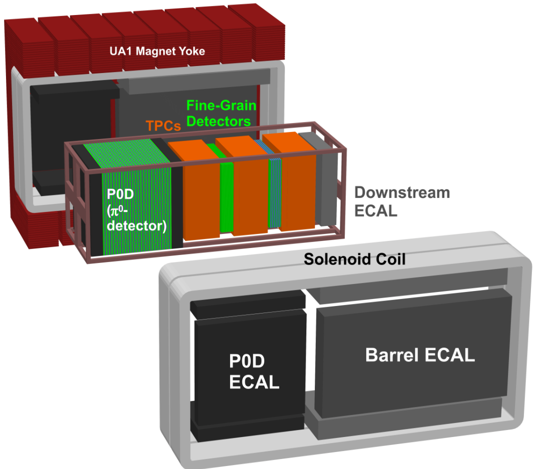
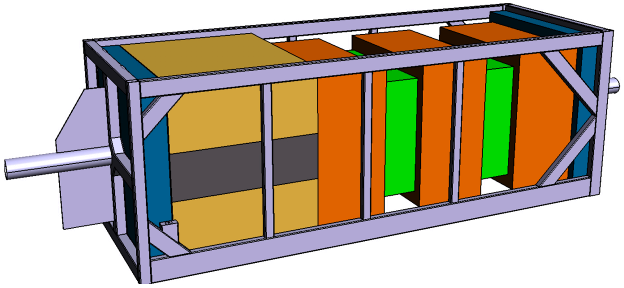
T2K第二フェーズに向けたND280前置検出器アップグレードの概要



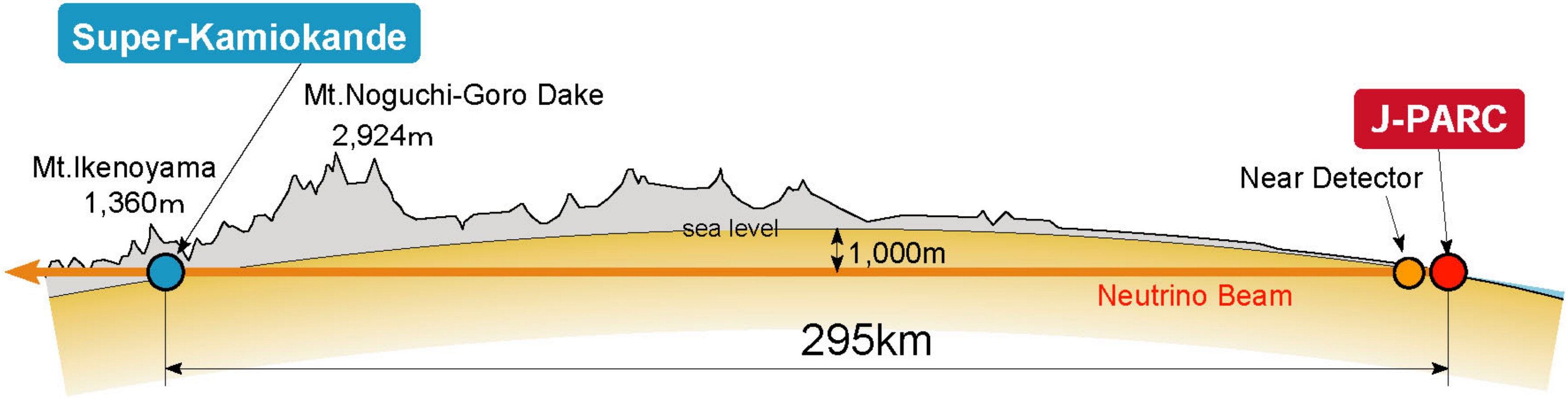
岩本康之介

東京大学

2018年2月19日



T2K実験



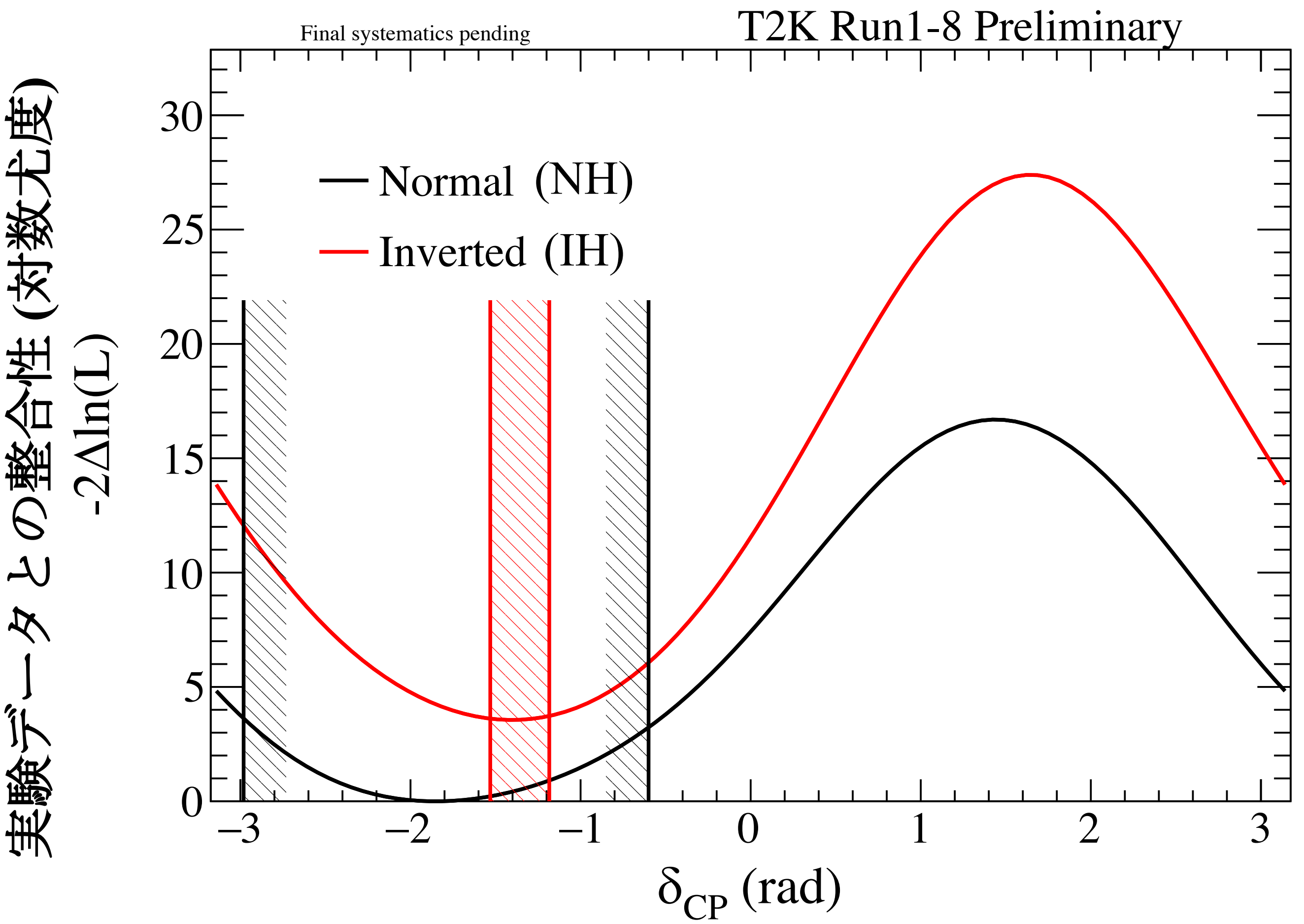
Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

2017年8月4日

http://www.icrr.u-tokyo.ac.jp/2017/08/04110000.html

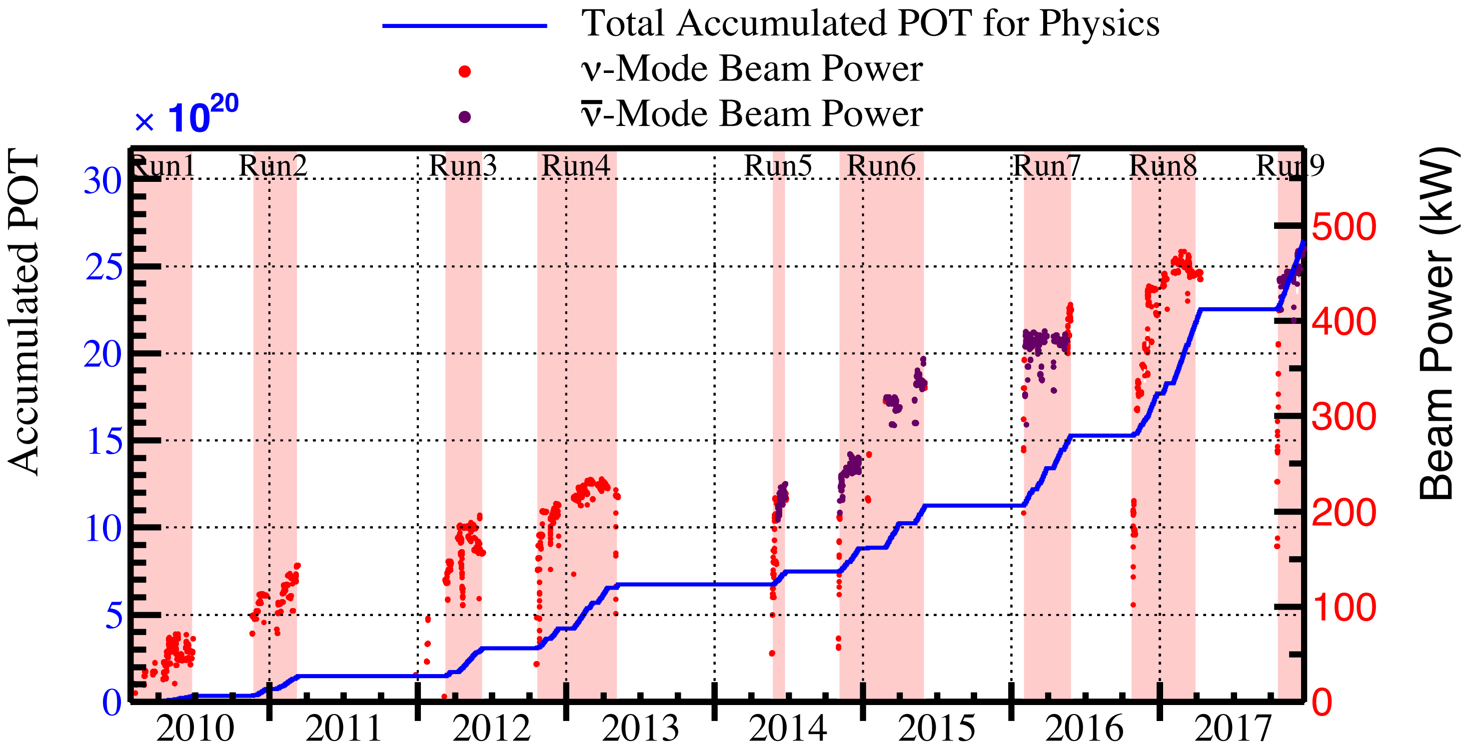
ニュートリノの「CP対称性の破れ」、可能性さらに高まる



$$\boldsymbol{\delta_{cp} = [-2.981, -0.600](NH), [-1.531, -1.184]\ (IH)}$$ **at 2σ CL**

T2K実験は「CP対称性の破れがない」ことを信頼度（確率）95%で棄却

これまでのT2K（2018年2月19日現在）



ビームパワーと取得した観測実験データ

23 Jan. 2010 - 22 Dec. 2017

POT total: 2.65 x 10^{21}

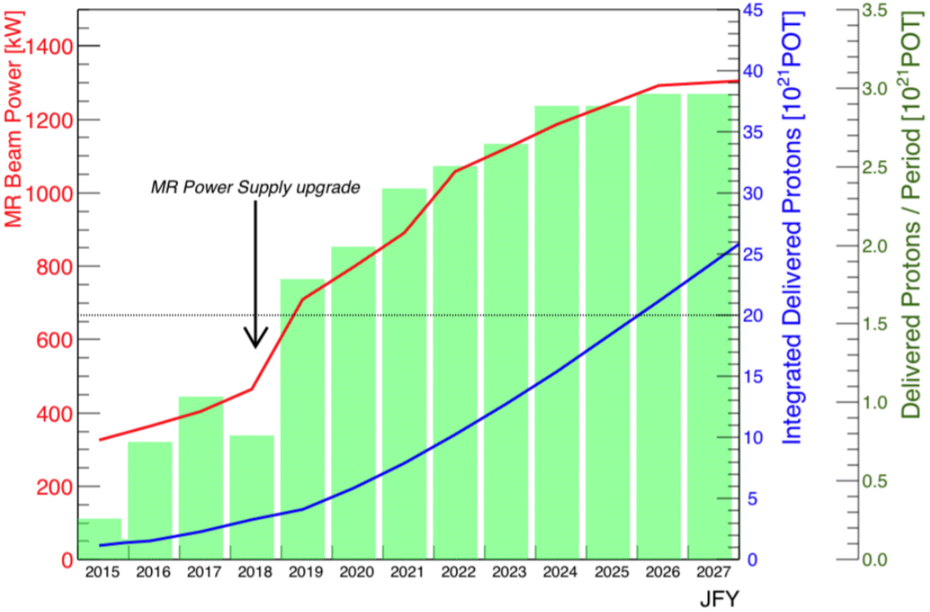
ν-mode 1.51 x 10^{21} (57.14%)

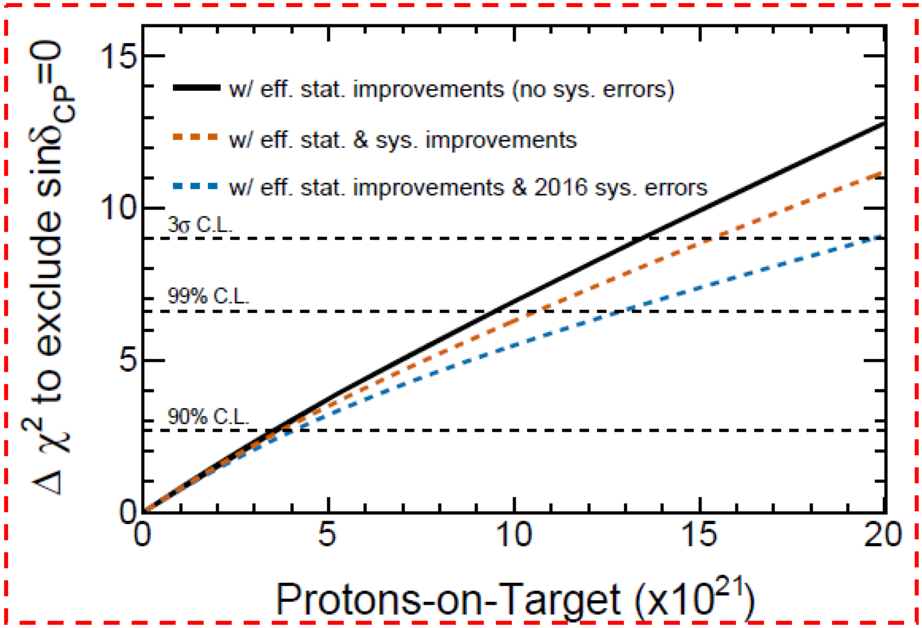
$\bar{\nu}$-mode 1.14 x 10^{21} (42.86%)

- ニュートリノの統計は2016-2017の一年間で倍になった
- 反ニュートリノの統計は2018年夏の終わりに倍になると予想
  - 2017年12月22日にはその目標の半分に到達

これからのT2K（2021年〜2026年）

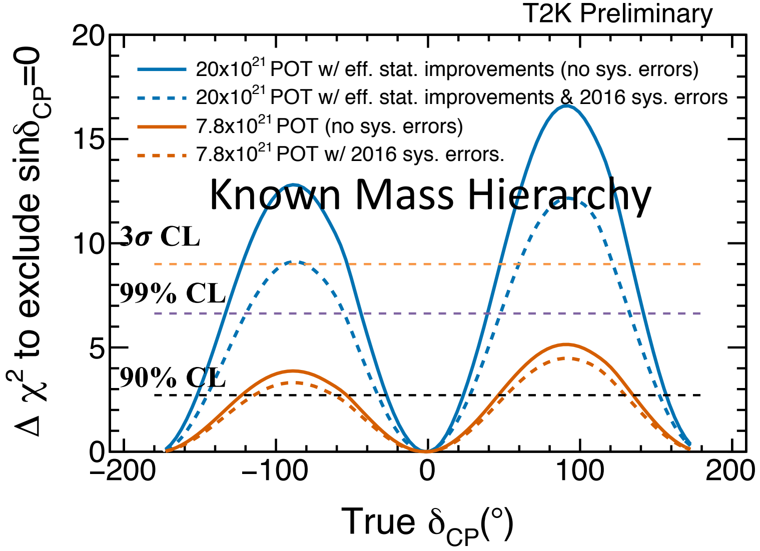
arXiv:1609.04111





T2K-II

- ビームパワーの増強
  (0.46 MW→1.3 MW)
- 2026年までに20×10^{21} POTの統計を収集する計画
- 高統計と系統誤差の抑制により，
  > 3σ の感度でCP対称性保存の破却

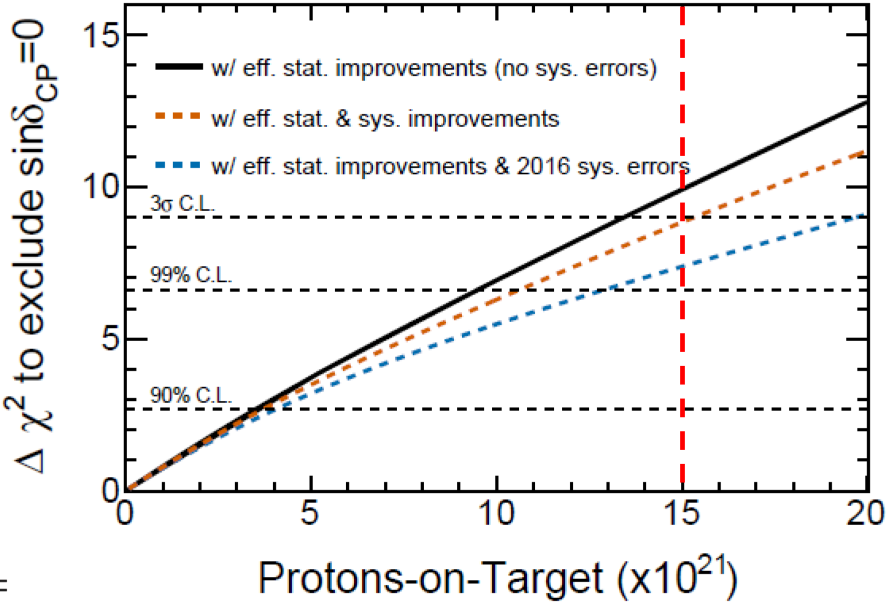


これからのT2K（2021年〜2026年）

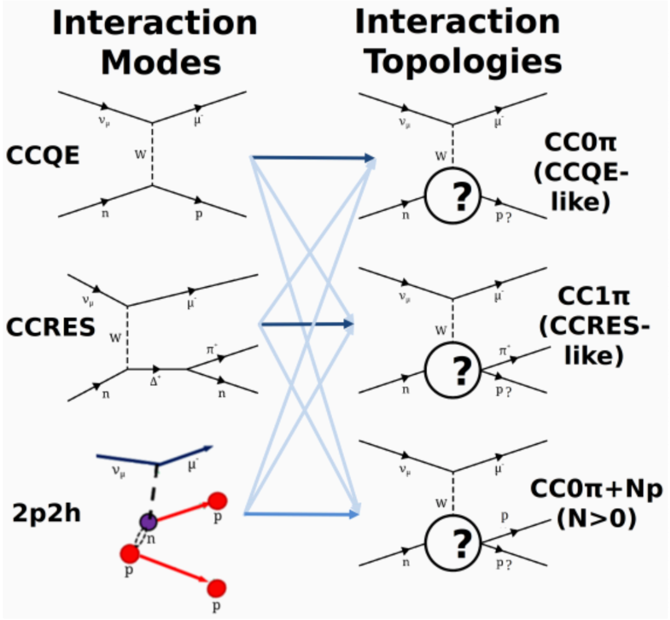
arXiv:1609.04111

T2K-IIに向けた系統誤差の抑制:

- 外部実験によるフラックスへの理解 (eg. NA61/SHINE 等)
- 検出器からくる不定性
- **ニュートリノ反応による不定性**



Source (%)	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	0.7	3.0	0.8	3.3
Flux and ND280-constrained cross section	2.8	2.9	3.3	3.2
Super-Kamiokande detector systematics	3.9	2.4	3.3	3.1
Final or secondary hadron interactions	1.5	2.5	2.1	2.5
Total	5.0	5.4	5.2	6.2

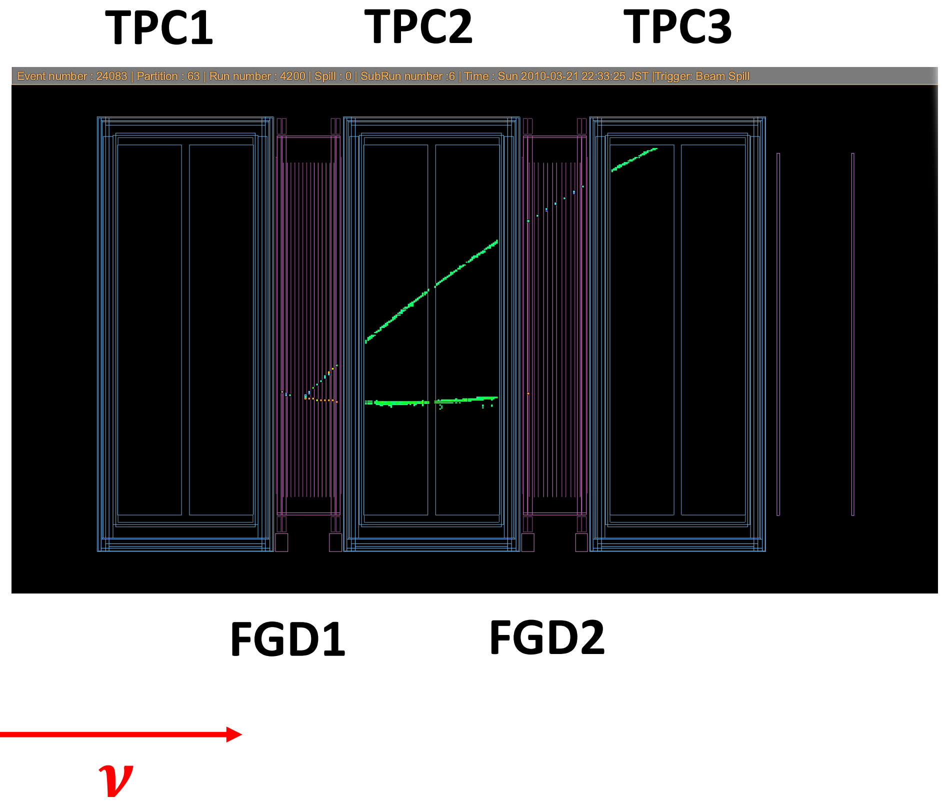


→系統誤差を~6%から~4%まで抑えることが目標

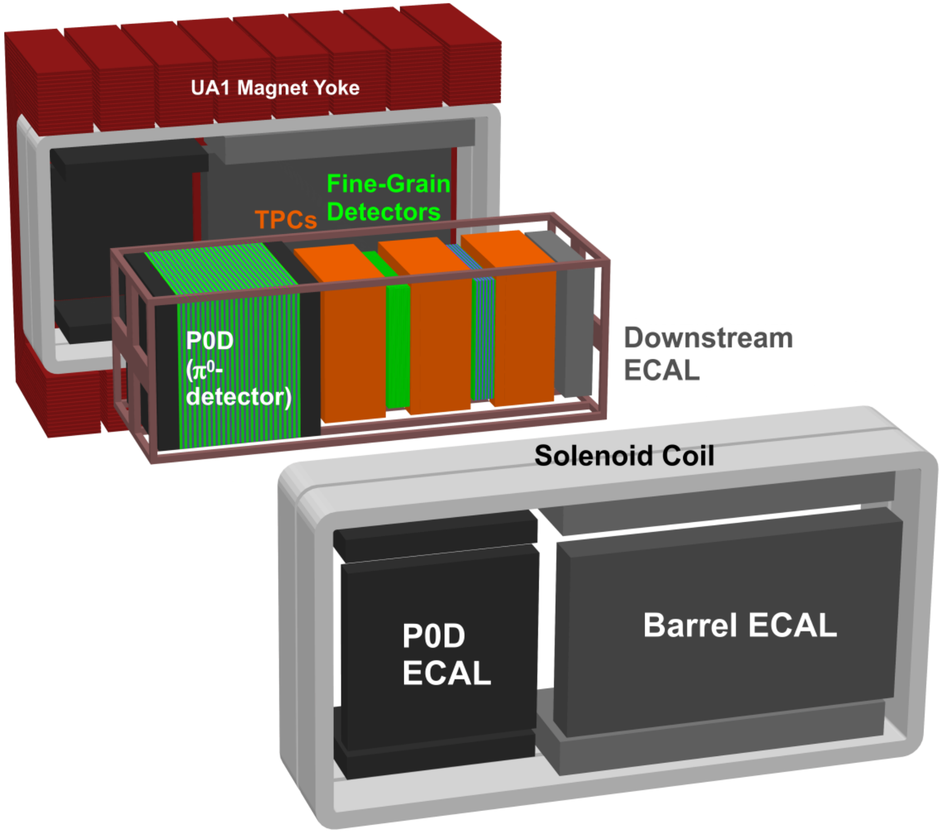
→ND280前置検出器アップグレードの計画

ND280 Measurements

- 振動前のニュートリノ反応を測定するための前置検出器
  - TPCとXYの層構造のプラスチックシンチレータ(FGD)による荷電粒子の運動量,方向を測定
  - T2Kのフラックス由来のニュートリノの反応断面積を測定
  - SKでのニュートリノフラックスと反応断面積の理論モデルに制限をかける



Event number : 24083 | Partition : 63 | Run number : 4200 | Spill : 0 | SubRun number :6 | Time : Sun 2010-03-21 22:33:25 JST |Trigger: Beam Spill



Goals of ND280 Upgrade (1)

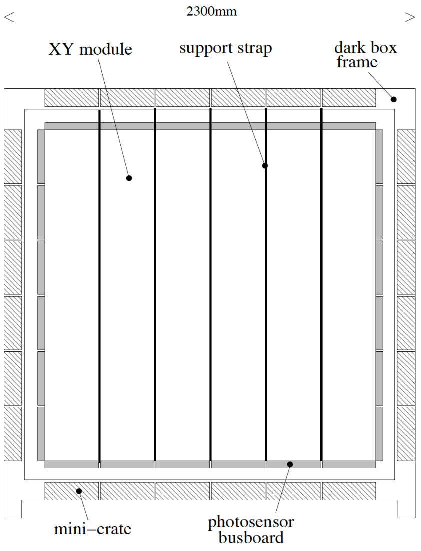
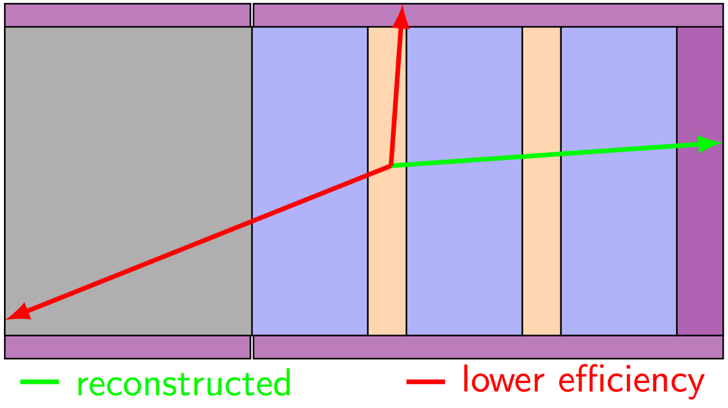
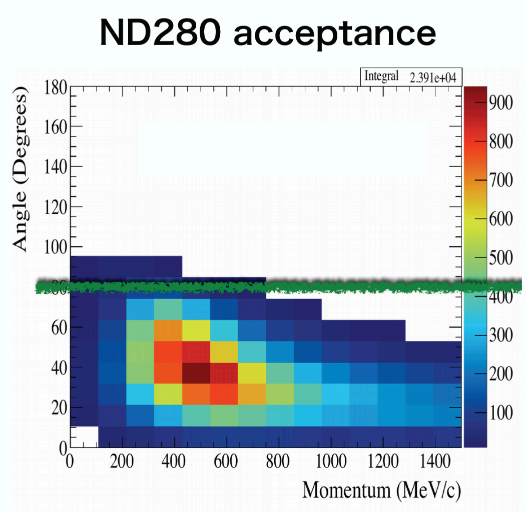


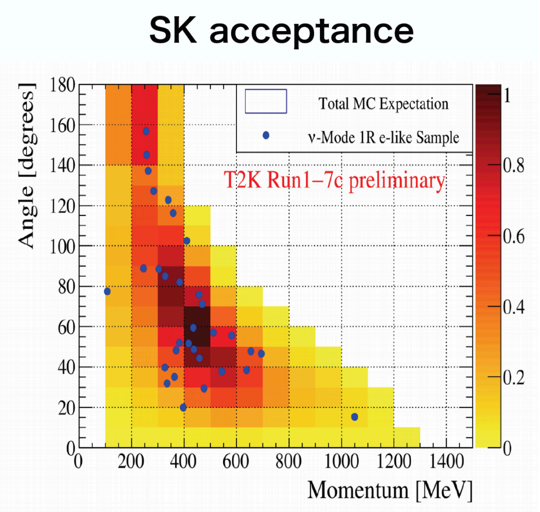
Figure 2: Cross-sectional view of an FGD, showing the locations of the scintillator modules, photosensors, support straps, electronics minicrates, and dark box.

arXiv:1204.3666

- **4πに対するアクセプタンス**
  - 現在のND280は前方に対する高いアクセプタンスがある
    - VerticalやBackward trackにはEfficiencyが低い
    - SK同様に4πに対して一様なアクセプタンスがあれば,より広い位相で反応断面積モデルに制限をかけられる

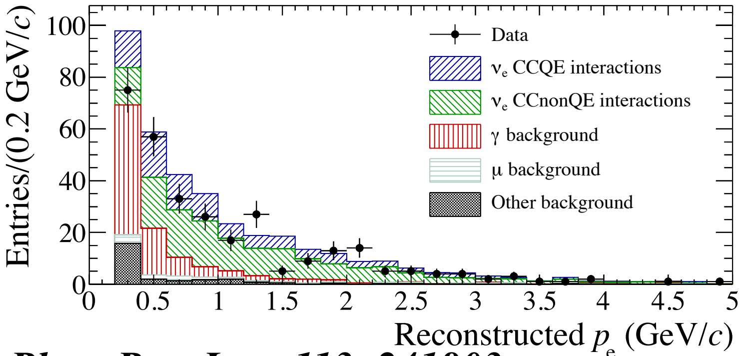




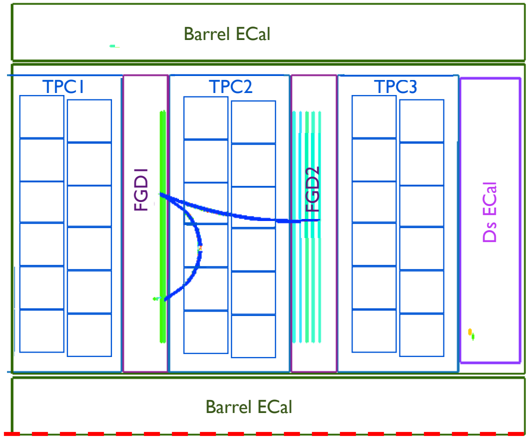


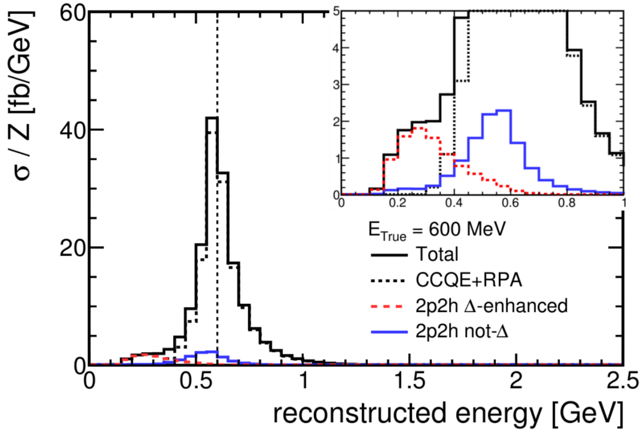
Goals of ND280 Upgrade (2)

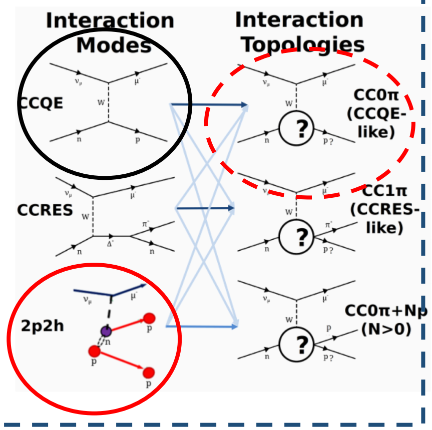
- 低い運動量を持つ荷電粒子の測定
  - **CCQEと2p2hの識別**
    - T2Kのエネルギー再構成に対するバイアス
  - **ν_e由来とγ由来の事象の識別**
    - NDでのν_e CC事象選択の約23%がγ由来の背景事象
- より高いグラニュラリティを持つ検出器で短いトラックの測定



Phys. Rev. Lett. 113, 241803







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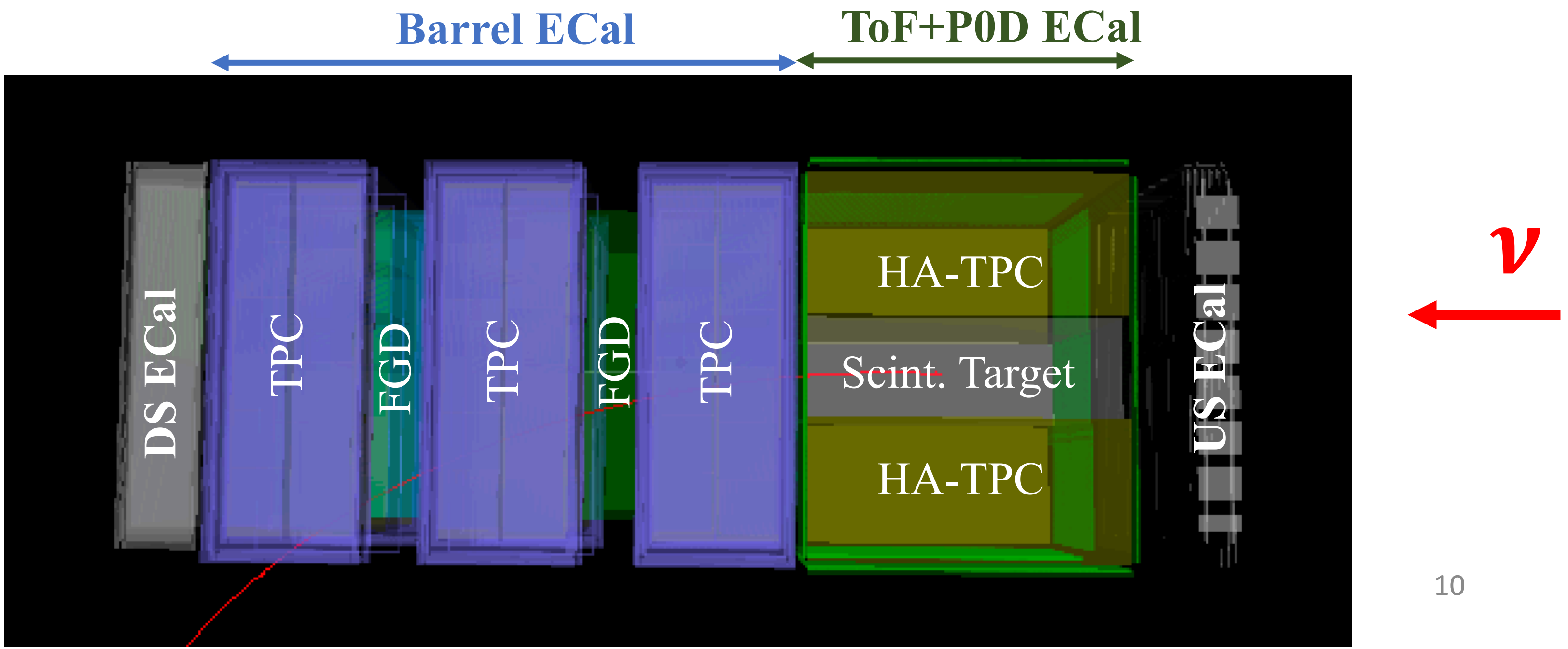
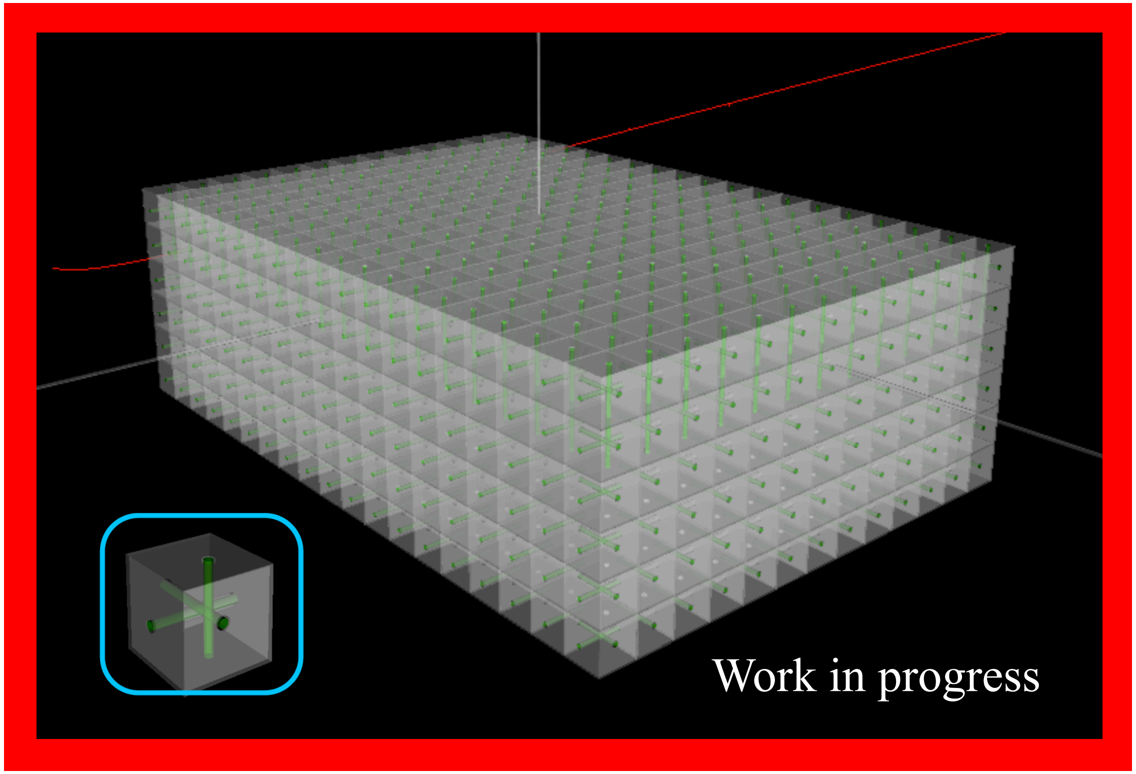
ND280 Upgrade

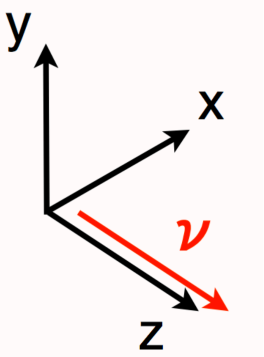
- 現在のトラッカー(TPC＋FGD)はそのまま
- 上流に新しいトラッカーを実装する計画
  - **2 High-Angle TPCs (HA-TPCs)**
  - **よりFine-Grainedなシンチレータ検出器**
  - **新しいトラッカーの囲うようにTime-of-Flight (ToF) counterを設置**



SuperFGD



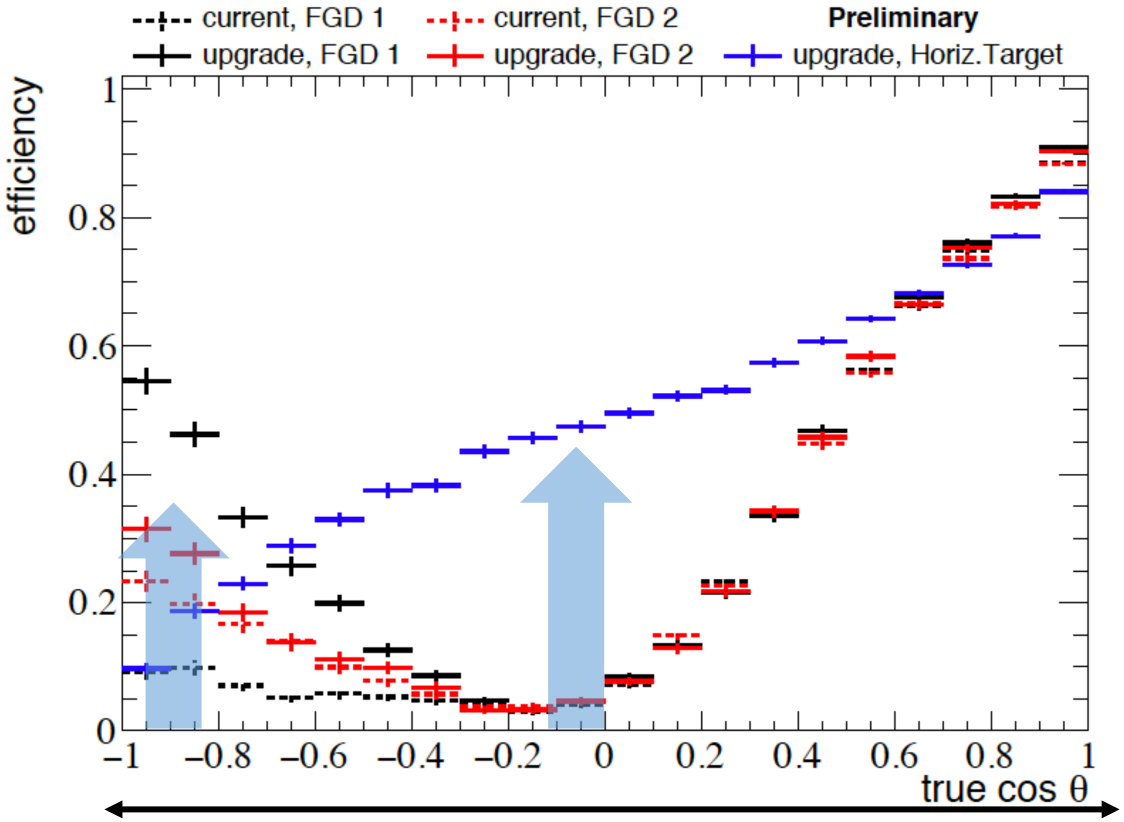
Parameter	Cube edge: 1 cm
# of cubes	2,160,000
# of channels	58,800
Total fiber length	65 km



- 体積: 1.8 x 0.6 x 2.0 m^3
- 体積1 x 1x 1 cm^3 のシンチレータキューブによって構成
  - 反射材によるコーティング
- 各キューブに3本の波長変換ファイバーをXYZの方向に通し,MPPCで三次元の光量を測定

Wide Angle Acceptance

- T2Kのフラックスを考慮したν_μシミュレーション(1×10^{21} POT)による性能評価
- 従来のND280同様の各TPCによる事象選択を行い,そのEfficiencyを比較
- 新しいHA-TPCとシンチレータ検出器によってEfficiencyが向上

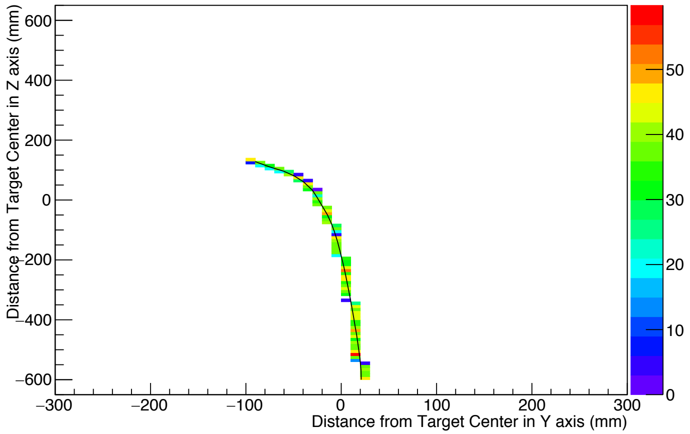


Backward-going **Forward-going**

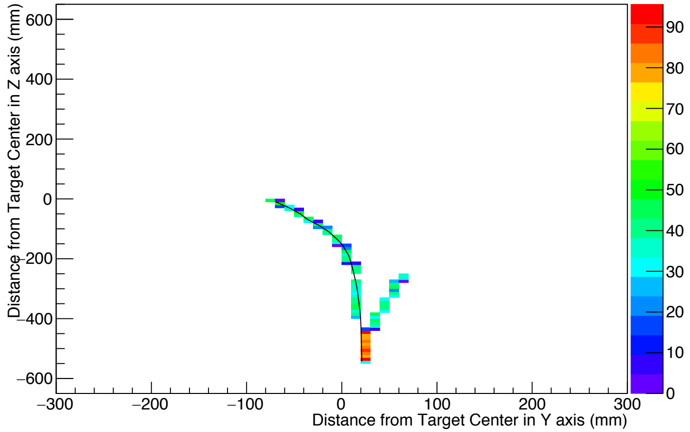
High Granularity

- Hit情報を用いて３方向からのイベントディスプレイを作成
- SuperFGD内での事象選択のアルゴリズムを製作中
  - Vertex近傍の単一キューブから見えるhit数でν_e由来とγ由来の事象識別が可能？(1 MIP vs 2 MIP)

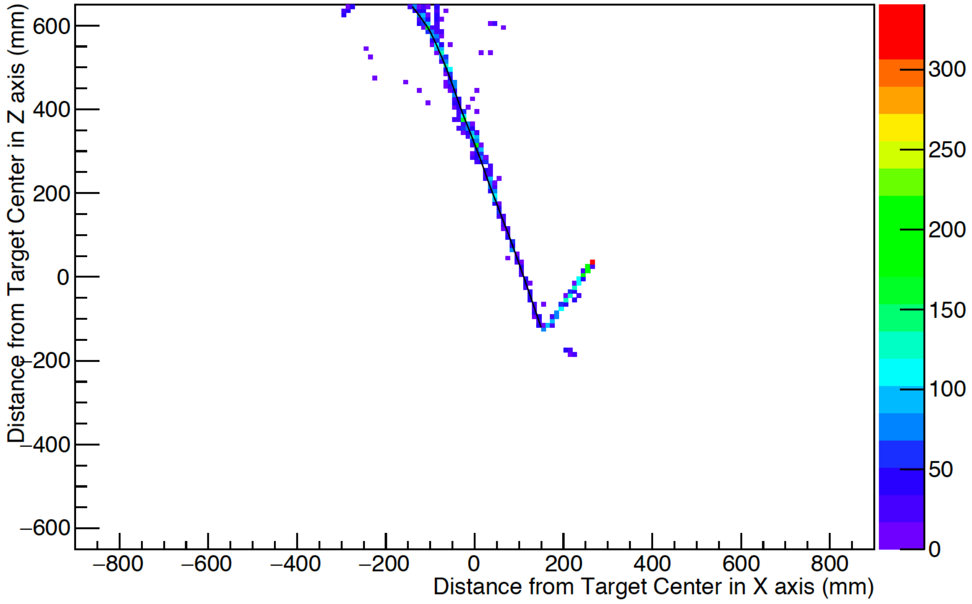
e



γ

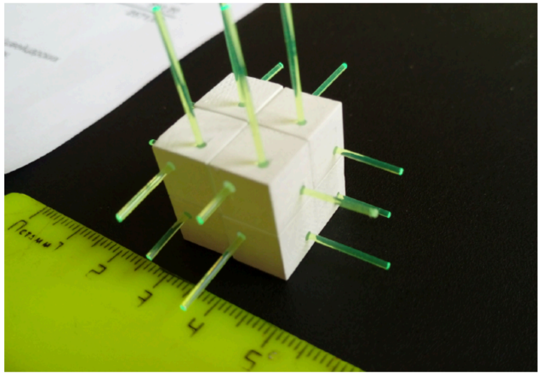


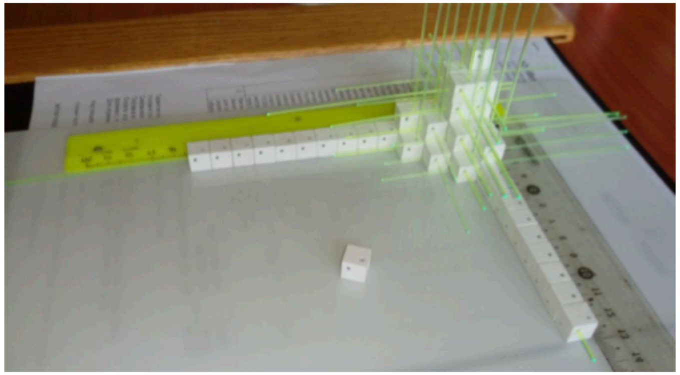
ν_e CCQE

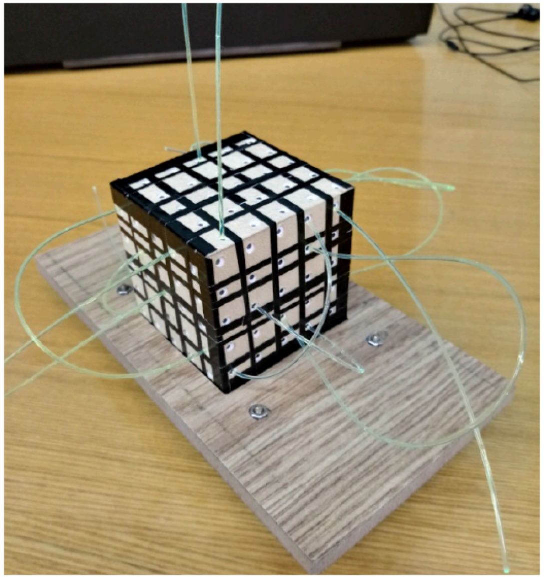


SuperFGD R&D

- ロシアINRによるキューブ(1 x 1x 1 cm^3)の開発
- 5x5x5キューブのプロトタイプ検出器でCERNビームテストを行った(2017年10月)
  - Cross-talk, light yield, timing resolution
  - 現在解析中
- 日本で4x4x6キューブのプロトタイプ検出器で宇宙線テスト中 (東大藤田)
- 日本でも東北大学でビームテストを計画 (KEK松原)
- アセンブリのStudyも進行中

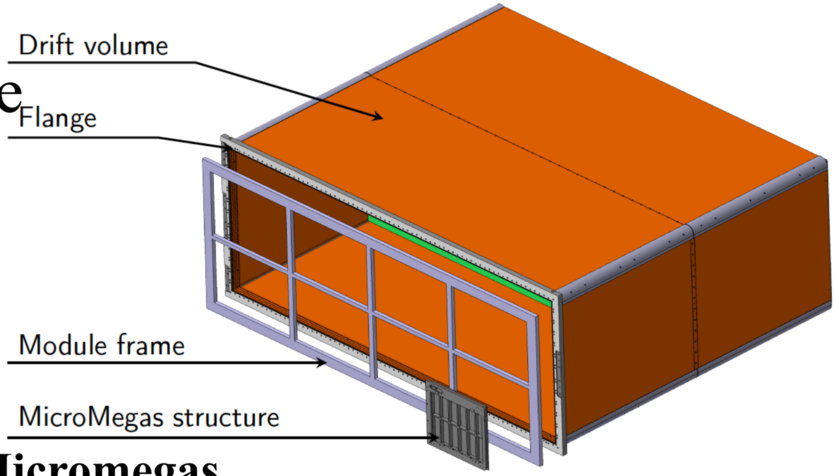






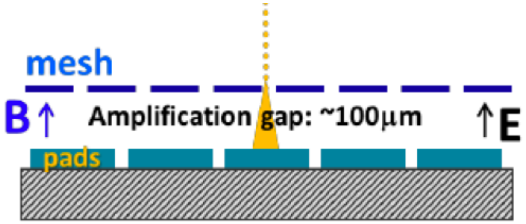
High-Angle TPC R&D

- 主にEUのグループが担当
- 現在のND280でのデザインを踏まえつつ,主に2つの変更:
  - Resistive Micromegas
    - Pads covered by resistive foil
    - Allows the charge detection for small drifts
  - Field Cage Design
    - Maximizing tracking volume for large angle track

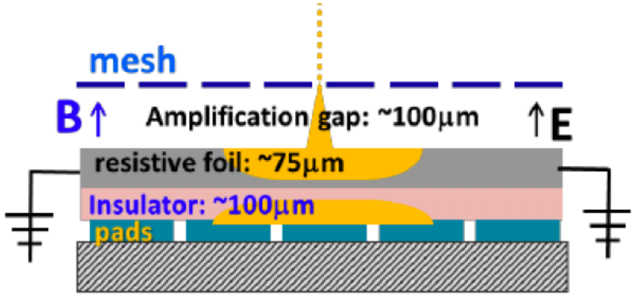


2.3 x 0.8 x 2.0 m^3

Nominal Micromegas

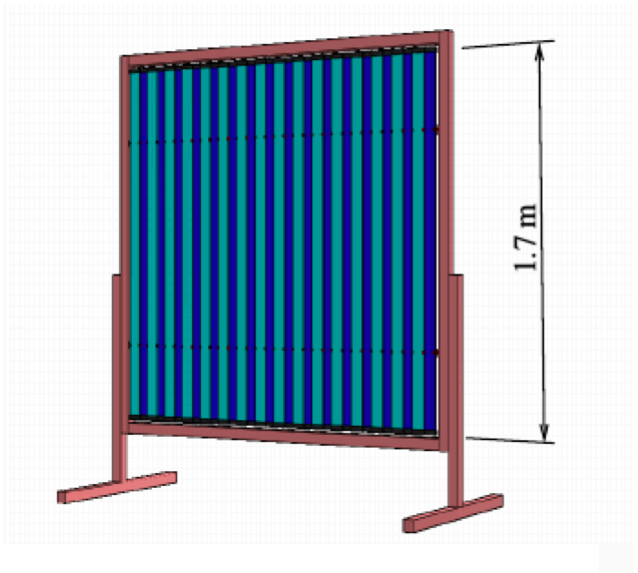


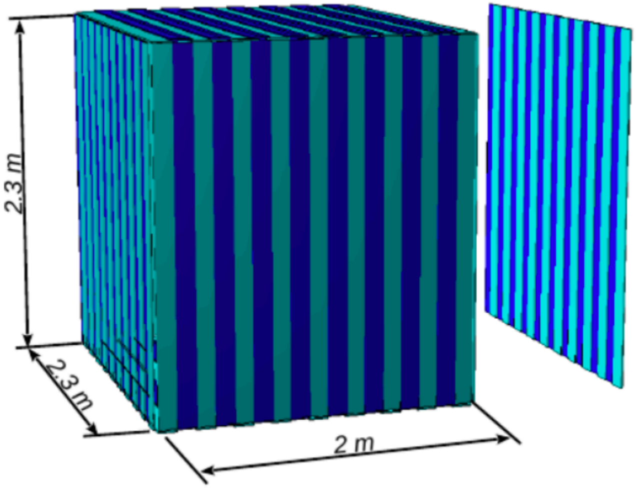
Resistive Micromegas



Time-of-Flight Counter

- 荷電粒子のentering/exiting timeを測定
  - 検出器外部からの背景事象の識別
  - トラックの方向と粒子の識別(PID)の向上
- 新しいトラッカーを囲うように配置
- R&D with cast/extruded scintillator bars with SiPM/WLS fibers ongoing





ND280 Upgrade Project Timeline

- 2015 10月 :ND280 Upgrade Task Force was launched
- 2017 1月 : **Expression of Interest** submitted to SPSC@CERN (CERN-SPSC-EOI-015)
- 2017 2月 : **T2Kの公式プロジェクトとして承認**
- 2018 1月 : Proposal (SPSC@CERN & PAC@J-PARC)
- 2018: Technical Design Report, prototype
- 2019-2020: Production, Construction
- **2021: Installation, commissioning**

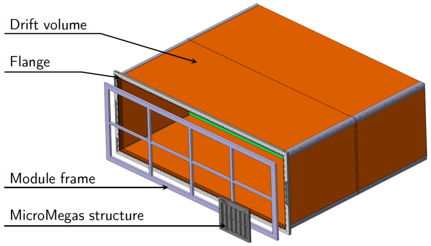
7 open workshops held so far:

# & Location	Date	URL
1 (CERN)	Nov 2016	https://indico.cern.ch/event/568177/
2 (CERN)	Mar 2017	https://indico.cern.ch/event/613107/
3 (Tokai)	May 2017	https://indico.cern.ch/event/633840/
4 (CERN)	Aug 2017	https://indico.cern.ch/event/644360/
5 (Tokai)	Oct 2017	https://indico.cern.ch/event/667631/
6 (CERN)	Nov 2017	https://indico.cern.ch/event/673242/
7 (Tokai)	Feb 2018	https://indico.cern.ch/event/698927/
8 (CERN)	**Apr 2018**	

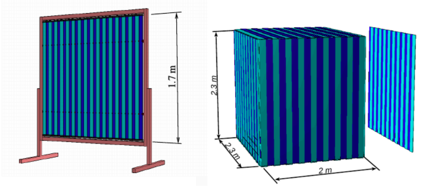
まとめ

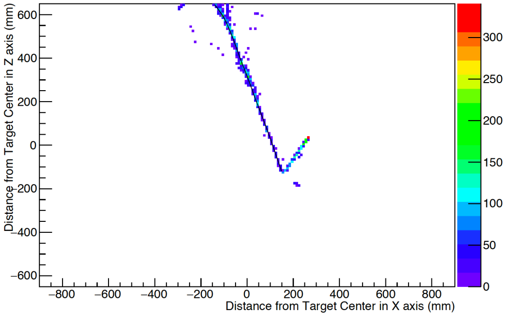
- **T2K-II**
  - 2026年までに20×10^{21} POTの統計を収集する計画
  - **高統計**と**系統誤差の抑制**により,$> 3\sigma$ の感度で
CP対称性保存の破却
  - **ND280 Upgrade**でニュートリノ反応による系統誤差を抑える
- **ND280 Upgrade**
  - 大角度に対するアクセプタンスと低い運動量をもつ荷電粒子の測定
  - **HA-TPC, SuperFGD, ToF**によるトラッカーを実装する計画
  - **R&D and simulation studies are ongoing!!**
  - **2021のInstallation**に向けて活動中

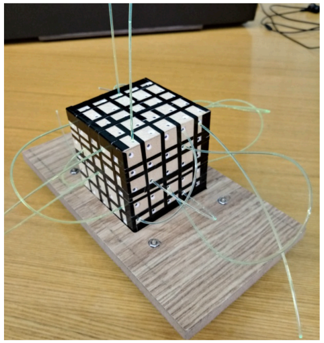
CERN-SPSC-2018-001 ; SPSC-P-357

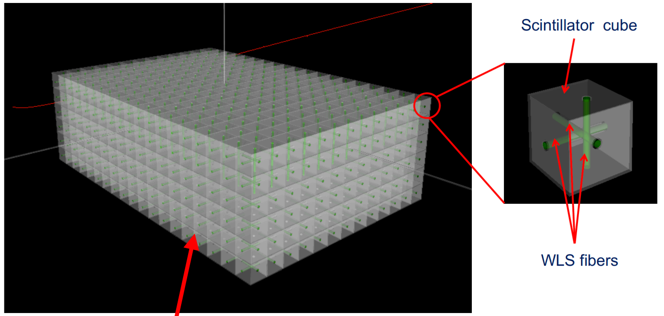


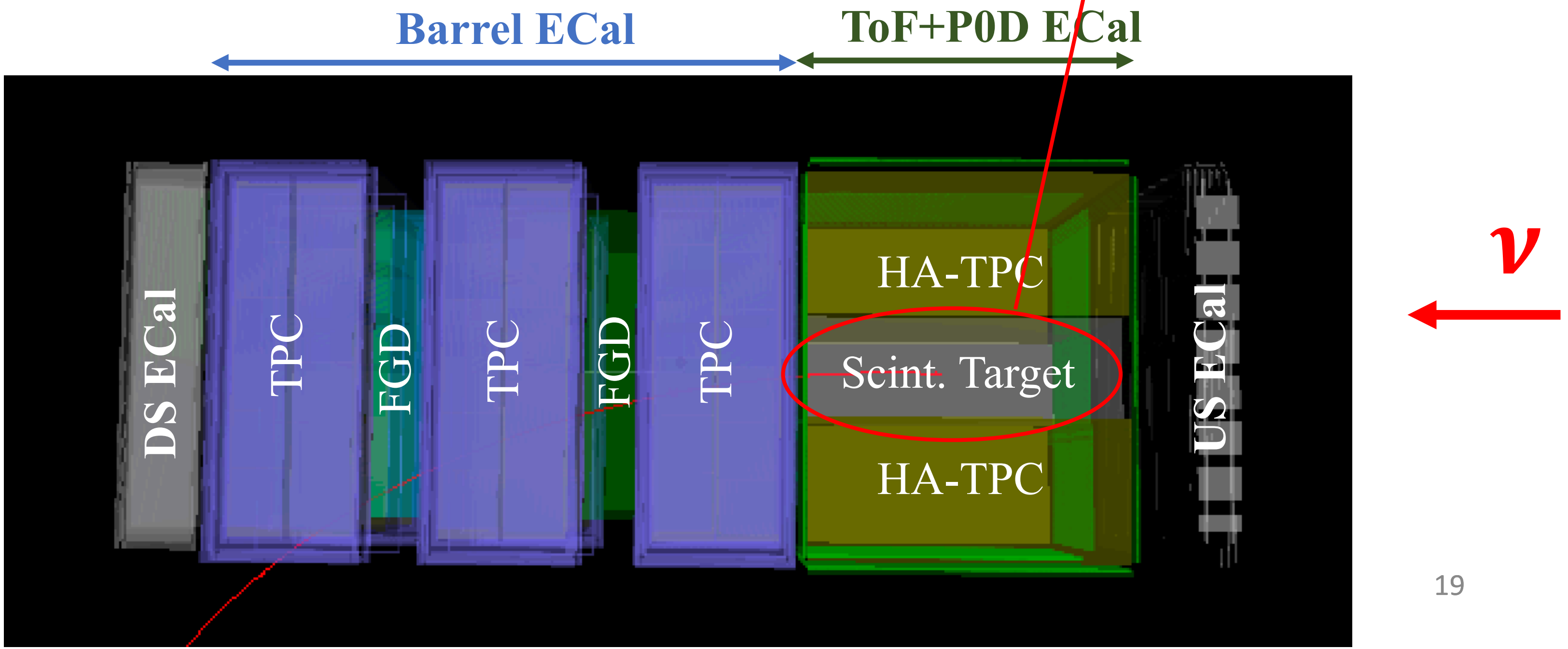
Thank you very much!!





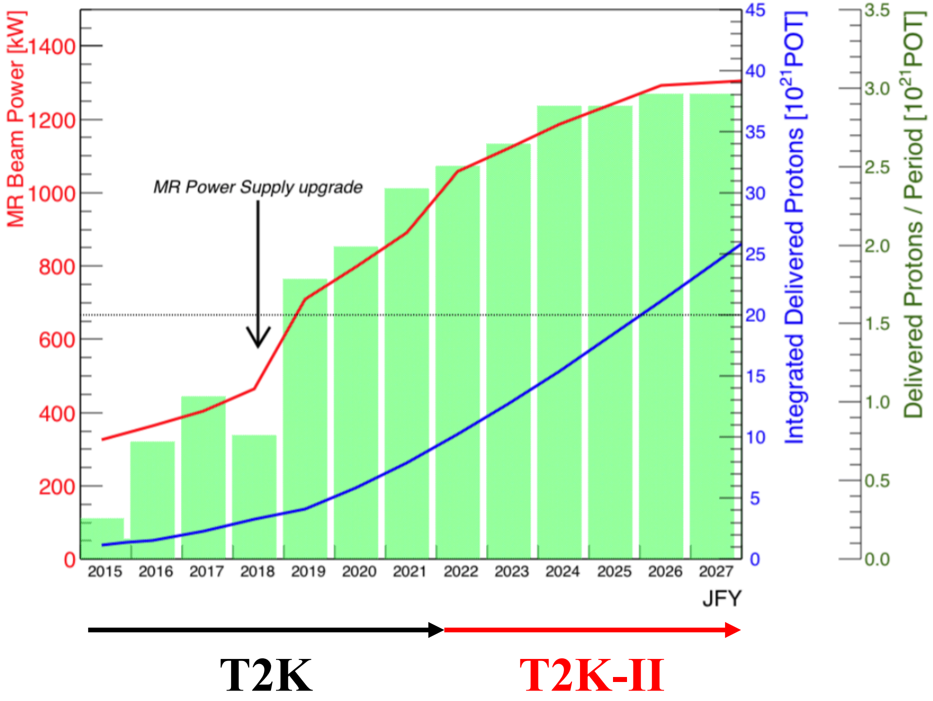






これからのT2K（2021年〜2026年）

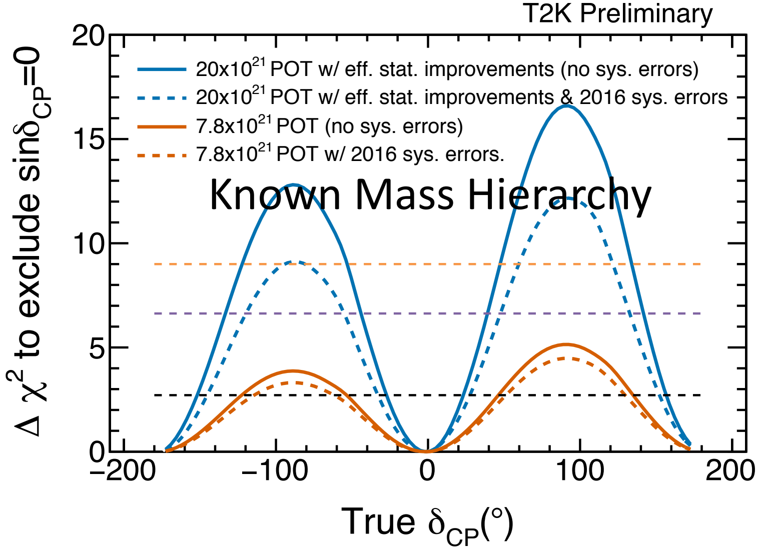
arXiv:1609.04111



T2K-IIに向けたPOTあたりの統計増加:

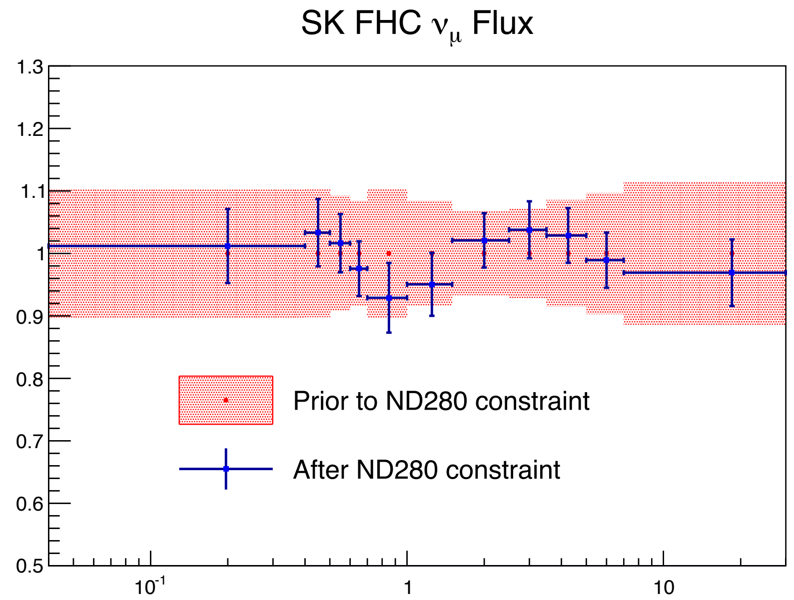
- ビームパワーの増強
  (0.46 MW→1.3 MW）
- 電磁ホーンの電流強化
  (250kA→320kA)
- 新しい解析サンプルの追加
  (eg. ν_e CC1π^+ サンプル)
- 解析ツールの向上による有効体積の拡大
  ($\nu_e/\bar{\nu}_e$サンプルの統計が20/30 %増加)

- 2026年までに20×10^{21} POTの統計を収集する計画
- 高統計と系統誤差の抑制により，
  > 3σ の感度でCP対称性保存の破却

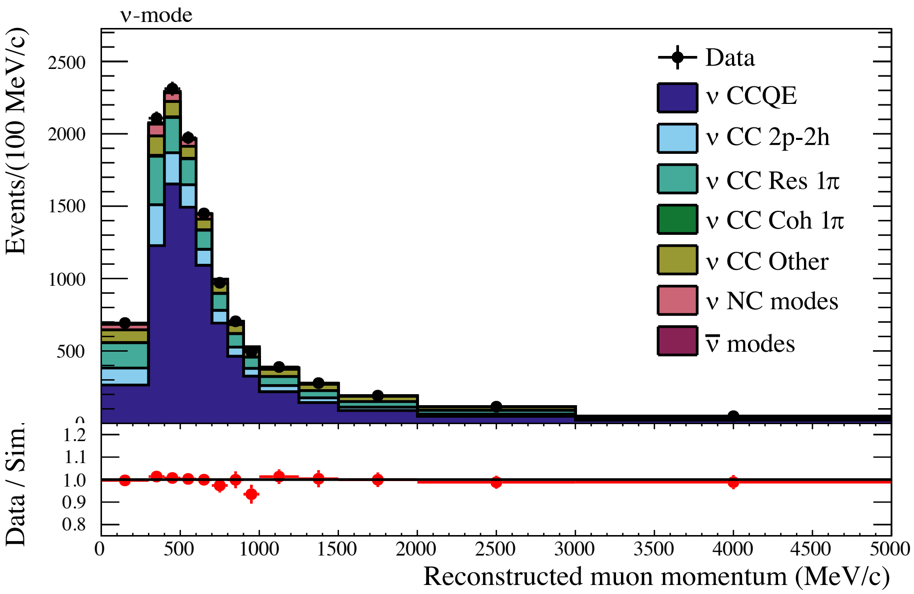


Near Detector Fit

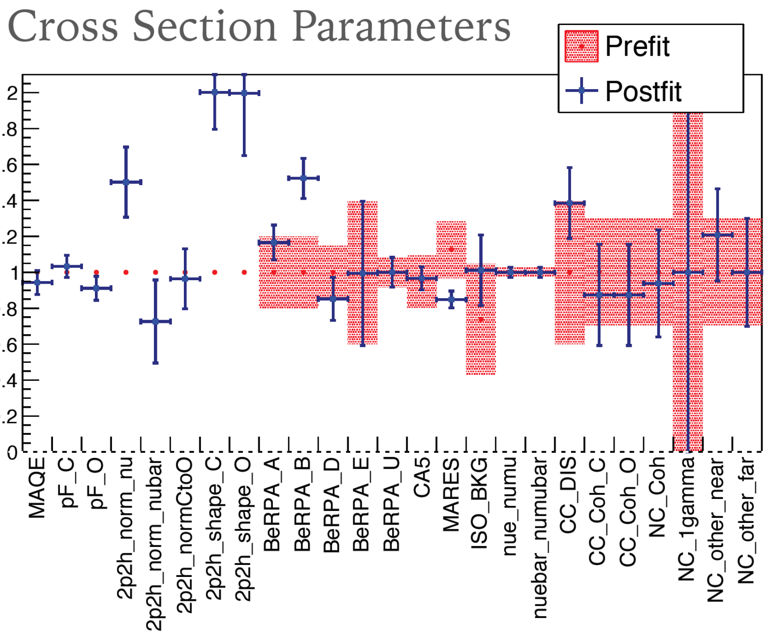
- ND280での測定を用いてフラックスと反応断面積モデルに制限をかける
  - データの分布に合わせてMCのparameterを調節
- Post fit parameterをSKでの測定を用いた振動解析に使う



PRELIMINARY



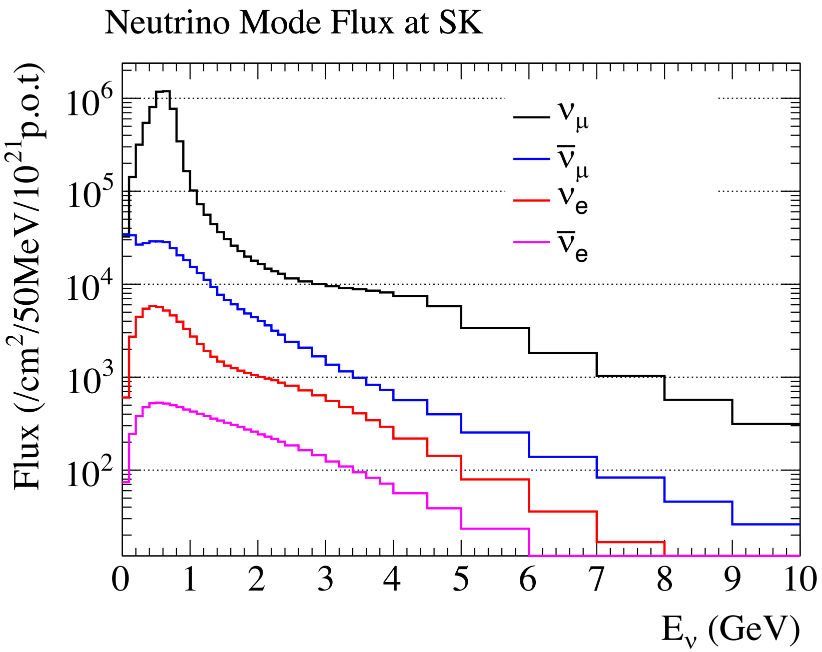
PRELIMINARY

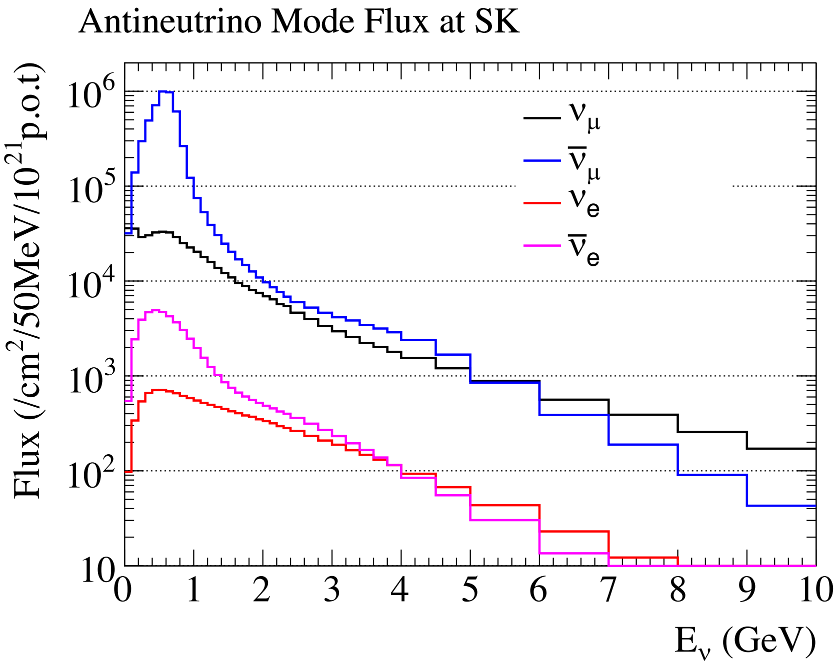


Intrinsic ν_e Beam Component in T2K Beam

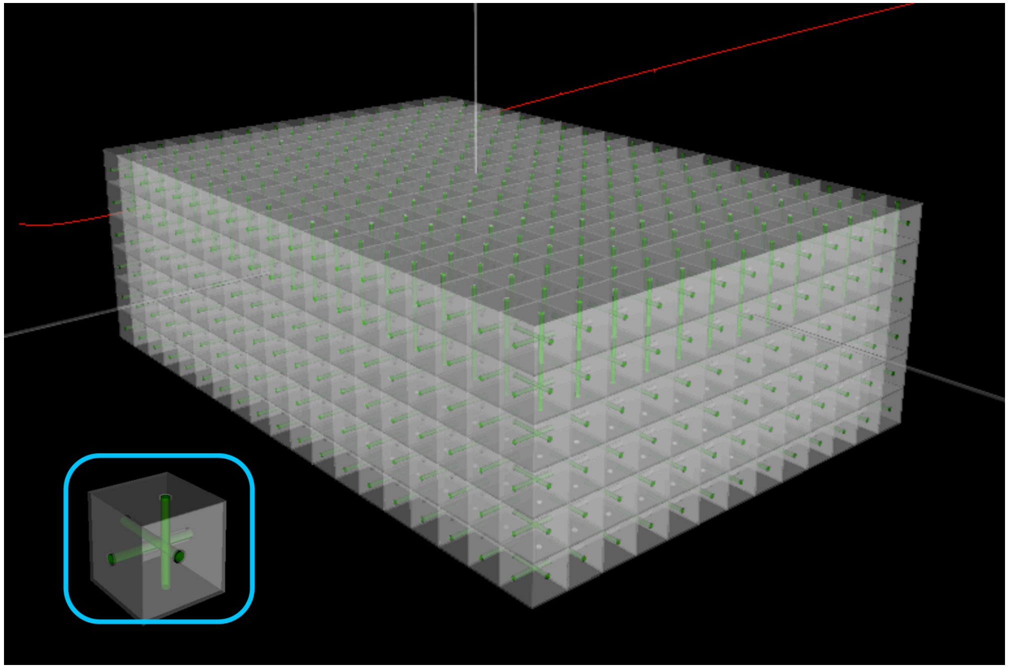
- Consists 1.2% of the total $\nu(\overline{\nu})$ flux in T2K beam
  - Mainly produced from muon and kaon decays

- Major source of background to measure δ_{CP} through $\nu_\mu(\overline{\nu}_\mu) \rightarrow \nu_e(\overline{\nu}_e)$ appearance analysis


Neutrino Mode Flux at SK

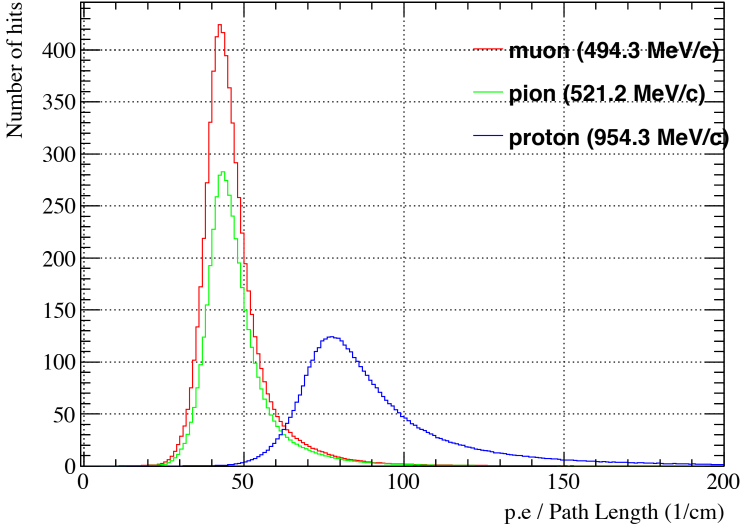

Antineutrino Mode Flux at SK

SuperFGD Target Validation: MIP Peak

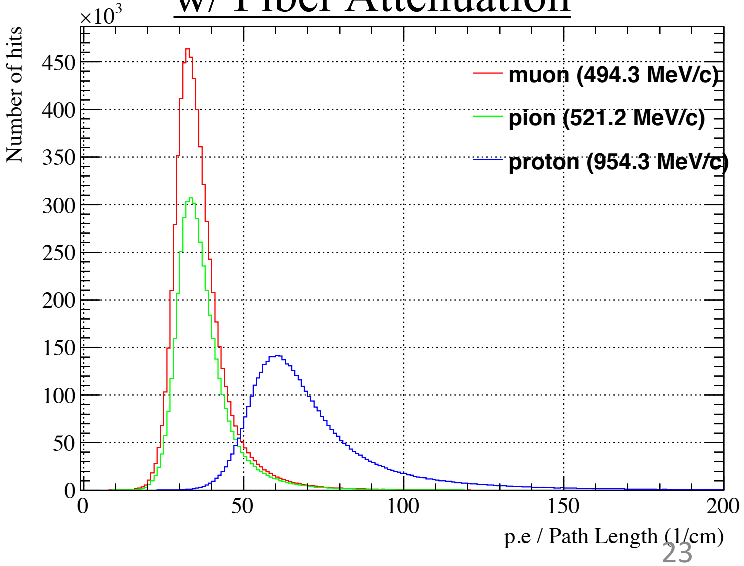


- Dimension: 1800 x 600 x 1300 mm^3
- Plastic scintillator cube size: 10 mm^3

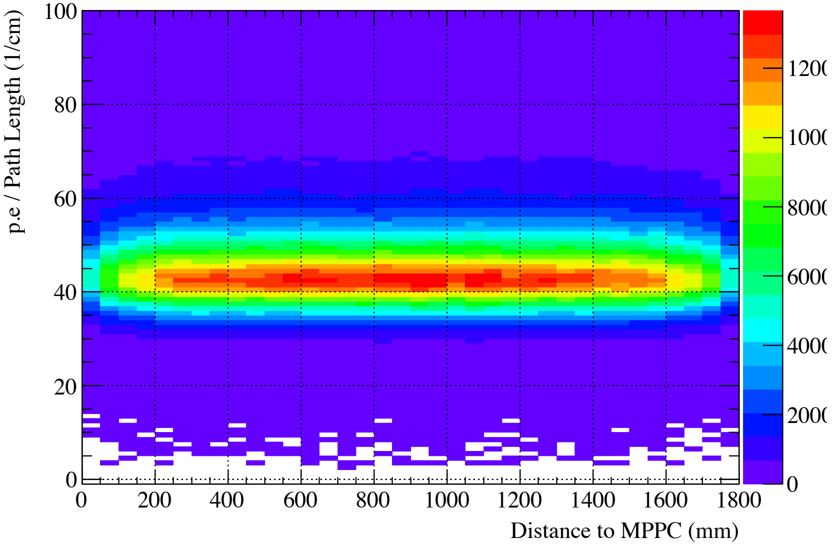
w/o Fiber Attenuation

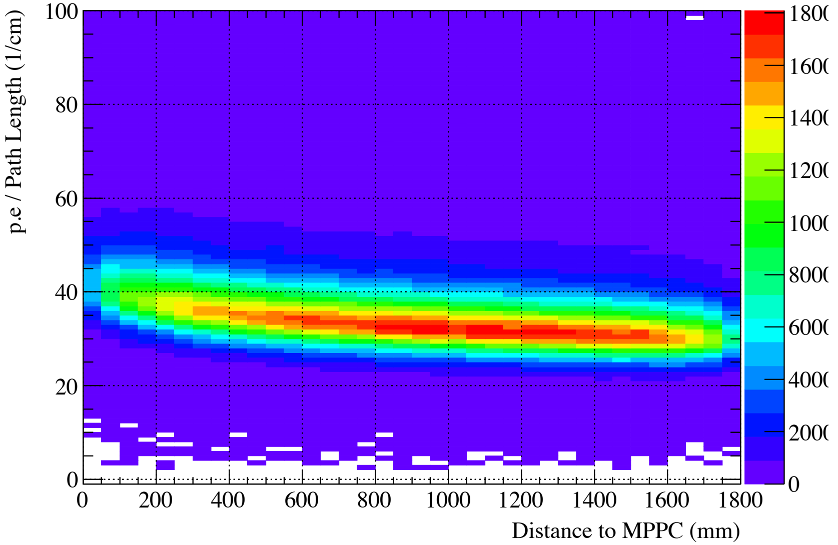


w/ Fiber Attenuation



SuperFGD Target Validation: Fiber Attenuation


w/o Fiber Attenuation


w/ Fiber Attenuation

Fitting the fiber attenuation:

$$N(x) = p_0 \left(a\, e^{\frac{-x-d}{p_1}} + (1-\mathrm{a})\, e^{\frac{-x-d}{p_2}} \right)$$

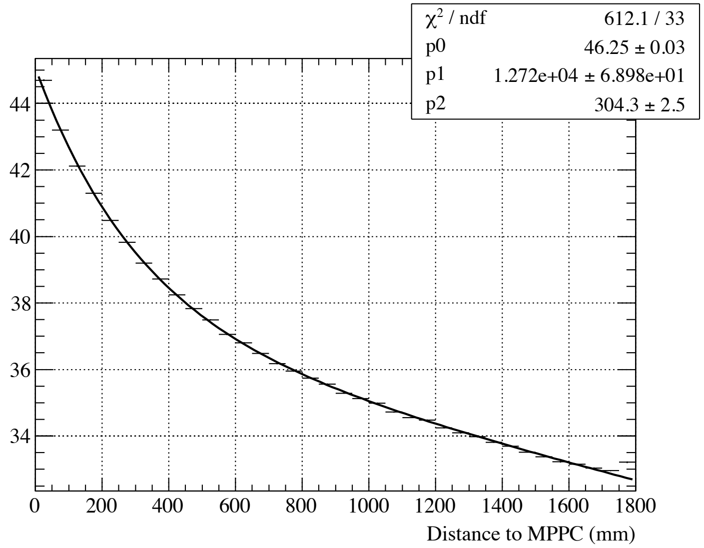
Fit range: p.e = (20, 80)

d = 41 mm, MPPC-scintillator distance

p_1 = 11926 mm, long attenuation length

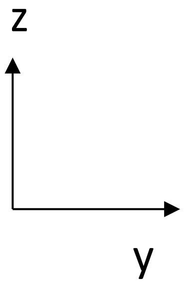
p_2 = 312 mm, short attenuation length

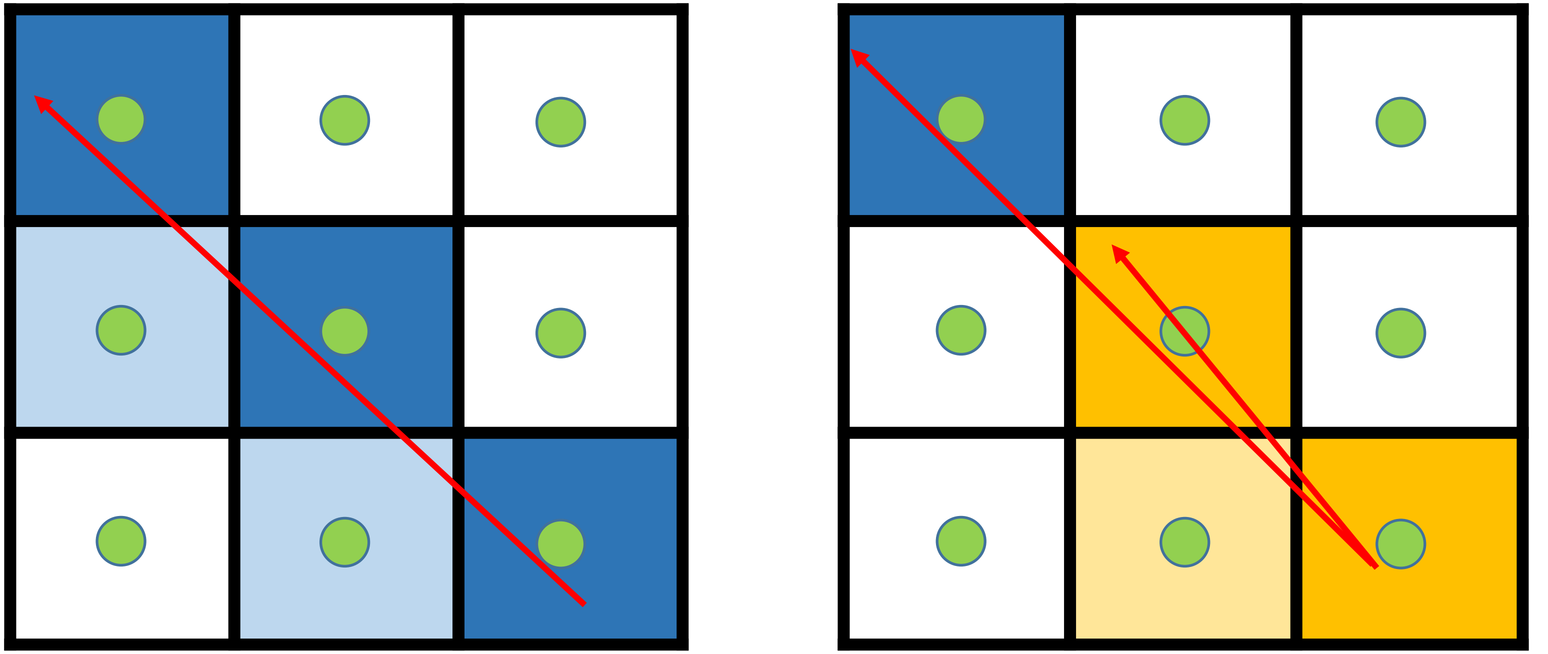
a = 0.816, long attenuation component fraction



e/γ Separation in ND280 Upgrade Target

- Goal to distinguish e/γ events that are single-track, electron-like, low momentum ($200 < p < 600$ MeV/c)
- Distinction between 1 (e^-) and 2($\gamma \rightarrow e^- e^+$) MIP events using the MPPC light yield from the tracks
  - Considering the light yield before and after the $e^- e^+$ tracks split into different scintillator segments

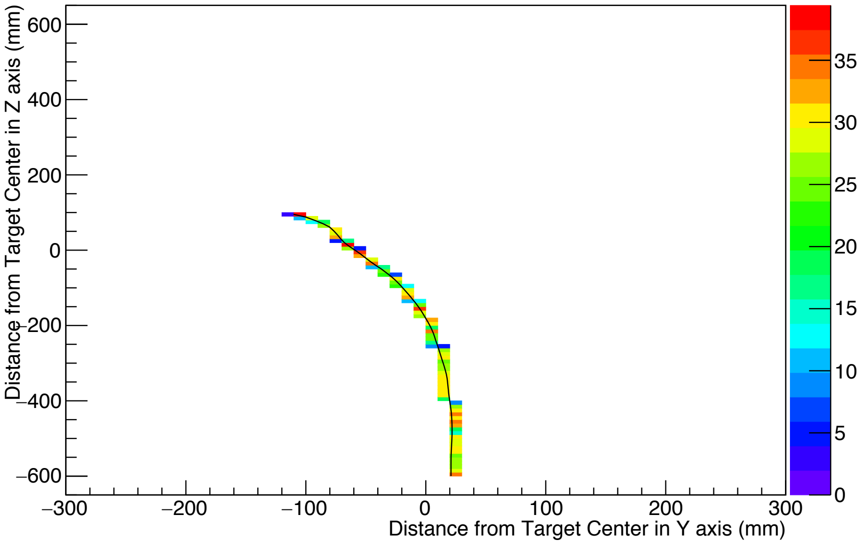




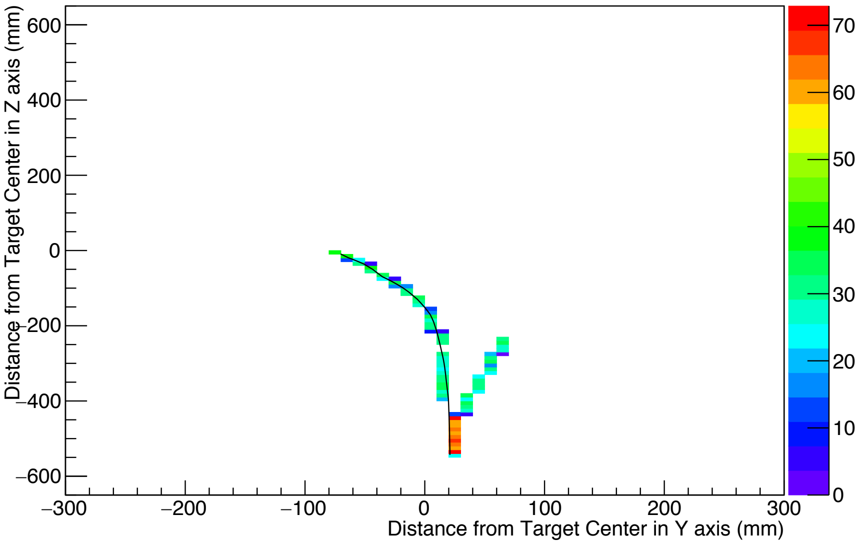
e/ γ Separation using Light Yield

- Preliminary algorithm to separate e/γ events using the total light yield for each view (YZ, XZ, XY)
  1. Locates the single electron track and the starting point using truth information
     - "Perfect pattern recognition"
  2. Split the track into two segments where the ratio between the mean values of the total p.e. is the largest
     - Ignores the first and last MPPC hits to avoid short path length

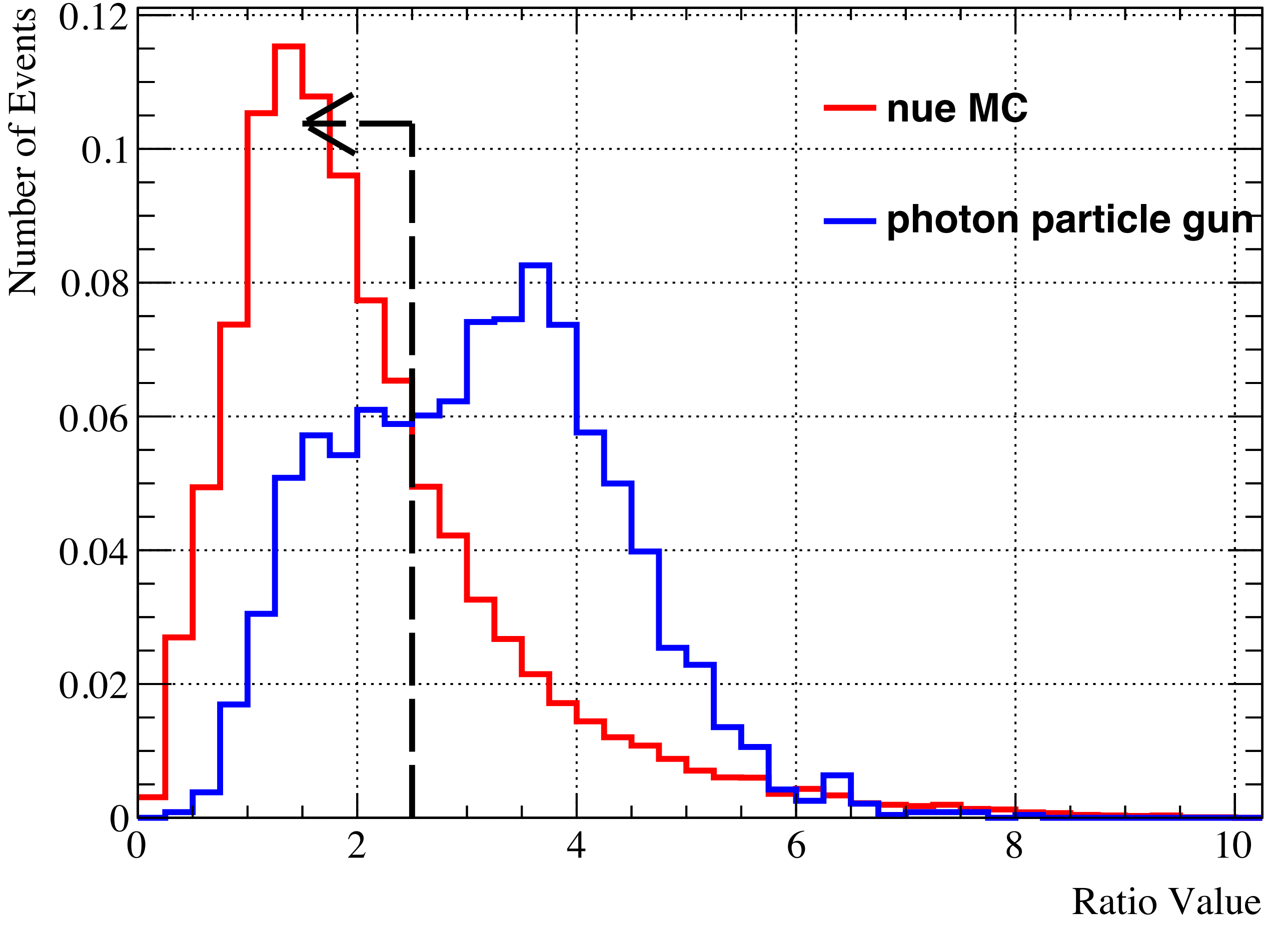
***e* Sample**



γ Sample

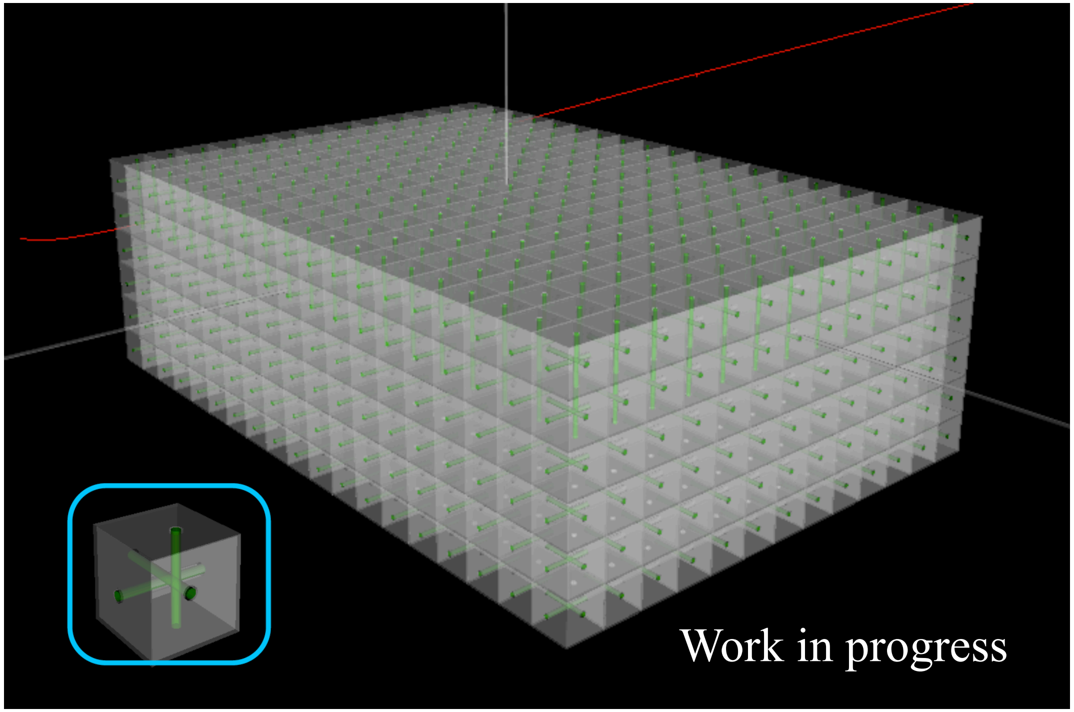


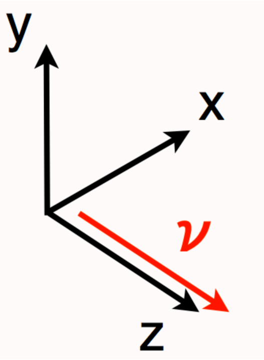
SuperFGD: ν_e MC and γ 4π p-gun Comparison



77% efficiency to accept ν_e CC
39% to mis-ID γ p-gun sample
(19% if 2-trk-like count as rejected)

SuperFGD: Different Configurations

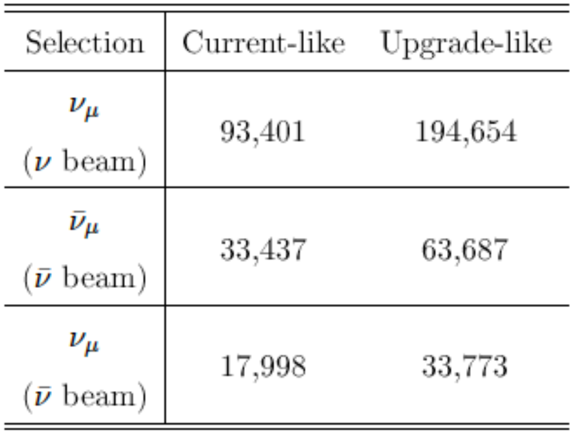

Work in progress



Parameter	Cube edge: 1 cm	Cube edge: 1.5 cm	Cube edge: 2 cm
# of cubes	2,160,000	638,400	270,000
# of channels	58,800	26,080	14,700
Total fiber length	65 km	29 km	16 km

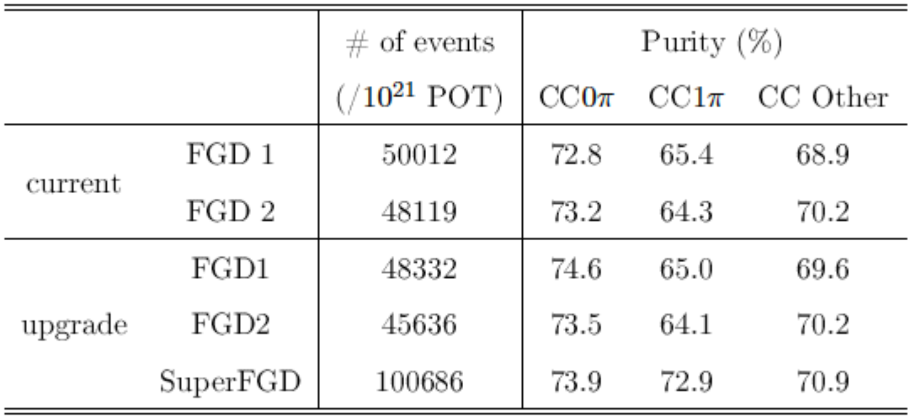
ND280 Upgrade ν_μ Selection

Comparison of predicted event rate of selected events (1×10^{21} POT) between ND280 current and upgrade:



Selection	Current-like	Upgrade-like
ν_μ (ν beam)	93,401	194,654
$\bar{\nu}_\mu$ ($\bar{\nu}$ beam)	33,437	63,687
ν_μ ($\bar{\nu}$ beam)	17,998	33,773

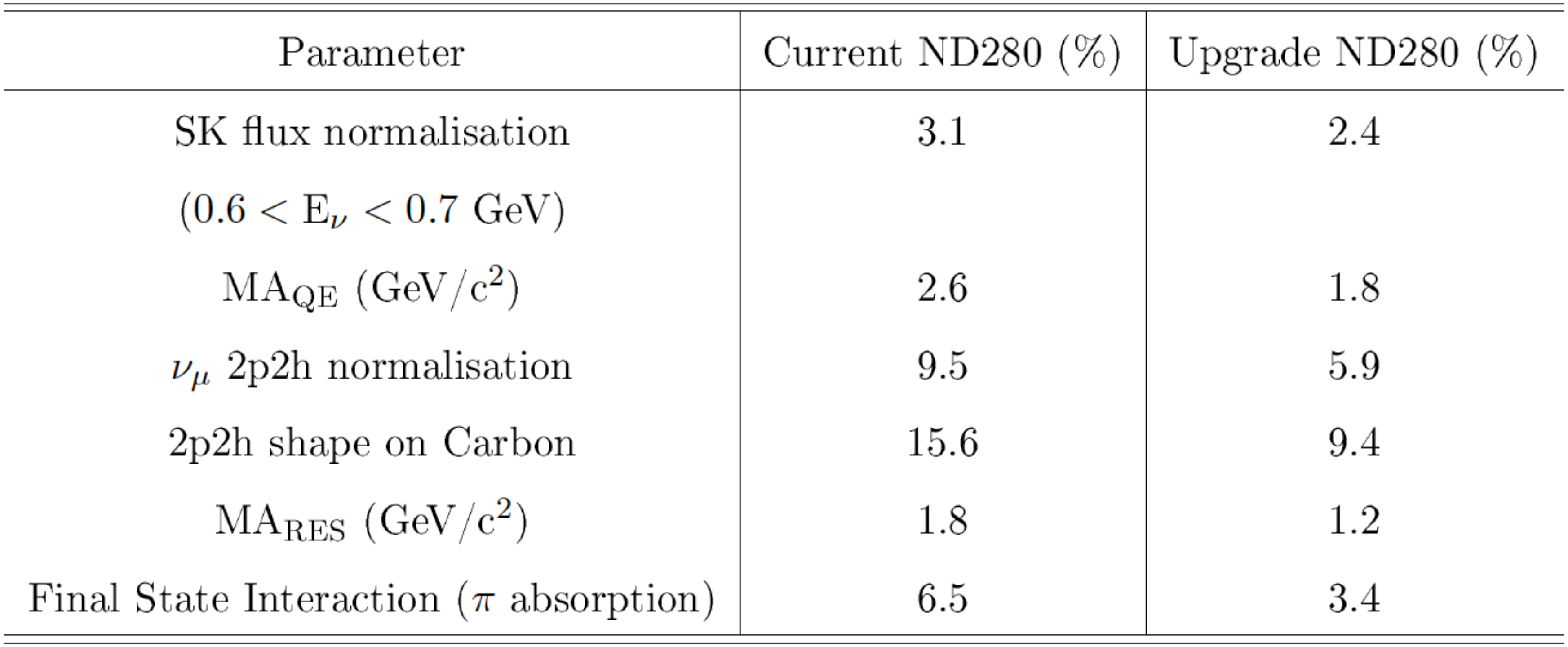
ν_μ CC



		# of events (/10^{21} POT)	Purity (%)		
			CC0π	CC1π	CC Other
current	FGD 1	50012	72.8	65.4	68.9
	FGD 2	48119	73.2	64.3	70.2
upgrade	FGD1	48332	74.6	65.0	69.6
	FGD2	45636	73.5	64.1	70.2
	SuperFGD	100686	73.9	72.9	70.9

ND280 Upgrade Sensitivity

ND data fit tool adapted to ND280 Upgrade to evaluate how much the systematic uncertainties are reduced (8×10^{21} POT) :



Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation ($0.6 < E_\nu < 0.7$ GeV)	3.1	2.4
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

On average the systematic uncertainties are reduced by about 30%

Intrinsic ν_e Component in the Flux

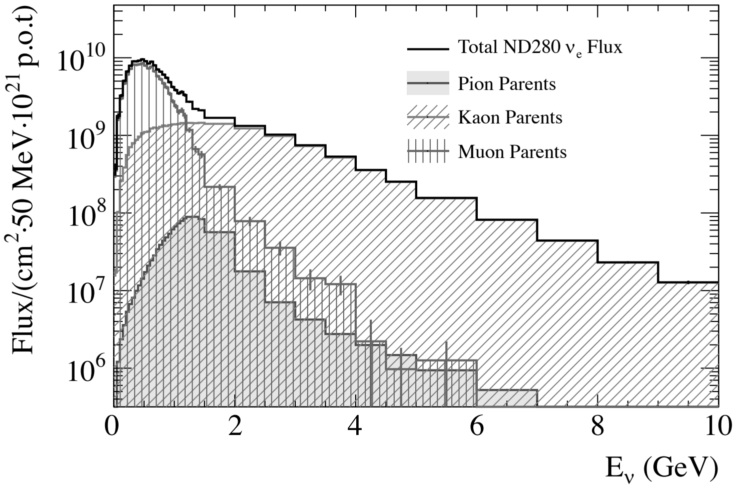
Phys. Rev. D. 89, 092003 (2014)

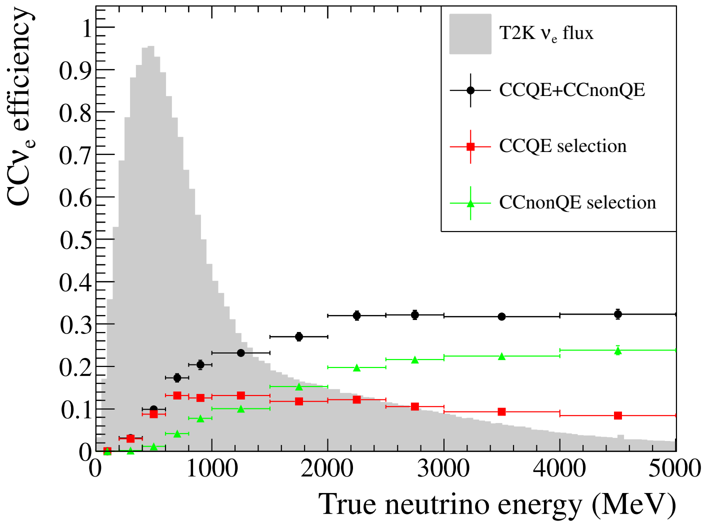
- Expected scaling factor obtained with 6.0e20 POT:

$$\begin{aligned} R(\nu_e) &= 1.01 \pm 0.06(\mathrm{stat}) \pm 0.06(\mathrm{flux} \oplus x.\,\mathrm{sec}) \\ &\quad \pm 0.05(\mathrm{det} \oplus \mathrm{FSI}) \\ &= 1.01 \pm 0.10, \end{aligned} \tag{4}$$

- $E_\nu < 1.2$ GeV dominated by muon decay:

$$\begin{aligned} R(\nu_e(\mu)) &= 0.68 \pm 0.24(\mathrm{stat}) \pm 0.11(\mathrm{flux} \oplus x.\,\mathrm{sec}) \\ &\quad \pm 0.14(\mathrm{det} \oplus \mathrm{FSI}) \\ &= 0.68 \pm 0.30 \end{aligned} \tag{5}$$





CC ν_e Inclusive Cross Section on Carbon

Phys. Rev. Lett. 113, 241803

- Total flux averaged cross section obtained with 6.0e20 POT:

$$\langle\sigma\rangle_\phi = 1.11 \pm 0.10(\mathrm{stat}) \pm 0.18(\mathrm{syst}) \times 10^{-38}\,\mathrm{cm}^2/\mathrm{nucleon}$$

- Dominant components of systematic uncertainties:
  - Flux (13%)
  - Detector (8%)
  - Others (6%)