The Hyper-Kamiokade project

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@JPARC2019
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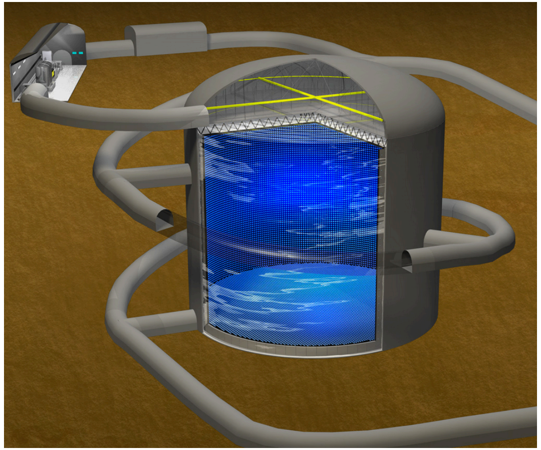
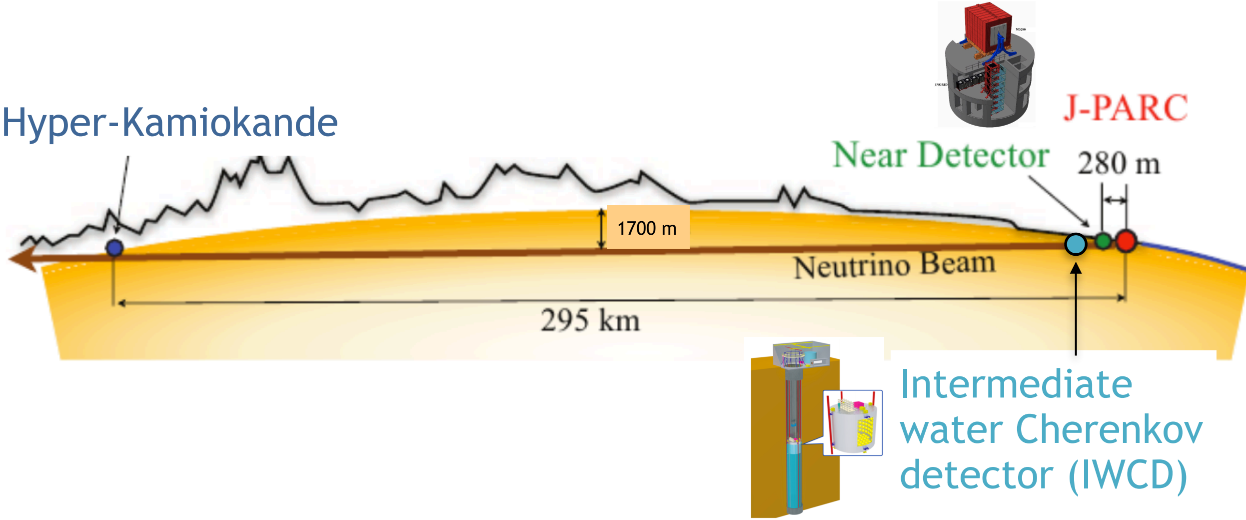
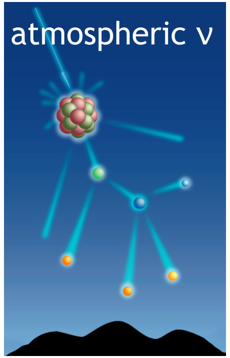
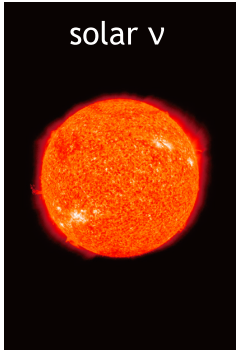
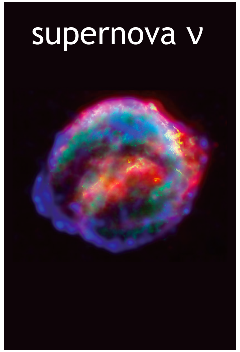


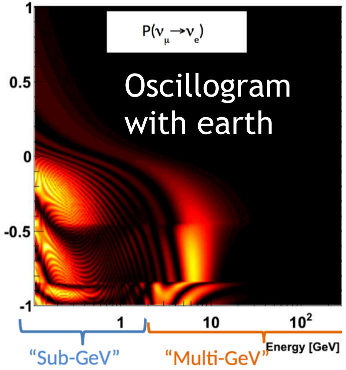


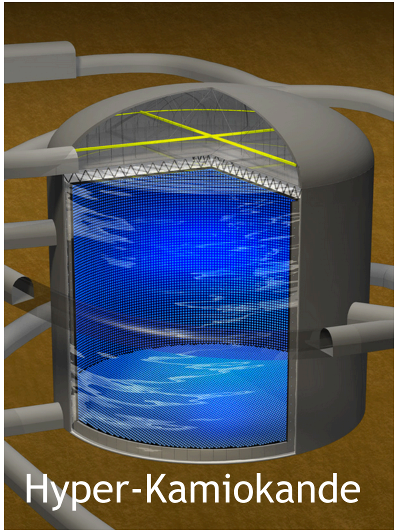
Hyper-Kamiokande

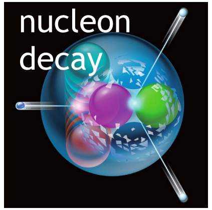












- 188kton (fid.) water Cherenkov
  - 8 times larger than SuperK
- Physics goal
  - precision ν oscillation
    - long baseline neutrinos
    - atmospheric neutrinos
  - neutrino astronomy
    - supernova & solar neutrino
  - new physics
    - nucleon decays
    - dark matter
    - non-standard ν interaction (NSI)
- Construction to start in 2020
  - in the MEXT FY2020 budget

MEXT budget announcemnt (Aug.29, 2019)

世界の学術フロンティアを先導する大規模プロジェクトの推進

令和2年度要求・要望額 40,826百万円
(前年度予算額 34,382百万円)

参考

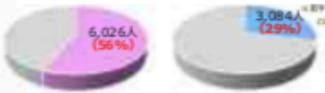
目的
- ○ 最先端の大型研究装置等により人類未踏の研究課題に挑み、**世界の学術研究を先導**。
- ○ 国内外の優れた研究者を結集し、**国際的な研究拠点を形成**するとともに、国内外の研究機関に対し**研究活動の共通基盤を提供**。

- ○ **日本学術会議**において科学的観点から策定した**マスタープラン**を踏まえつつ、専門家等で構成される**文部科学省の審議会**において戦略性・緊急性等を加味し、**ロードマップを策定**。
- ○ ロードマップの中から大規模学術フロンティア促進事業として実施するプロジェクトを選定の上、国立大学法人運営費交付金等の基盤的経費により戦略的・計画的に推進。原則、**10年間の年次計画を策定**し、審議会における**厳格な評価・進捗管理**を実施。
- ○ 現行の13プロジェクトに加え、**令和2年度より、ニュートリノ研究の次世代計画である「ハイパーカミオカンデ計画」に新たに着手**。

主な成果

- ○ **ノーベル賞受賞につながる画期的研究成果**
(受賞歴：H14小柴昌俊氏、H20小林誠氏、益川敏英氏、H27梶田隆章氏)

- ○ **年間約1万人の共同研究者が集結**し、国際共同研究を推進。このうちの**半数以上が外国人研究者、3割程度が若手研究者と割合が高い**。



共同研究者数：10,683人（H29実績）

- ○ 天文分野では、すばる望遠鏡、アルマ望遠鏡の**TOP10%論文割合や国際共著論文割合は、分野全体と比較しても高い**。

天文学・宇宙物理学分野	論文数	Top10%割合	国際共著割合
すばる望遠鏡	644	18.5%	86.3%
アルマ望遠鏡	878	27.3%	89.0%
日本全体	8,938	12.9%	68.0%
世界全体	103,445	9.6%	50.6%

※ 大学共同利用機関法人自然科学研究機構が「InCites」(Web of Sc...)、2013-2017の5年間に出版された天文学・宇宙物理学分野の論文を分析（2019年7月）。「日本全体」は、著者住所に日本を含む論文...

大規模学術フロンティア促進事業等の主な事業

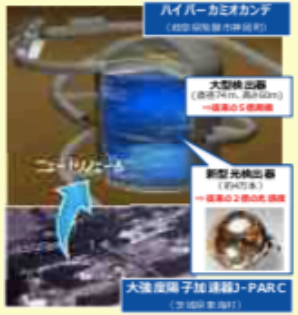
大型電波望遠鏡「アルマ」による国際共同利用研究の推進
〔自然科学研究機構国立天文台〕

宇宙・銀河系・惑星系の誕生過程を解明するため、日米欧の国際協力により、南米チリのアタカマ高地（標高5,000m）に建設した「アタカマ大型ミリ波サブミリ波干渉計」による**国際共同利用研究を推進**。2019年4月にM87銀河の中心にある**超巨大ブラックホールの「影」の撮影に世界で初めて成功した国際プロジェクトに参加**し、高い感度の観測機能により、その成果に大きく貢献。

新しいステージに向けた学術情報ネットワーク(SINET)整備
〔情報・システム研究機構国立情報学研究所〕

国内の大学等を高速通信回線ネットワークで結び、共同研究の基盤を提供。全国900以上の大学や研究機関、約300万人の研究者・学生が活用する**我が国の教育研究活動に必須の学術情報基盤**。

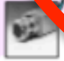
NEW ハイパーカミオカンデ(HK)計画の推進
〔東京大学宇宙線研究所〕
〔高エネルギー加速器研究機構〕

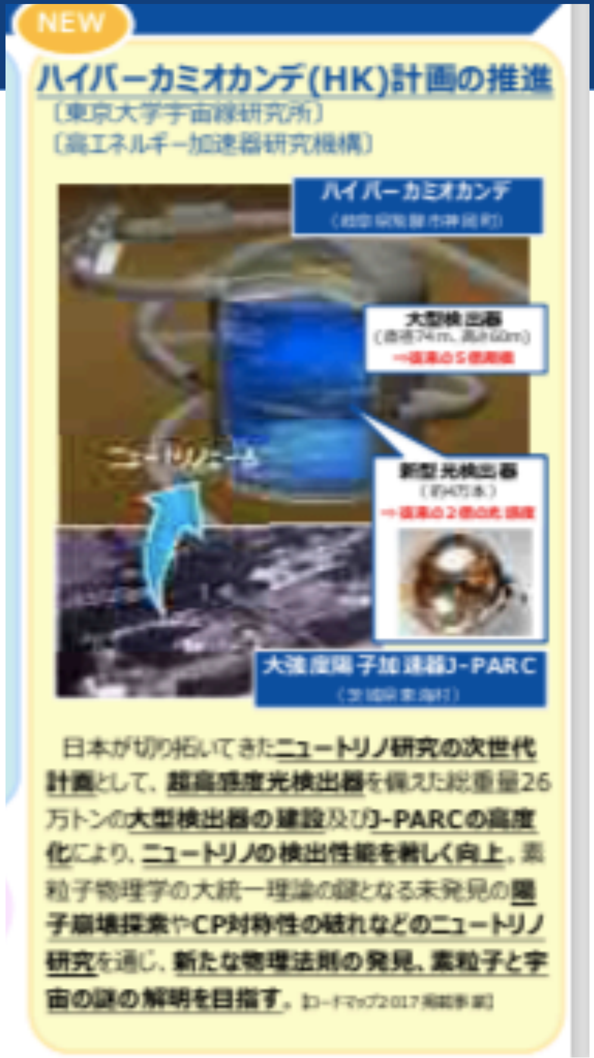


日本が切り拓いてきた**ニュートリノ研究の次世代計画**として、**超高感度光検出器**を備えた総重量26万トンの**大型検出器の建設**及び**J-PARCの高度化**により、**ニュートリノの検出性能を著しく向上**。素粒子物理学の大統一理論の鍵となる未発見の**陽子崩壊探索**や**CP対称性の破れなどのニュートリノ研究**を通じ、**新たな物理法則の発見、素粒子と宇宙の謎の解明を目指す**。

<産業等への波及>

- ○ 産業界と連携した最先端の研究装置開発により、イノベーションの創出にも貢献
（例）・【すばる望遠鏡】超高感度カメラ技術→**医療用X線カメラへの応用**
・【放射光施設】加齢による毛髪のハリ・コシの低下が毛髪内の亜鉛と関係性を解明→亜鉛を毛髪に浸透させる**新しいヘアケア技術の開発・製品化に成功**

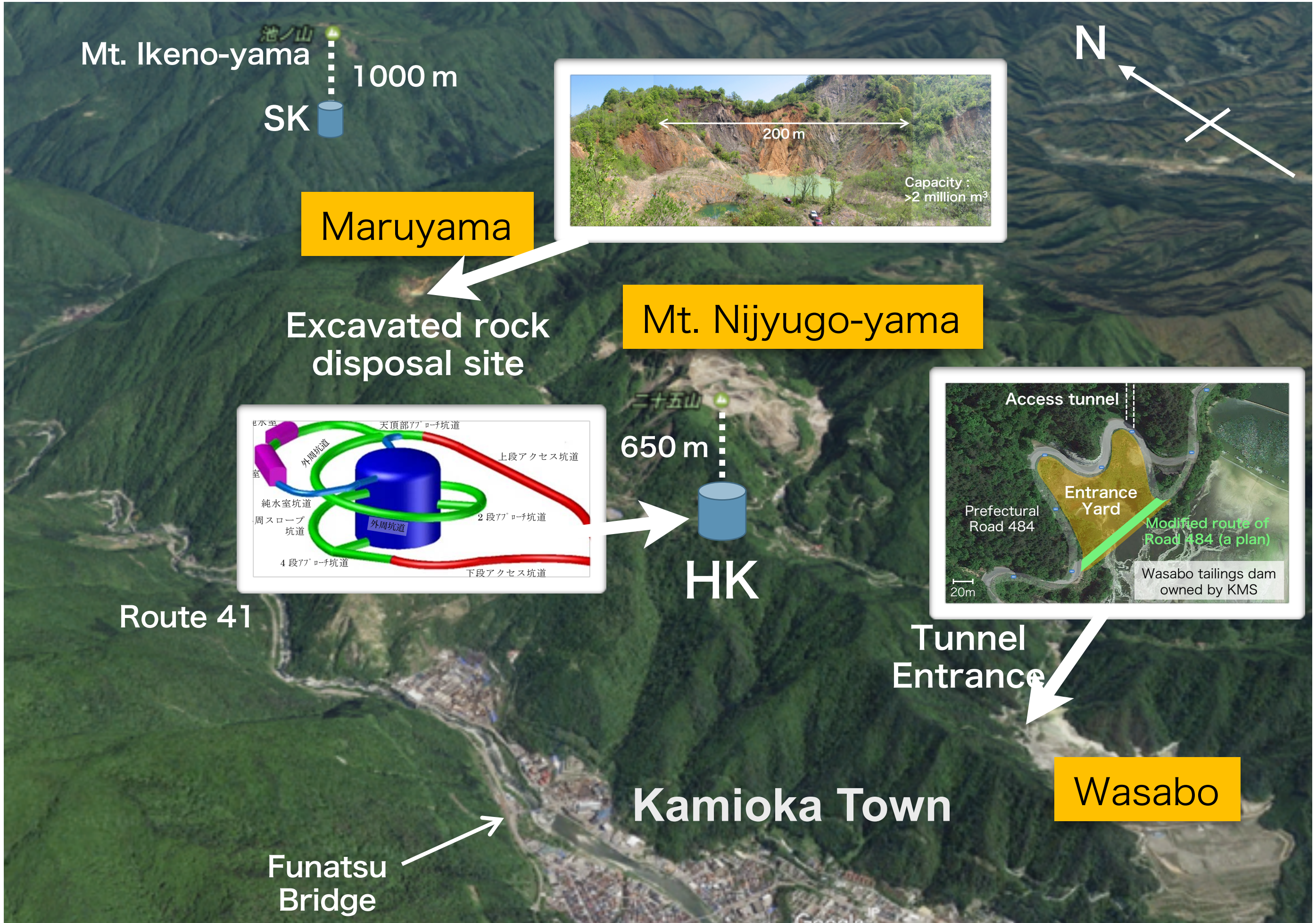





Funding process in Japan

- Hyper-Kamiokande is on the MEXT budget
- “In addition to the ongoing 13 large-scale projects, the next-generation neutrino research project Hyper-Kamiokande, will be newly launched in FY2020”
  - This is the first official statement of MEXT to declare that they shall start the HK project.
- Next steps (for the entire government budget)
  - Dec. 2019:
    - approval by the Ministry of finance and cabinet
  - Mar. 2020:
    - approval by the Diet

Hyper-Kamiokande site



Focus of this talk

- Accelerator based neutrino program at J-PARC leading to HyperK
  - Overview:
    - Keynote talks by Kajita-san and Ooguri-san
    - PN review session Kuze-san: Neutrino Experiments at J-PARC
  - T2K
    - PN-NP1 Matsubara-san: T2K status and ND280 upgrade
    - PN-CS Kendall Mahn: ND280 neutrino cross section results
  - Accelerator and beam line upgrades for T2K and HyperK
    - PN-NP1 Matsubara-san on the intensity upgrade
      - **Upgrade of J-PARC accelerator and ν beamline from 0.5MW to 1.3MW**
      - **x20 more sensitivity in HyperK compared to T2K**

- This talk will focus on
  - Long baseline neutrino physics of HyperK
  - Intermediate Water Cherenkov Detector (IWCD)

Large CP violation effect in neutrino oscillation possible

Unlike quark mixing (CKM),
lepton mixing (PMNS) is large:

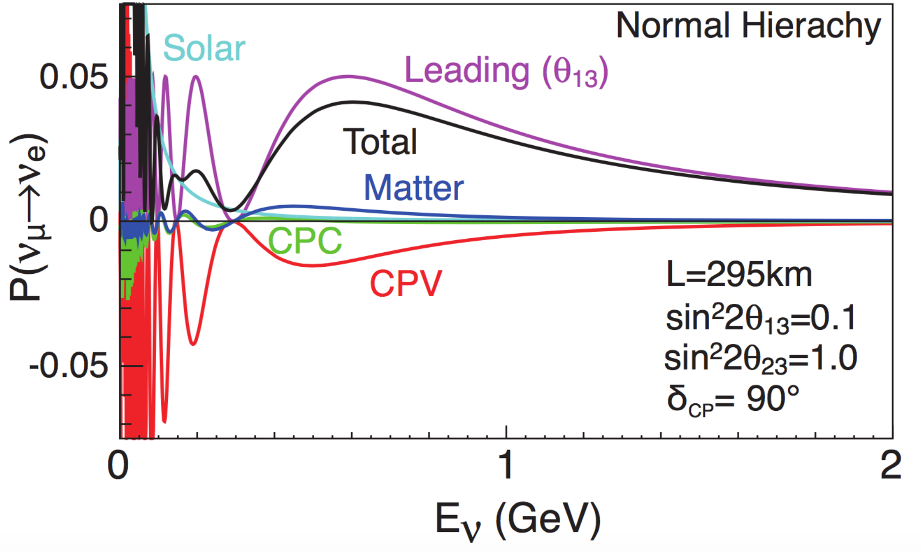
V_{CKM} (Quark mixing)

$$\begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

V_{PMNS} (Lepton mixing)

$$\begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

→ Large CP violation effect possible



T2K/HyperKamiokande case:

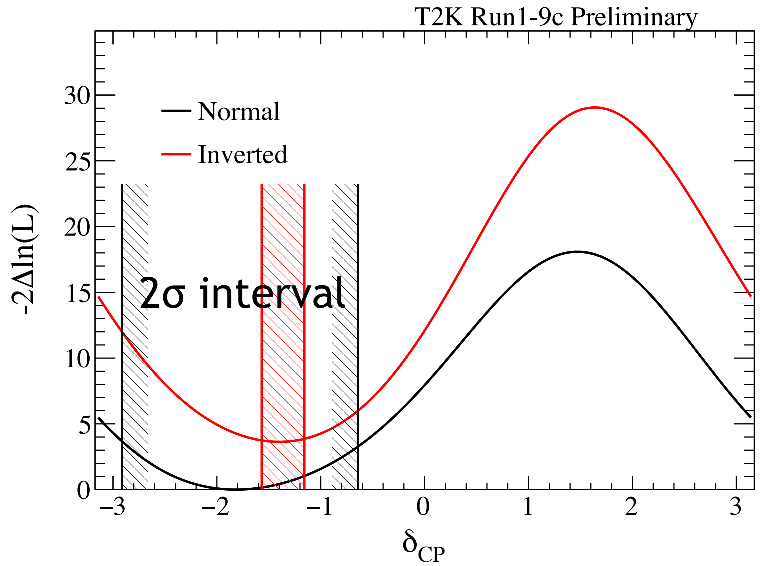
At the peak of E_ν=0.6GeV

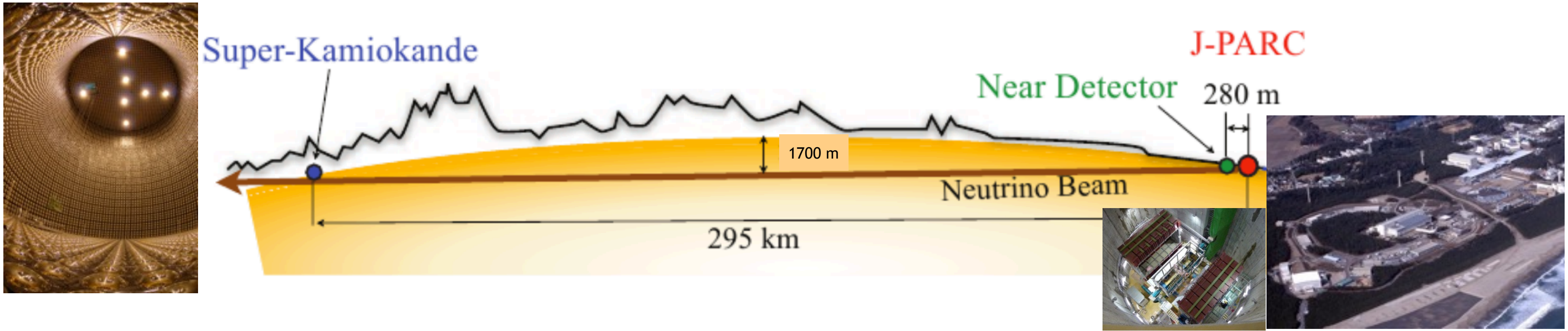
$$\frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq -0.28 \sin \delta_{CP} + 0.07$$

matter effect

Tokai-to-Kamioka (T2K) long baseline neutrino experiment

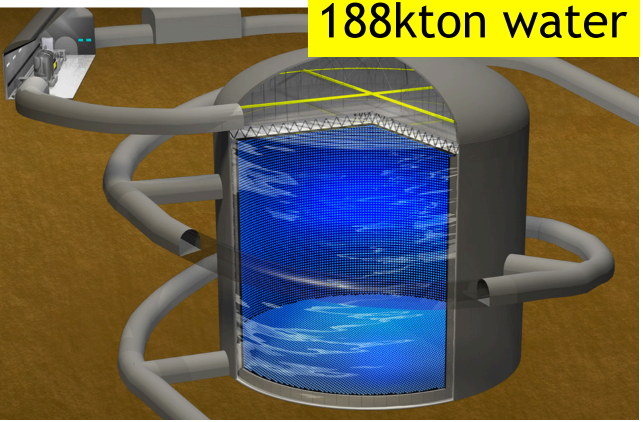
- 295km of neutrino travel
  - observed $\nu_\mu \rightarrow \nu_e$ oscillation
- Disfavour CP conserving $\delta_{CP}=0,\pi$ at 2σ level

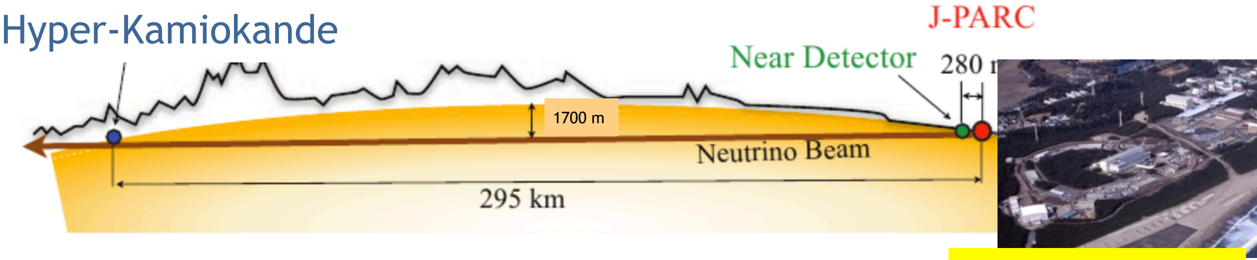




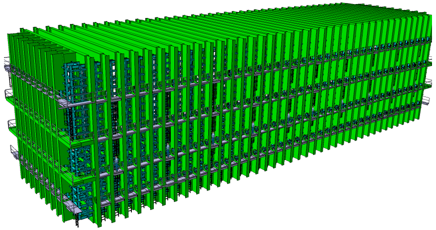
Future long baseline experiments for leptonic CP

188kton water

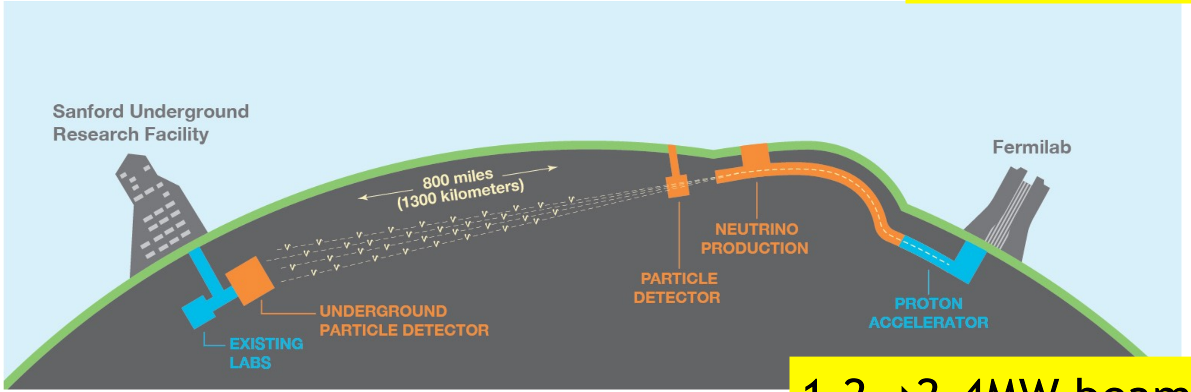




1.3MW beam



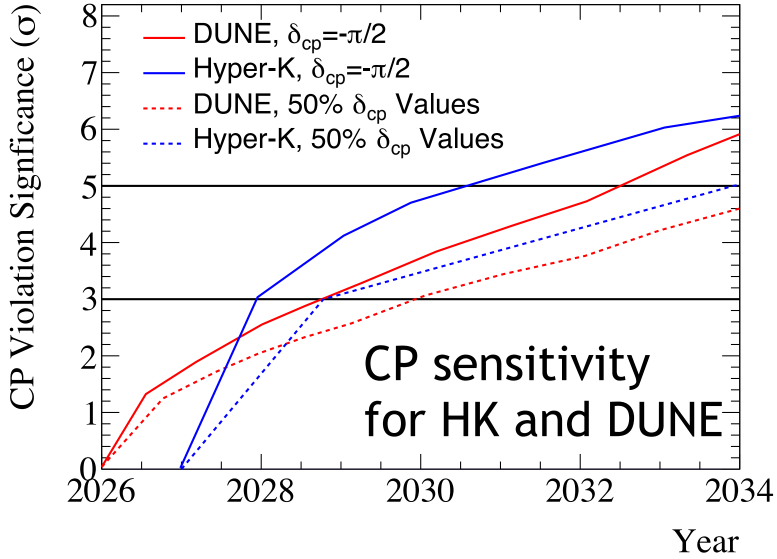
20→40kton liquid Ar

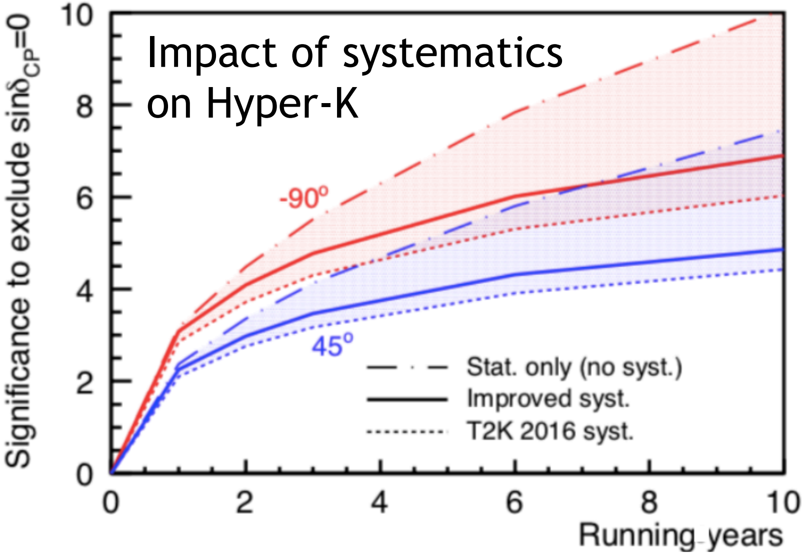


1.2→2.4MW beam

- Two experiments are in preparation: HyperK and DUNE

CP sensitivity





- HyperK and DUNE have similar sensitivities
  - Fiducial volume: HyperK 188kton DUNE 20-40kton
  - Beam power: 1.3MW 1.2-2.4MW
  - Running time: 10^7 sec/year 2×10^7 sec/year
- Systematic uncertainty limited: “systematic error goals” are assigned
  - Big challenge to suppress systamatic error significantly less than the statistical error of 3%

Systematic uncertainties of T2K

	1-Ring μ		1-Ring e			
Error source	ν mode	ν̄ mode	ν mode	ν̄ mode	ν mode cc1π	ν̄/ν ratio
SK Detector	2.40 %	2.01 %	2.83 %	3.79 %	13.16 %	1.47 %
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b "binding energy"	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87

detector

cross section

- Statistical error of HyperK: 3%
  - Systematics need to be reduced well below 3%
  - current systematic uncertainty is 8.8%
    - in particular due to neutrino interactions with model uncertainties

Sub-GeV data

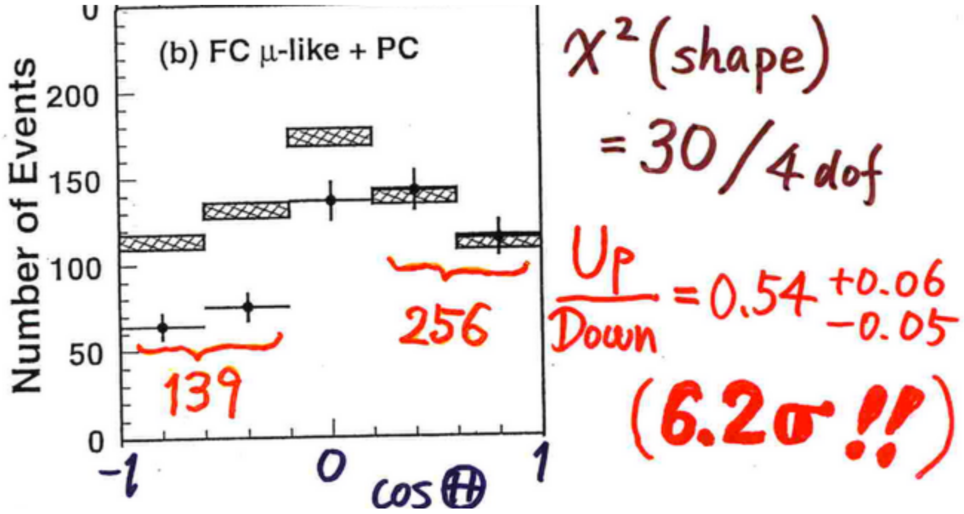
$$\frac{(\mu/e)_D}{(\mu/e)_{MC}} = 0.63 \pm {}^{0.026}_{0.025}\ (\text{stat}) \pm 0.05\ (\text{syst + MC stat})$$

Kam. $= 0.60\ {}^{+0.06}_{-0.05} \pm 0.054$

Multi—GeV data

$$\frac{(\mu/e)_D}{(\mu/e)_{MC}} = 0.65 \pm 0.05\ (\text{stat}) \pm 0.08\ (\text{syst + MC stat})$$

Kam. $= 0.57\ {}^{+0.08}_{-0.07} \pm 0.07$



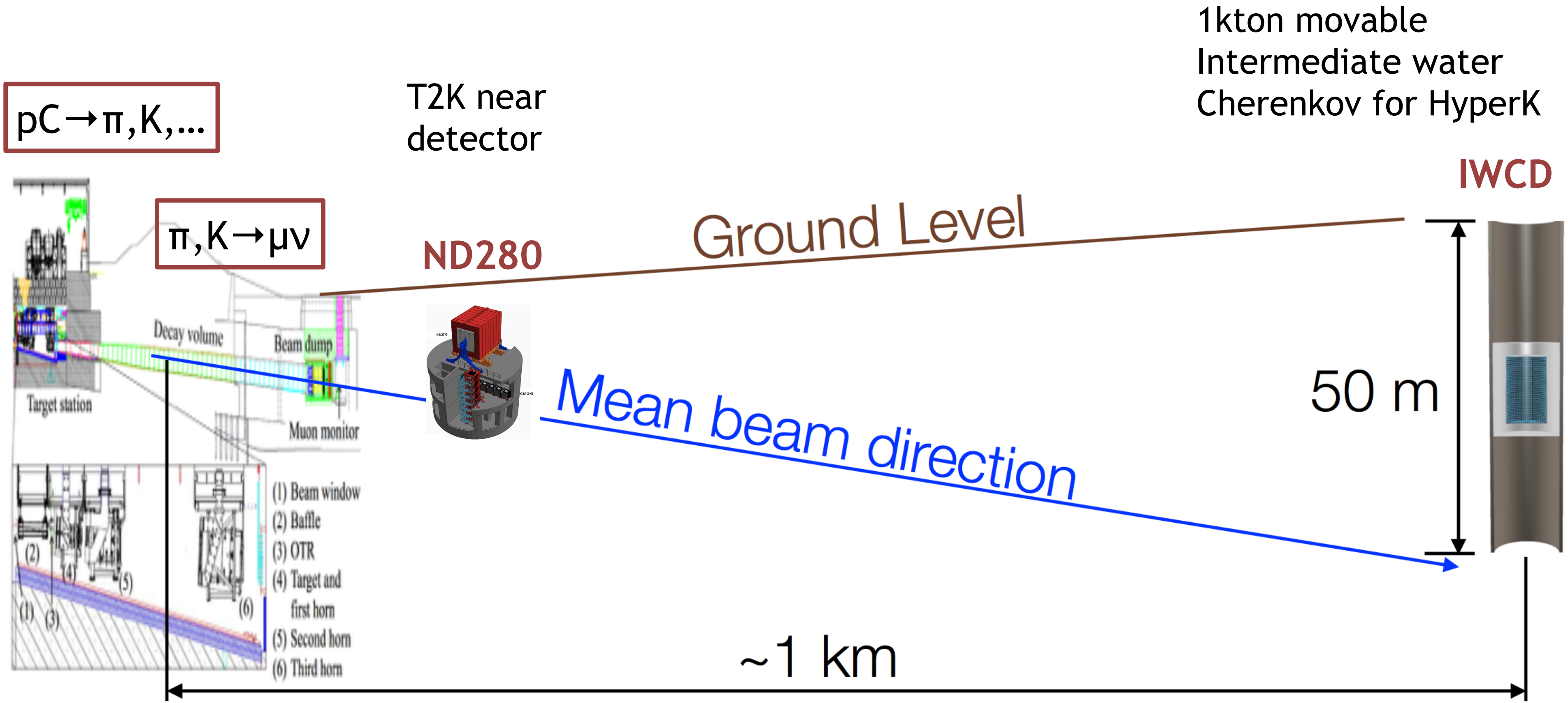
Kamiokande already observed 5σ effect
(5 years before the SuperK discovery!)
but not enough for the discovery

- Up/Down asymmetry
  - before/after oscillation
  - data driven without relying on the atmospheric ν model

Far/Near ratio

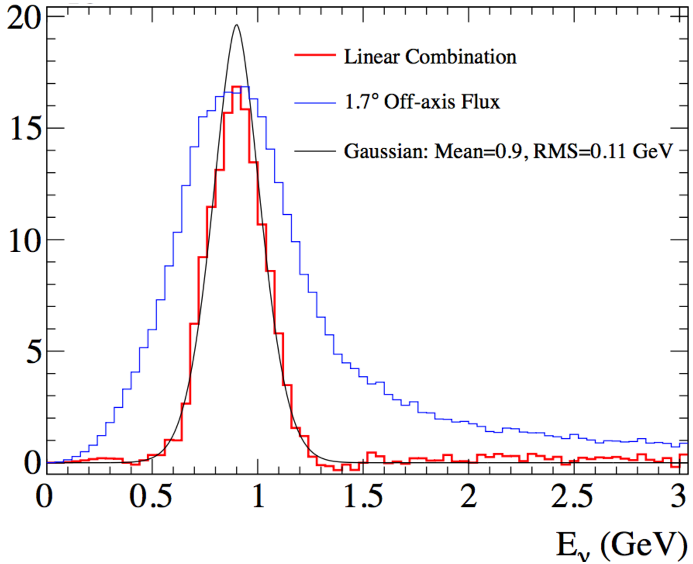
- Far/Near detector ratio in ν event rate like up/down ratio in atmospheric ν:
  - Provide data-driven cancellation of systematic uncertainties
  - First order cancellation demonstrated by T2K → 8.8% syst. error

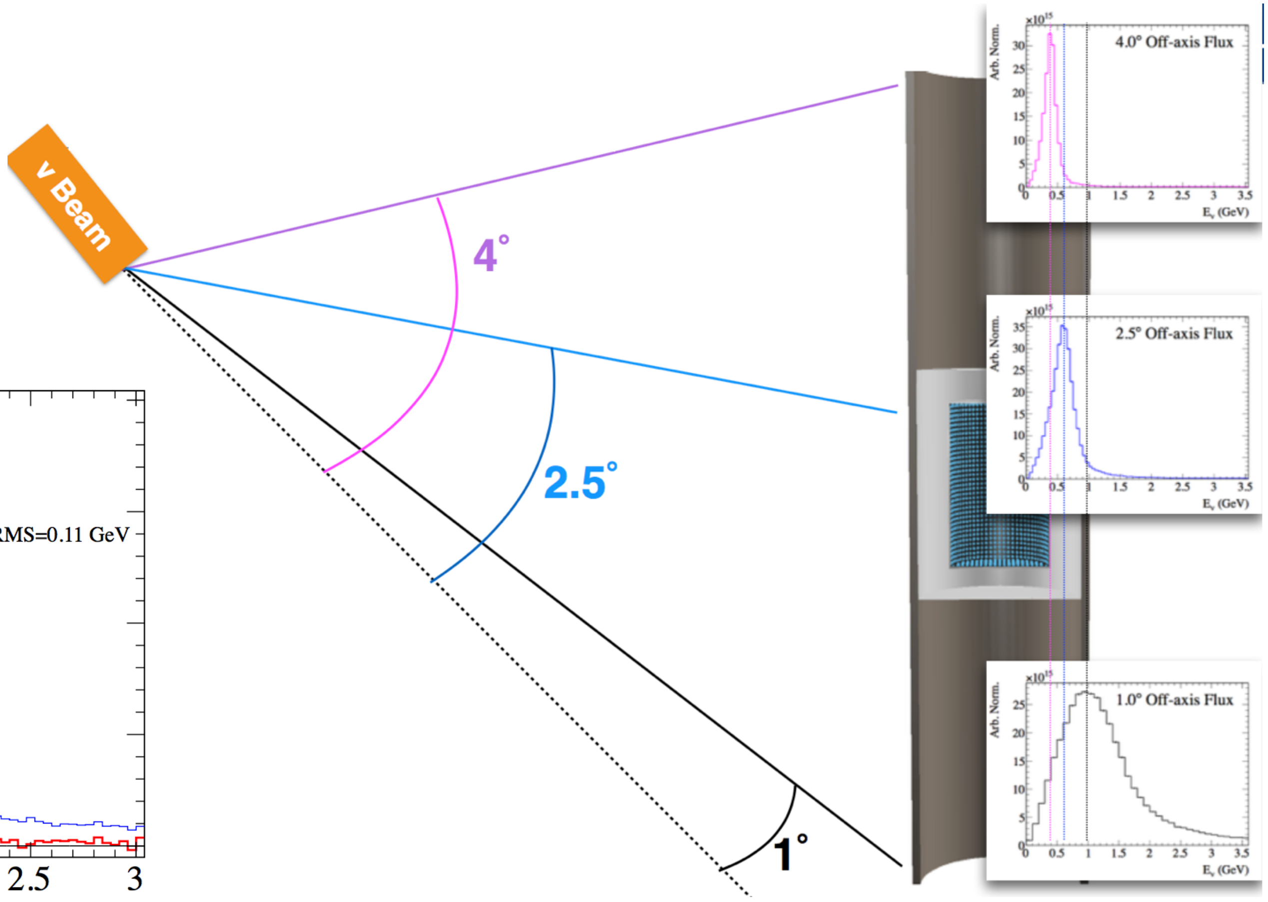
- Sources that limit Far/Near cancellation in systematic uncertainties
  - [A] Energy dependence of Far/Near event rate [flux] x [cross section]
    - near and far neutrino energy distributions are different due to oscillation:
      - energy dependence in cross section prevents cancellation of systematic uncertainties
    - replicate the far detector flux shape at near site by **IWCD**
  - [B] Near detector observes ν_μ and far detector observes ν_e
    - cross sections are different by 15% due to m_μ vs. m_e differece
    - currently purely theoretical uncertainty: **IWCD $\sigma(\nu_e)/\sigma(\nu_\mu)$ measurement**
  - [C] Far/Near detector efficiencies
    - same water Cherenkov detector is needed for the near detector: **IWCD**
    - different sizes for near and far detectors: improved calibration is essential


1kton movable
Intermediate water
Cherenkov for HyperK
T2K near
detector
pC→π,K,...
π,K→μν
IWCD
ND280
Ground Level
Decay volume
Beam dump
Target station
Muon monitor
Mean beam direction
50 m
(1) Beam window
(2) Baffle
(3) OTR
(4) Target and
first horn
(5) Second horn
(6) Third horn
~1 km

Linear combination of events at different off-axis position:

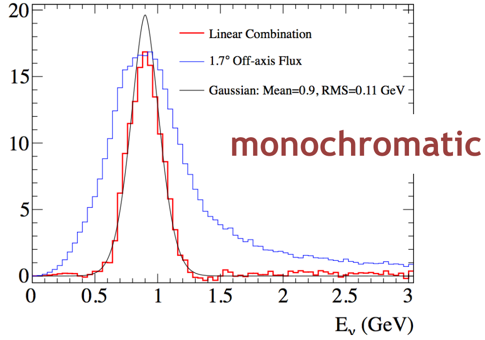
➜ Monochromatic ν beam response

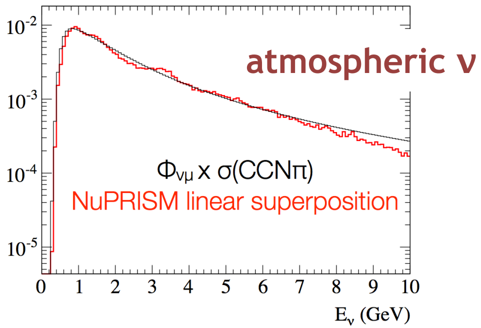


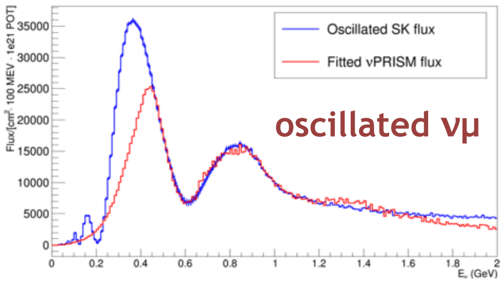


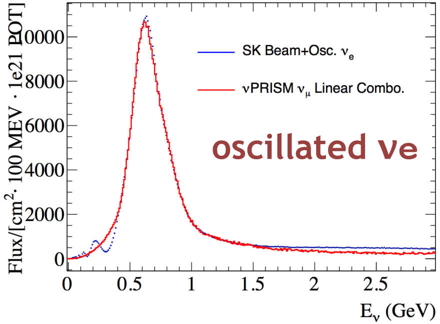
IWCD (NuPRISM) linear combination

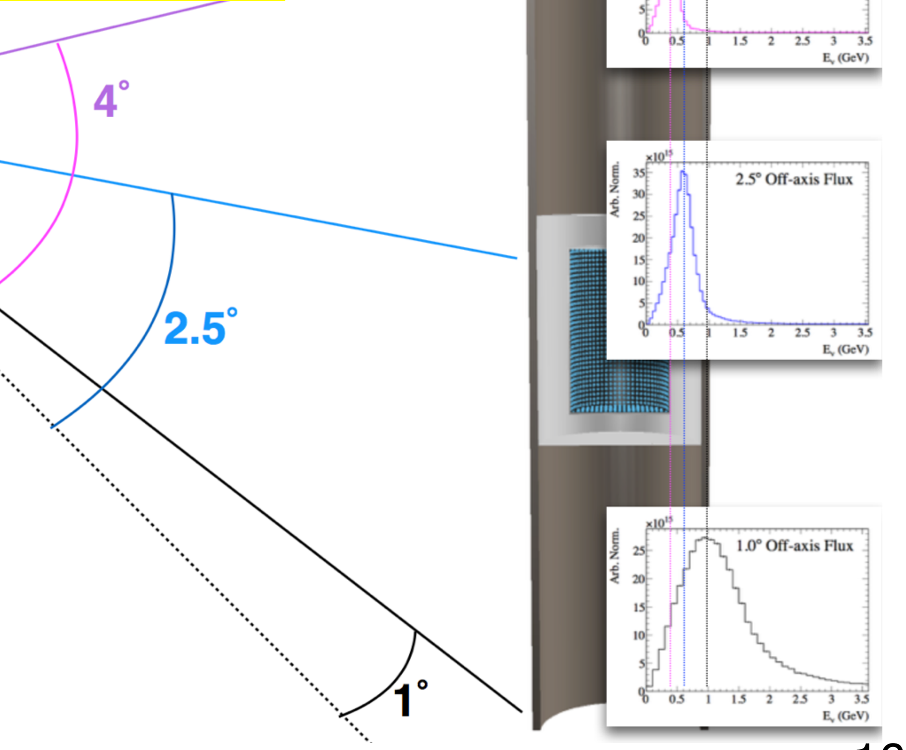
match the far spectrum by a linear combination of the near detector spectra





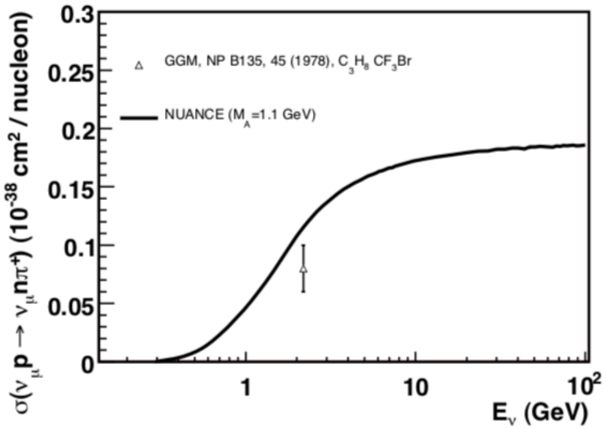


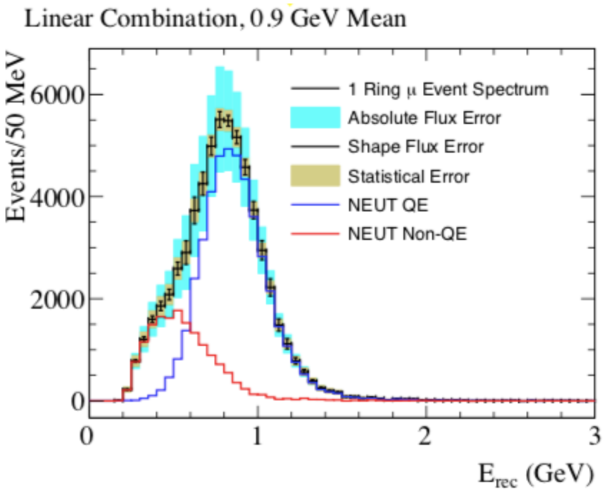


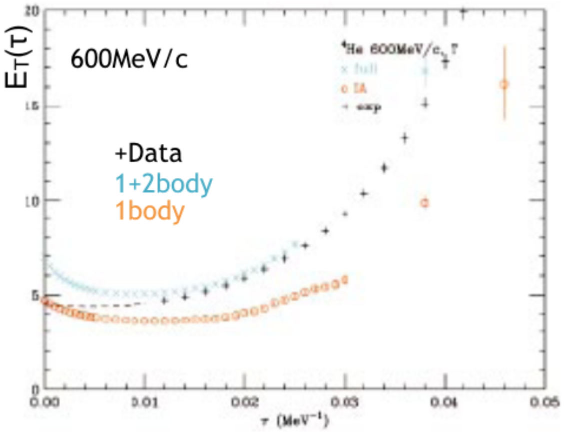


IWCD cross section study with momochromatic beam

- Monochromatic ν beam: unique first time measurements
  - NC cross section as a function of E_ν
  - isolate the multi-nucleon (2p-2h) contribution
  - Study the nuclear dynamics of the neutrino interaction: S(Q,ω)
    - similar to neutron, Xray and electron scattering like J.Carlson (2002)

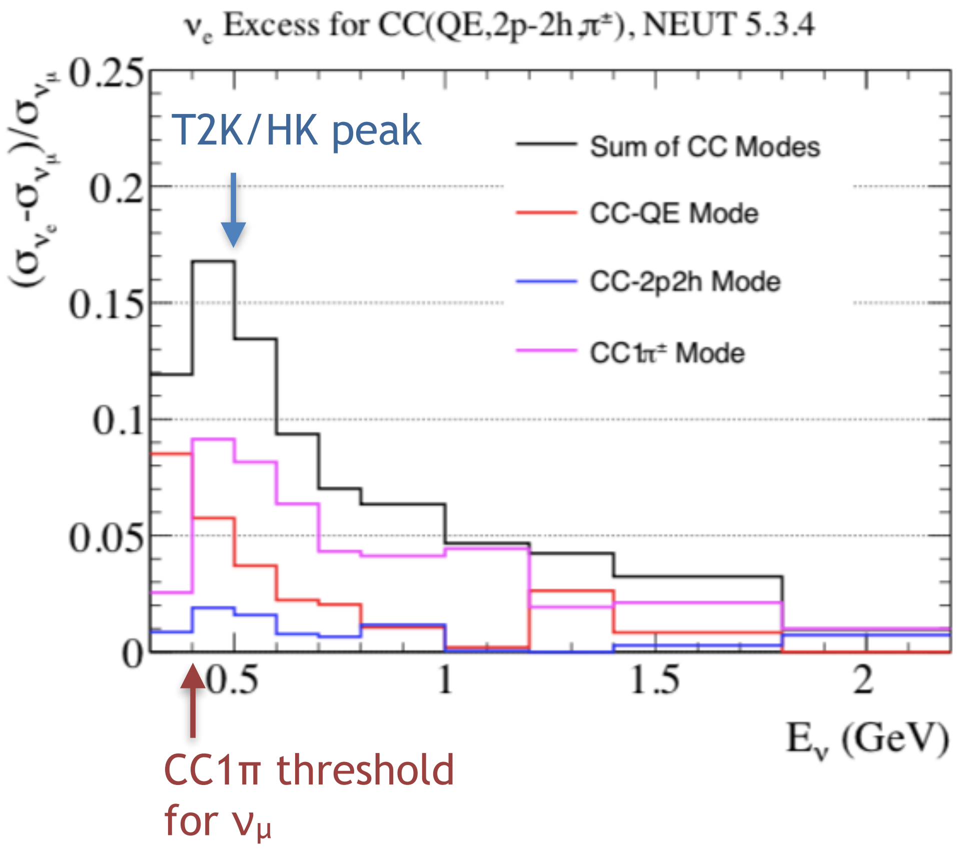






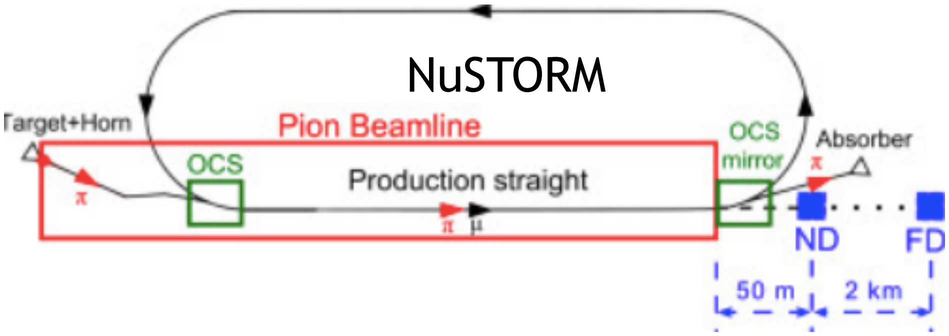
[B] $\sigma(\nu_e)/\sigma(\nu_\mu)$ cross section difference

- ~15% expected difference in $\sigma(\nu_e)/\sigma(\nu_\mu)$ cross section ratio at the HK peak energy
  - e/μ universality (symmetry) is broken due to e/μ mass difference
- Requirements:
  - significantly better than 3% statistical uncertainty
  - Constrain the error by data

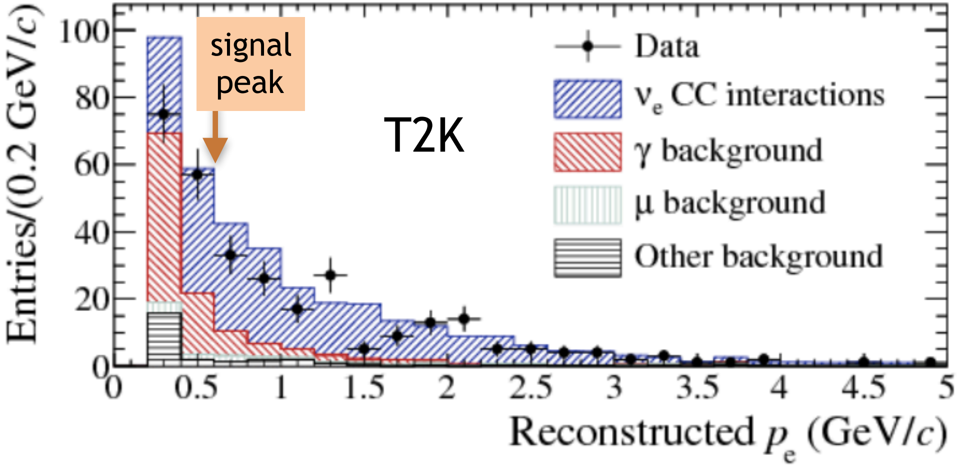


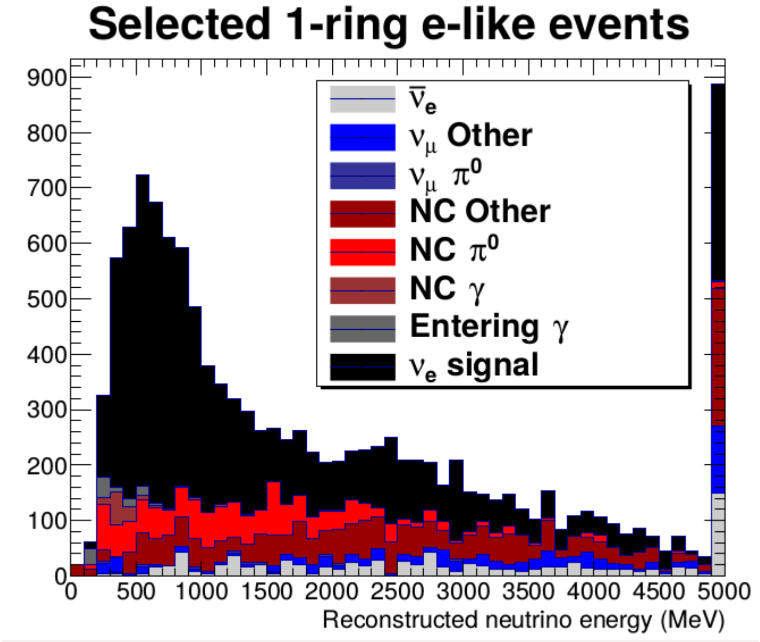
$\sigma(\nu_e)/\sigma(\nu_\mu)$ measurement

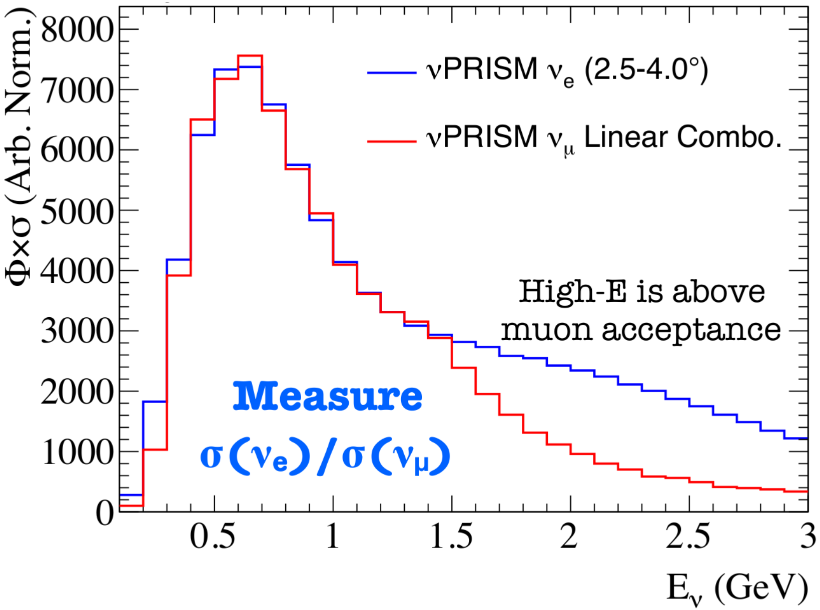
- Flux systematics is large: 5-10%
  - NuSTORM/ν-factory is proposed
    - precise flux but expensive
  - Match the ν_e/ν_μ flux in IWCD and cancel the flux systematics instead
    - relative measurement



- T2K near detector is limited by external γ backgrounds
  - fully active shielding of outer veto is essential for ν_e detection (IWCD)



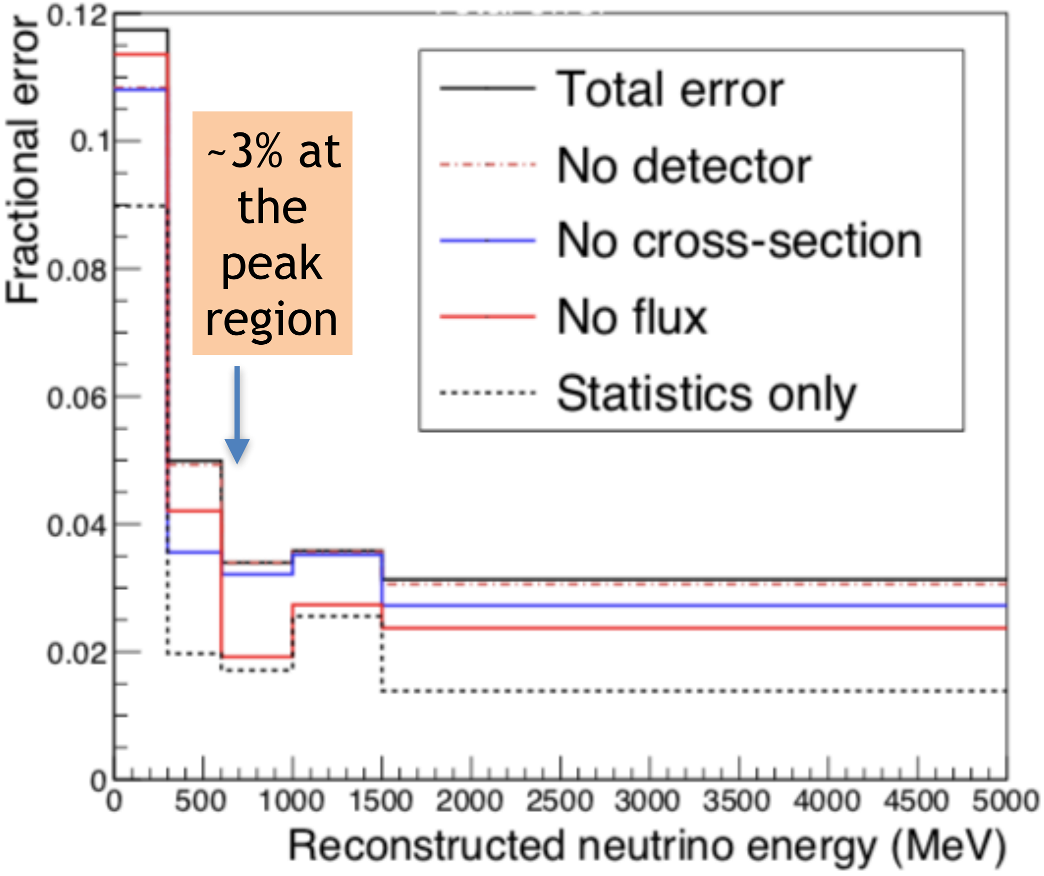




- good background suppression for IWCD
- match the IWCD ν_e flux by IWCD ν_μ flux linear combination
  - cancelling the flux systematics
    - precisely test the difference in the kinematical phase space

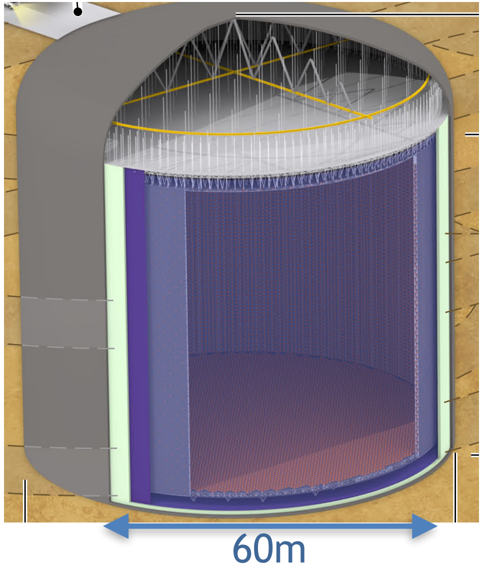
Systematic error in IWCD ν_e measurement

- Flux uncertainty dominates above 600-1500MeV/c
- NCγ and flux uncertainties are both significant at 300-500MeV/c
  - NA61, EMPHATIC hadron production exp.
  - e/γ separation in IWCD
    - Optical TPC (discussed later)

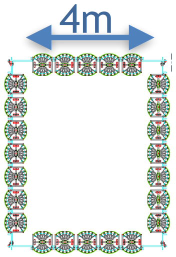


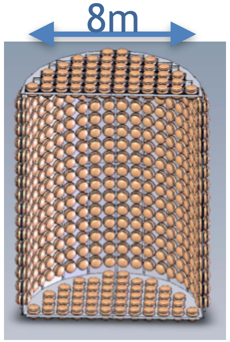
[C] IWCD detector systematics

- Spacial requirement is more stringent for IWCD
  - Fiducial volume (vertex) systematics
    - 1% uncertainty: $2\Delta R/R=1\% \rightarrow \Delta R=0.5\%R$
    - HK:15cm, IWCD:2cm
  - Finer granularity and better timing are required:
    - HK: 20-inch PMT, TTS(σ)=1.1nsec ~ 20cm
    - IWCD: 3-inch PMT, TTS(σ)=0.6nsec ~ 12cm

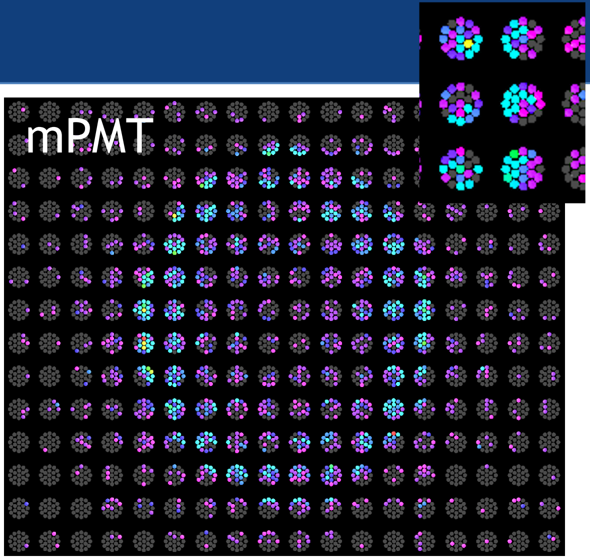


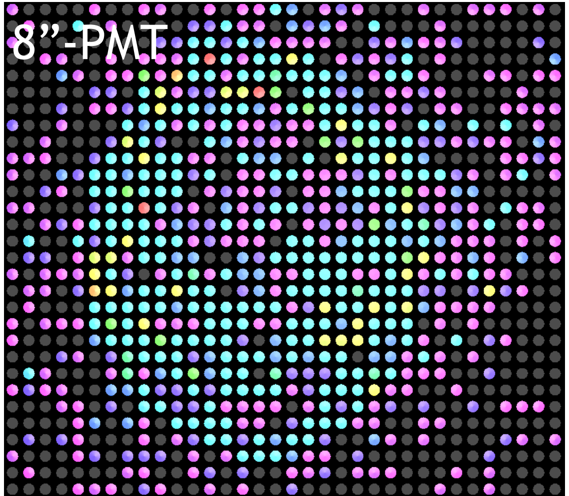
- Precision calibration
  - Precise position information
    - Photogrammetry
  - Precise detector response
    - IWCD test beam experiment at CERN



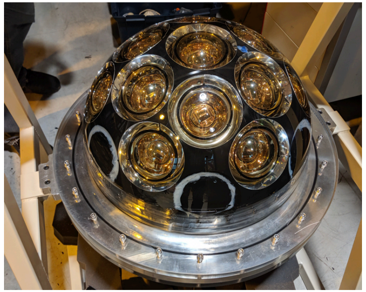


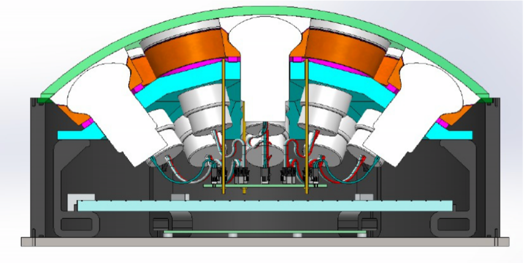
multi-PMT for finer granularity

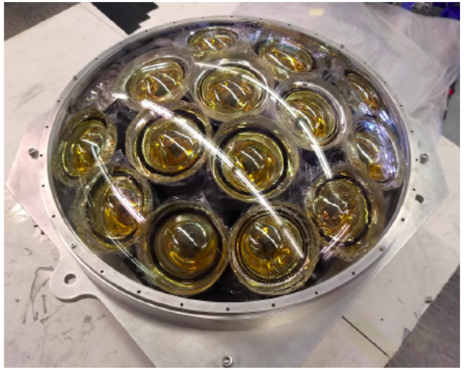




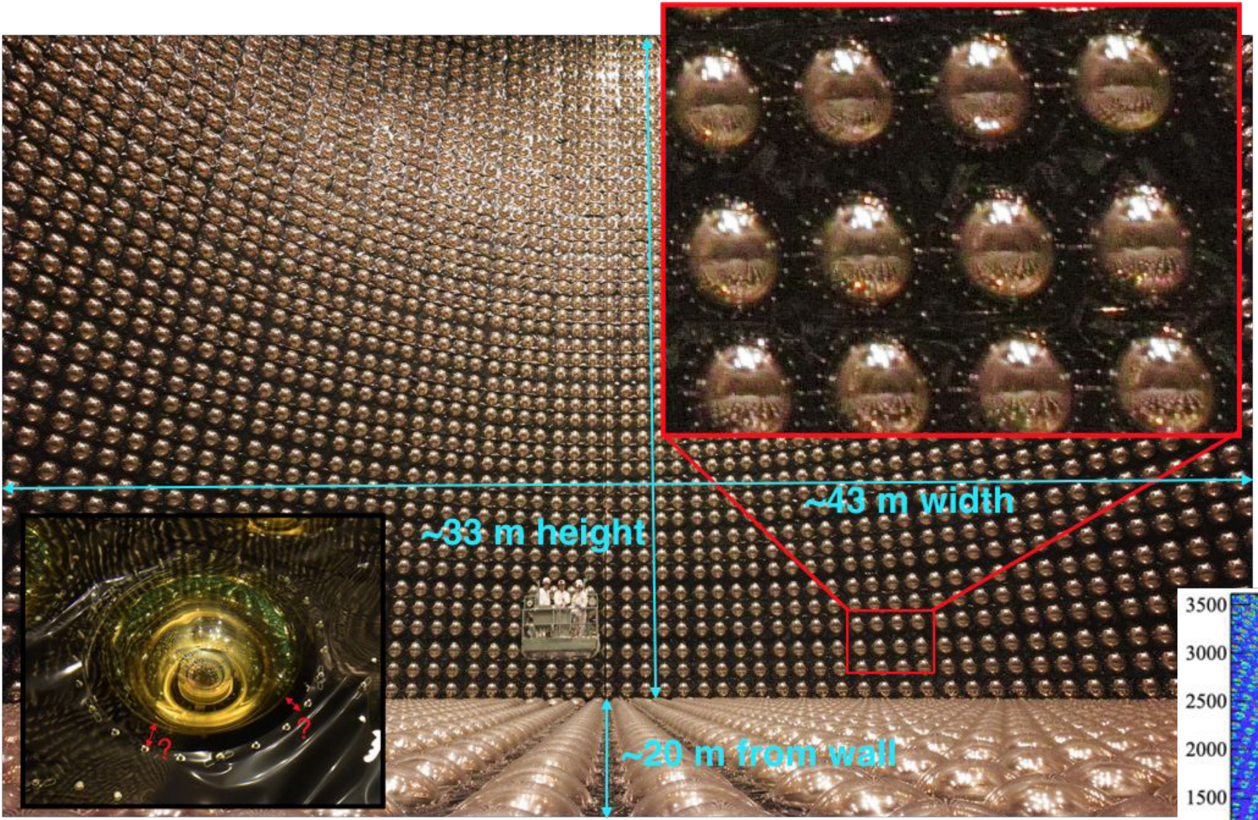
- multi-PMT (mPMT)
  - Concept from KM3NeT
  - 19 of 3” PMT’s in a vessel
    - economical 3” PMT’s
- mPMT for IWCD
  - finer granularity
  - x2 better timing resolution than 20” PMT
    - TTS(σ)=0.6nsec



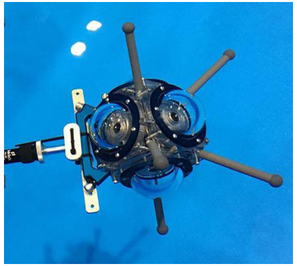


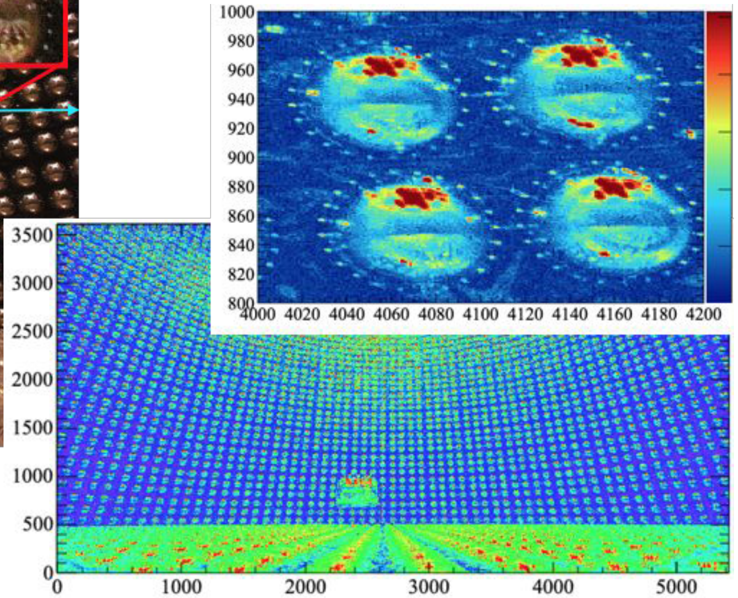


Photogrammetry being considered for SK



360Abyss underwater camera

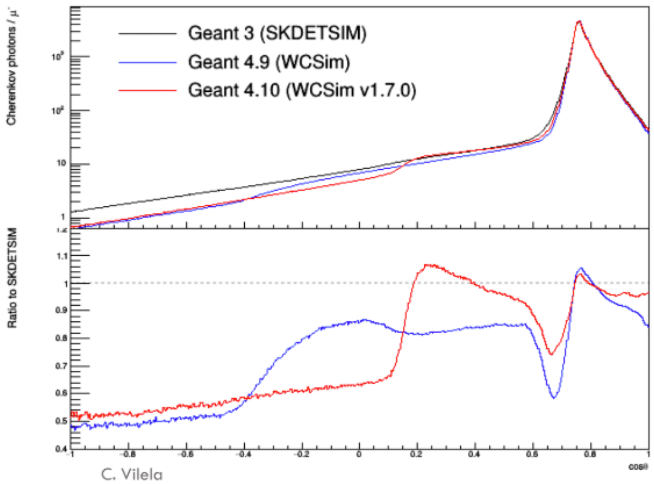


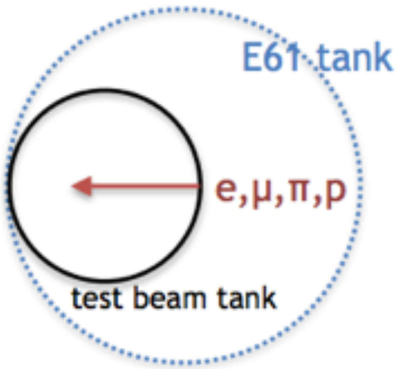


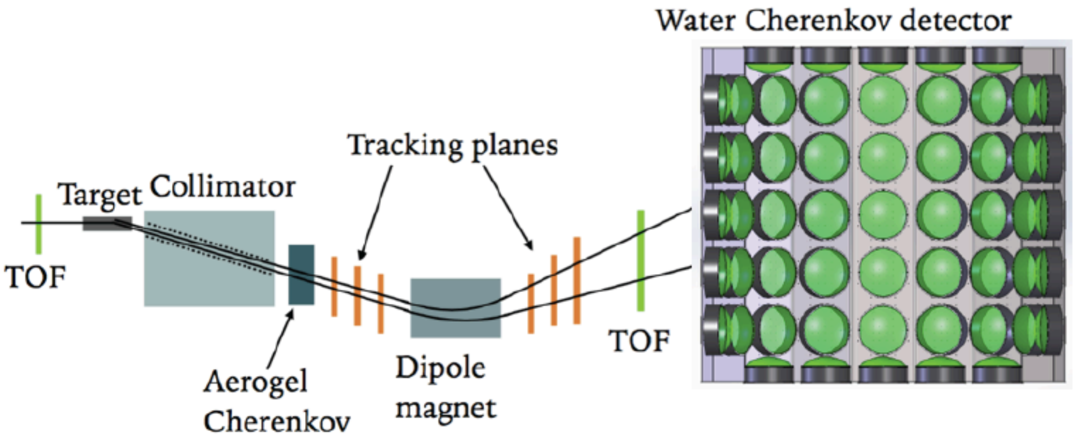
IWCD beam test

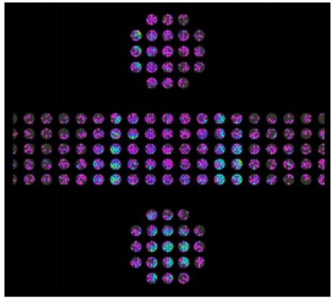
- Precise calibration of water Cherenkov response
  - backward light uncertainty in GEANT: impact on vertex
    - difference observed in delta ray simulation models
  - hadron interactions in water
  - stopping muons: range and charge calibration

- Prototype IWCD detector test at CERN in 2021-22
  - Collaboration launched at CERN meeting in July 2019



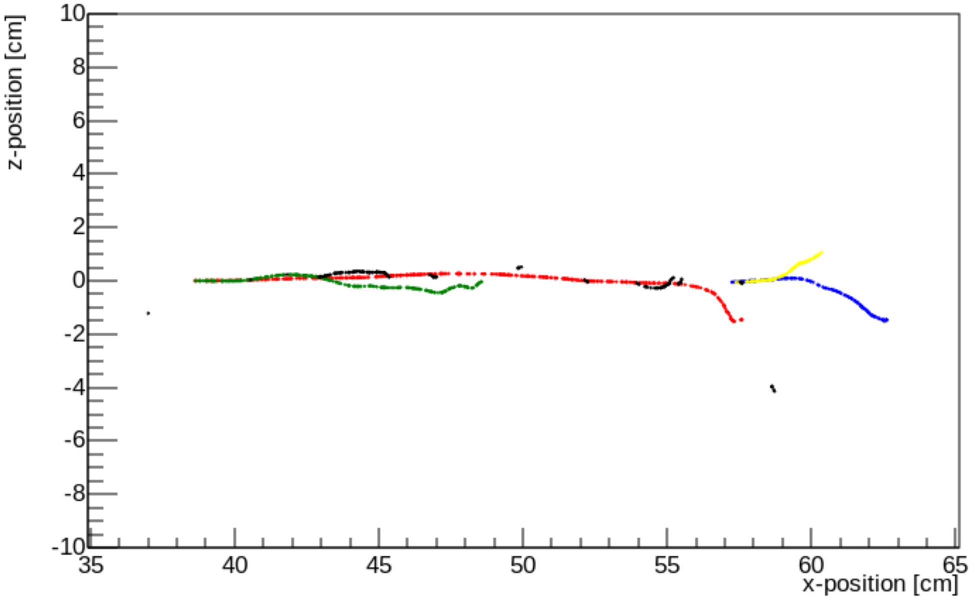


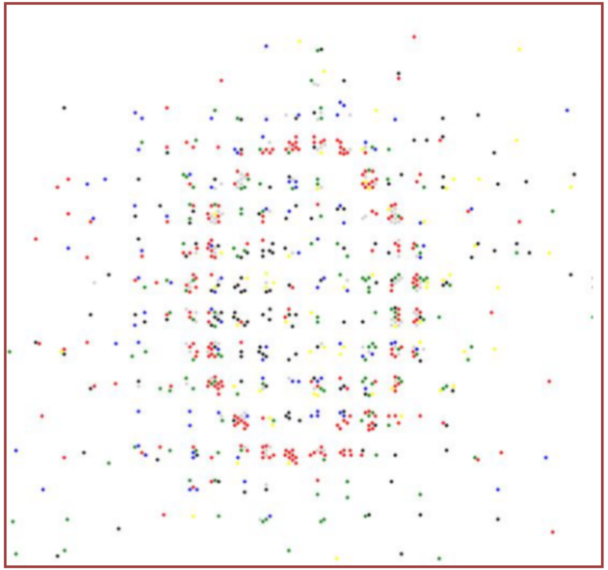




mPMT hits from 100MeV photon (Optical TPC)

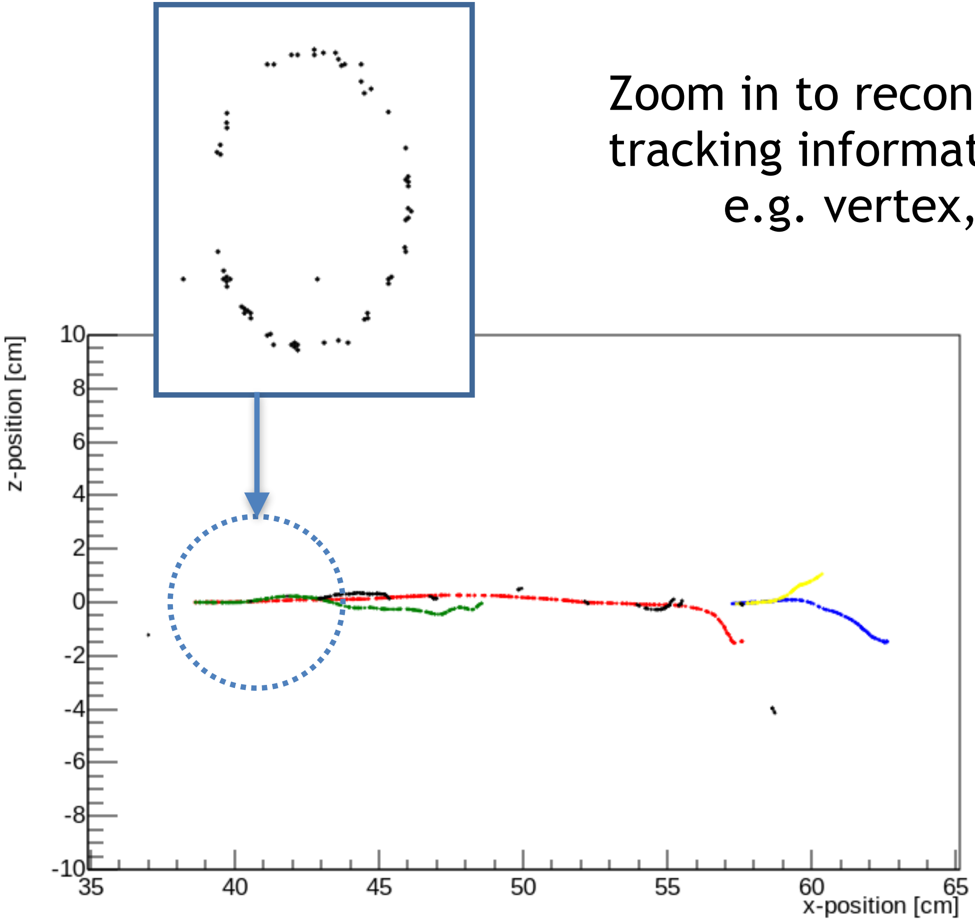
Tracing back origin of each hit in the ring





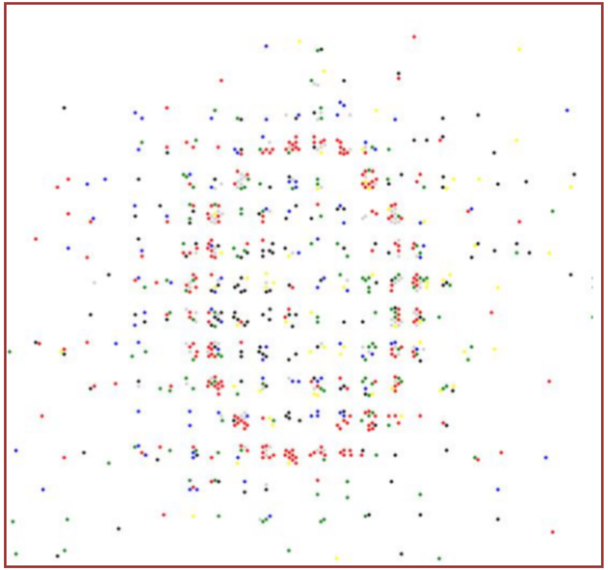
Plots by Nick Prouse

mPMT hits from 100MeV photon (Optical TPC)



Zoom in to reconstruct the detailed tracking information

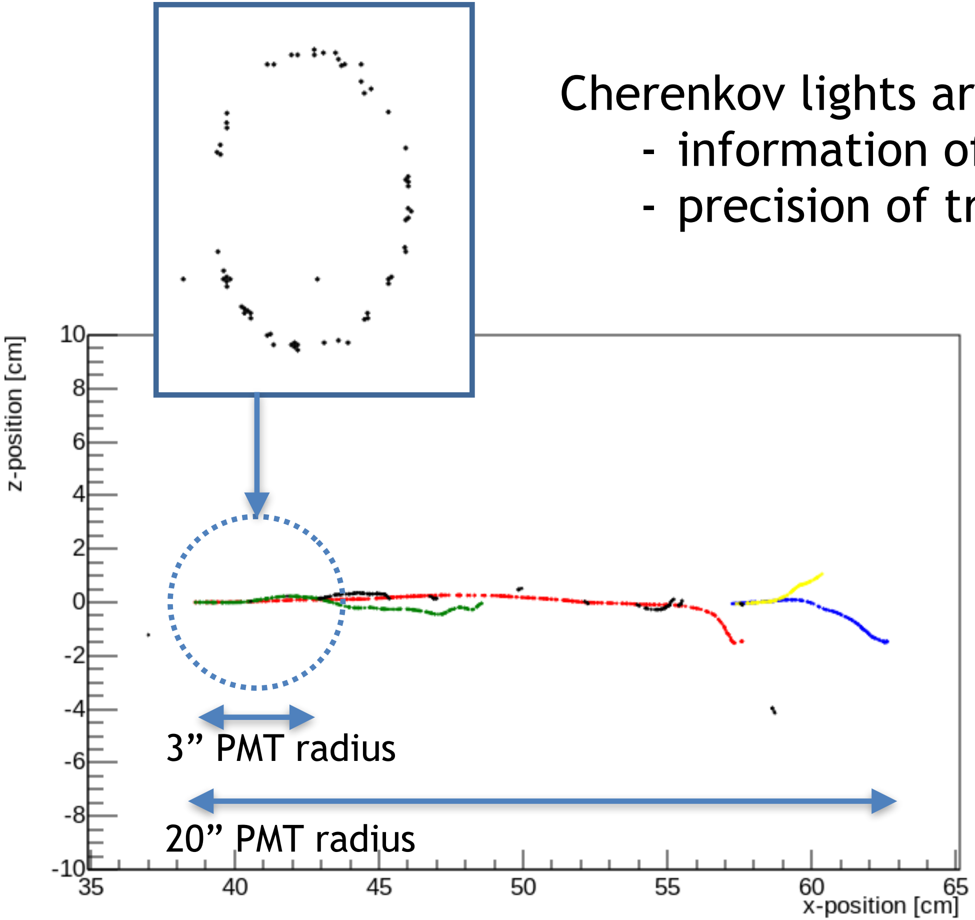
e.g. vertex, e/γ separation

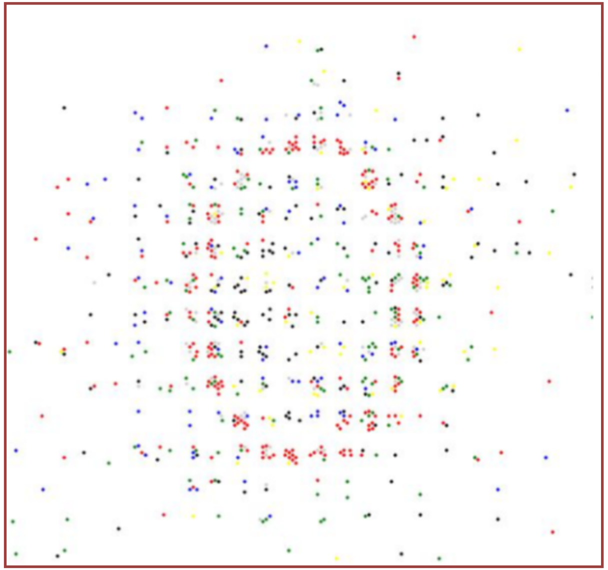


Plots by Nick Prouse

mPMT hits from 100MeV photon (Optical TPC)

Cherenkov lights are emitted at constant angle (ß=1)
- information of the track is projected on the wall
- precision of tracking is determined by the PMT size

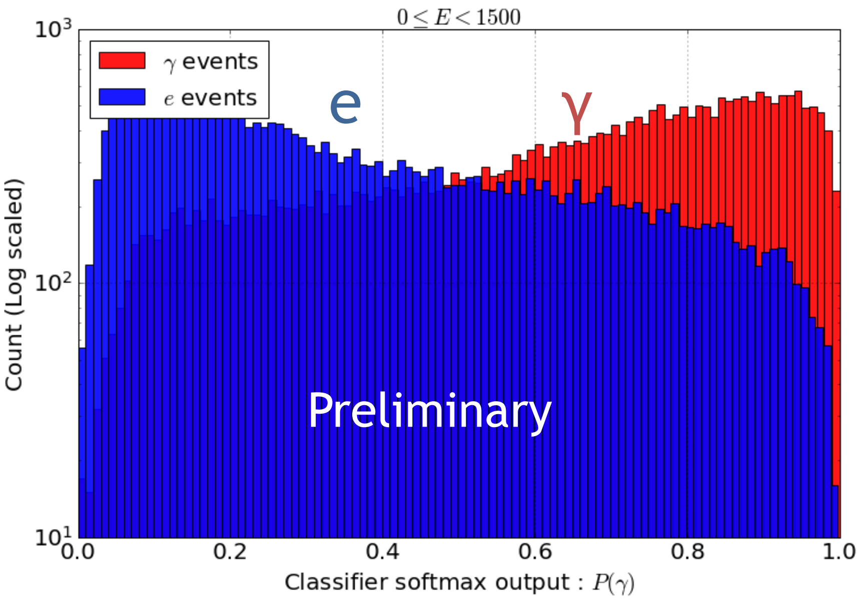


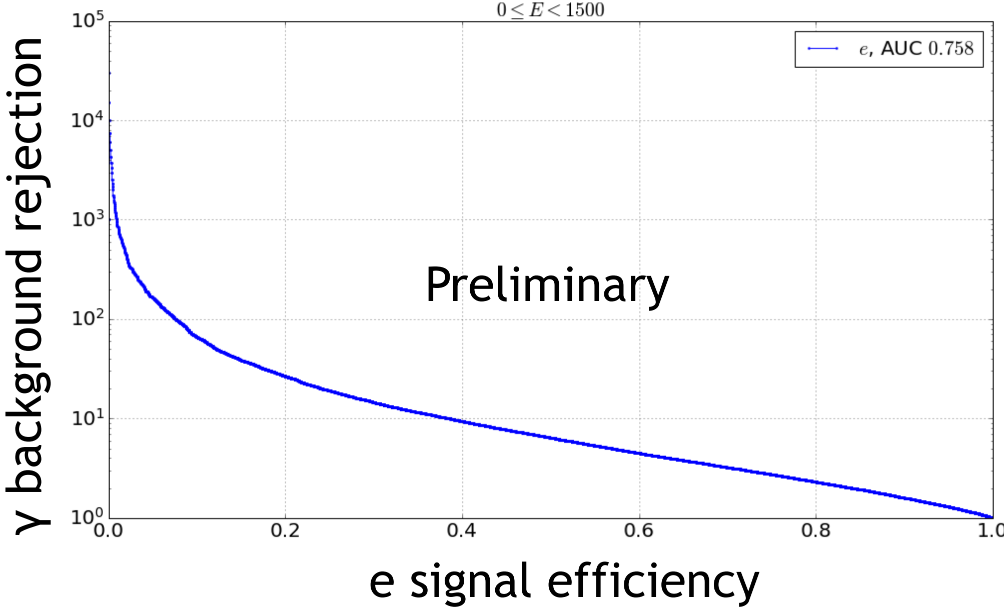


Plots by Nick Prouse

Preliminary study of electron/γ separation

- Initial look shows significant e/γ separation for IWCD MC
  - Convolutional Neural Network on e/γ/μ Monte Carlo samples





- Diverse physics program for HyperK
  - Precision neutrino oscillation; CP violation, mass hierarchy
  - Neutrino astronomy; supernova, solar, GRB
  - Search for new physics; nucleon decay, dark matter, NSI
- Control of systematic uncertainty essential for CP study
  - IWCD provides data driven cancellation of systematic errors
    - flux shape to be matched between IWCD and HyperK
    - direct measurement of ν_e cross section
    - same water Cherenkov detector with precise calibration
- Hyper-K is on the FY2020 MEXT budget
  - "Hyper-Kamiokande will be newly launched in FY2020"

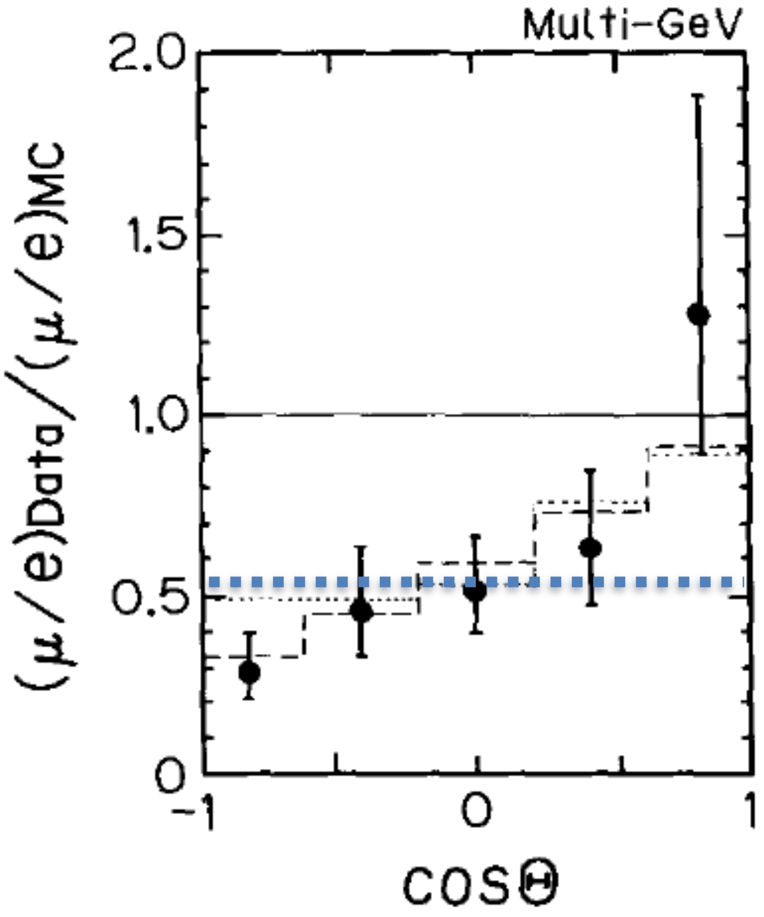
Summary of systematics requirements and sensitivities

Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
$\sigma(\nu_e)/\sigma(\nu_\mu)$	3-5%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$, θ_{23} precision at $\sin(\theta_{23})\sim0.5$	IWCD	3.5-5%
$\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	3-5%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$, θ_{23} precision at $\sin(\theta_{23})\sim0.5$	IWCD	4-7%
Wrong-sign background normalization	9%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$	ND280	TBD (expect $<9\%$)
Intrinsic ν_e,$\bar{\nu}_e$ and NC backgrounds	3-4%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$	IWCD	2.3% (neutrino)
Normalization of non-QE with E_ν>0.7 GeV	5%	θ_{23} precision at $\sin(\theta_{23})\neq0.5$	IWCD	5% (neutrino)
Normalization of non-QE with all energies	5%	δ_{cp} precision at $\sin(\delta_{cp})\sim0$, Δm^2_{32} precision	IWCD, ND280*	5% (IWCD neutrino), $<4\%$ (N280 neutrino), $<7\%$ (ND280 antineutrino)

Summary of systematics requirements and sensitivities

Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
Beam Direction	0.6 mrad (4 MeV shift)	δ_{cp} precision at $\sin(\delta_{cp})\sim 0$ Δm^2_{32} precision	INGRID	<0.3 mrad (<2 MeV)
Removal (binding) energy	4 MeV*	δ_{cp} precision at $\sin(\delta_{cp})\sim 0$ Δm^2_{32} precision	IWCD, ND280	2.6 MeV (IWCD on O) ~1 MeV (ND280 on C)**
High angle measurement ($\cos\theta<0.2$)	4%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim 0$	IWCD, ND280	<4% statistical precision in both detectors
Beam rate monitoring	~1% per day	General monitoring of beam quality	INGRID	<0.5% per day for neutrinos and antineutrinos
Neutron Multiplicity	TBD	Atmospheric neutrino Nucleon decay	IWCD, ND280	<5% IWCD <4% ND280
$\mu\pi^0$ cross section & neutron multiplicity	TBD	$e\pi^0$ proton decay	IWCD	TBD

Kamiokande result: PLB335(1994)237



$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.57^{+0.08}_{-0.07}(\text{stat.}) \pm 0.07(\text{syst.})$$

(based on Flux A),

which suggests that the atmospheric $(\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e)$ ratio is smaller than expected for the multi-GeV energy range. This result agrees well with that obtained in the sub-GeV data [1]. (See also a de-