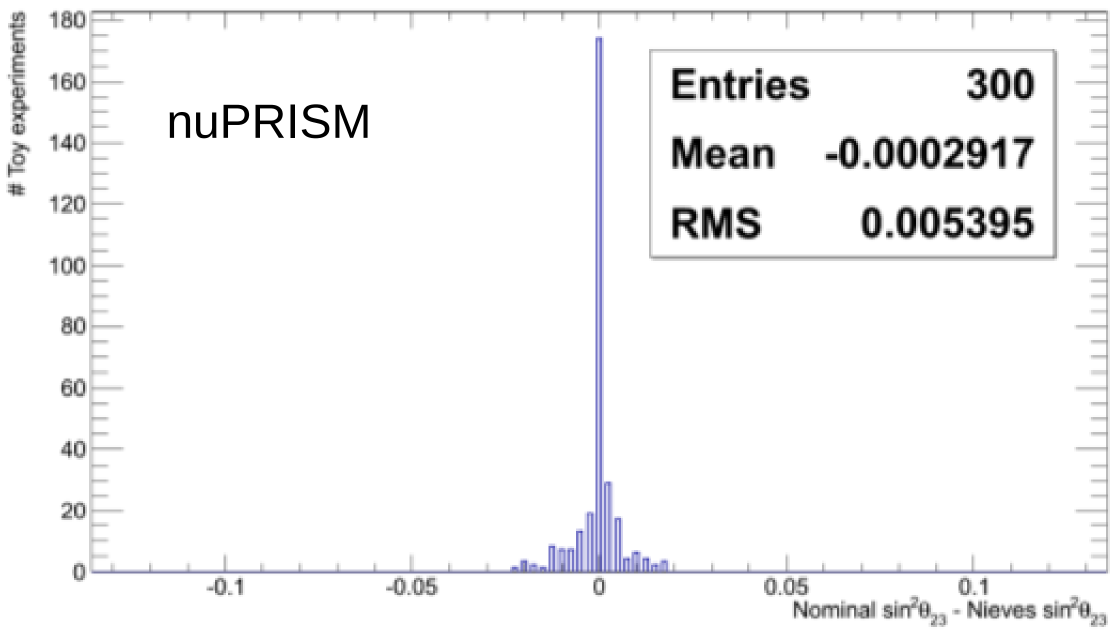


MEC uncertainty with νPRISM

Flux combination to reproduce the oscillated spectrum → reduced impact of multi-nucleon events on θ_{23} ("dip-filling" can be measured)

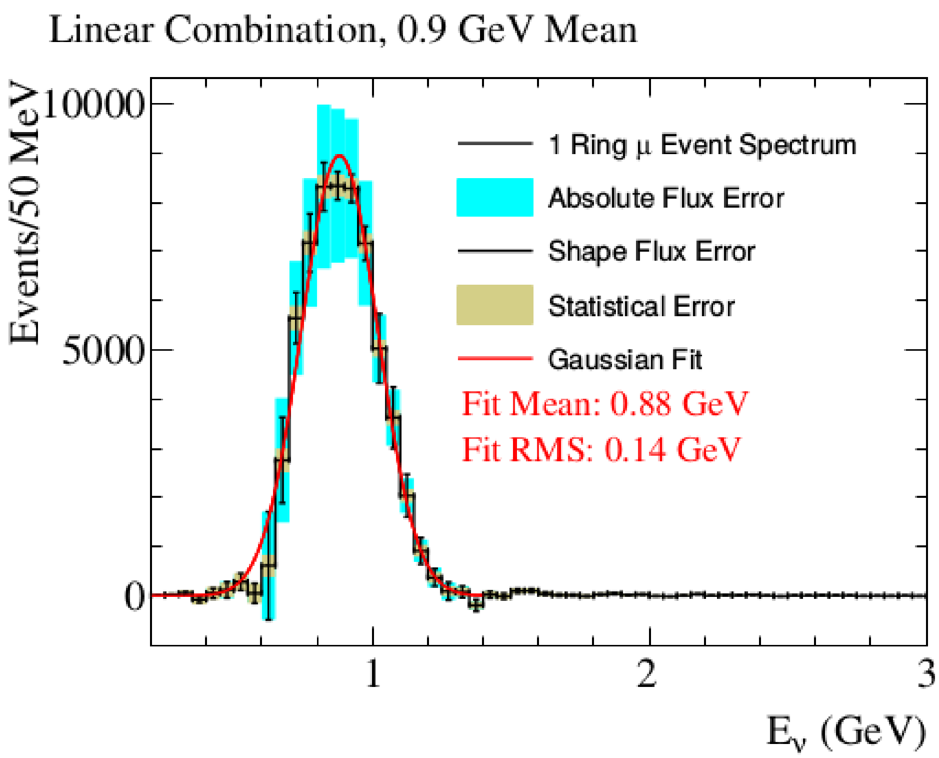


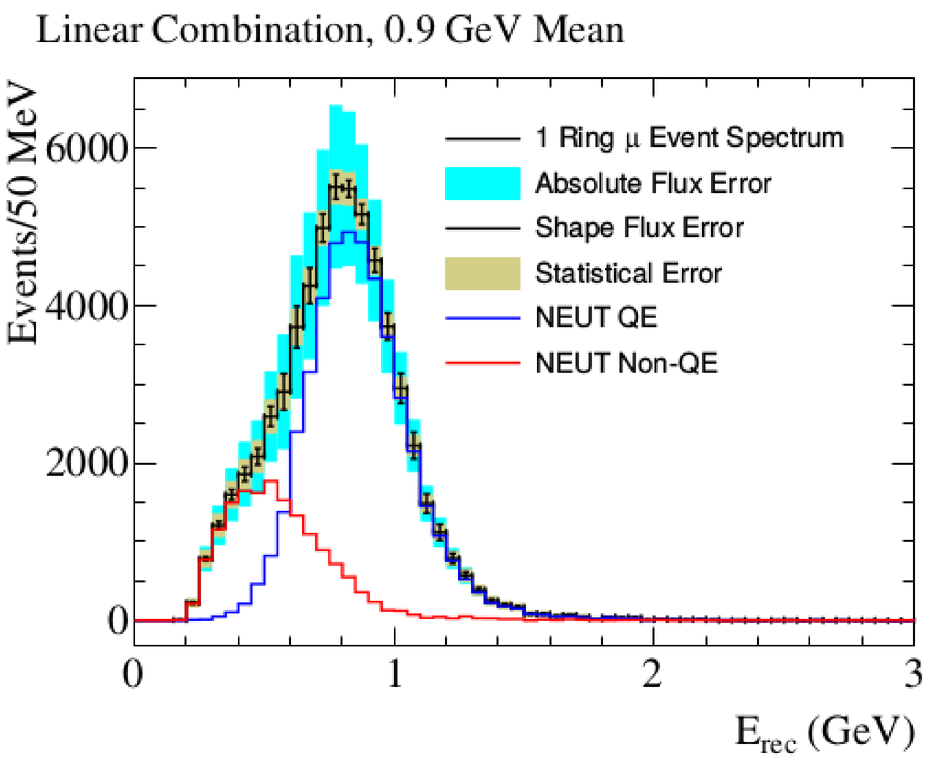




νPRISM

Appropriate linear combinations of the measurements in each slice:
→"Gaussian" beams at energies between 0.4 and 1.2 GeV



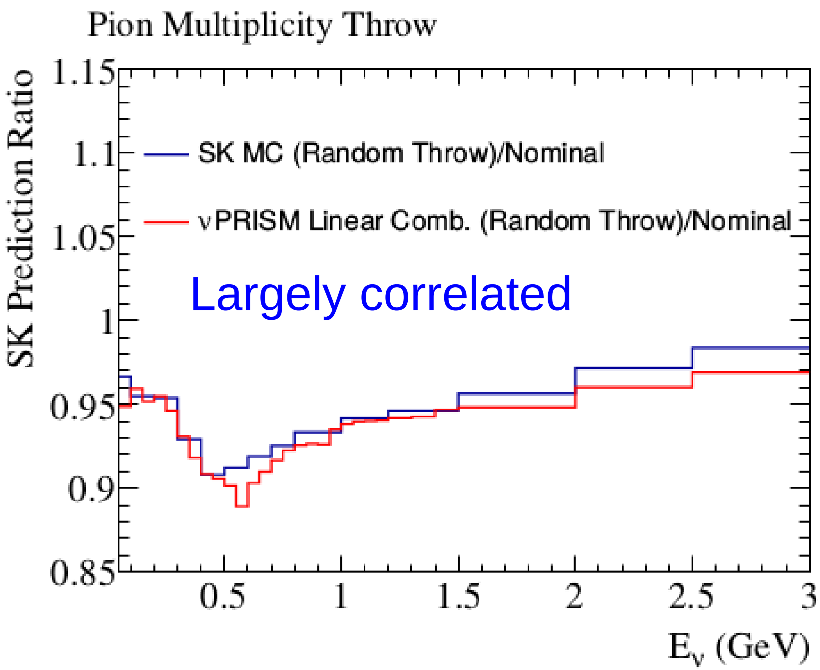


Predict the effect of non-quasi-elastic scatters in oscillation measurements
Provide a constraint on nuclear models of these processes

Remarks on νPRISM method

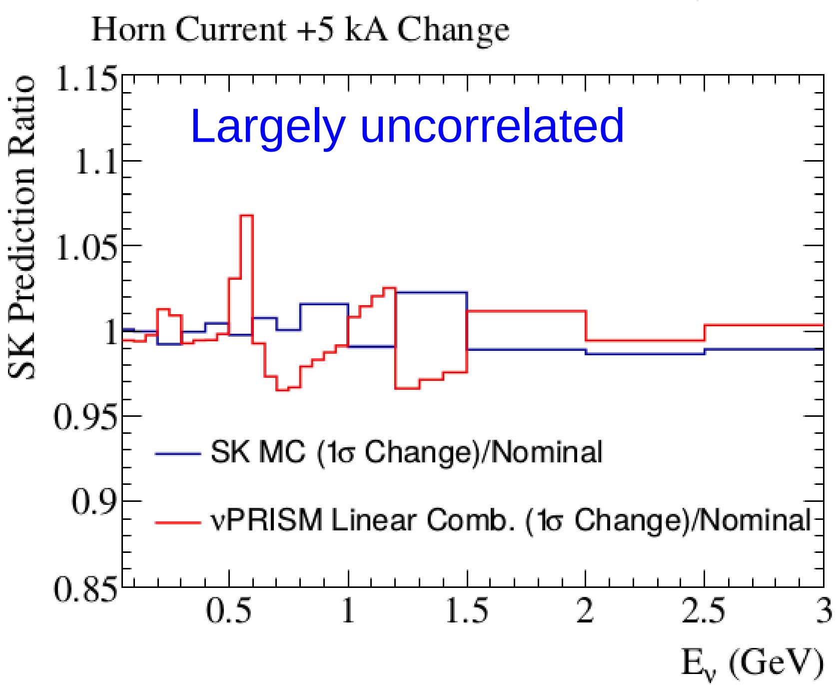
Uncertainties in **ν cross section modeling** effectively shifted into **flux prediction systematic** uncertainties

Advantages:
- many flux systematic uncertainties cancel
- Hadro-production uncertainties can be measured (to a certain extent) by dedicated experiments (f.e. NA61)



More problematic uncertainties exist. Those affecting the off-axis angle:

- horn current
- proton beam positioning

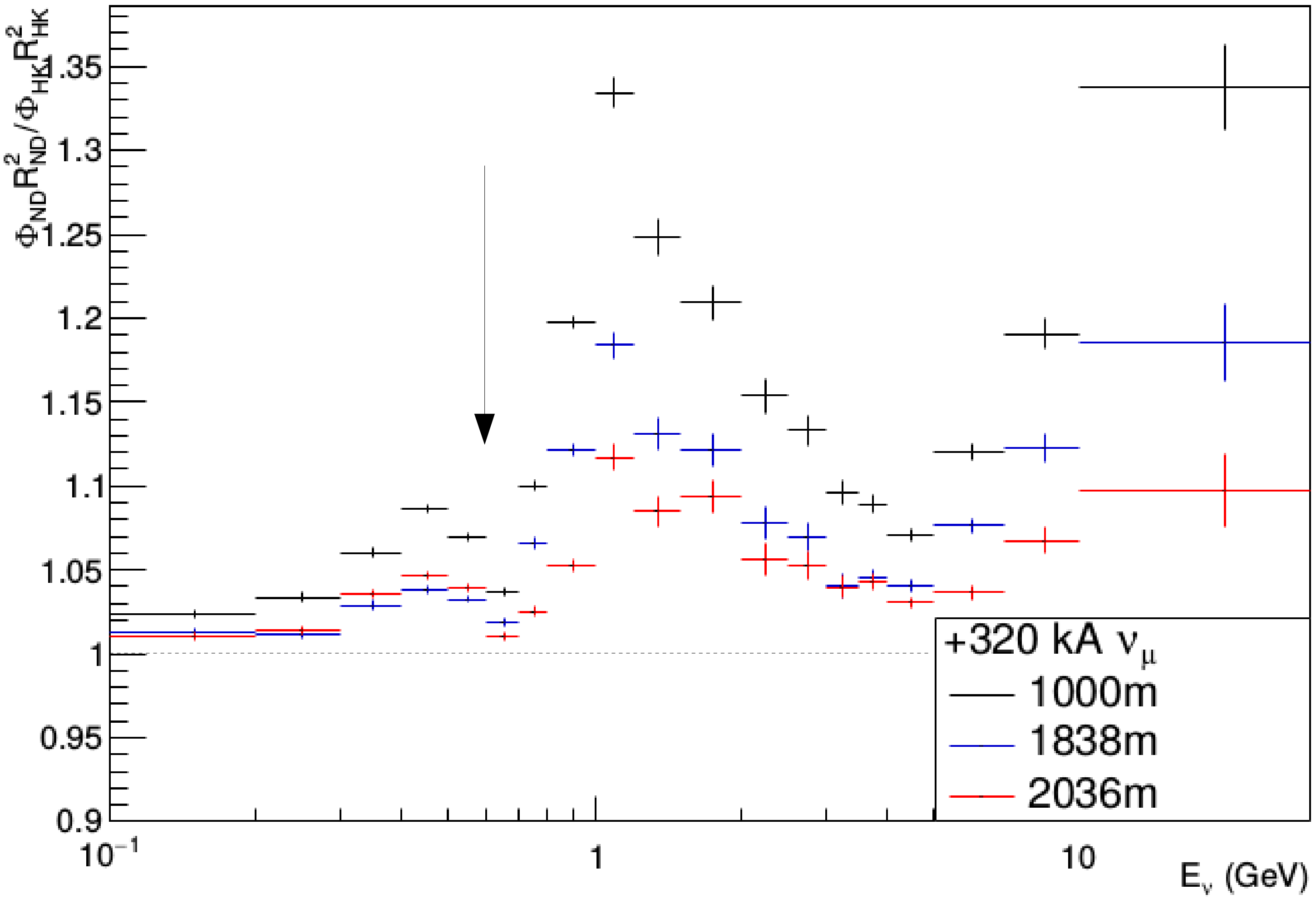


Impact Super-K and the nuPRISM linear combinations differently.

Conclusions

- Main goal is reducing **systematics for CP violation** in the 2020-25 phase
- Big impact on **understanding of GeV neutrino cross-sections** thanks to
  - improved acceptance, purity, sensitivity to multi-nucleon effects/FSI.
- Several interesting proposals:
  - **WAGASCI**: already on its way. $\sigma(H_2O/CH)$ at 3%.
  - **TITUS**: probably the most "straightforward". R&D on neutron tagging with LAPPD detectors within ANNiE at FNAL.
  - **High Pressure-TPC**: precise measurement of nuclear effects down to very low thresholds. Not ideal for water (better for Ar). Quite challenging, not cheap.
  - **νPRISM**: interesting idea. Implementation is demanding (excavation, logistics).
- Final note: all these projects subdominant ν_e component → low purity. They miss a real breakthrough for **ν_e/ν_μ cross section** issue. Alternative solutions (tagged ν_e beams, see talk by Ludovici).

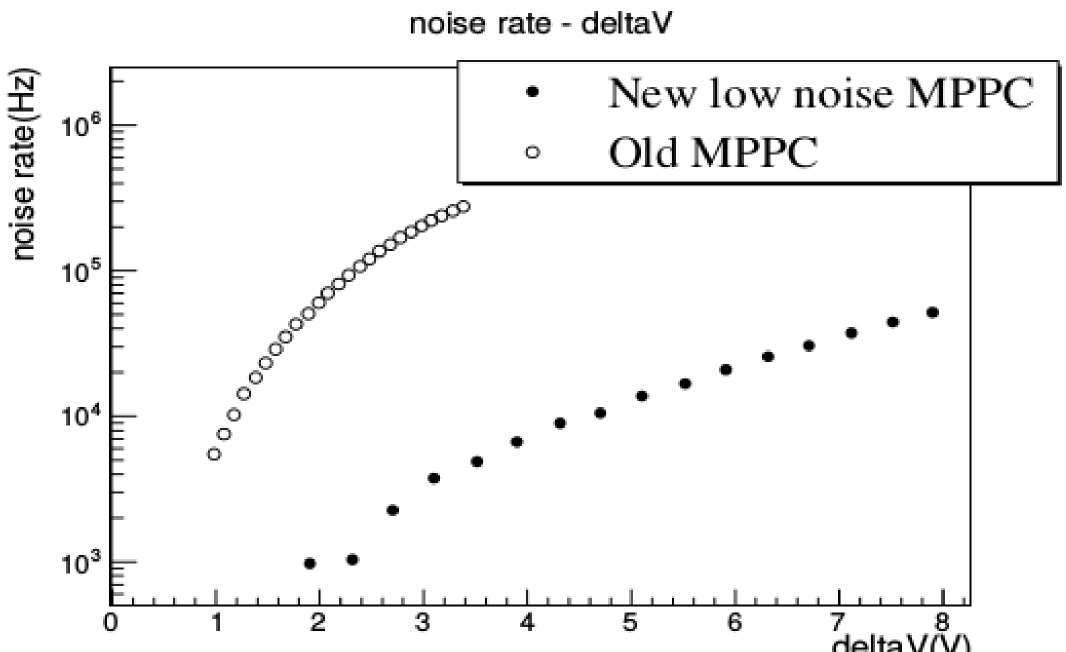
Near/Far ratio (TITUS)

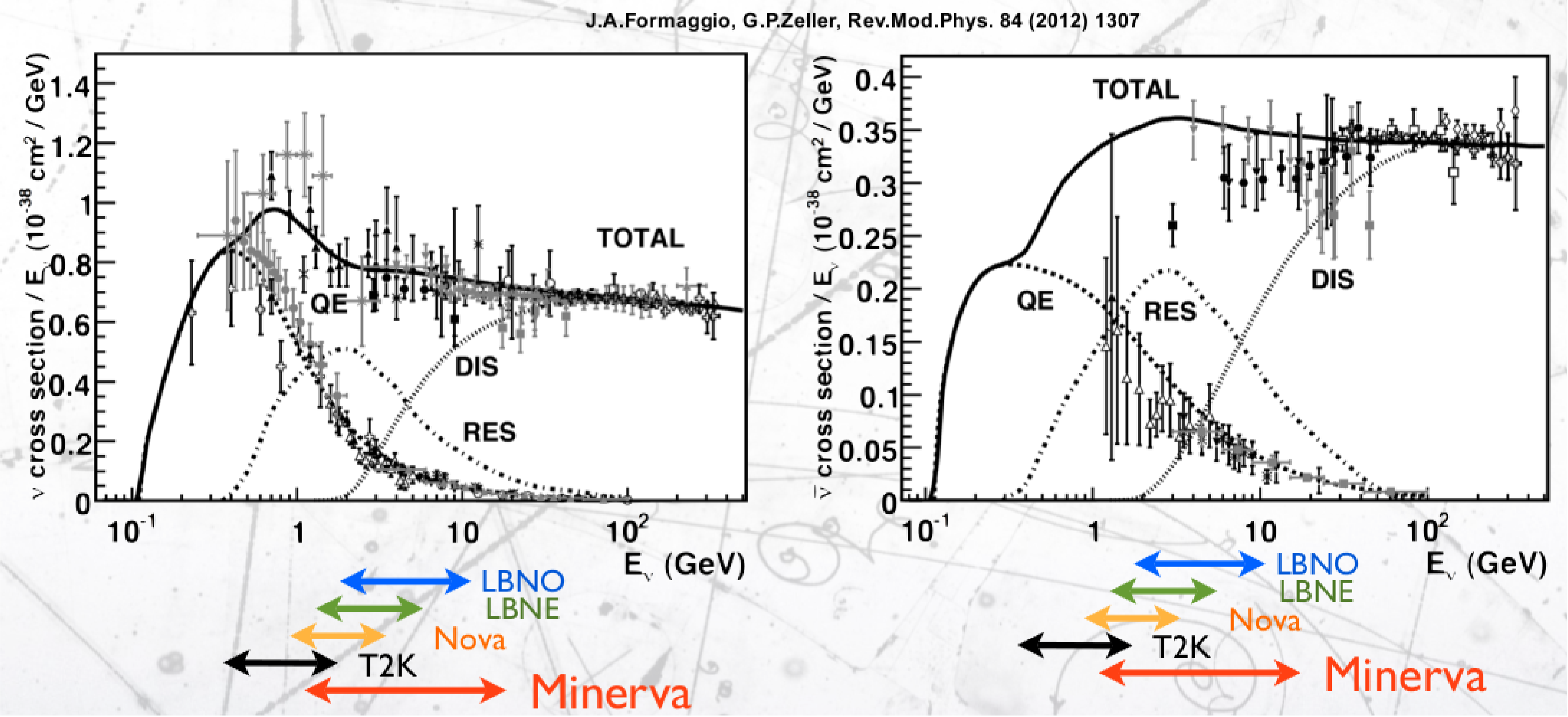


WAGASCI

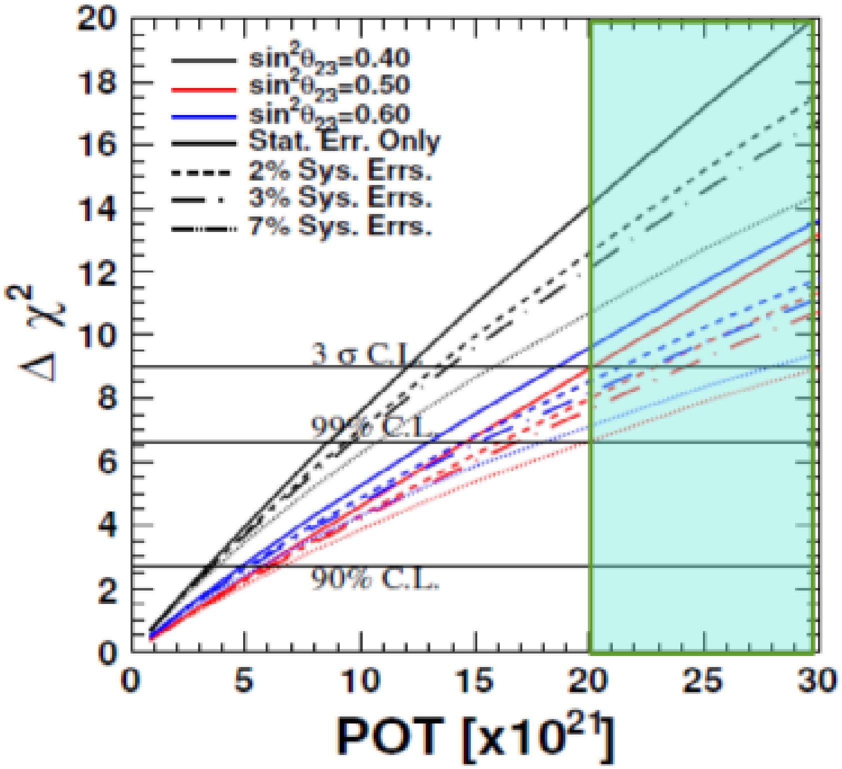
Central detector		Size	100×100×200 cm^3
		Size of the each target part	100×100×50 cm^3
		Target masses (H_2O, CH)	1 ton each
		Size of scintillators in the target region	100×2.5×0.3 cm^3
		Size of scintillators for TOF	120×5×1 cm^3
		Number of channels	10,240
MRD	Side	Size	80×200×300 cm^3
		Thickness of iron plates	3 cm (10 planes)
	Downstream	Size	400×200×230 cm^3
		Thickness of iron plates	3 cm (10 planes) / 6 cm (10 planes)
	Total	Size of scintillators	200×20×0.7 cm^3
		Number of channels	1,460

Better Hamamatsu MPPC
(Silicon PhotoMultipliers)




J.A.Formaggio, G.P.Zeller, Rev.Mod.Phys. 84 (2012) 1307
TOTAL
QE
DIS
RES
E$_\nu$ (GeV)
LBNO
LBNE
Nova
T2K
Minerva

Effect of Reduction of Systematic Errors



50% ν- + 50% $\bar{\nu}$-mode
True $\delta_{CP} = -90°$, true MH = NH

- $\Delta\chi^2$ for resolving non-zero δ_{CP} vs. POT
- Systematic error size matters!
  $\rightarrow$T2K measurement of δ_{CP} is systematics limited at high statistics
- Sensitivity depends on true value of $\sin^2\theta_{23}$ (and δ_{CP}, of course)
  - If errors can be reduced to 2%, T2K can make a $>3\sigma$ measurement of non-zero δ_{CP} for any value of $\sin^2\theta_{23}$ (at $\delta_{CP} = -90°$, NH)

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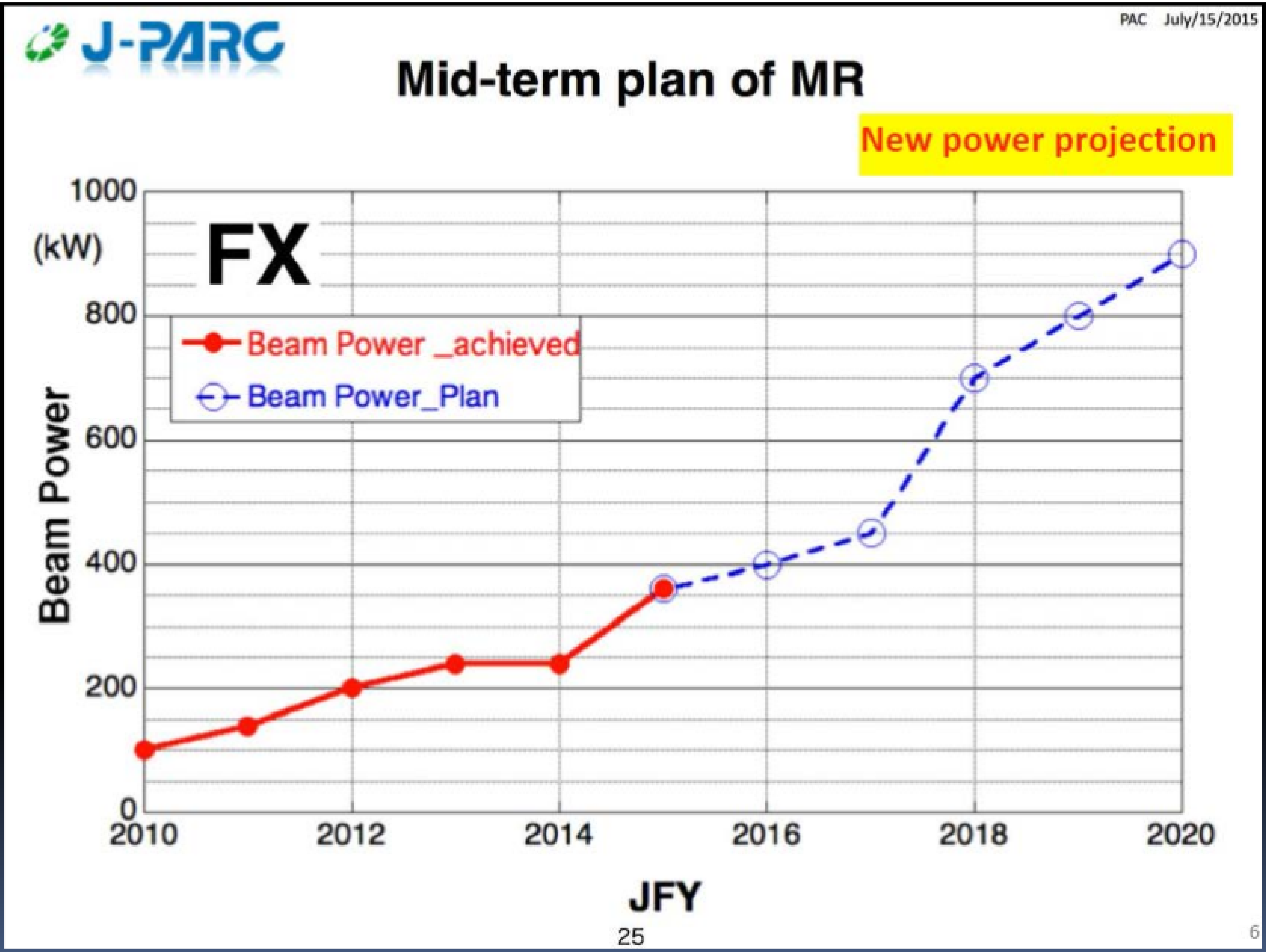
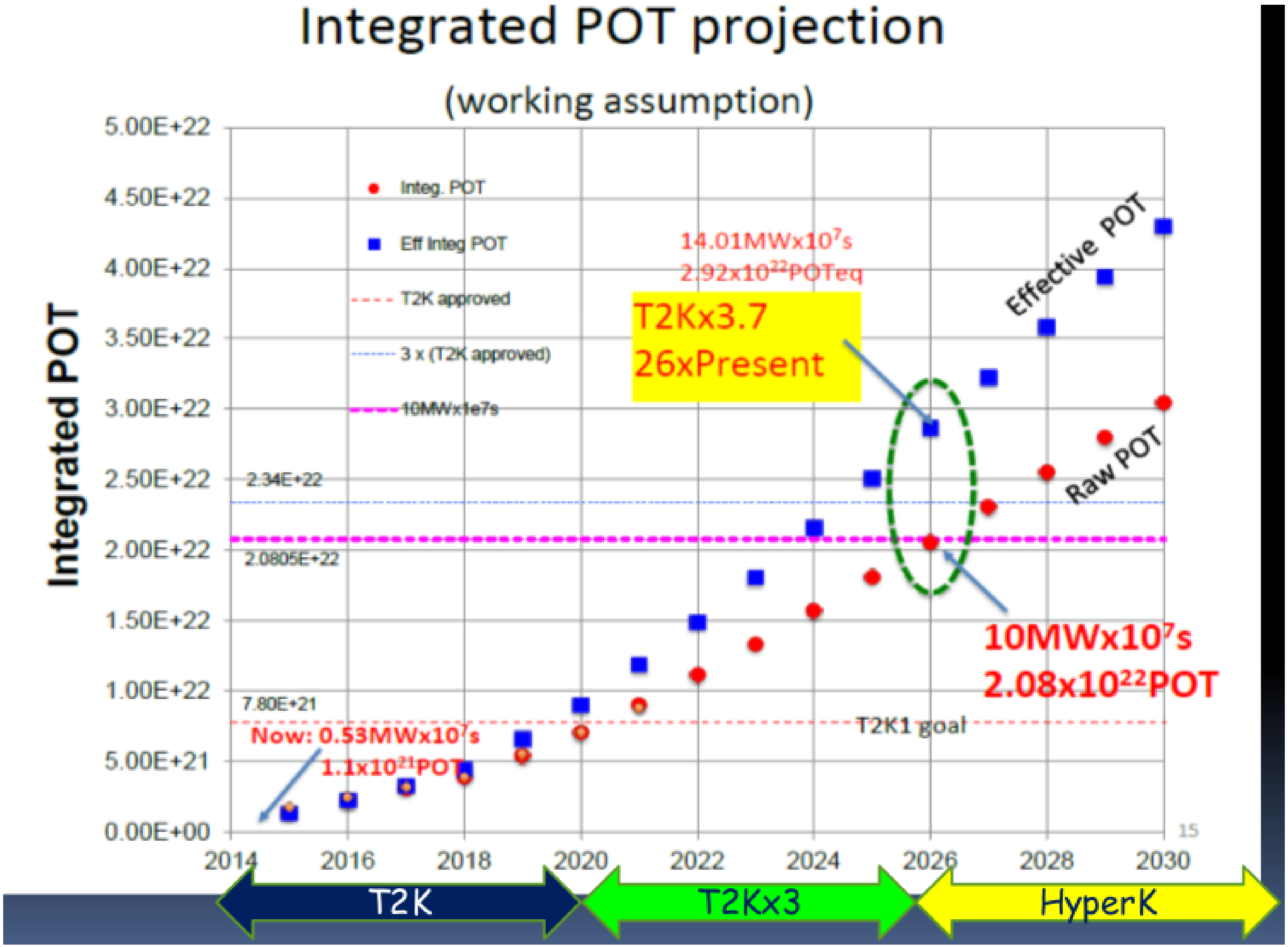
La riduzione degli errori sistematici e' fondamentale->
<u>Xsec errors (water, NC, ν_e)</u>

Upgrade dei Near Detectors necessaria gia' nel 2020 ben prima di HyperK (2025)



MR Upgrade Approved !

- An intermediate phase: "T2K x 3"
  - 3x T2K statistics (20×10^{21} POT)

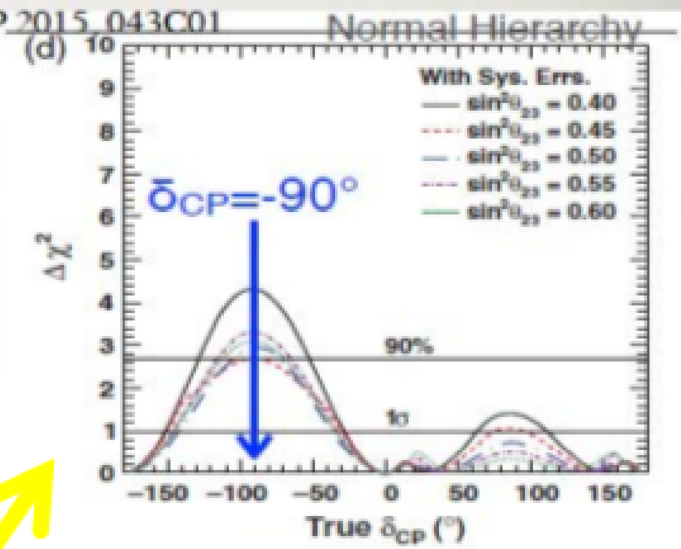


LOOKING FORWARD

- So far, accumulated ~14% of full T2K projected POT
  - ν-mode: 6.9×10^{20} POT, $\bar{\nu}$-mode: 4.0×10^{20} POT
- Short-term: ~1 year
  - Expect ~9.5E20 POT: ~2σ level sensitivity for null $\bar{\nu}_e$ app. hypothesis exclusion
    - ~60% chance for 99% CL observation
- Long-term (full T2K data)
  - Expect ~10 times larger stat. in $\bar{\nu}$-mode data
    - 50% ν, 50% $\bar{\nu}$-mode running
  - May exclude $\delta_{CP}=0$ w/ $\gtrsim$90% CL
  - Impact of θ_{23} degeneracy
  - $\bar{\nu}_\mu$ disappearance measurement is also important

9.5E20 POT			
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$
NH [events (sig)]	8.8 (4.6)	10.2 (6.2)	11.5 (7.8)
IH [events (sig)]	9.9 (5.9)	11.5 (7.7)	12.9 (9.3)

PTEP 2015 043C01



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Aspettando gli esperimenti della prossima generazione si puo' fare di piu ?

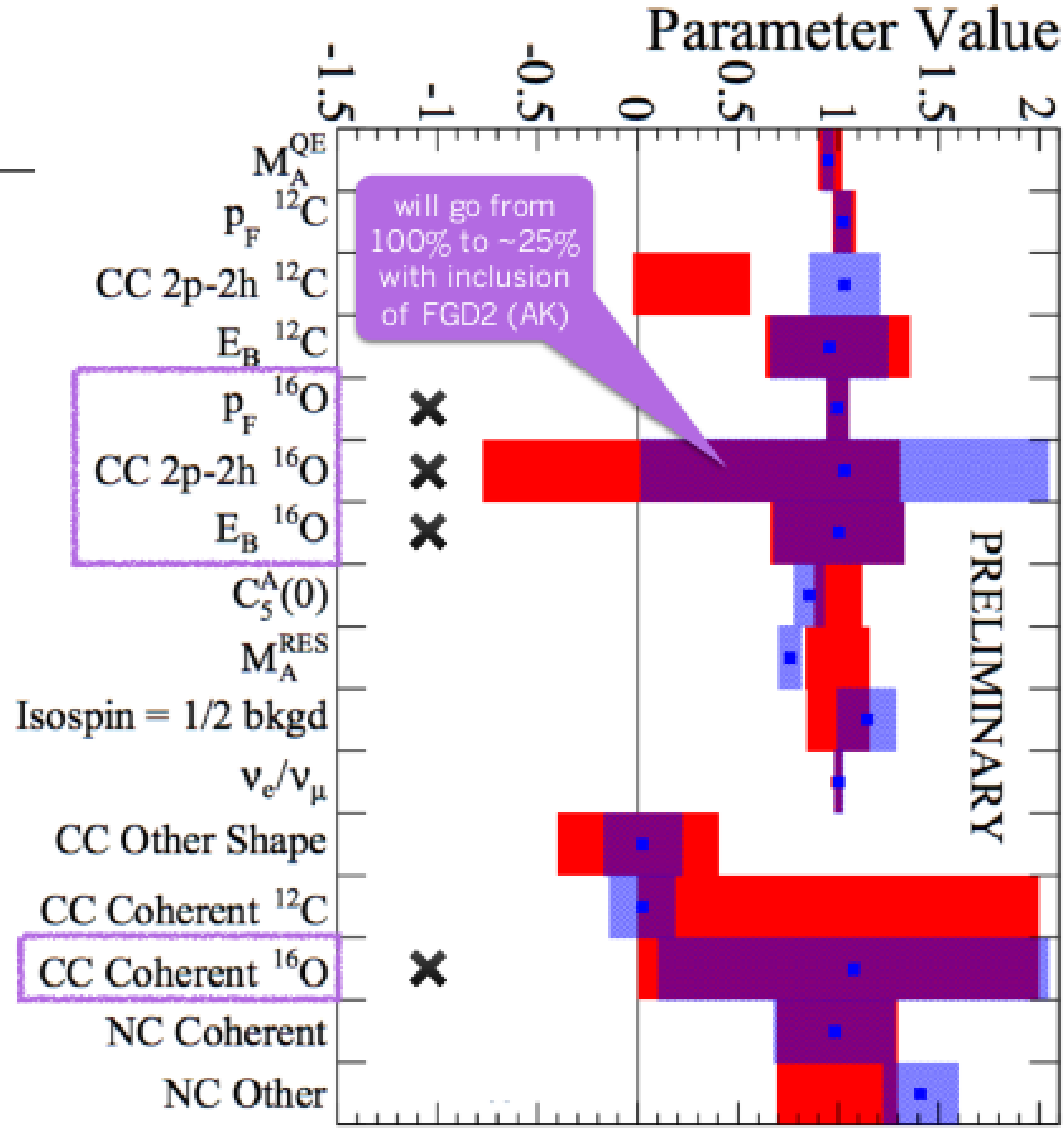
νPRISM

TABLE III. Expected number of events in the fiducial volume of nuPRISM for 4.5×10^{20} POT, separated by true interaction mode in NEUT.

Int. mode	1-2°	2-3°	3-4°
CC inclusive	1105454	490035	210408
CCQE	505275	271299	128198
$CC1\pi^+$	312997	111410	39942
$CC1\pi^0$	66344	23399	8495
CC Coh	29258	12027	4857
NC $1\pi^0$	86741	32958	12304
NC $1\pi^+$	31796	11938	4588
NC Coh	18500	8353	3523

A water target is a key feature

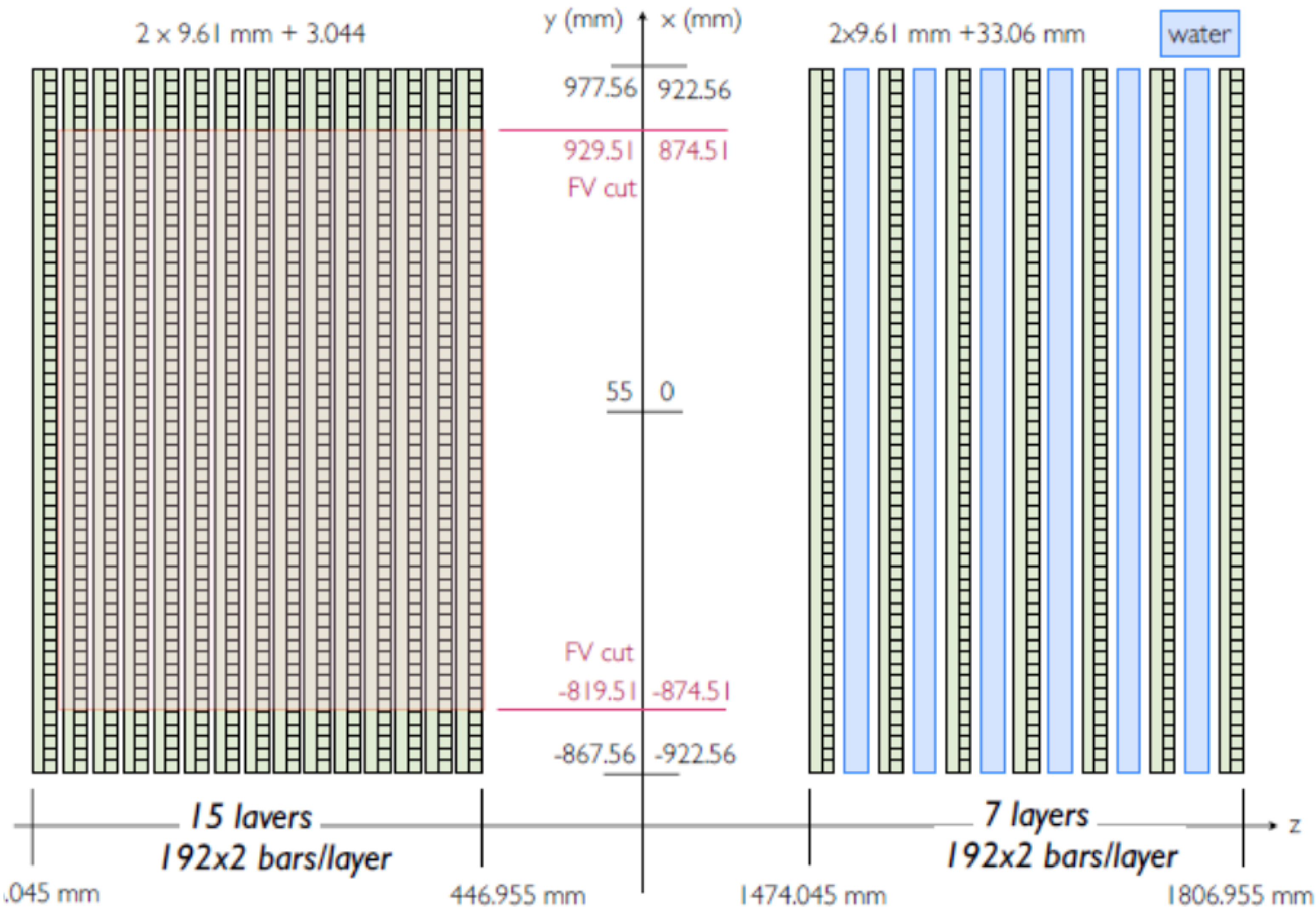
…and we get improvements and simplifications here



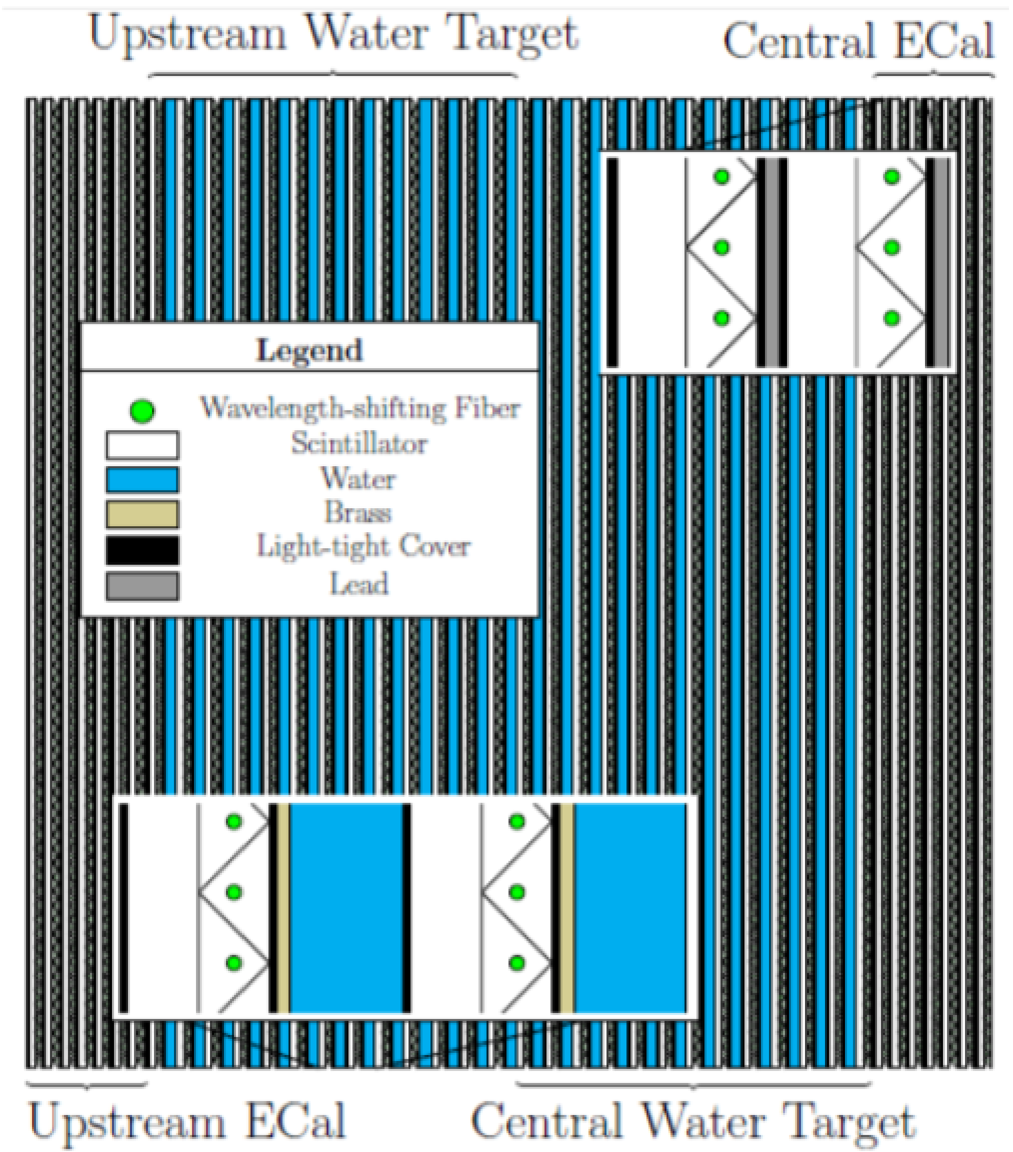
J. Myslik, BANFF report, June 2015 T2K meeting

- Prior to ND280 Constraint
- After ND280 Constraint
- ✖ not constrained

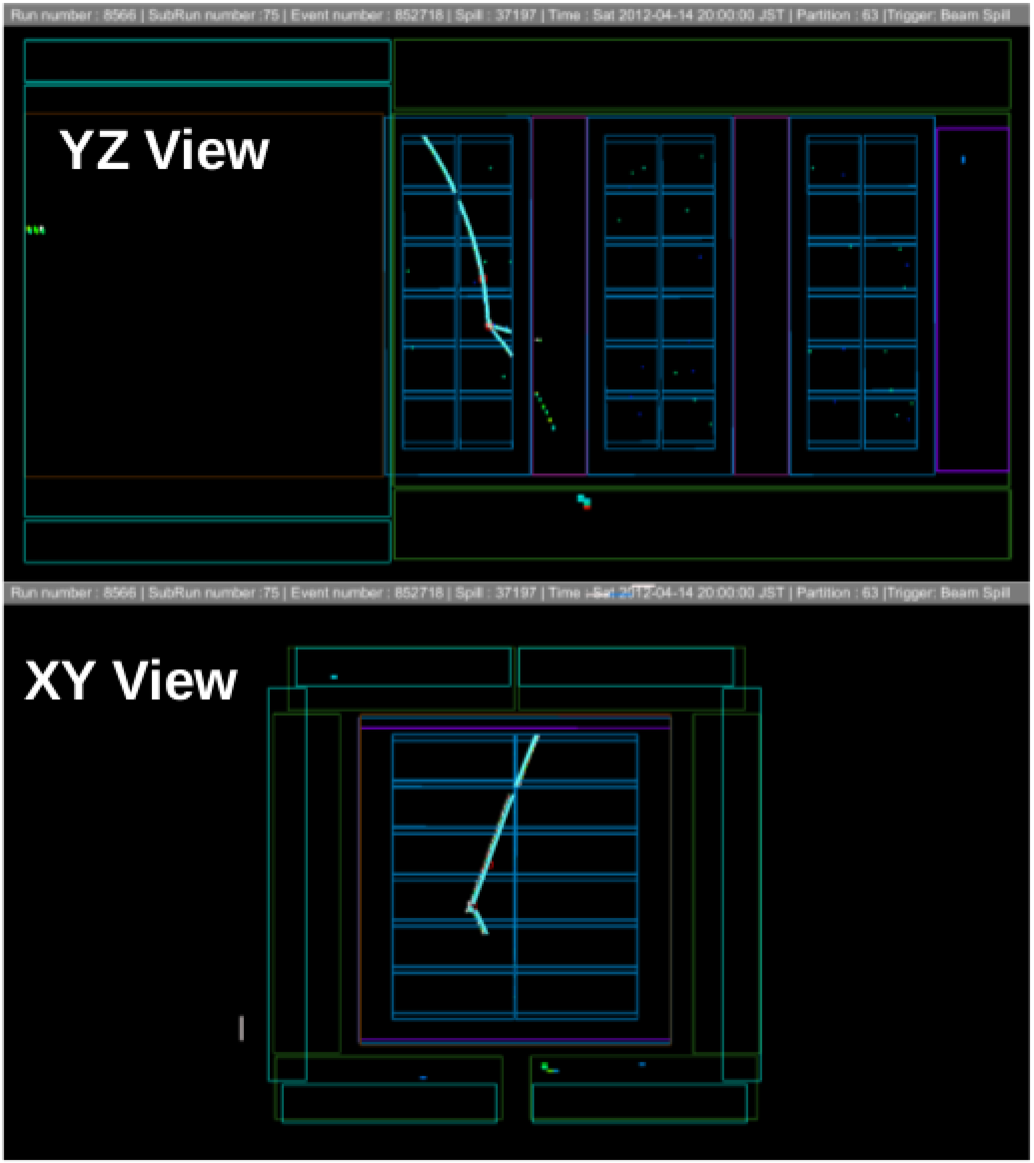
ND280 target

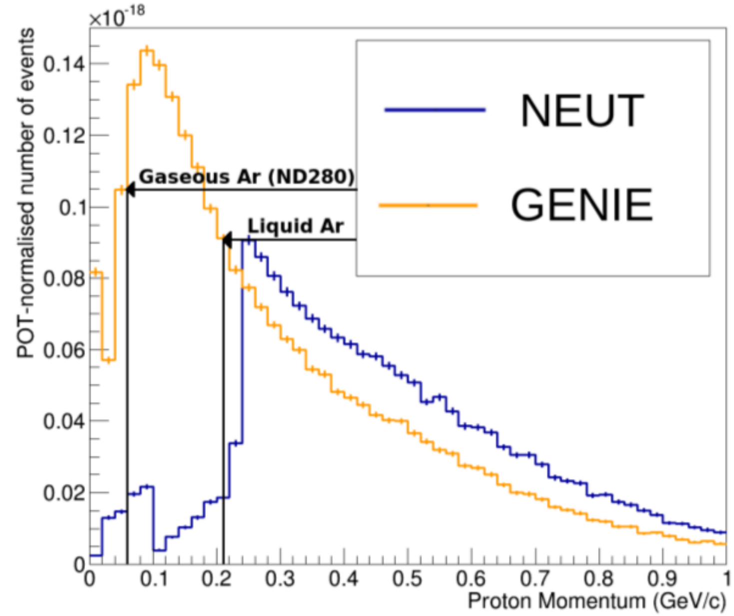


ND280 P0D target

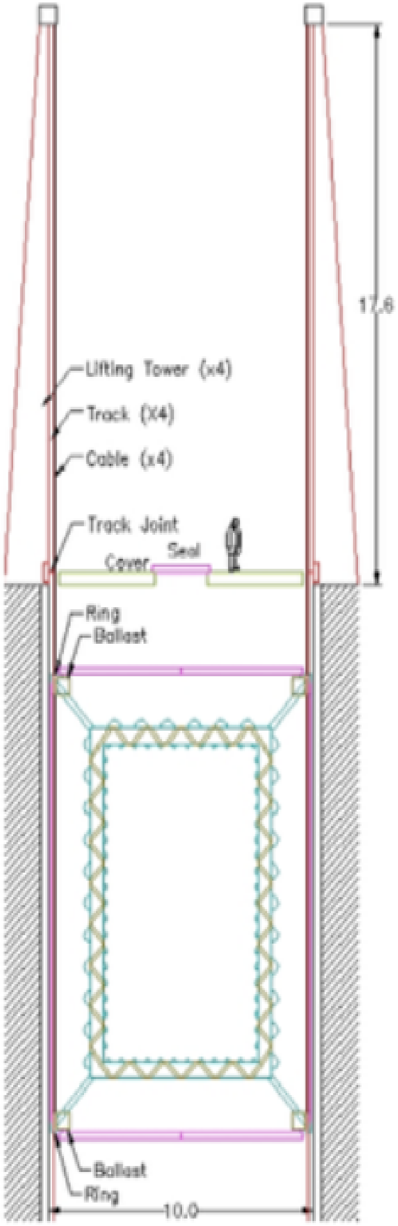


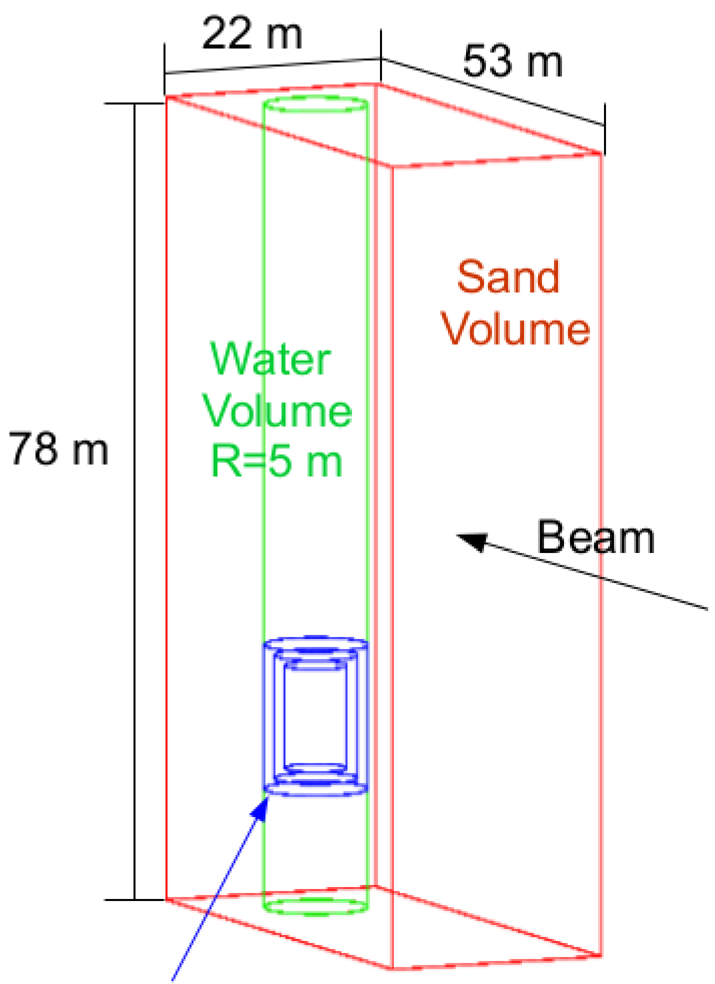
Interactions in the ND280 TPC gas





$Ar : CF_4 : iC_4H_{10}$ (95:3:2)


17.6
Lifting Tower (x4)
Track (X4)
Cable (x4)
Track Joint
Seal
Cover
Ring
Ballast
Ballast
Ring
10.0


22 m
53 m
78 m
Sand Volume
Water Volume R=5 m
Beam
ID, OD and intermediate volumes

Impact on δ_{CP}

(%)

Systematic	N^{HK}_{FHC}	N^{TITUS}_{FHC}	N^{HK}_{RHC}	N^{TITUS}_{RHC}	R_{FHC}	R_{RHC}	$\frac{(R_{RHC})}{(R_{FHC})}$
Interaction Syst.	24.1	24.4	11.4	12.0	4.2	4.5	1.9
Flux Syst.	6.5	6.6	6.0	6.3	0.9	1.0	1.3
Total Syst.	21.8	21.9	14.2	14.4	4.5	4.3	2.4
Statistical	2.5	0.1	3.2	0.2	2.5	3.1	4.3
Stat. + Syst.	21.4	21.4	11.8	11.2	5.1	5.6	4.9