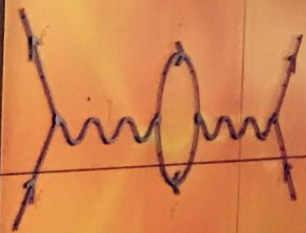


DIE NATURWISSENSCHAFT BRAUCHT DER MENSCH
ZUM ERKENNEN, DEN GLAUBEN ZUM HANDELN.

MAX PLANCK
Erhitzte Körper senden Licht aus. Der Nobelpreisträger für Physik von 1918 formulierte das Strahlungsgesetz mit einer neuen Naturkonstanten. Durch das Wirkungsquantum konnte der Atomaufbau verstanden und die moderne Quantenphysik begründet werden, in der Wahrscheinlichkeiten die Gewissheit der klassischen Physik ersetzen.

1858 - 1947

Max Planck

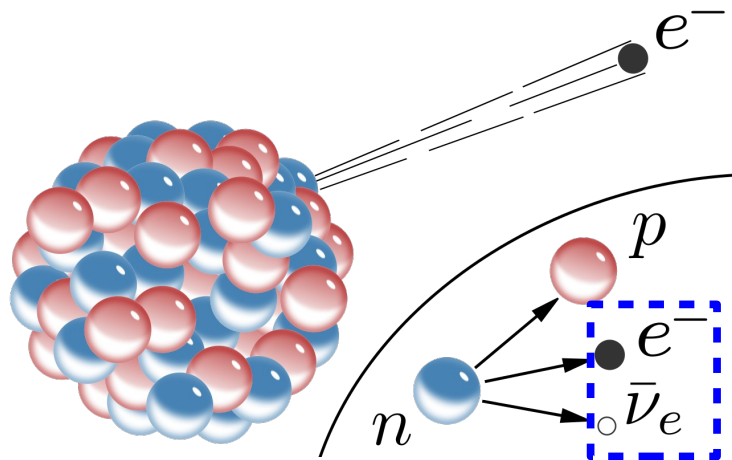


Neutrino Physics with Accelerators

Xianguo LU/ 卢显国
University of Oxford

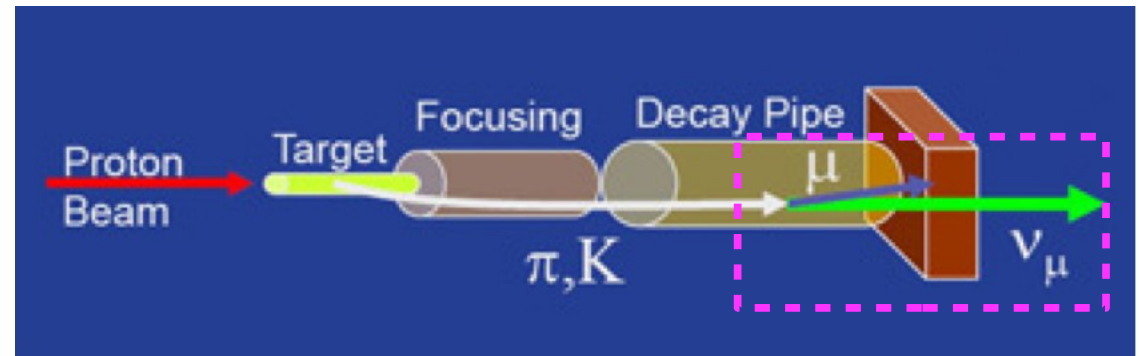
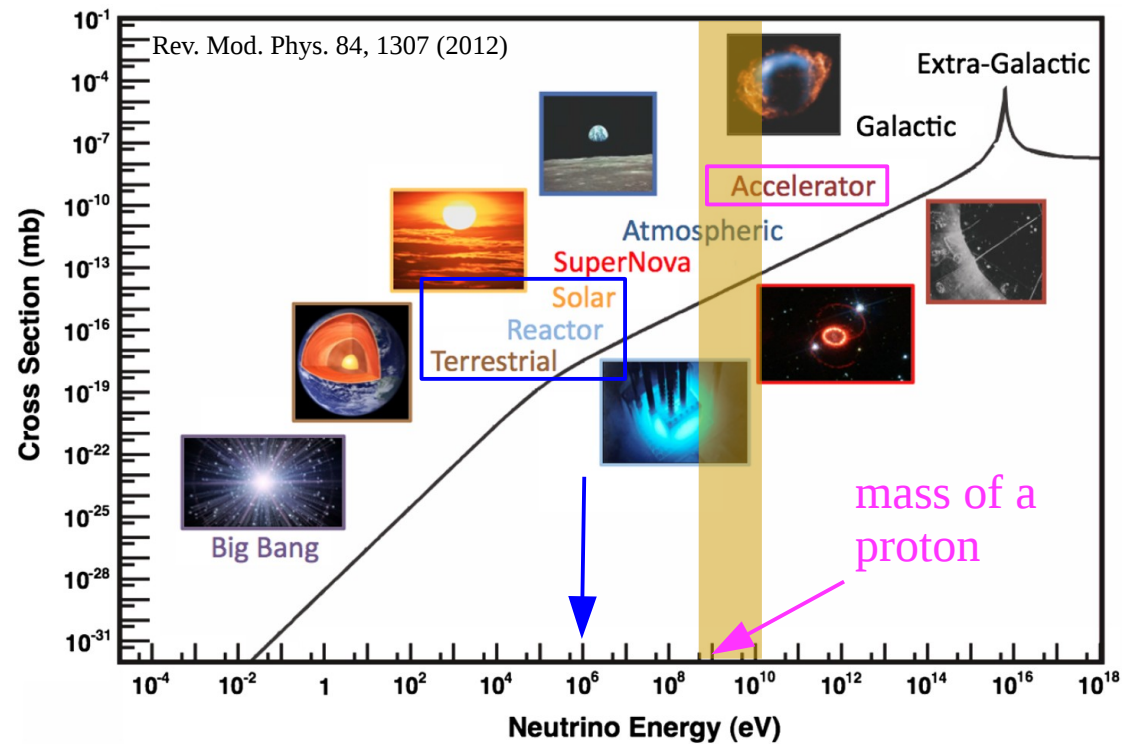
Gravity, Information and Fundamental Symmetries
Research Area Workshop of the Max Planck Society
Garching, 4 November 2019

Neutrino



By Inductiveload

Nuclear β decay

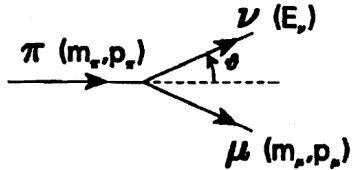
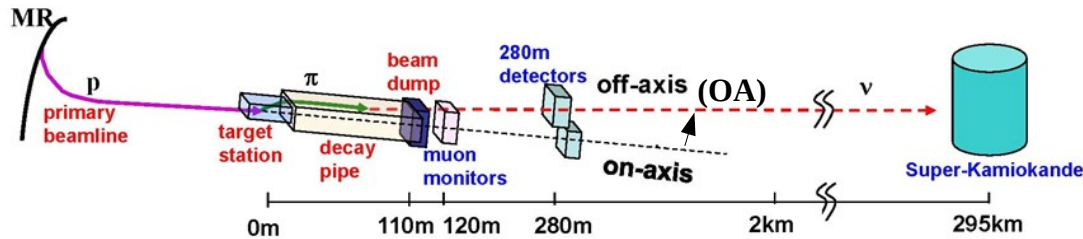


<https://lbnf.fnal.gov/beam.html>

Neutrino beams from accelerators → Directional
 “ β decay” of energetic collision products
 (mostly ν_μ from π)

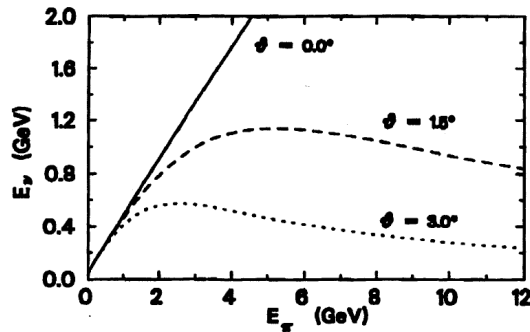
Accelerator Neutrino

– A unique source



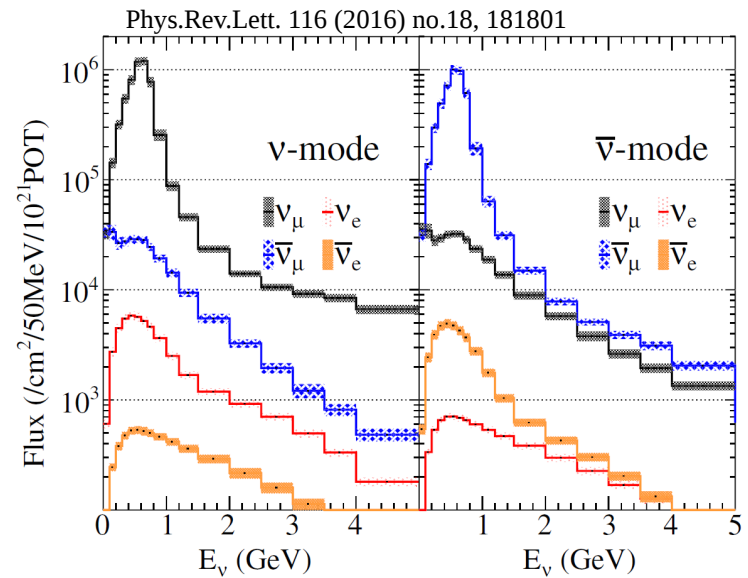
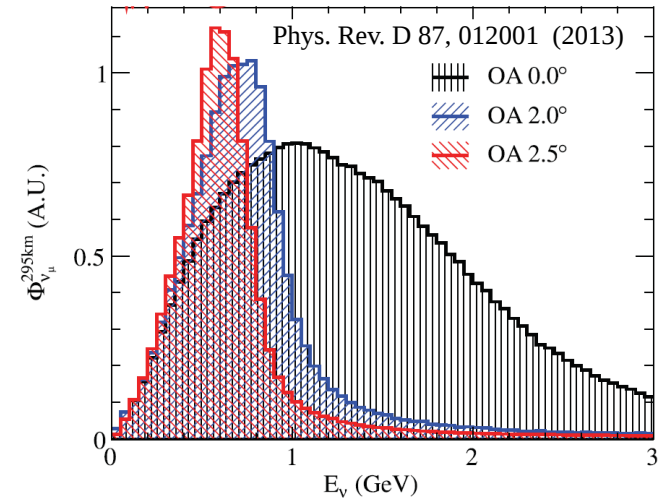
From energy, momentum conservation

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos \theta)}$$



- Off-axis
→ **Narrow-band beam**
- Quasi-mono-energetic
D. Beavis, et al., P889: long baseline neutrino oscillation experiment at the AGS, Report No. BNL-52459, April, 1995
- Charge selection on π
→ **ν or $\bar{\nu}$ beams**
- Quasi-pure beams

T2K flux



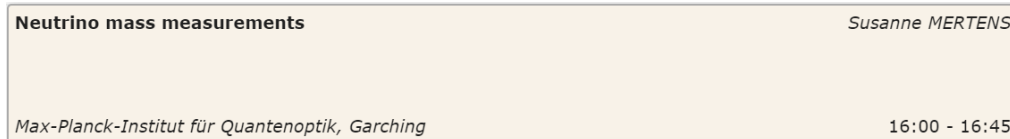
Neutrino Mass

– Physics Beyond Standard Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{array}{c} \text{Pontecorvo–Maki–Nakagawa–Sakata} \\ \text{PMNS matrix} \end{array} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- What is the absolute neutrino mass and why is this mass so small?

(See Susanne Mertens' talk for neutrino mass measurements)

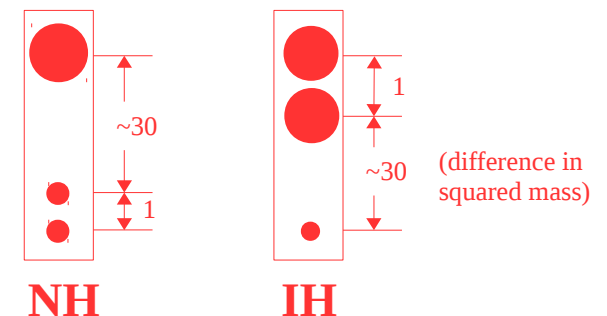


- **How is the different mass ordered?**

→ 3σ hint for NH from *global* fit

[de Salas *et al.*, *Status of neutrino oscillations 2018: 3σ hint for normal mass ordering and improved CP sensitivity*, Phys.Lett. B782, 633 (2018)]

“Normal” or “Inverted” Hierarchy/ordering



Charge-Parity Symmetry (CP) Violation?



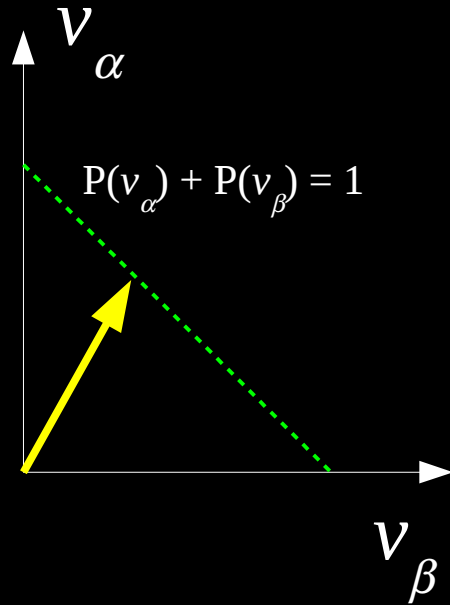
NASA-HQ-GRIN NGC 4414

Matter

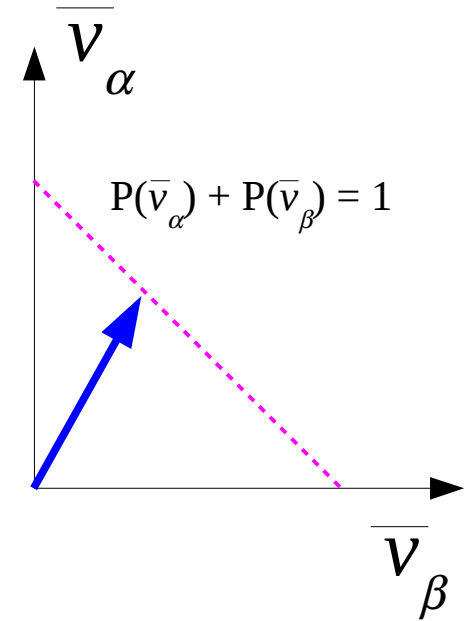
Antimatter

Neutrino Oscillation

– 2-flavor



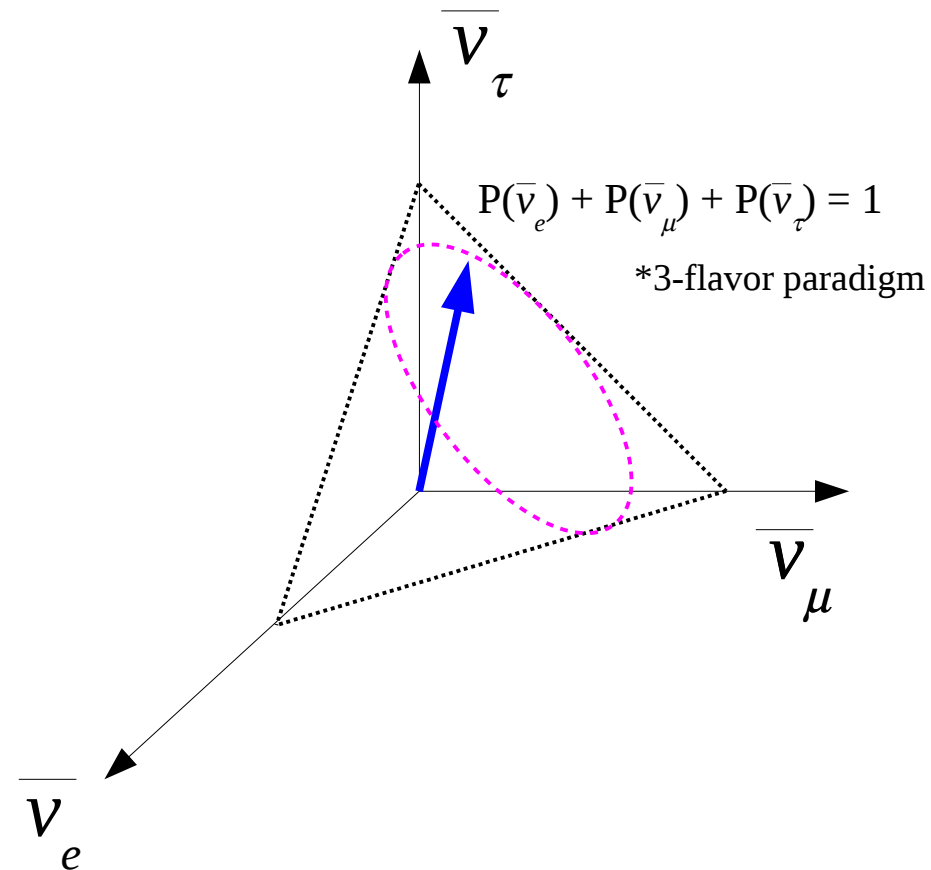
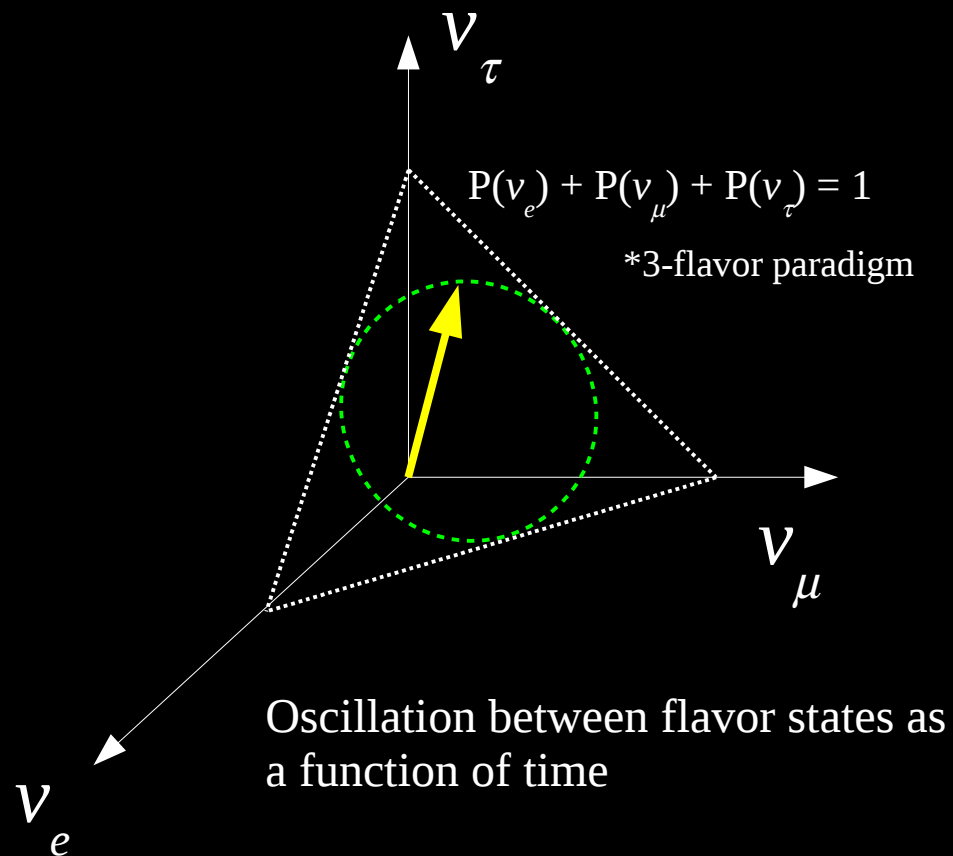
Oscillation between flavor states as a function of time



If only **2 flavors**, same oscillation pattern
 → **CP violation not accessible**

Neutrino Oscillation

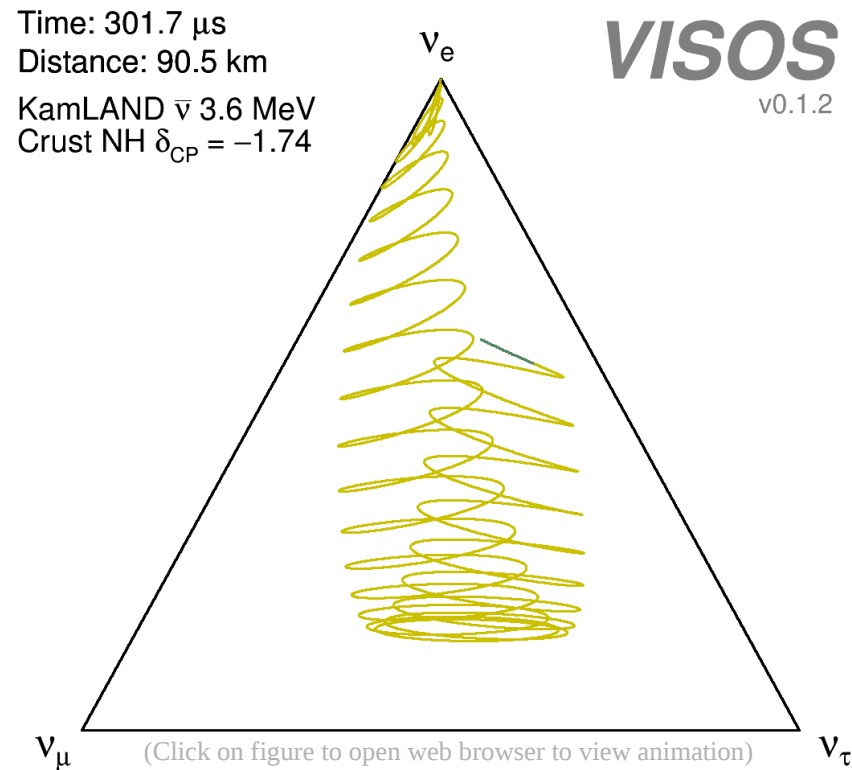
– 3-flavor and CP violation



3-flavor oscillation difference
 → **CP violation**

Neutrino Oscillation

– 3-flavor



3-flavor oscillation in Nature: **two different-scale (fast and slow_{x30}) oscillations**

Neutrino Oscillation

– 3-flavor and CP violation

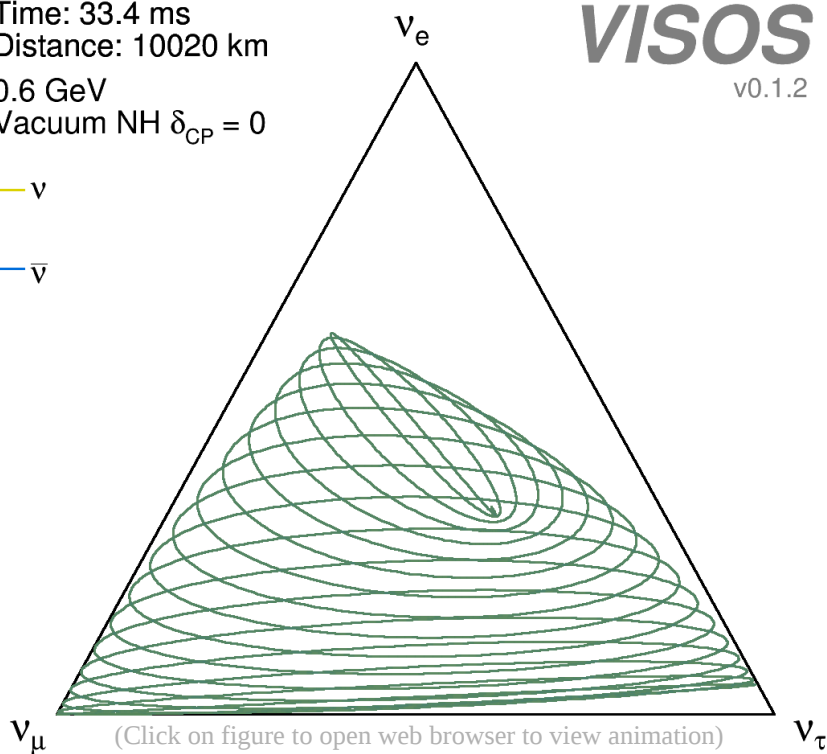
VISOS (VISualisation of OScillation)

Time: 33.4 ms
Distance: 10020 km
0.6 GeV
Vacuum NH $\delta_{CP} = 0$

— ν

— $\bar{\nu}$

VISOS
v0.1.2



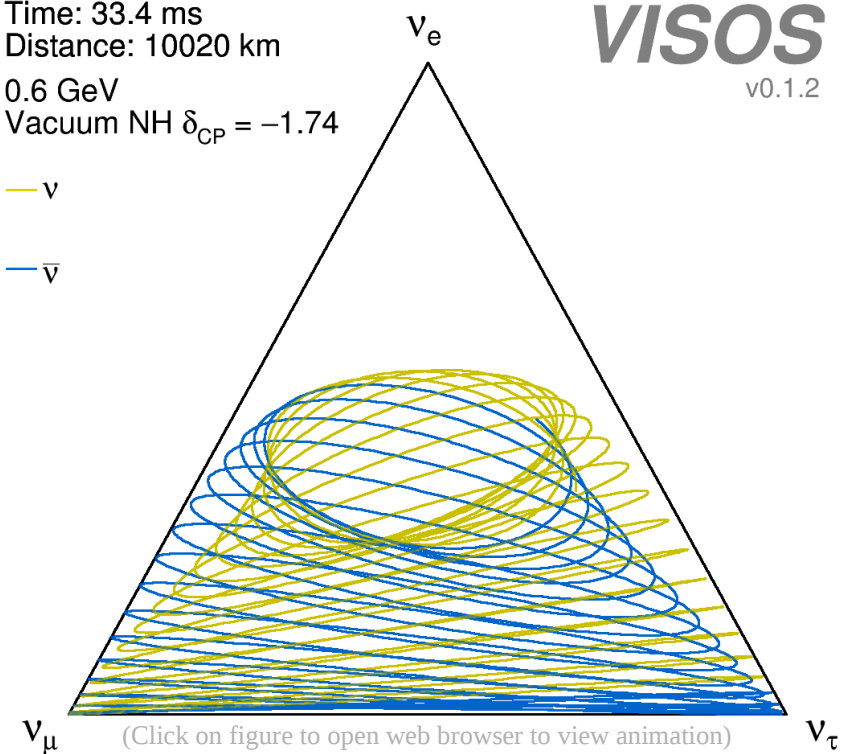
CP conserved

Time: 33.4 ms
Distance: 10020 km
0.6 GeV
Vacuum NH $\delta_{CP} = -1.74$

— ν

— $\bar{\nu}$

VISOS
v0.1.2



CP violated

CP Violation

– with accelerator neutrinos

Neutrino oscillations depend on mixing parameters and mass differences.

$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$

PMNS matrix

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

$\theta_{13} \neq 0 \rightarrow \delta_{CP}$ can be observed

CP Violation

– with accelerator neutrinos

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$\theta_{13} \neq 0 \rightarrow \delta_{CP}$ can be observed

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right)$$

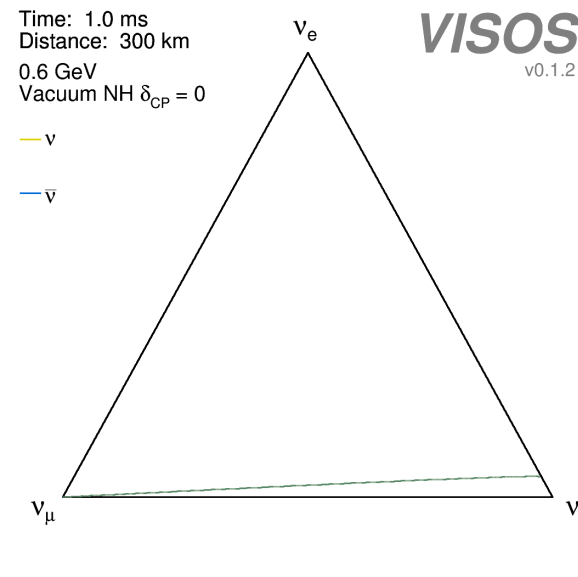
Oscillation probability
of ν_μ beam to ν_e

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

Phase $\sim \Delta m^2 L/E$

Fast oscillation



CP Violation

– with accelerator neutrinos

Neutrino oscillations depend on mixing parameters and mass differences.

$$c_{ij} = \cos \theta_{ij}$$

$$s_{ij} = \sin \theta_{ij}$$

PMNS matrix

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

$\theta_{13} \neq 0 \rightarrow \delta_{CP}$ can be observed

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right)$$

Oscillation probability
of ν_μ beam to ν_e

CP-odd term

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

Phase $\sim \Delta m^2 L/E$

CP Violation

– with accelerator neutrinos

Neutrino oscillations depend on mixing parameters and mass differences.

$$c_{ij} = \cos \theta_{ij}$$

$$s_{ij} = \sin \theta_{ij}$$

PMNS matrix

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

$\theta_{13} \neq 0 \rightarrow \delta_{CP}$ can be observed

Oscillation probability
of $\bar{\nu}_\mu$ beam to $\bar{\nu}_e$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} \left(+ \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right) \right)$$

flip sign

$\delta_{CP} \rightarrow$ CP violation

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

Phase $\sim \Delta m^2 L/E$

CP Violation

– with accelerator neutrinos

Neutrino oscillations depend on mixing parameters and mass differences.

$$c_{ij} = \cos\theta_{ij}$$

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Oscillation probability of $\bar{\nu}_\mu$ beam to $\bar{\nu}_e$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} + \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right)$$

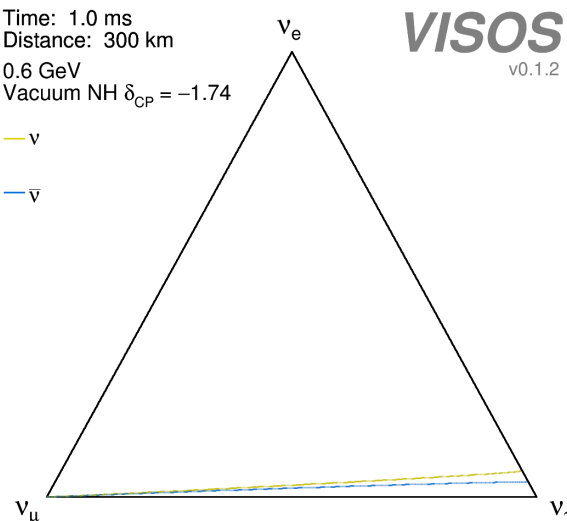
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

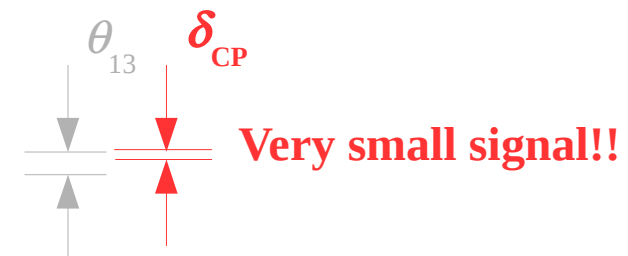
Phase $\sim \Delta m^2 L/E$

Time: 1.0 ms
Distance: 300 km
0.6 GeV
Vacuum NH $\delta_{CP} = -1.74$

ν
 $\bar{\nu}$



Slow oscillation



CP Violation

– with accelerator neutrinos

Neutrino oscillations depend on mixing parameters and mass differences.

$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$

PMNS matrix

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

$\theta_{13} \neq 0 \rightarrow \delta_{CP}$ can be observed

Oscillation probability of $\bar{\nu}_\mu$ beam to $\bar{\nu}_e$

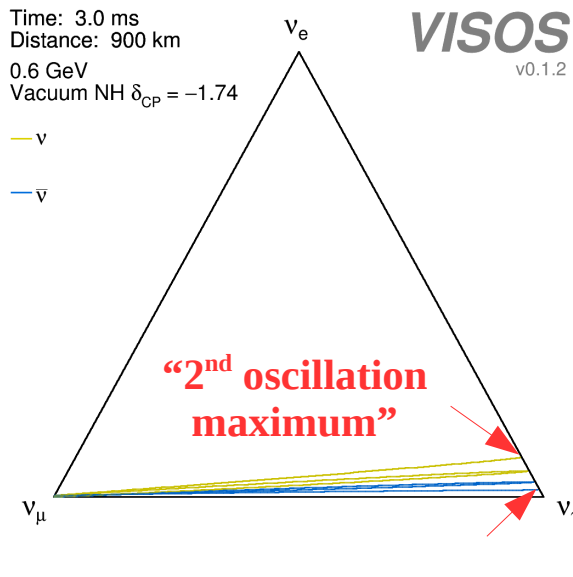
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} + \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right)$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

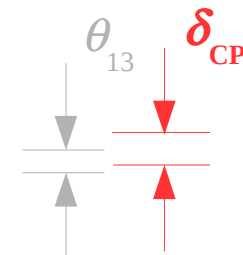
$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

Phase $\sim \Delta m^2 L/E$

Time: 3.0 ms
Distance: 900 km
0.6 GeV
Vacuum NH $\delta_{CP} = -1.74$



Slow oscillation

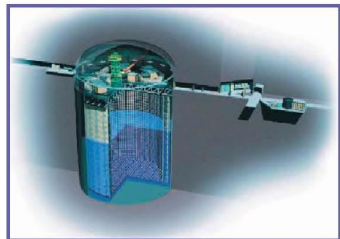


increase with L/E

Oscillation Measurements in a Nut Shell

– Accelerator neutrino experiments

NOvA (NuMI Off-Axis vs Appearance, US)
J.Phys.Conf.Ser. 396 (2012) 012034



Super-Kamiokande
(ICRR, Univ. Tokyo)

T2K (Tokai to
Kamioka, Japan)

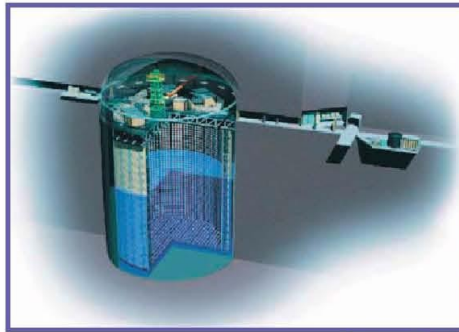


J-PARC Main Ring
(KEK-JAEA, Tokai)



Oscillation Measurements in a Nut Shell

– Accelerator neutrino experiments



Super-Kamiokande
(ICRR, Univ. Tokyo)

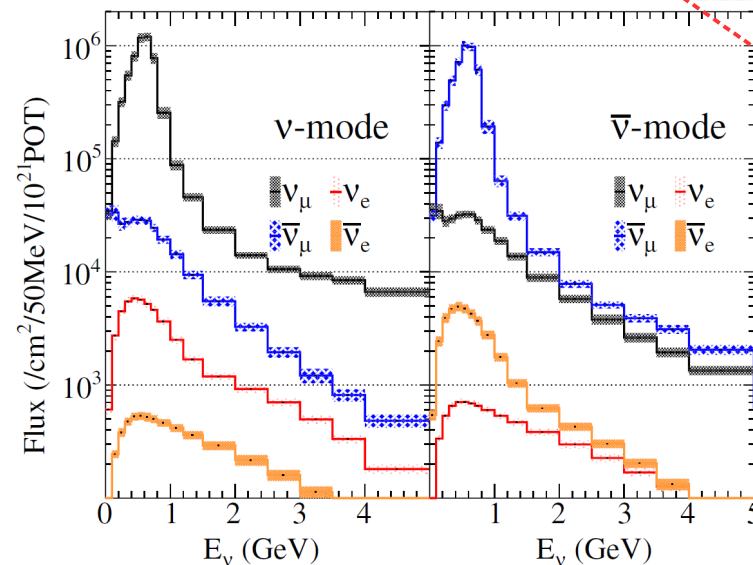


T2K

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



Far Detector

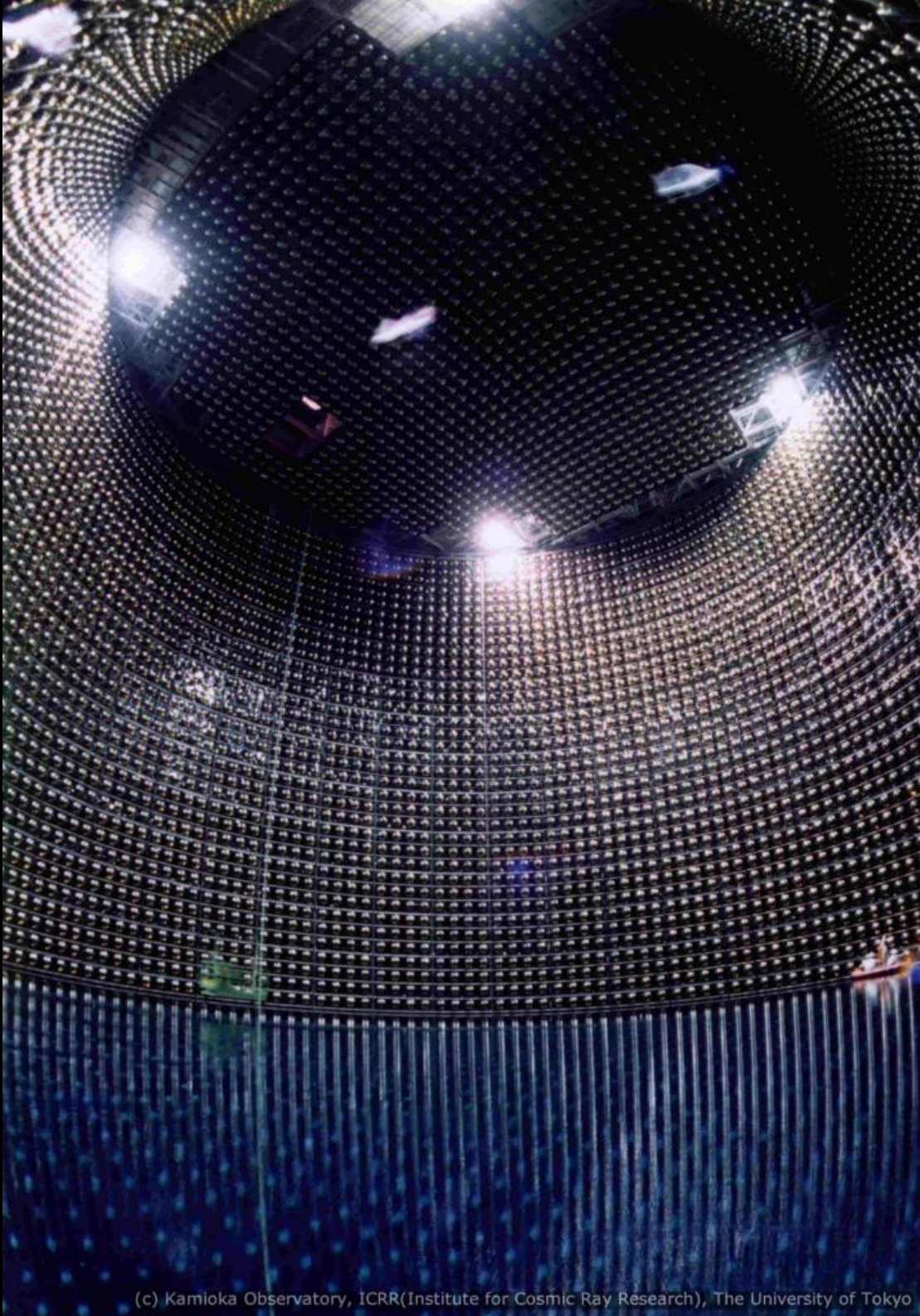


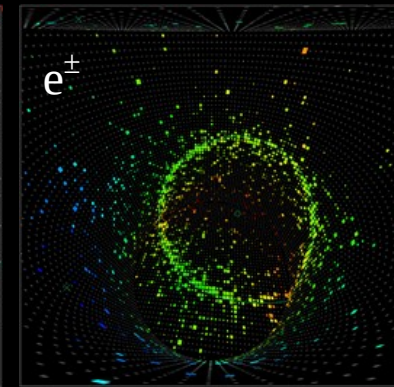
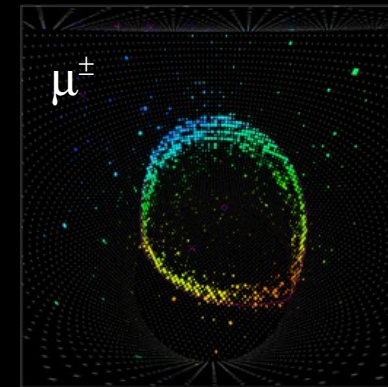
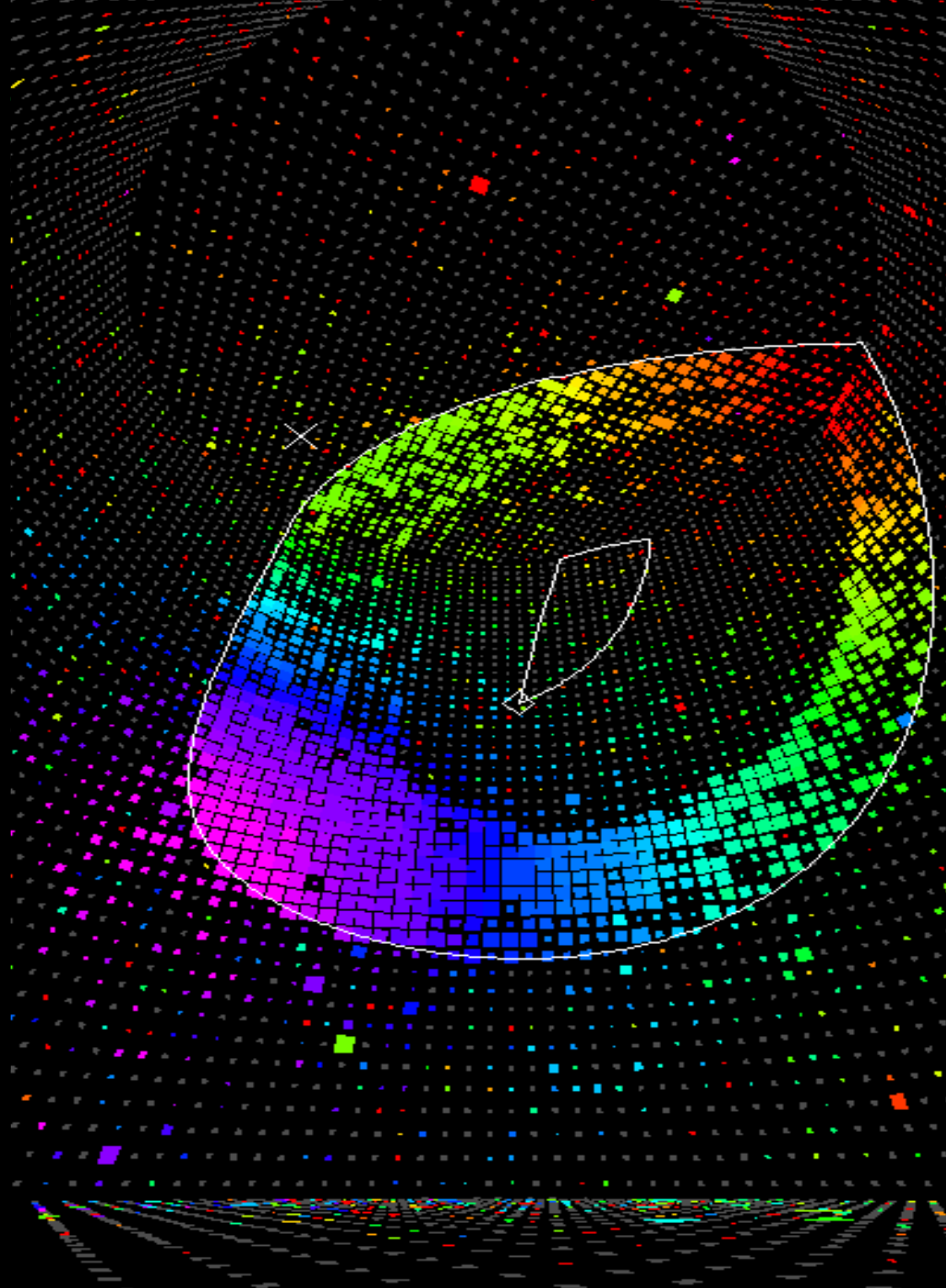
ν and $\bar{\nu}$ beams

Proton beam energy 30 GeV
Power 50 – 480 kW

T2K far detector: Super-Kamiokande

- 50 kt water-Cherenkov
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector





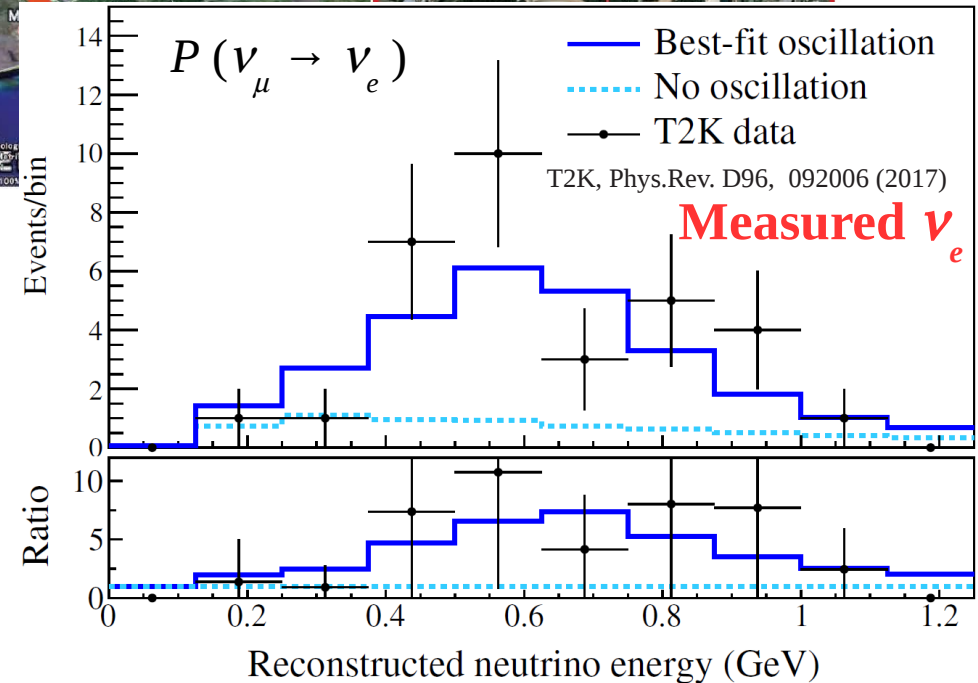
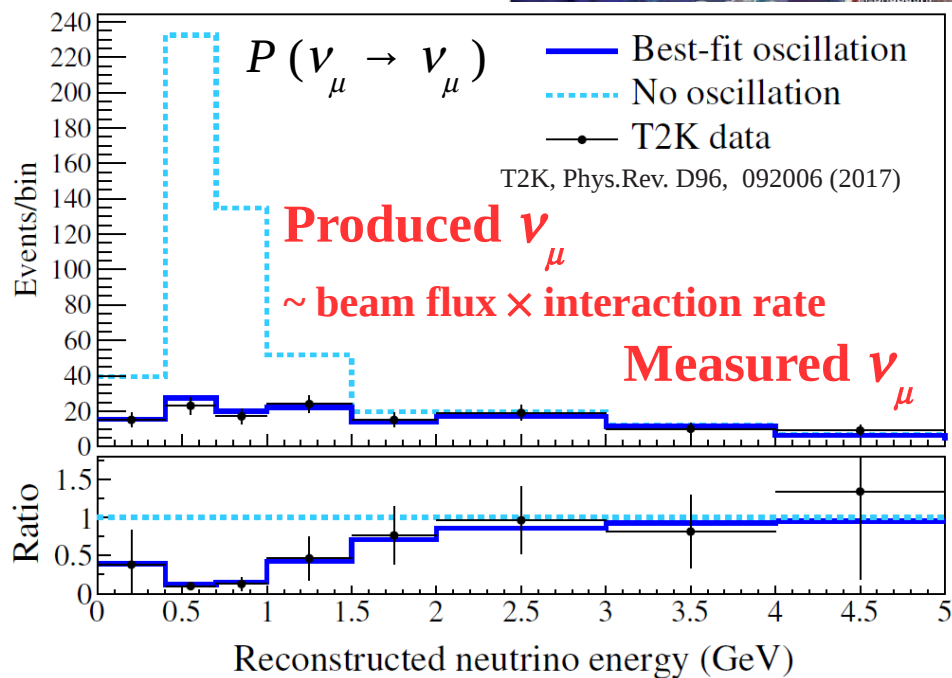
μ, e identification

→ detect propagated ν from J-PARC

→ E_ν rec. from μ/e kinematics

Oscillation Measurements in a Nut Shell

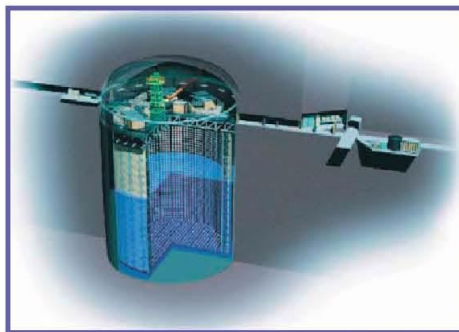
– Oscillation probability



Oscillation probability $P = \text{\#measured} / \text{\#produced}$

Oscillation Measurements in a Nut Shell

– ν and $\bar{\nu}$ measurements before oscillation



Super-Kamiokande
(ICRR, Univ. Tokyo)

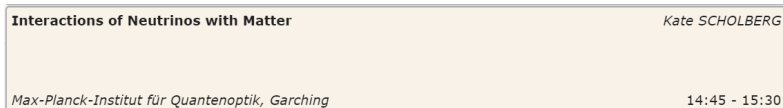


T2K

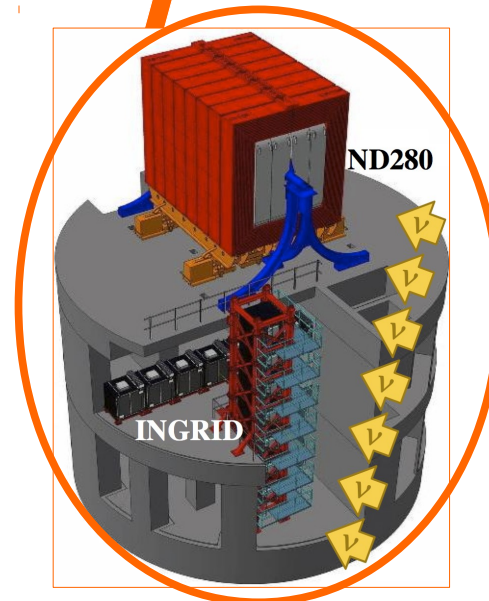
J-PARC Main Ring
(KEK-JAEA, Tokai)



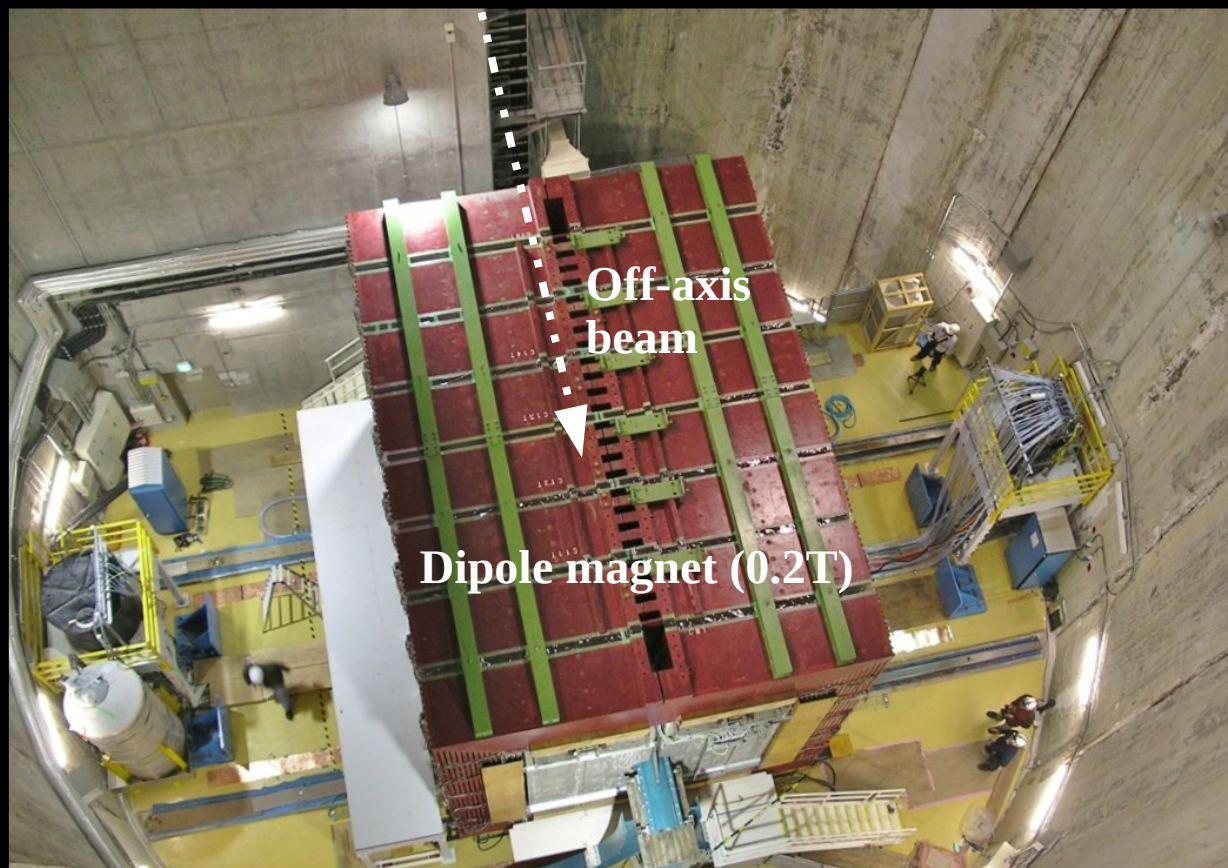
See Kate Scholberg's talk for neutrino interaction measurements



Near Detectors
@280m

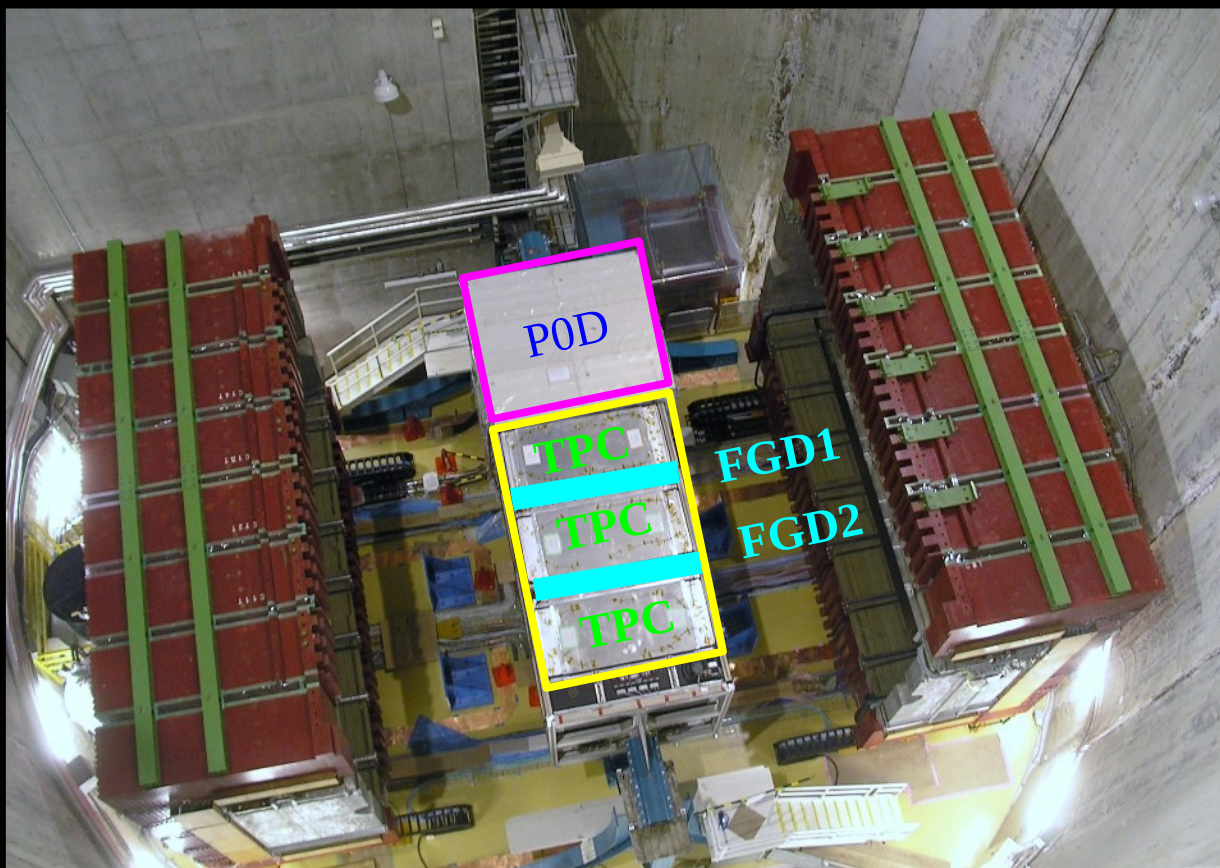


T2K off-axis near detector (ND280)



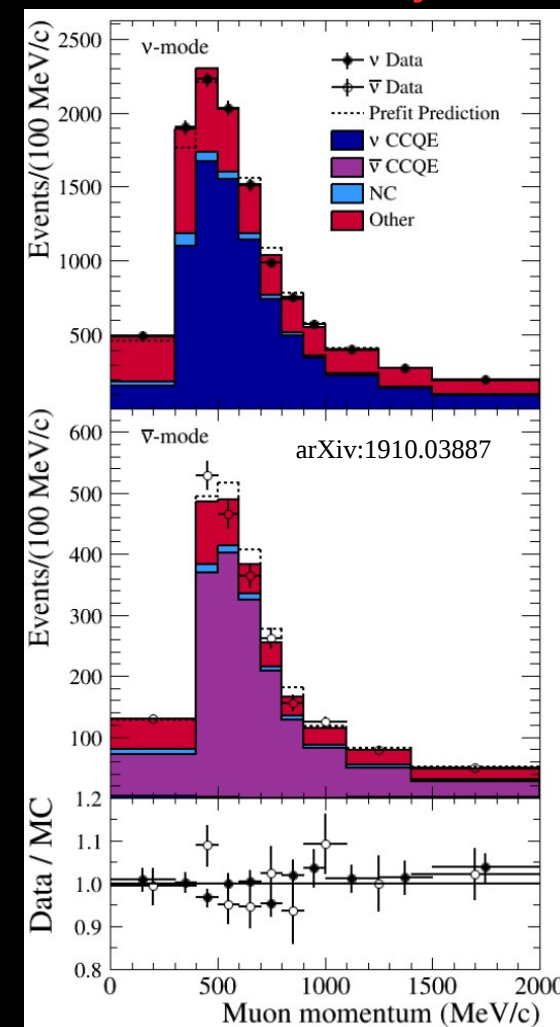
T2K off-axis near detector (ND280)

**Constrain beam flux and
interaction rate for
oscillation analysis**



P0D: π^0 Detector
Scintillator-based ECal

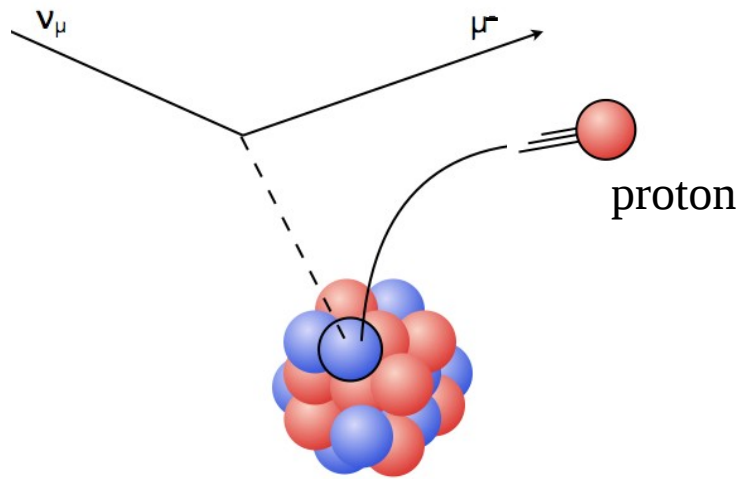
Tracker:
• FGD: Fine-Grained Detector
Active target
• Time Projection Chamber (TPC)



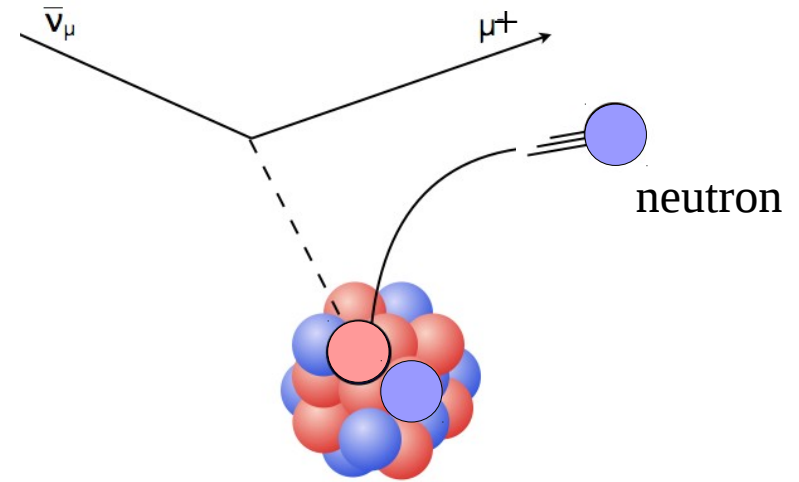
Oscillation Measurements in a Nut Shell

– ν and $\bar{\nu}$ interaction measurement

Cartoon by Marco Del Tutto



neutrino



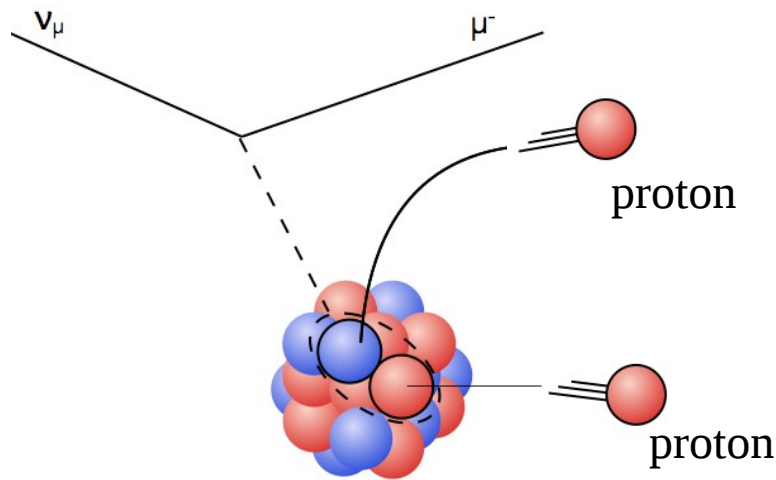
antineutrino

Intrinsic difference in even without CP violation

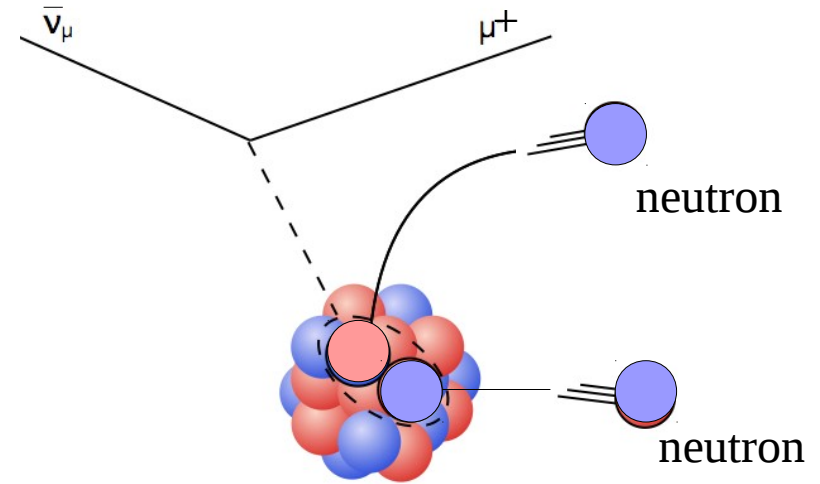
Oscillation Measurements in a Nut Shell

– ν and $\bar{\nu}$ interaction measurement

Cartoon by Marco Del Tutto



neutrino



antineutrino

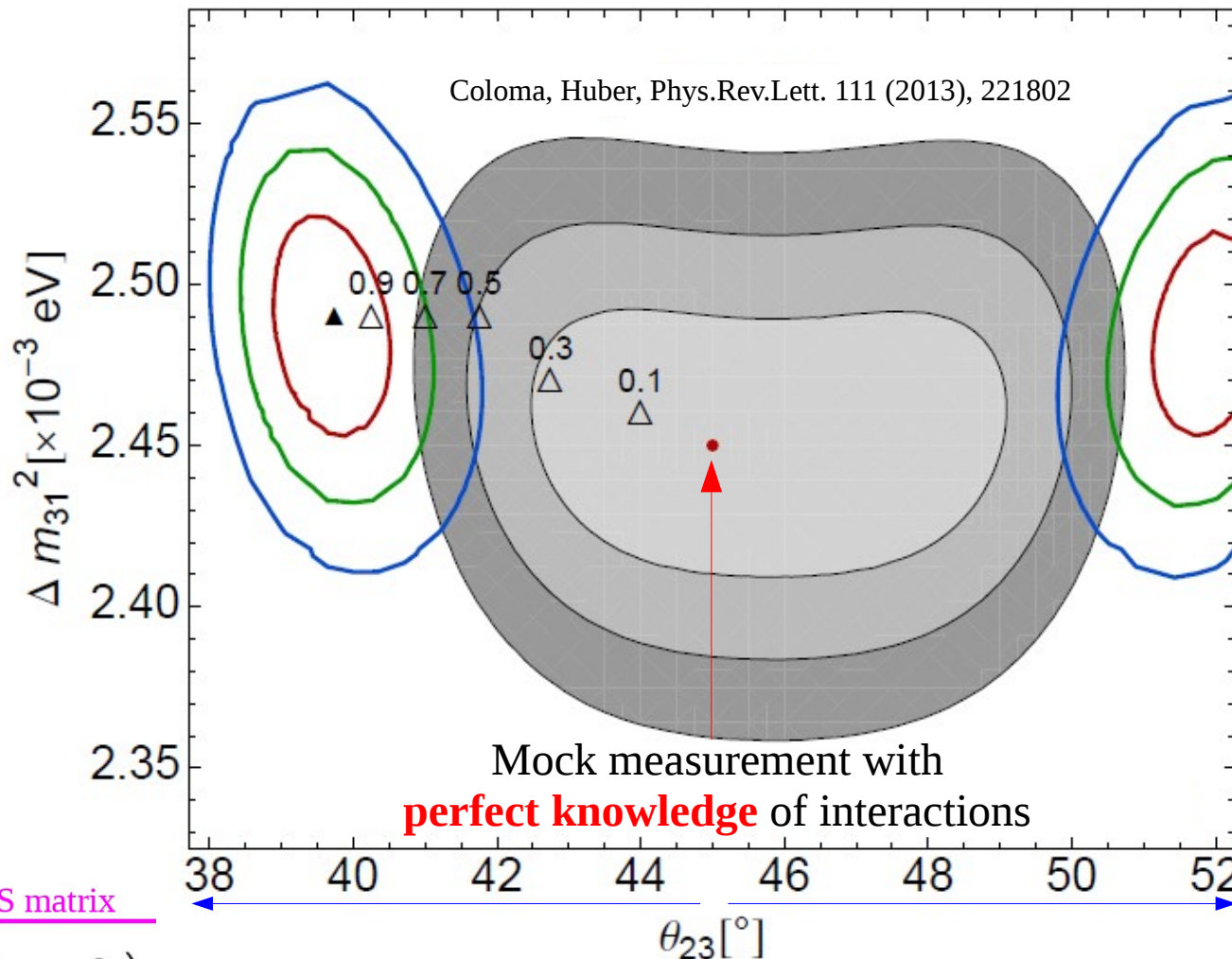
Nuclear effects like “2p2h” make it worse

Nuclear effects: all effects due to target $A > 1$

Proton and neutron have VERY different experimental signatures

Oscillation Measurements in a Nut Shell

– ν and $\bar{\nu}$ interaction measurement



Mixing between
 μ and τ flavors

$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

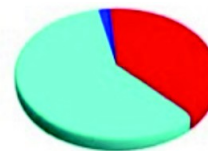
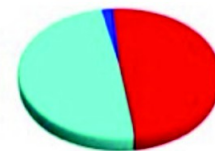
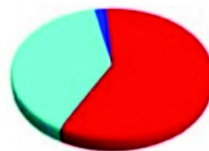
$$\sin^2 \theta_{23} =$$

0.4

0.5

0.6

ν_3



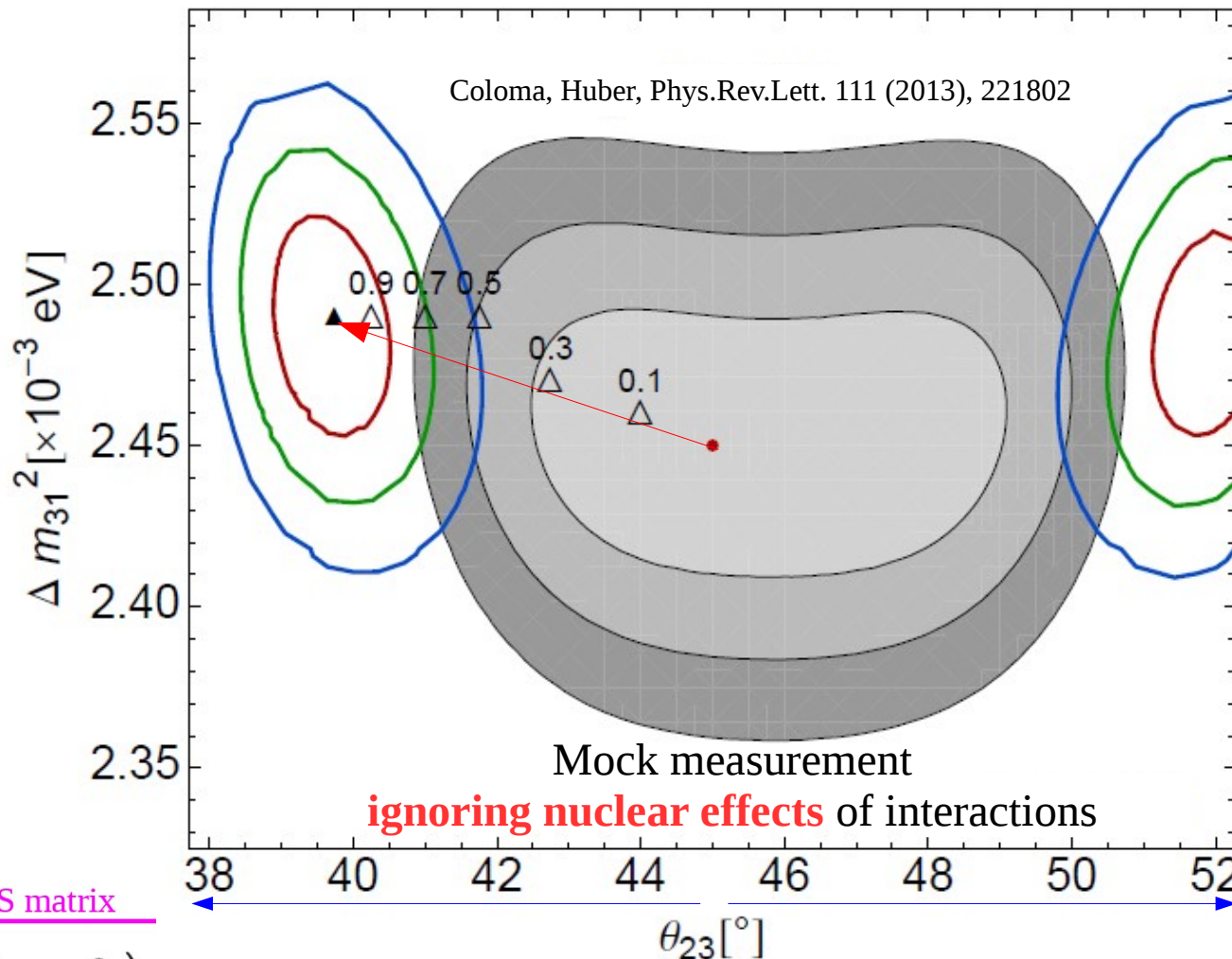
$\nu_e =$ ●

$\nu_\mu =$ ●

$\nu_\tau =$ ●

Oscillation Measurements in a Nut Shell

– ν and $\bar{\nu}$ interaction measurement



Mixing between
 μ and τ flavors

$$c_{ij} = \cos \theta_{ij}$$

$$s_{ij} = \sin \theta_{ij}$$

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

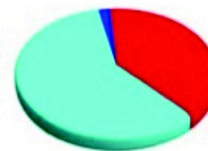
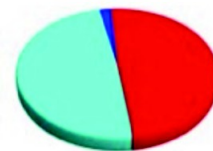
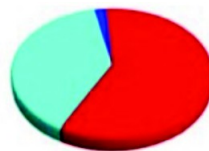
$$\sin^2 \theta_{23} =$$

0.4

0.5

0.6

ν_3



$\nu_e =$ ●

$\nu_\mu =$ ●

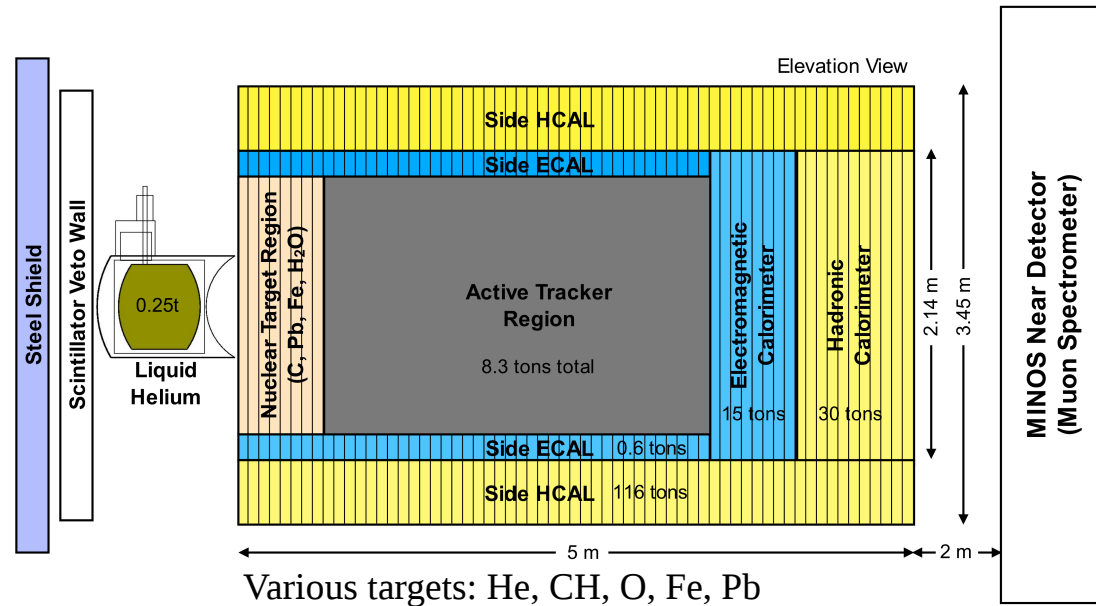
$\nu_\tau =$ ●

Oscillation Measurements in a Nut Shell

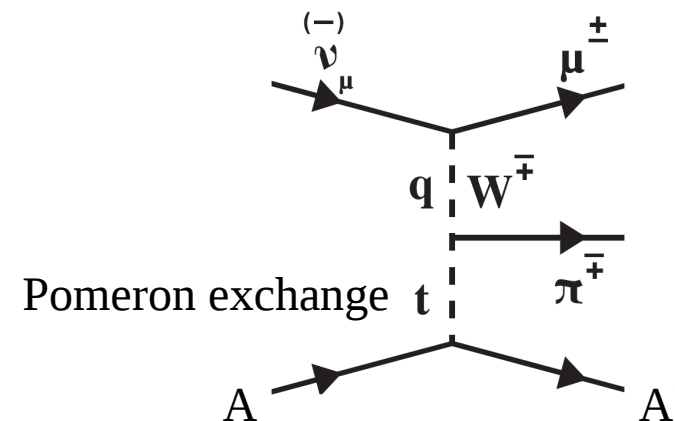
– Dedicated ν and $\bar{\nu}$ interaction measurement



MINERvA (Main Injector Experiment for ν -A, US)

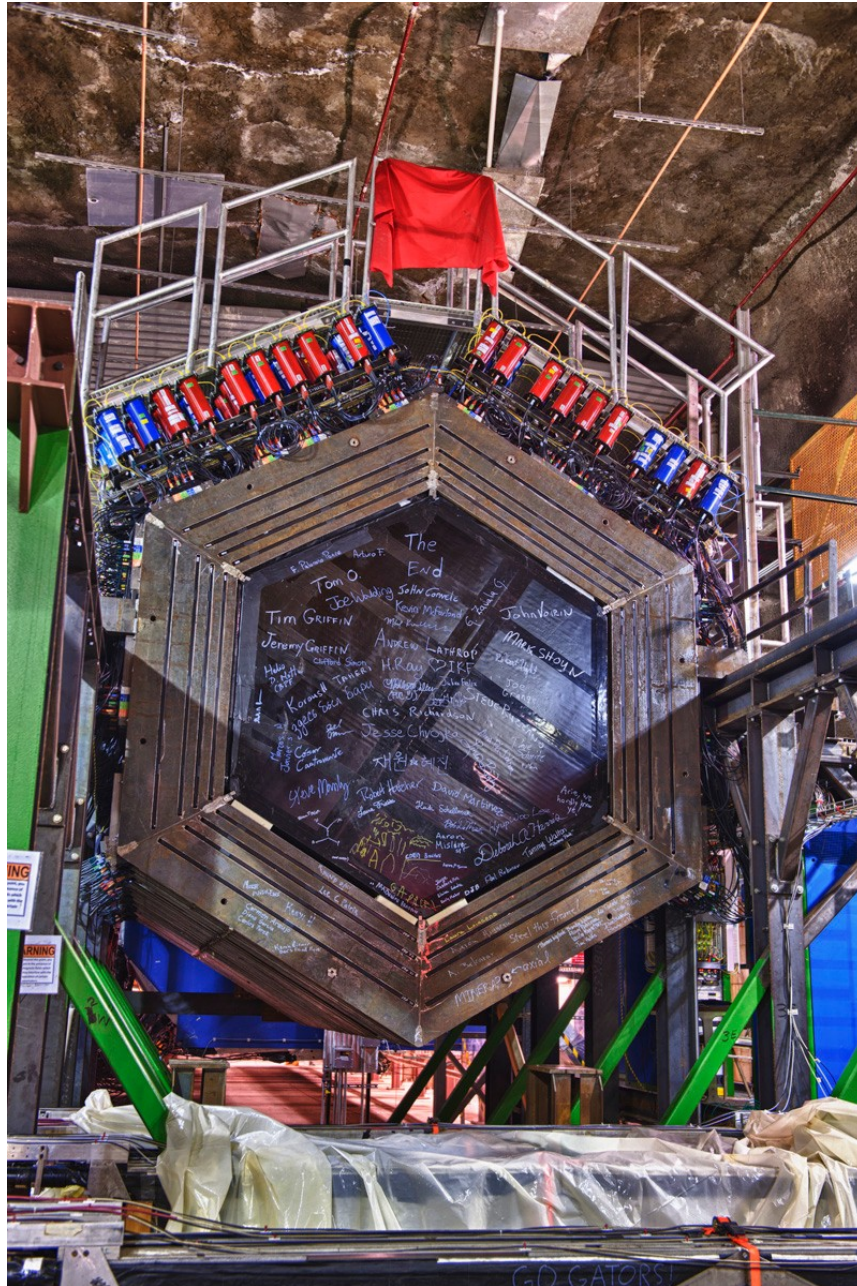


Charged-current *coherent* pion production:
Background of oscillation measurement

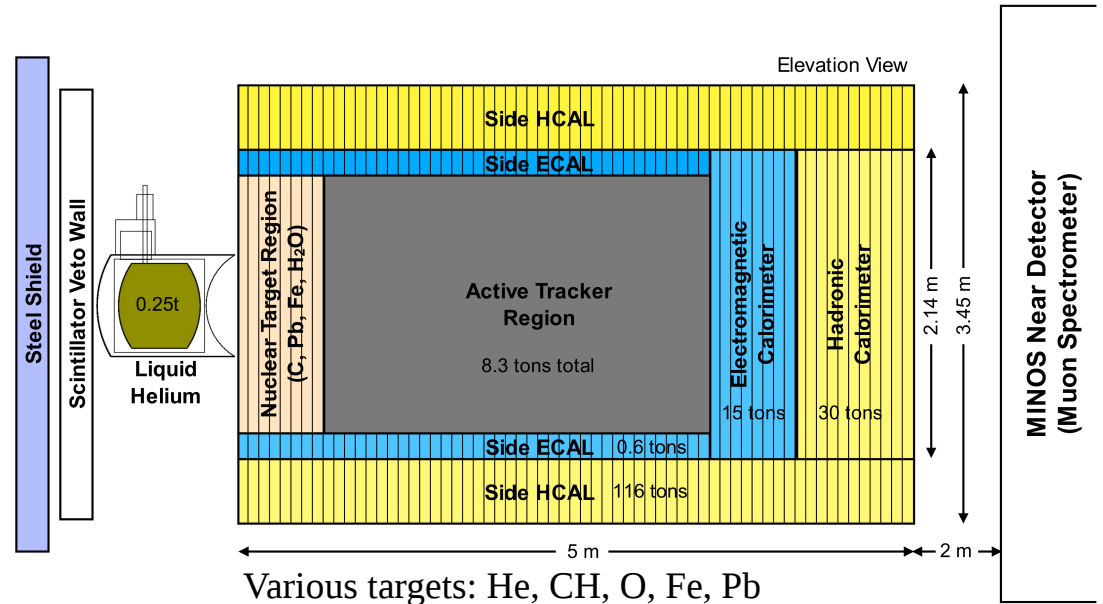


Oscillation Measurements in a Nut Shell

– Dedicated ν and $\bar{\nu}$ interaction measurement

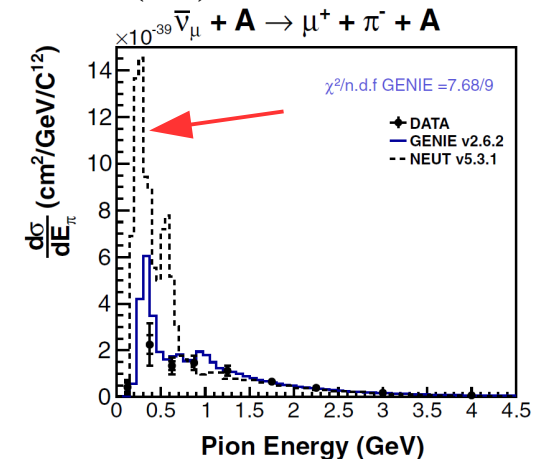
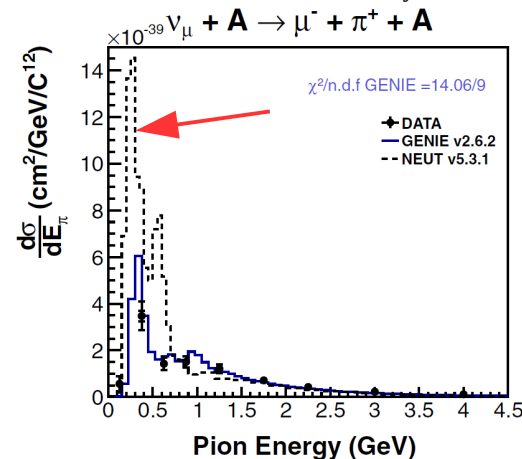


MINERvA (Main Injector Experiment for ν -A, US)



Various targets: He, CH, O, Fe, Pb

Phys. Rev. Lett. 113, 261802 (2014)

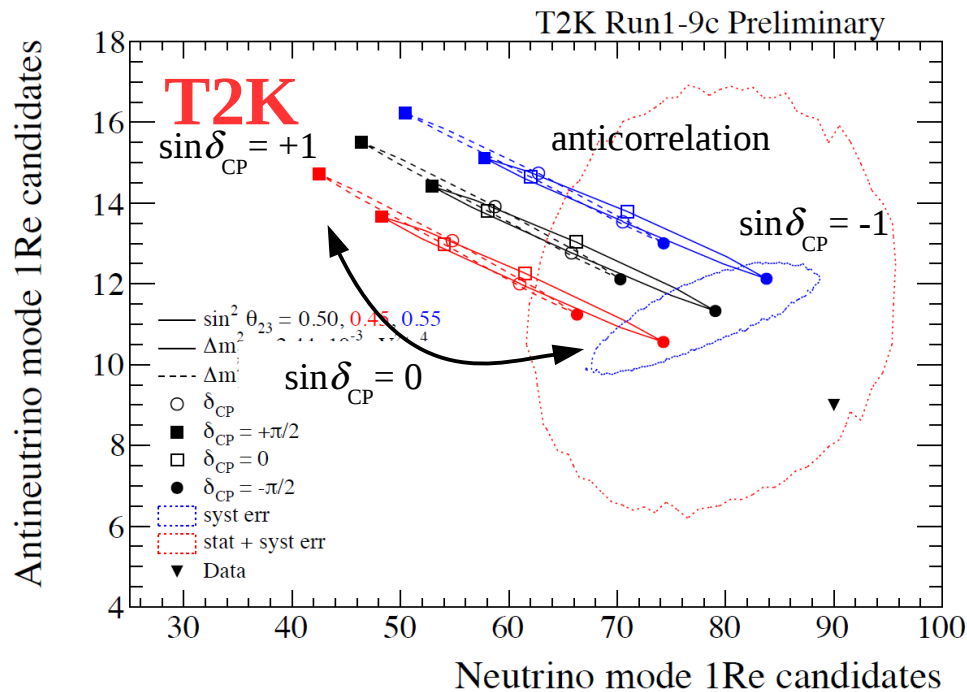


Constrain models used in oscillation measurements

Where Do We Stand?

– T2K and NOvA @Neutrino2018

Wascko, Morgan. (2018, June). T2K Status, Results, and Plans. Zenodo.
<http://doi.org/10.5281/zenodo.1286752>



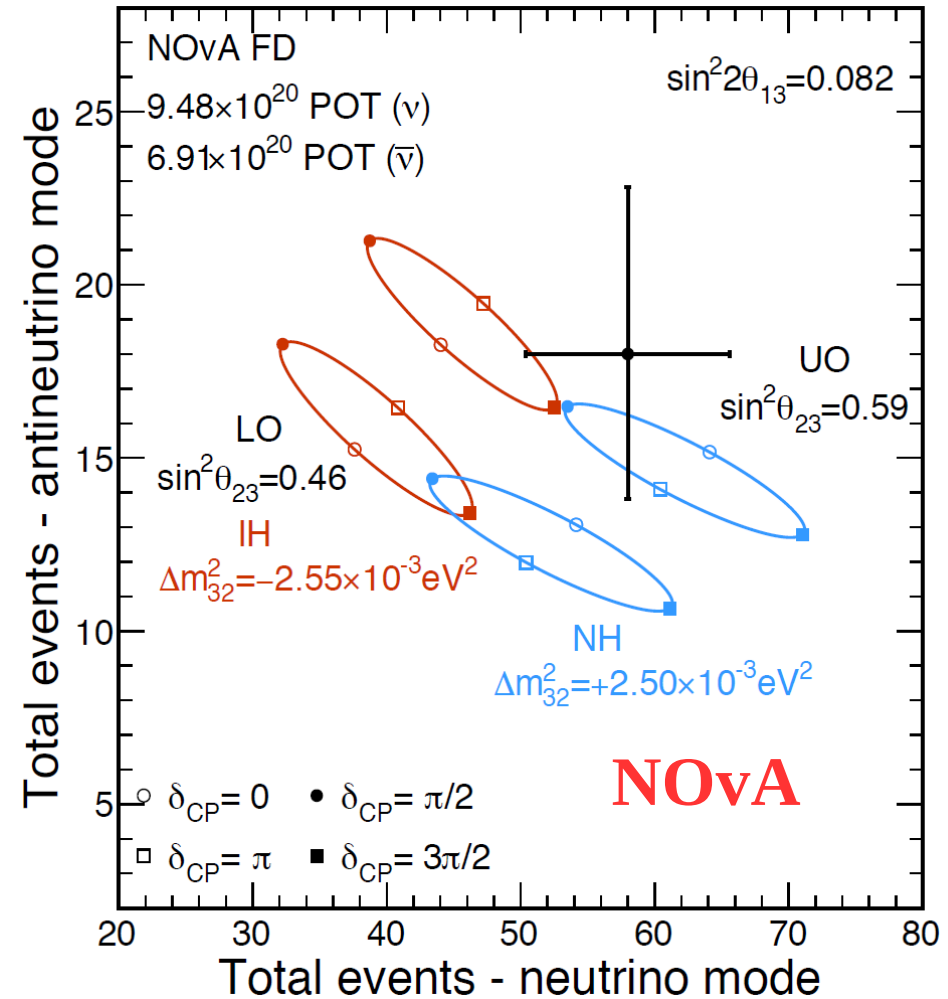
$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right)$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} + \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right)$$

$$P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx \delta_{CP}\text{-independent}$$

Bi-event/probability plot [JHEP 0110, 001 (2001)]

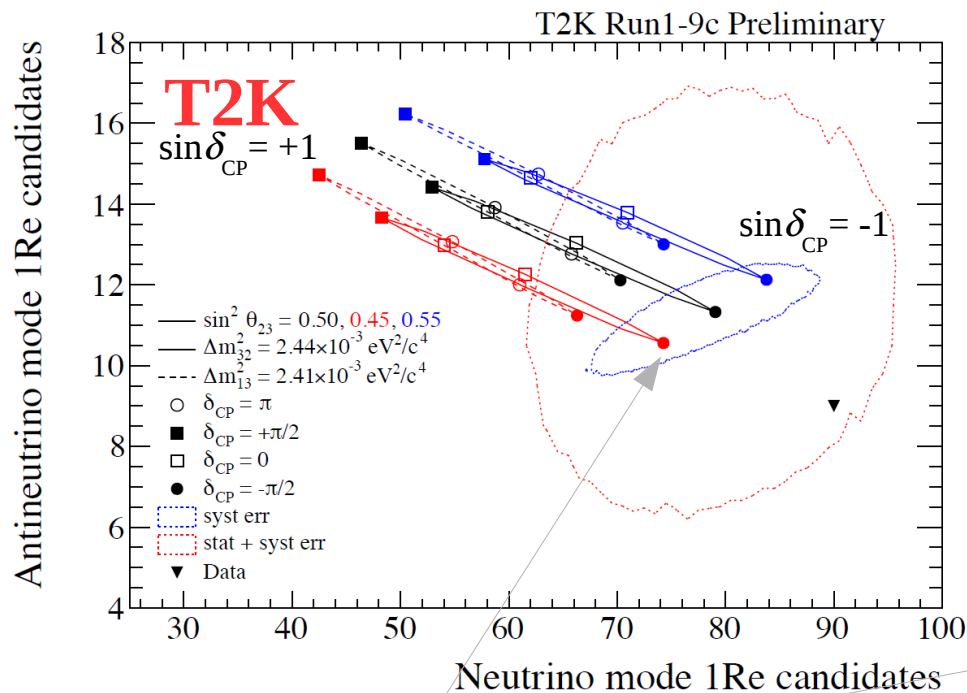
Sanchez, Mayly. (2018, June). NOvA Results and Prospects.
 Zenodo. <http://doi.org/10.5281/zenodo.1286758>



Where Do We Stand?

– T2K and NOvA @Neutrino2018

Wascko, Morgan. (2018, June). T2K Status, Results, and Plans. Zenodo.
<http://doi.org/10.5281/zenodo.1286752>

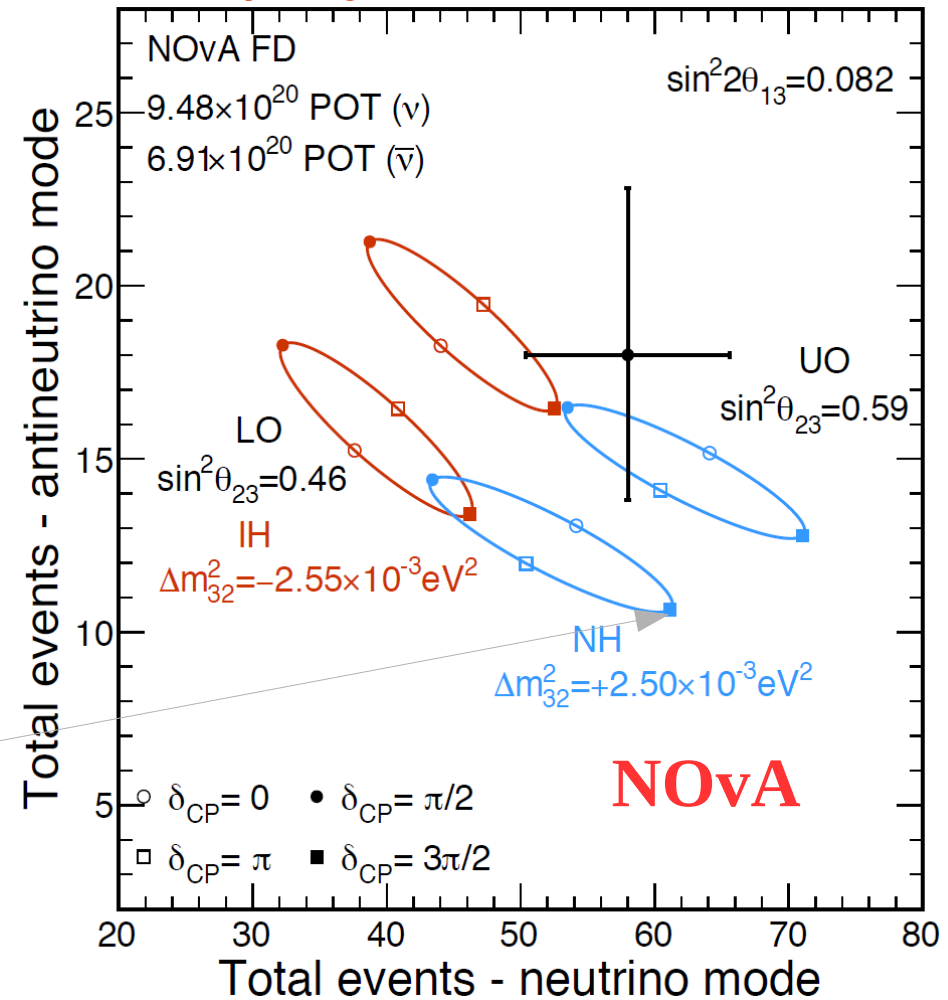


$\delta_{CP} = -\pi/2$ and $\sin^2 \theta_{23} = 0.45(6)$
 normal hierarchy



NH

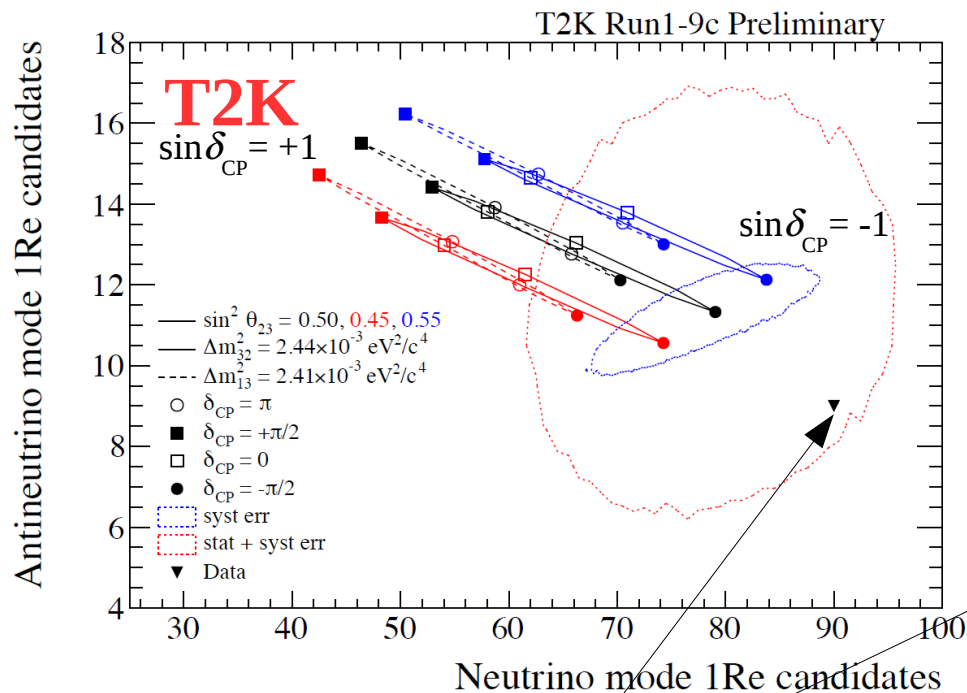
Sanchez, Mayly. (2018, June). NOvA Results and Prospects.
 Zenodo. <http://doi.org/10.5281/zenodo.1286758>



Where Do We Stand?

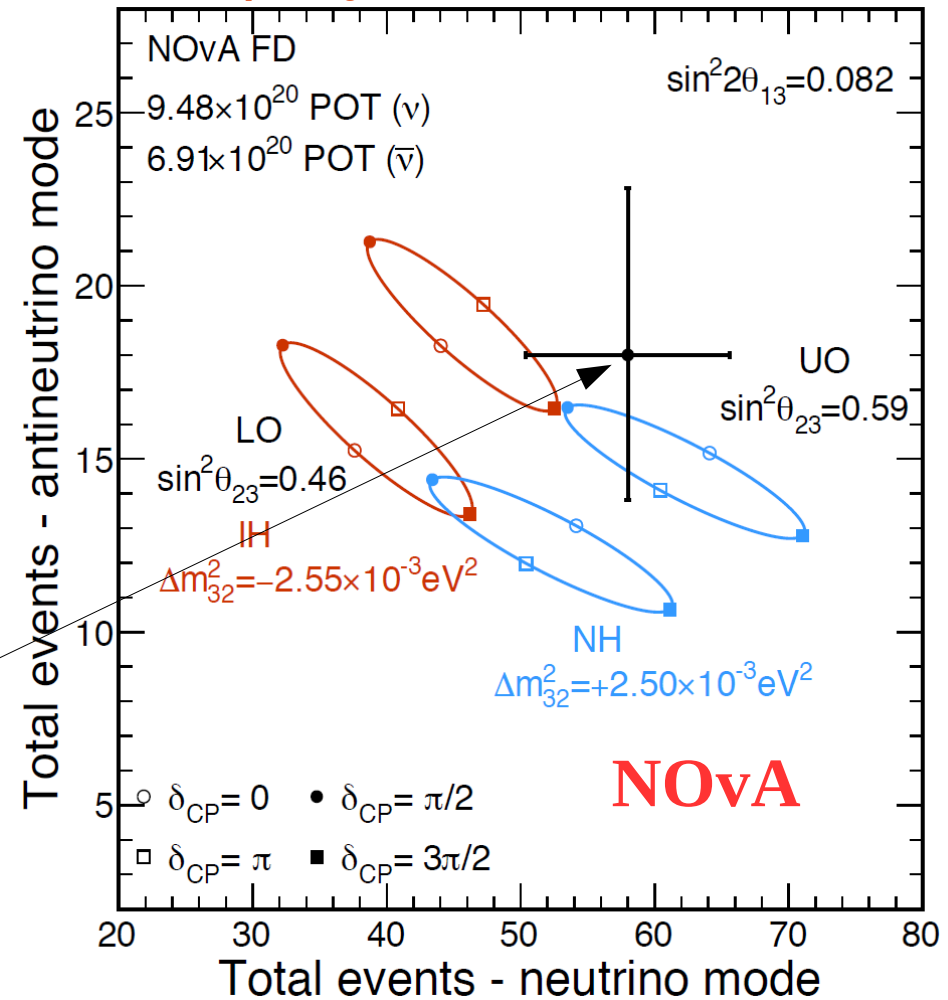
– T2K and NOvA @Neutrino2018

Wascko, Morgan. (2018, June). T2K Status, Results, and Plans. Zenodo.
<http://doi.org/10.5281/zenodo.1286752>



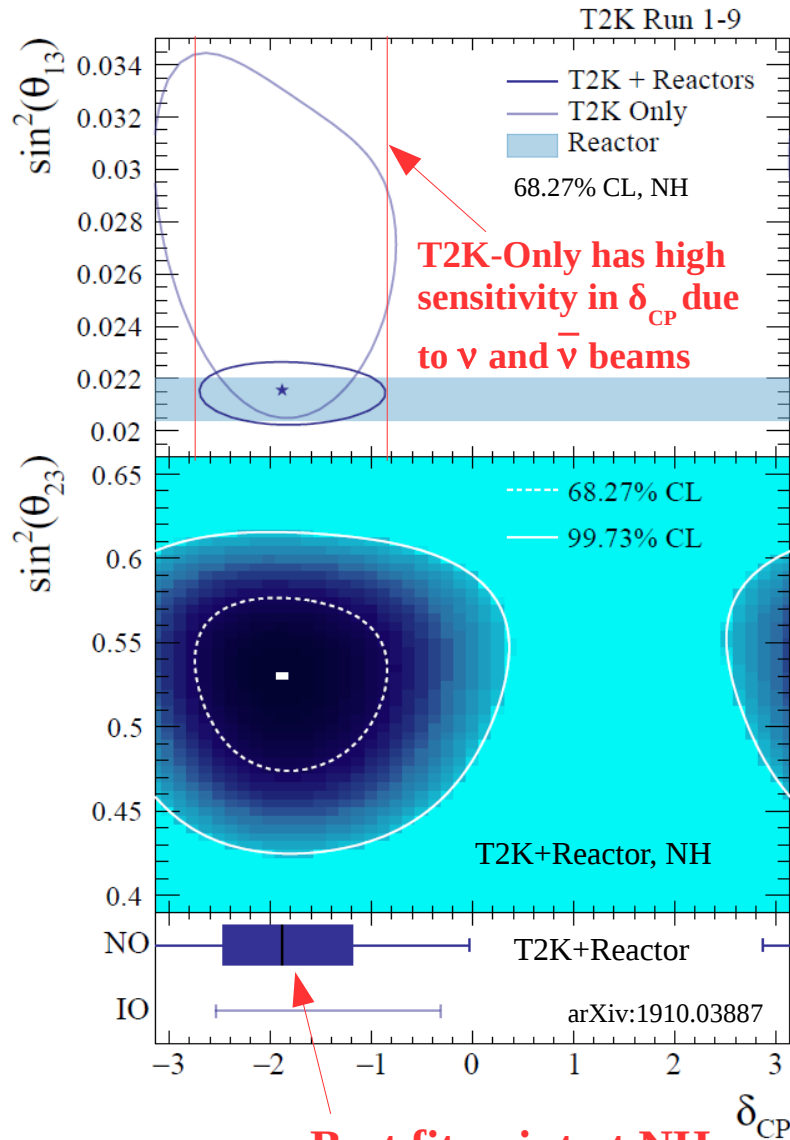
Data
 Both statistically limited

Sanchez, Mayly. (2018, June). NOvA Results and Prospects.
 Zenodo. <http://doi.org/10.5281/zenodo.1286758>

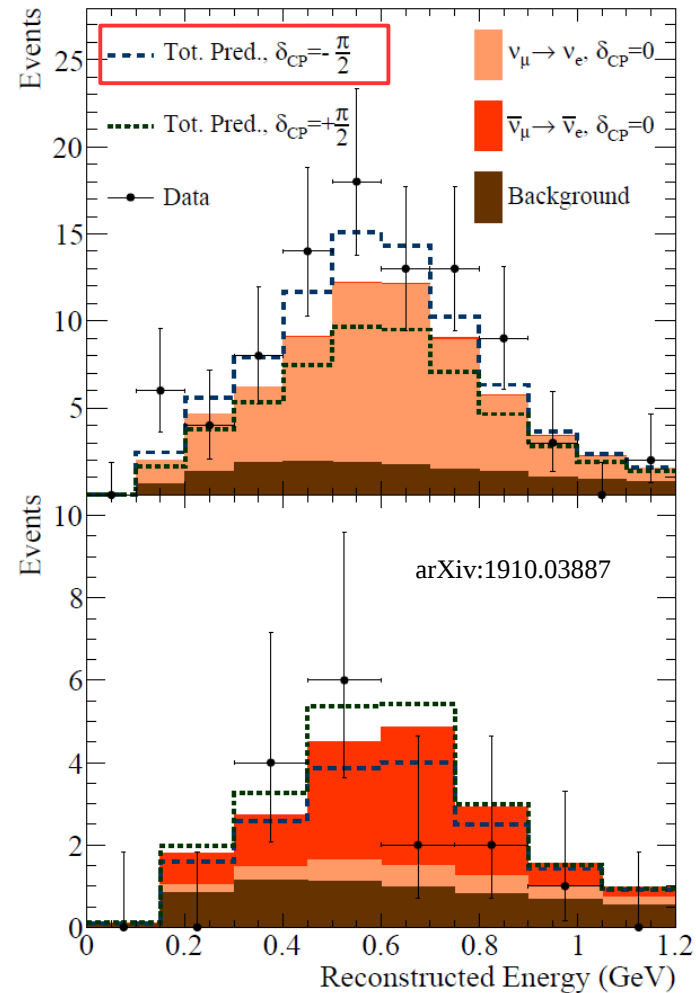


Where Do We Stand?

– T2K update 2009-2018 data $\nu(\bar{\nu})$ 1.49 (1.64) E21 POT

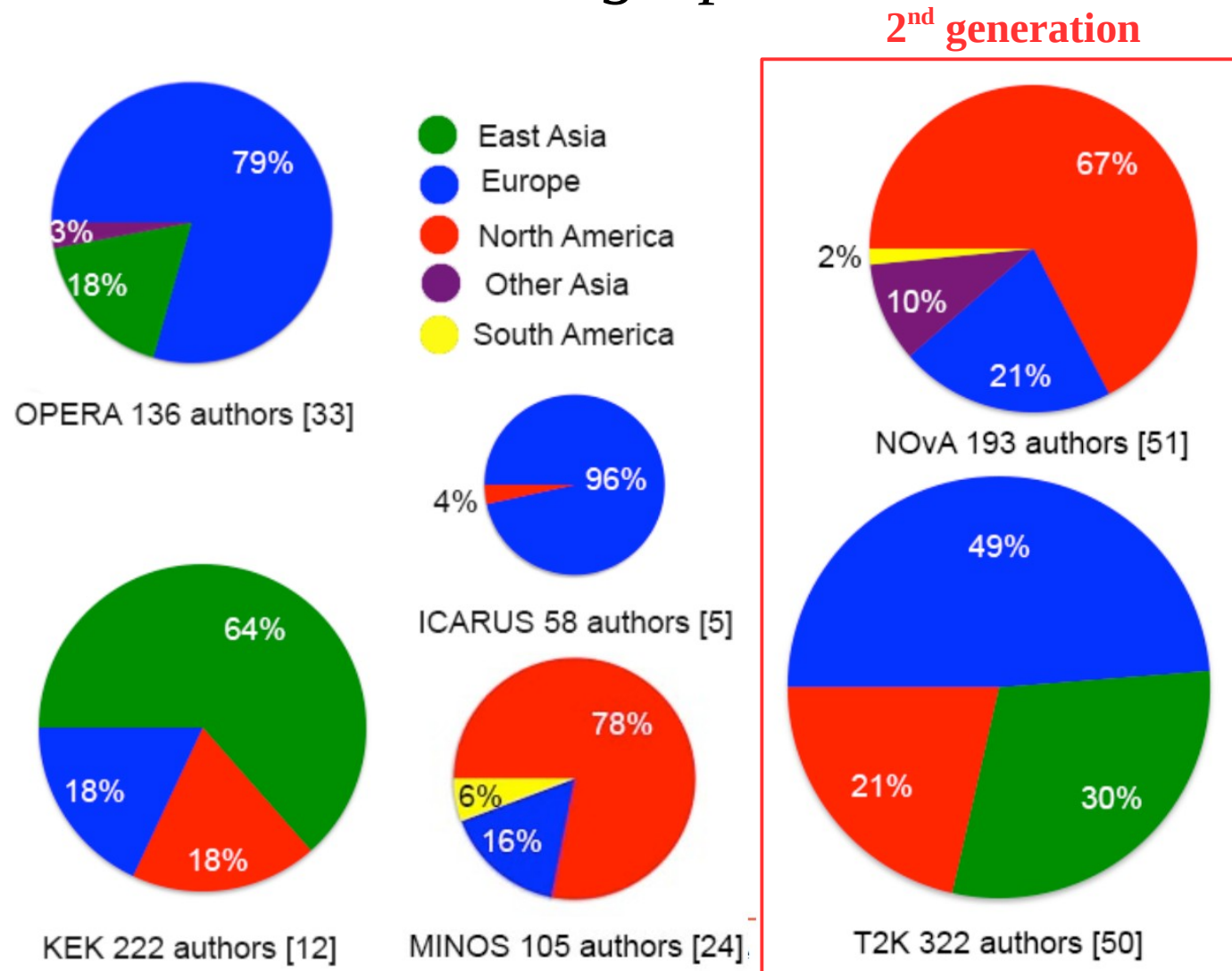


Best fit point at NH
NH/IH Bayes factor 8



“This is the first time closed 99.73% (3σ) intervals on the CP-violating phase δ_{CP} have been reported (taking into account both mass orderings) and a large range of values around $\pm \pi/2$ are excluded.”

1st - and 2nd -Generation Experiments – Demographics



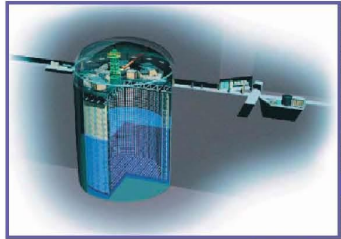
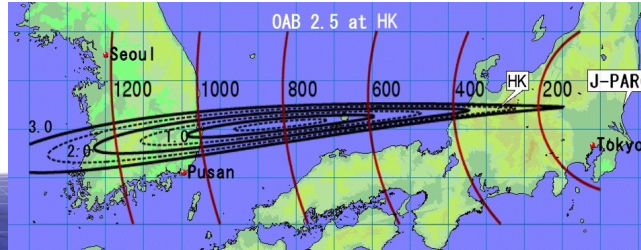
Gary Feldman, *Long-Baseline Accelerator Neutrino Experiments*, International Conference on the History of the Neutrino, 6 September 2018

3rd-Generation Experiments – HK and DUNE

HK (Hyper-Kamiokande, Japan)

w/ 2nd detector in Korea → T2HKK

<https://indico.snu.ac.kr/indico/event/6/other-view?view=standard>



Super-Kamiokande
(ICRR, Univ. Tokyo)



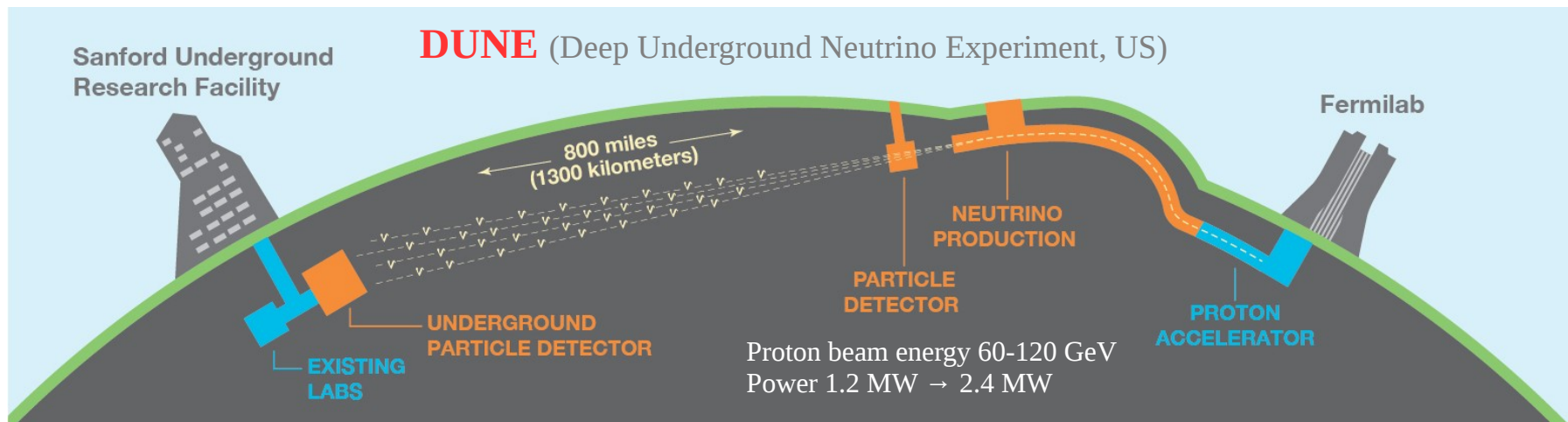
Proton beam energy 30 GeV
Power 50 – 480 kW

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



T2K (Tokai to
Kamioka, Japan)

NOvA (NuMI Off-Axis ve Appearance, US)
J.Phys.Conf.Ser. 396 (2012) 012034

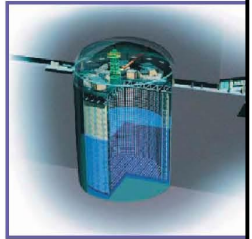


3rd-Generation Experiments – HK and DUNE

<https://indico.snu.ac.kr/indico/event/6/other-view?view=standard>

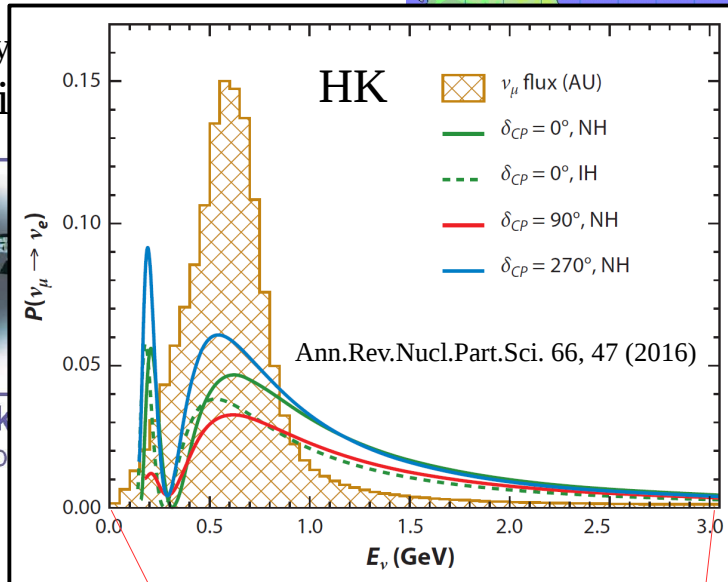
HK (Hyper-Kamiokande)

w/ 2nd detector in



Super-Kamiokande
(ICRR, Univ. To

T2K (Tokai to
Kamioka, Japan)

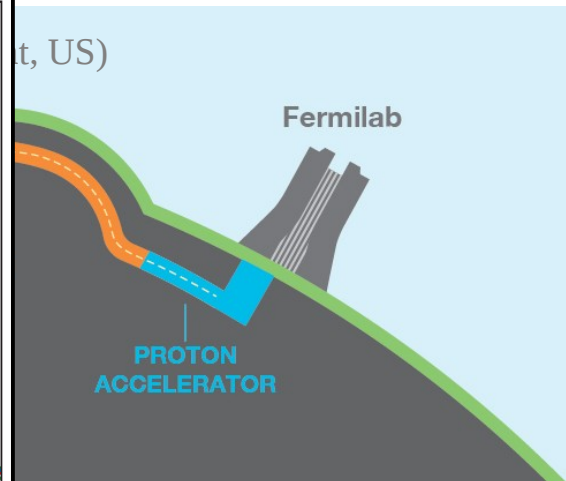
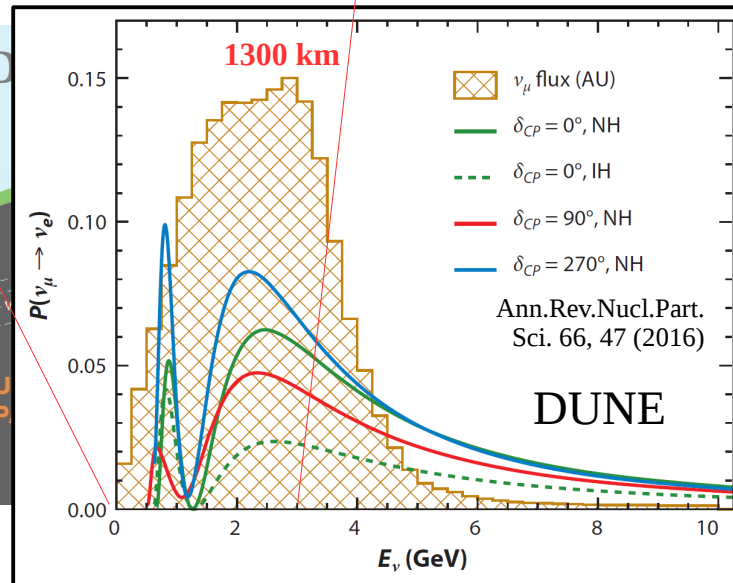
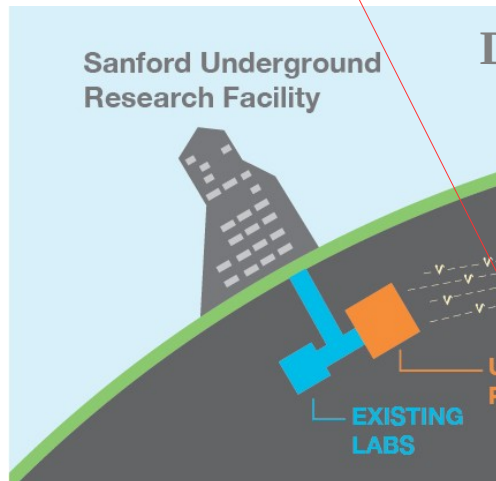


J-PARC Main Ring
(KEK-JAEA, Tokai)



NOvA (NuMI Off-Axis νe Appearance, US)

J.Phys.Conf.Ser. 396 (2012) 012034



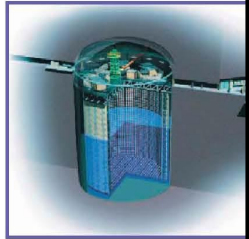
Xianguo Lu, Oxford

3rd-Generation Experiments – HK and DUNE

<https://indico.snu.ac.kr/indico/event/6/other-view?view=standard>

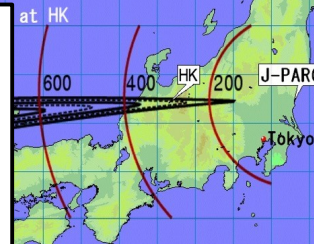
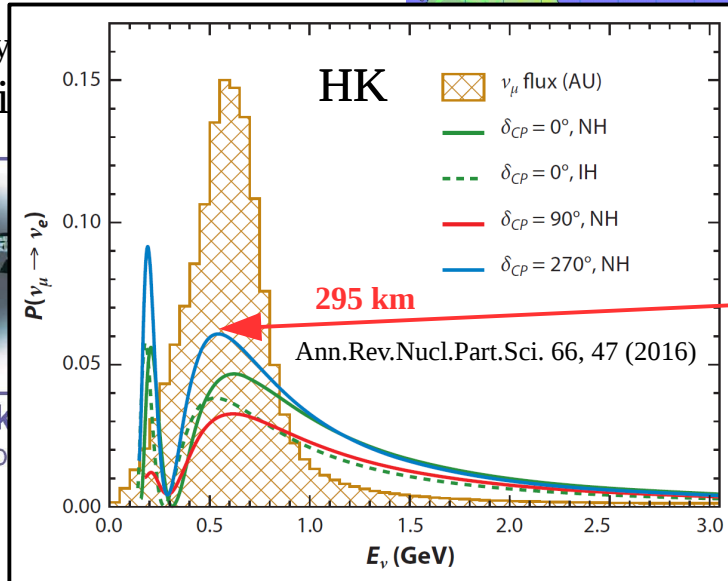
HK (Hyper-Kamiokande)

w/ 2nd detector in



Super-Kamiokande
(ICRR, Univ. To

T2K (Tokai to
Kamioka, Japan)



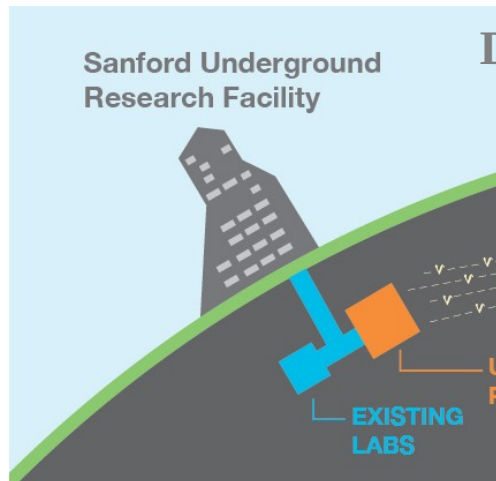
1st osc. maximum

ARC Main Ring
(KEK-JAEA, Tokai)

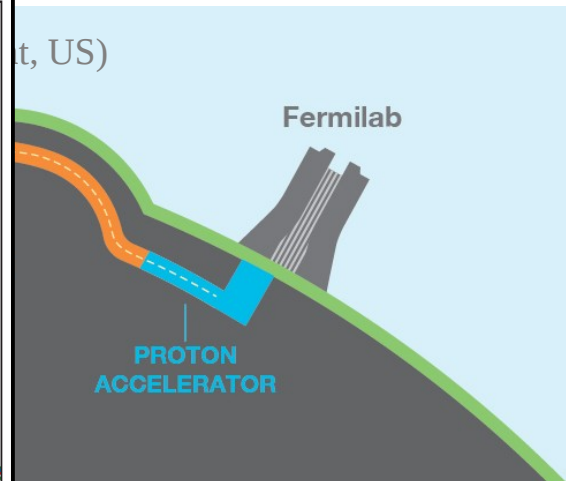
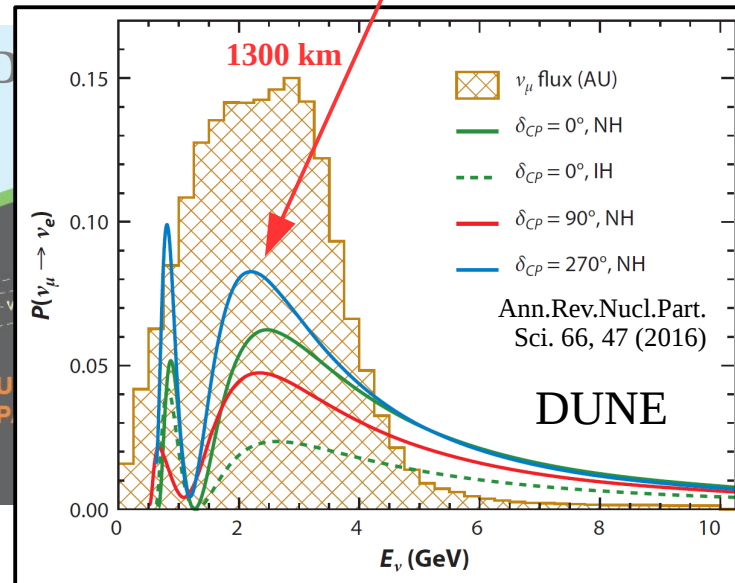


NOvA (NuMI Off-Axis vs Appearance, US)

J.Phys.Conf.Ser. 396 (2012) 012034



Xianguo Lu, Oxford



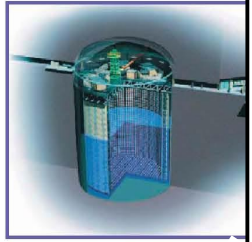
3rd-Generation Experiments – HK and DUNE

<https://indico.snu.ac.kr/indico/event/6/other-view?view=standard>

NOvA (NuMI Off-Axis vs Appearance, US)
J.Phys.Conf.Ser. 396 (2012) 012034

HK (Hyper-Kamiokande)

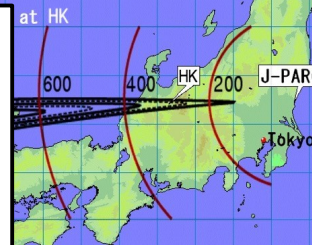
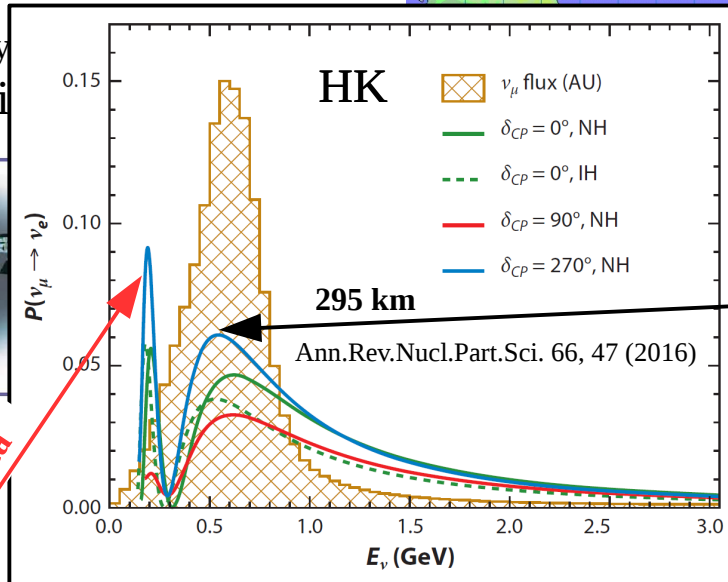
w/ 2nd detector in Japan



Super-Kamiokande
(ICRR, University of Tokyo)

T2K (Tokai to Kamioka)

Larger L to Korea



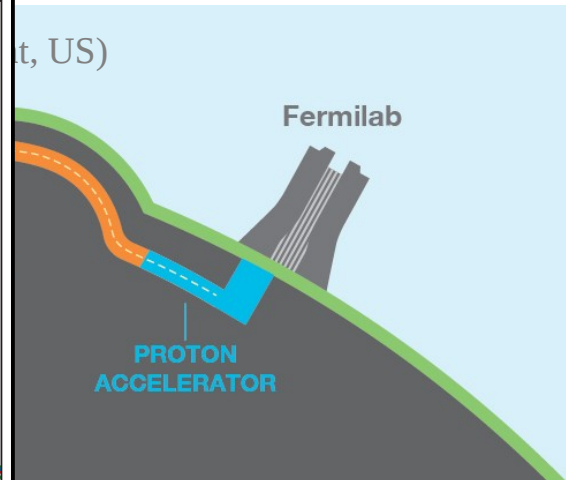
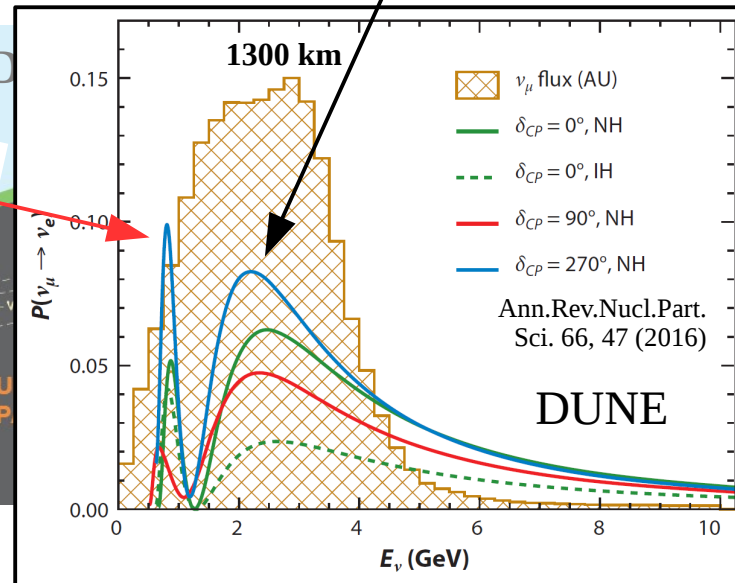
1st osc. maximum

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



At lower E (on-axis beam)

2nd osc. maximum
 $L/E \times 3$
Larger δ_{CP} effects



3rd-Generation Experiments – HK

MEXT budget announcement (Aug.29, 2019)

http://www.mext.go.jp/kaigisiryō/2019/10/_icsFiles/afieldfile/2019/10/25/1421954_003.pdf

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)

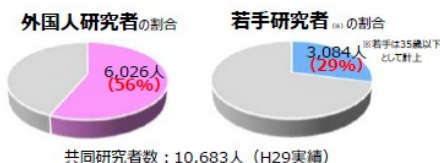


目的

- 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**。



- 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「InCites」(Web of Science) に基づき、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 (article/review) を分析 (2019年7月)。「日本全体」は、著作権所に日本を含む論文を抽出。

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)



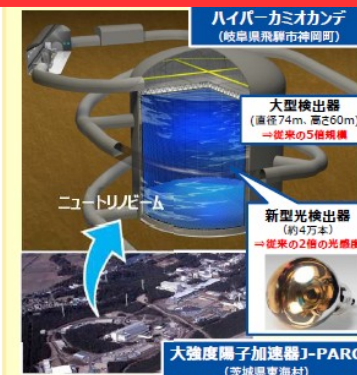
国内の大学等を高速通信回線ネットワークで結び、**共同研究の基盤を提供**。全国900以上の大学や研究機関、約300万人の研究者・学生が活用する我が国の教育研究活動に必須の**学術情報基盤**。

<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
(事例)・【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】加齢による毛髪のパリ・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

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**。[ロードマップ2017掲載事業]

NEW: 令和 (Reiwa) began on 1 May 2019



https://en.wikipedia.org/wiki/2019_Japanese_imperial_transition

Exciting time:

12/2019: Approval by the Ministry of Finance and Cabinet

3/2020: Final approval by the Parliament

3rd-Generation Experiments

– HK

MEXT budget announcement (Aug.29, 2019)

http://www.mext.go.jp/kaigisiryō/2019/10/_icsFiles/afieldfile/2019/10/25/1421954_003.pdf

Japan's 14 big projects

大規模学術フロンティア促進事業等の一覧（14プロジェクト）

日本語の歴史的典籍の国際共同研究ネットワーク構築計画 (人間文化研究機構国文学研究資料館)

日本語の歴史的典籍30万点を画像データベース化し、新たな異分野融合研究や国際共同研究の発展を目指す。古典籍に基づく過去のオーロラの研究、江戸時代の食文化の研究など他機関や産業界と連携した新たな取組を開始。



大型光学赤外線望遠鏡「すばる」の共同利用研究 (自然科学研究機構国立天文台)

米国ハワイ島に建設した口径8.2mの「すばる」望遠鏡により、銀河が誕生した頃の宇宙の姿を探る。約129億光年離れた銀河を発見するなど、多数の観測成果。



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)

日米欧の国際協力によりチリに建設した口径12mと7mの電波望遠鏡からなる「アルマ」により、生命関連物質の探索や惑星・銀河形成過程の解明を目指す。



30m光学赤外線望遠鏡（TMT）計画の推進 (自然科学研究機構国立天文台)

日米加中印の国際協力により口径30mの「TMT」を米国ハワイに建設し、太陽系外の第2の地球の探査、最初に誕生した星の検出等を目指す。



超高性能プラズマの定常運転の実証 (自然科学研究機構核融合科学研究所)

我が国独自のアイデアによる「大型ヘリカル装置(LHD)」により、高温高密度プラズマの実現と定常運転の実証を目指す。また、将来の核融合炉の実現に必要な学理の探求と体系化を目指す。



スーパーBファクトリーによる新しい物理法則の探求 (高エネルギー加速器研究機構)

加速器のビーム衝突性能を増強し、宇宙初期の現象を多数再現して「消えた反物質」「暗黒物質の正体」「質量の起源」の解明など新しい物理法則の発見・解明を目指す。前身となる装置では、小林・益川博士の「CP対称性の破れ」理論(2008年ノーベル物理学賞)を証明。



大強度陽子加速器施設（J-PARC）による物質・生命科学及び原子核・素粒子物理学研究の推進 (高エネルギー加速器研究機構)

日本原子力研究開発機構と共同で、世界最大級のビーム強度を持つ陽子加速器施設を運営。ニュートリノなど多様な粒子ビームを用いて基礎研究から応用研究に至る幅広い研究を推進。



高輝度大型ハドロン衝突型加速器（HL-LHC）による素粒子実験 (高エネルギー加速器研究機構)

CERNが設置するLHCについて、陽子の衝突頻度を10倍に向上し、現行のLHCよりも広い質量領域での新粒子探索や暗黒物質の直接生成等を目指す国際共同プロジェクト。日本はLHCにおける国際貢献の実績を活かし、引き続き加速器及び検出器の製造を国際分担。



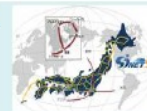
放射光施設による実験研究 (高エネルギー加速器研究機構)

学術研究、さらには産業利用を通じ物質の構造と機能の解明を目指す。白川先生(2000年ノーベル化学賞)、赤崎先生・天野先生(2014年ノーベル物理学賞)などの研究に貢献。



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100Gbpsの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。国内900以上の大学・研究機関、約300万人の研究者・学生が活用。



南極地域観測事業 (情報・システム研究機構国立極地研究所)

南極の昭和基地での大型大気レーダー(PANSY)による観測等を継続的に実施し、地球環境変動の解明を目指す。オン・ホールの発見など多くの科学的成果。



スーパーカミオカンデによるニュートリノ研究の推進 (東京大学宇宙線研究所)

超大型水槽(5万トン)を用いニュートリノを観測し、その性質の解明を目指す。2015年梶田博士はニュートリノの質量の存在を確認した成果によりノーベル物理学賞を受賞。また、2002年小柴博士は、前身となる装置でニュートリノを初検出した成果により同賞を受賞。



大型低温重力波望遠鏡（KAGRA）計画 (東京大学宇宙線研究所)

一辺3kmのL字型のレーザー干渉計により重力波を観測し、ブラックホールや未知の天体等の解明を目指す。日米欧による国際ネットワークを構築し、重力波天文学の構築を目指す。



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)

ニュートリノ研究の次世代計画として、超高感度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。



NEW

3rd-Generation Experiments

– DUNE

About the Collaboration

collaborators ~ baseline



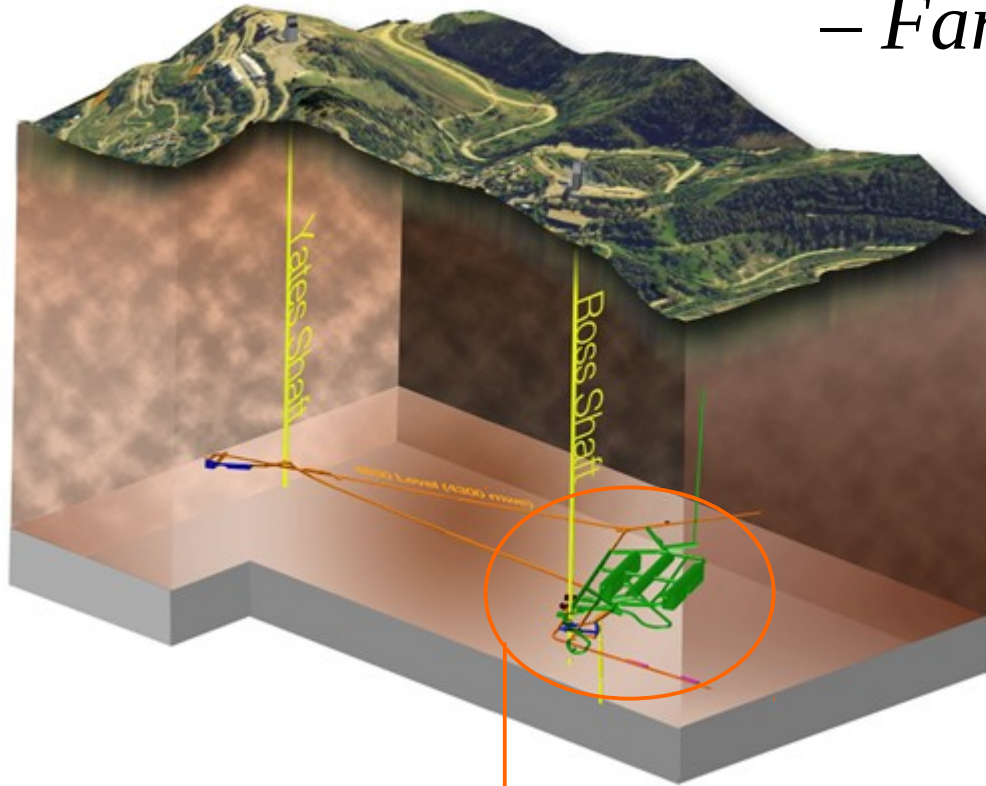
The DUNE Science Collaboration is currently made up of over 1000 collaborators from over 180 institutions in over 30 countries plus CERN. The collaboration works closely with the Long Baseline Neutrino Facility to ensure the coordinated development of facilities and detectors for the DUNE physics program.



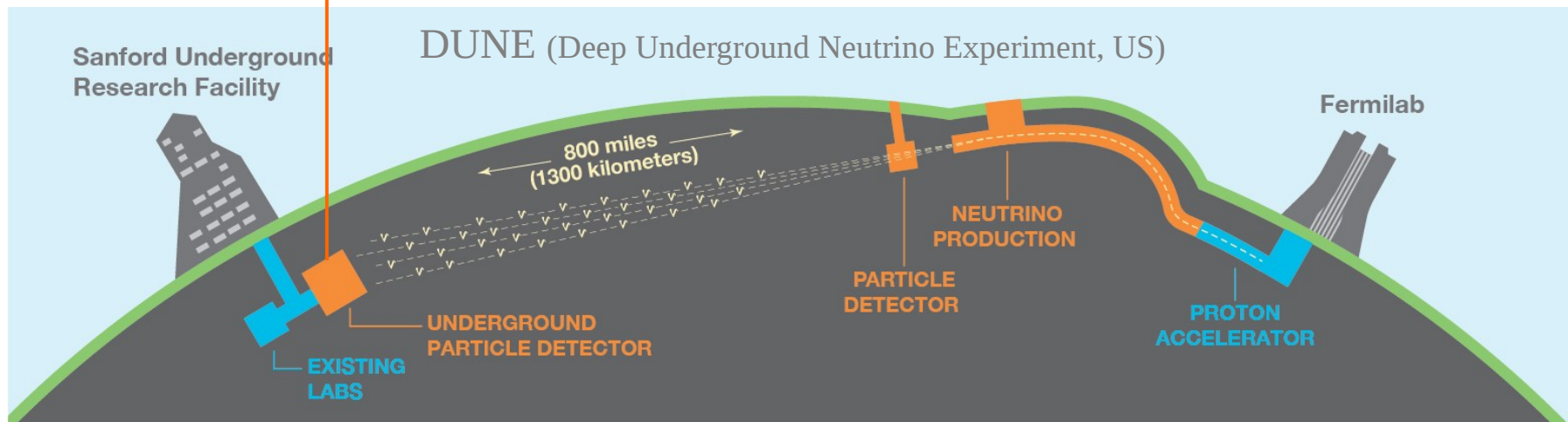
<https://www.dunescience.org/about-the-collaboration/>

DUNE

– Far detector

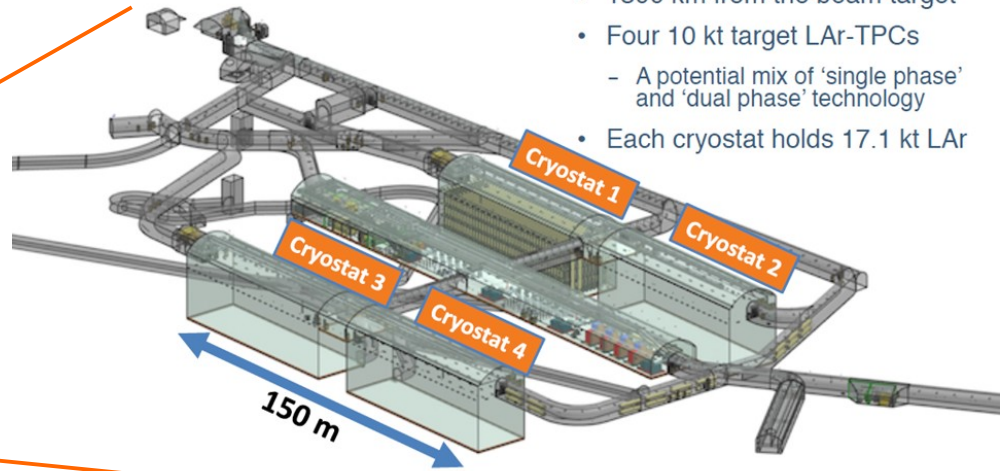
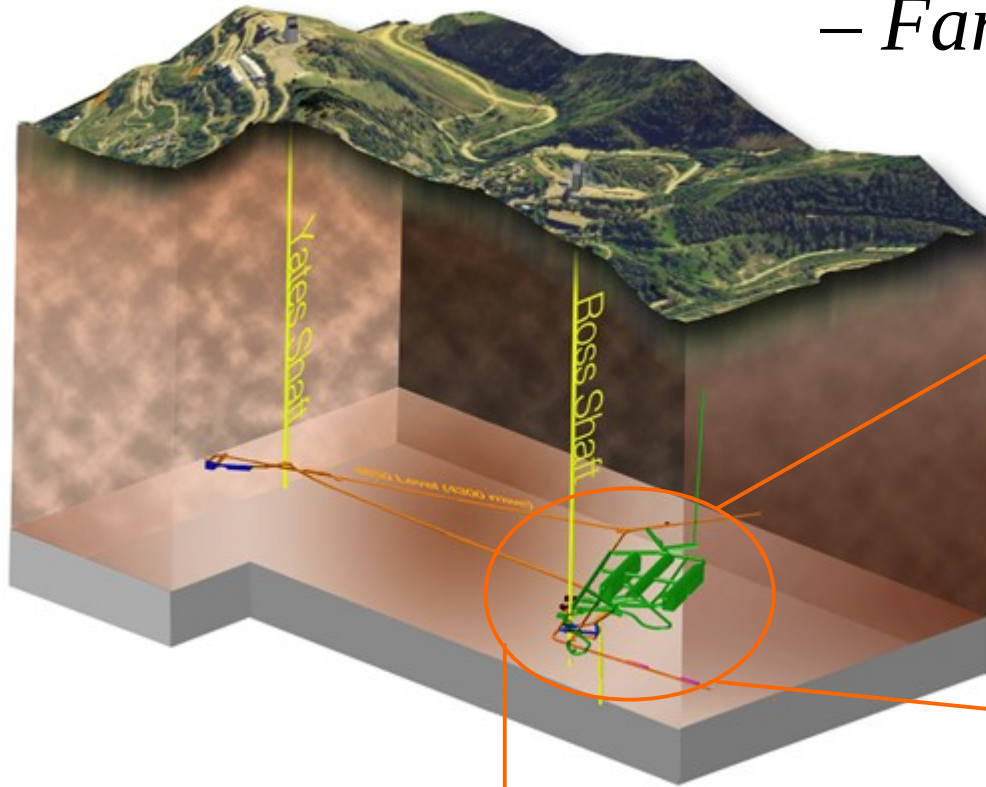


Far Detector: New excavation commenced in 2017

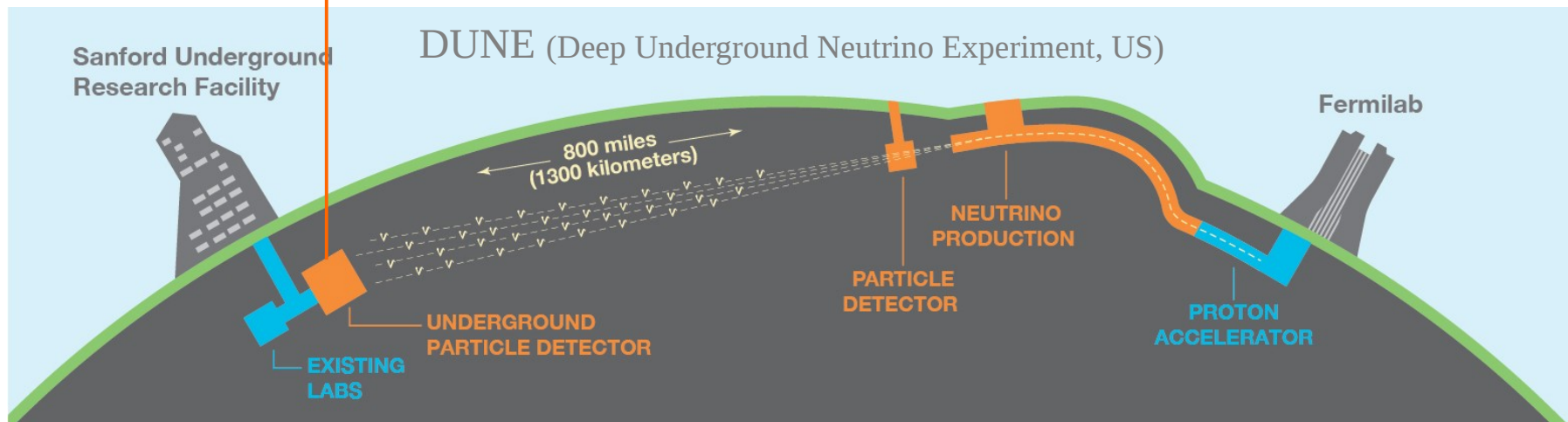


DUNE

– Far detector

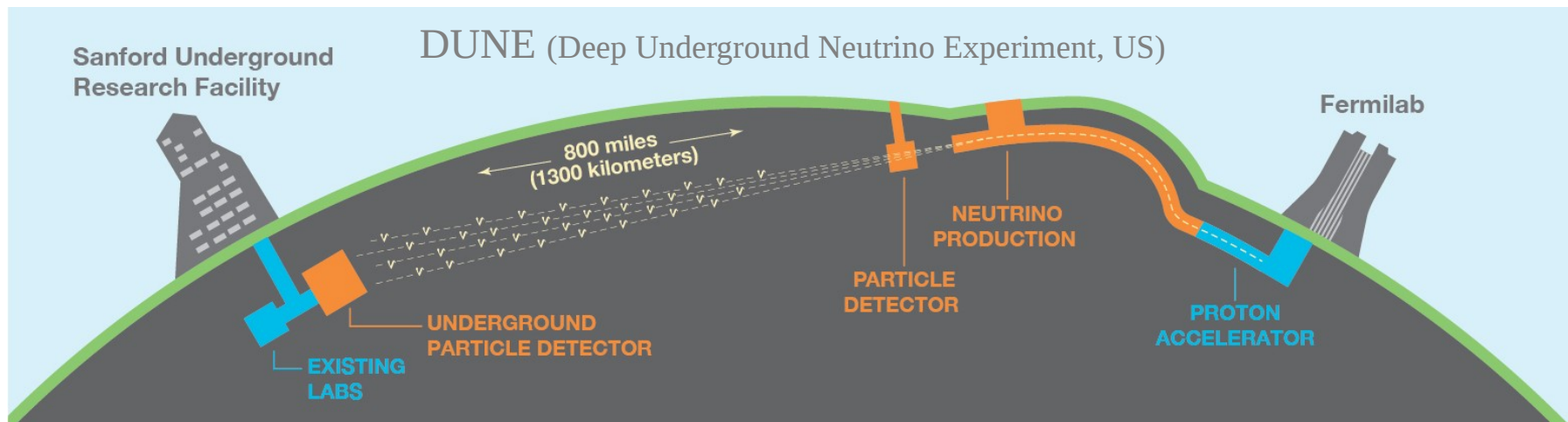
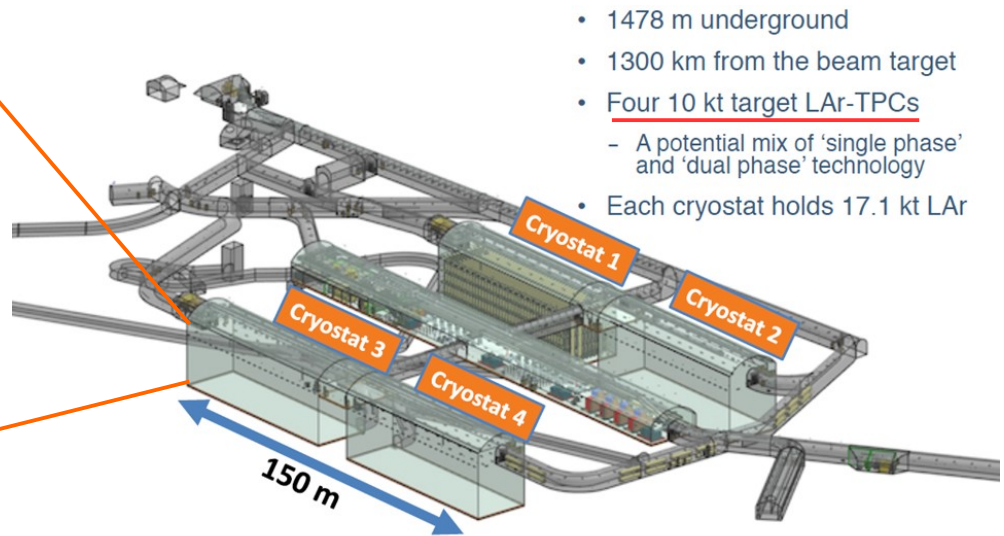
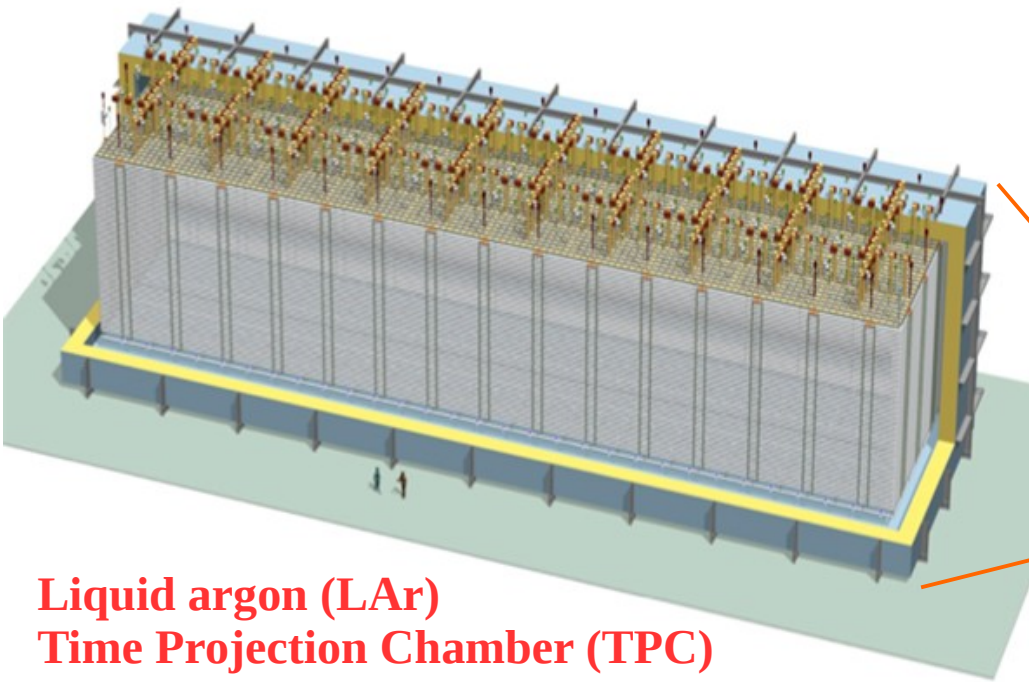


- 1478 m underground
- 1300 km from the beam target
- Four 10 kt target LAr-TPCs
 - A potential mix of 'single phase' and 'dual phase' technology
- Each cryostat holds 17.1 kt LAr



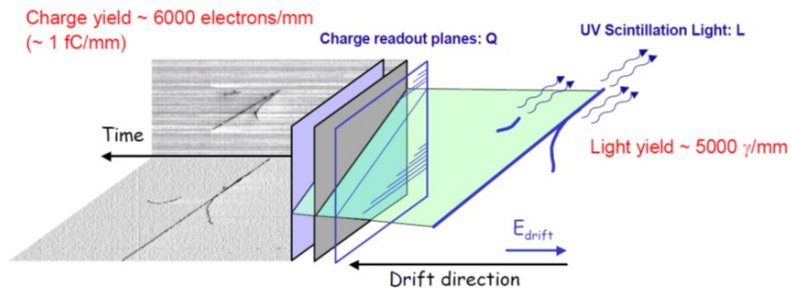
DUNE

– Far detector



protoDUNE

– DUNE far detector prototypes at CERN



LAr TPC

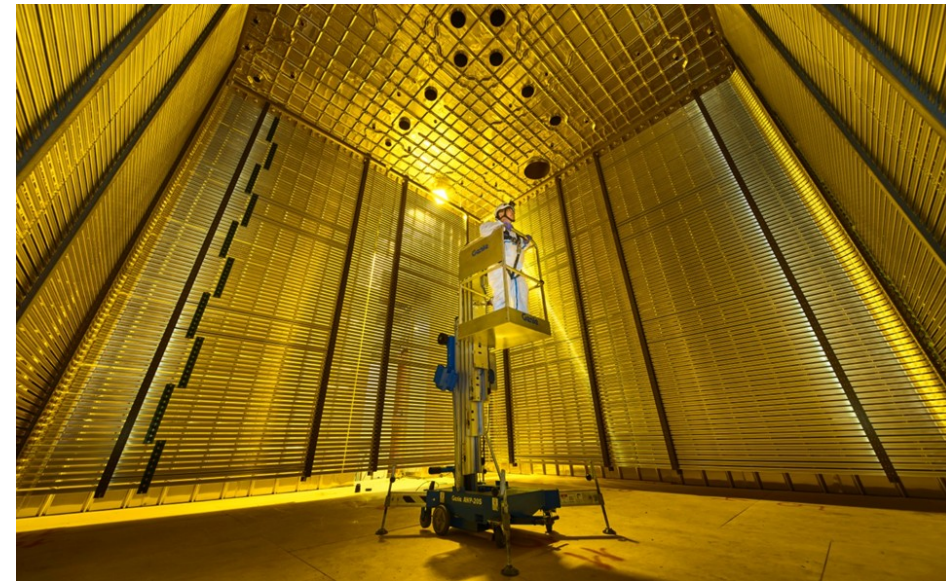
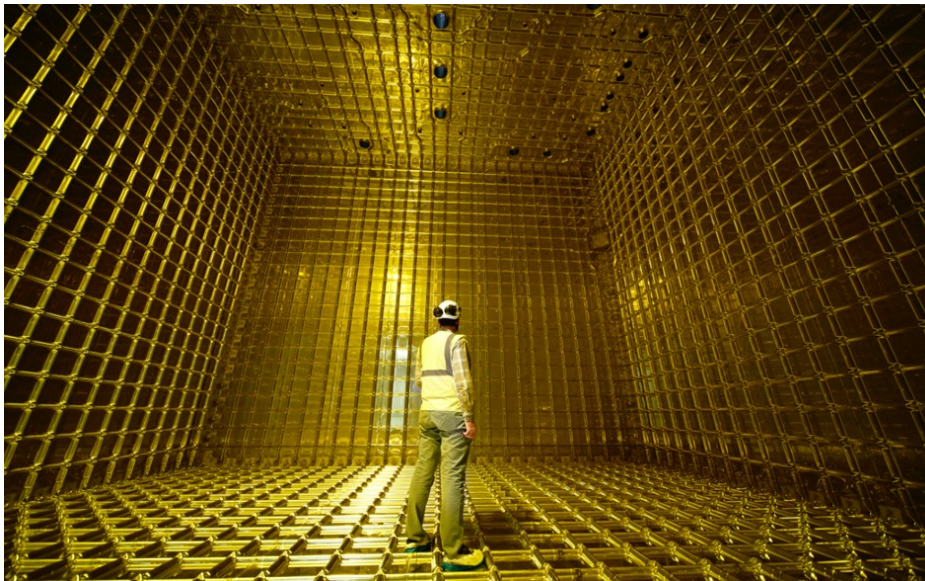
- 3-dimensional track reconstruction with both ionization and scintillation
- **Superb imaging quality**

Single phase (details see BACKUP)

- **Completed 6/2018, data taking 9/2018**
- **World's largest LAr TPC**

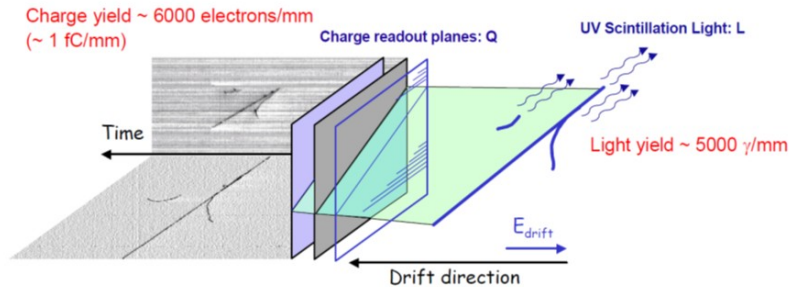
Dual phase (details see BACKUP)

- **Commissioning, first tracks seen**
- **Cosmic runs**



protoDUNE

– DUNE far detector prototypes at CERN



LAr TPC

- 3-dimensional track reconstruction with both ionization and scintillation
- **Superb imaging quality**

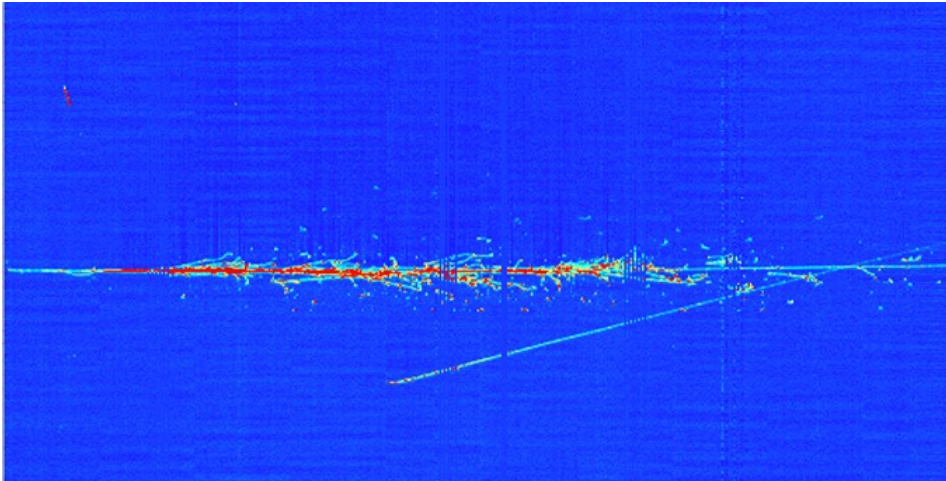
Single phase (details see BACKUP)

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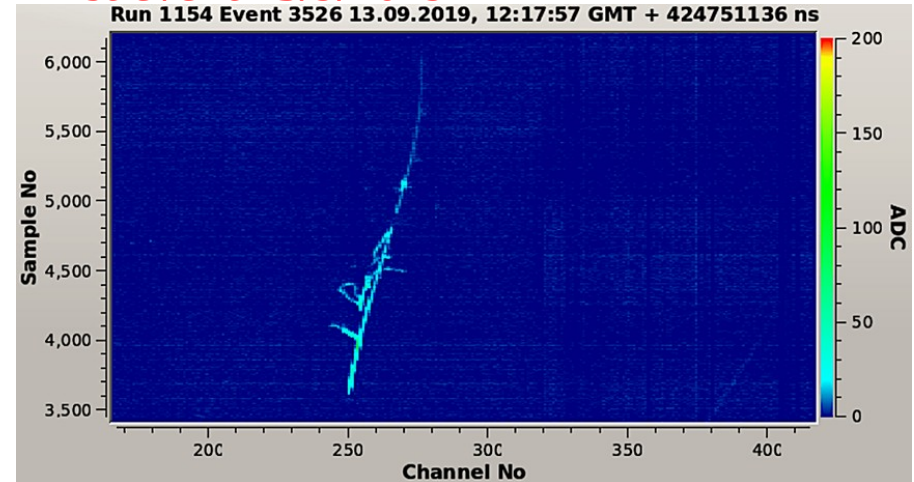
Dual phase (details see BACKUP)

- **Commissioning, first tracks seen**
- **Cosmic runs**

Beam real events



First event 13/9/2019

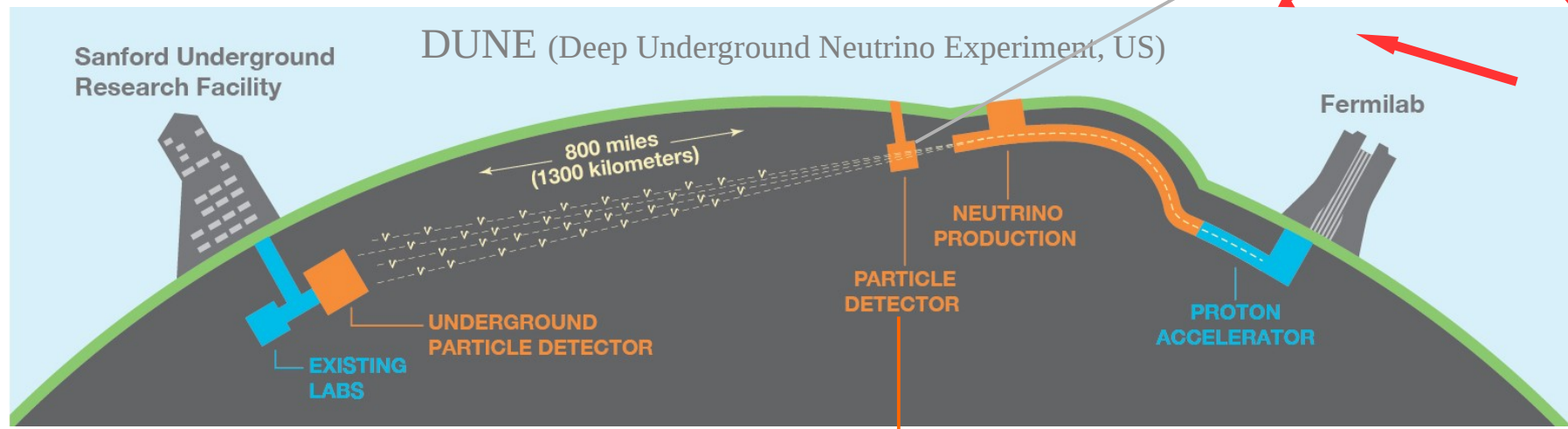
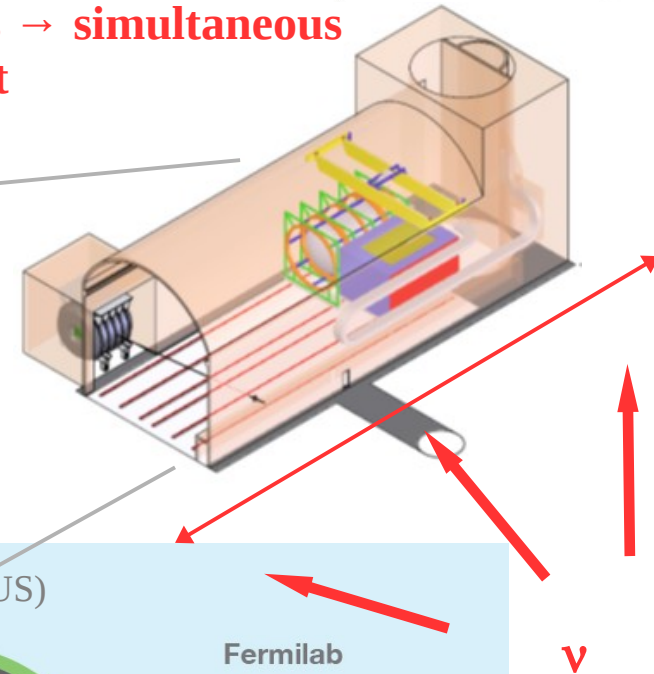
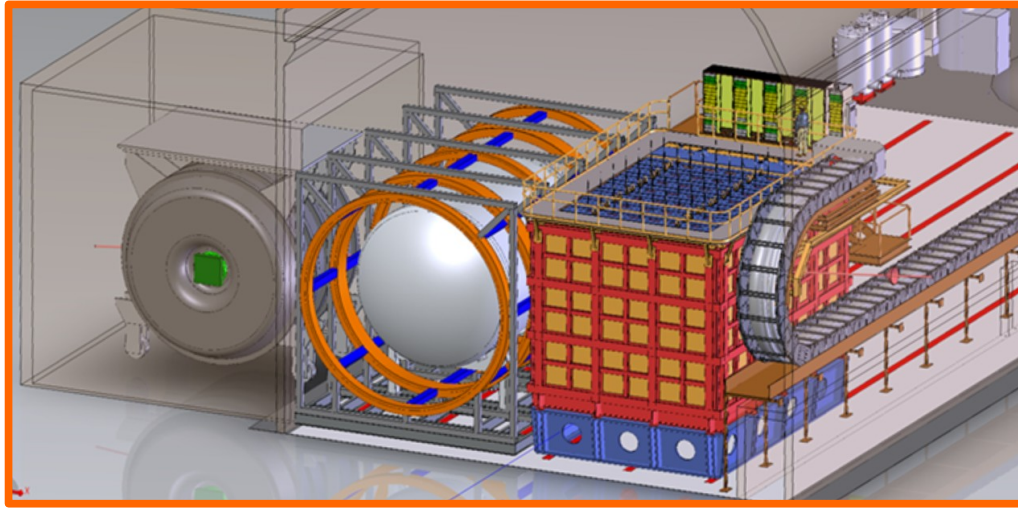
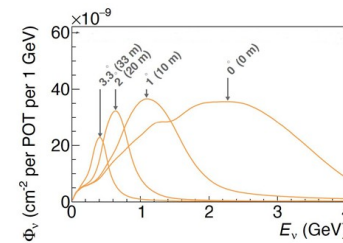


DUNE

– Near detector

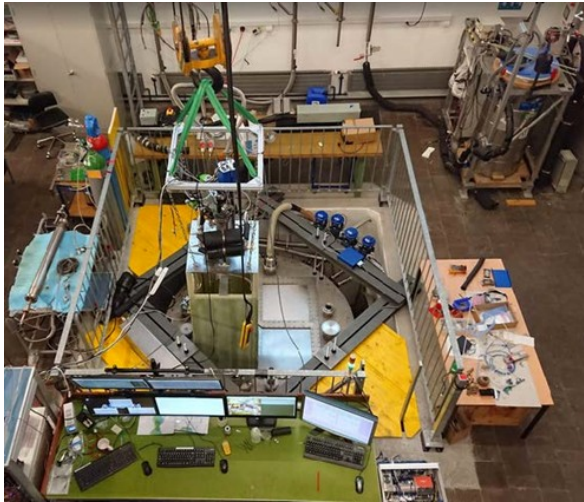
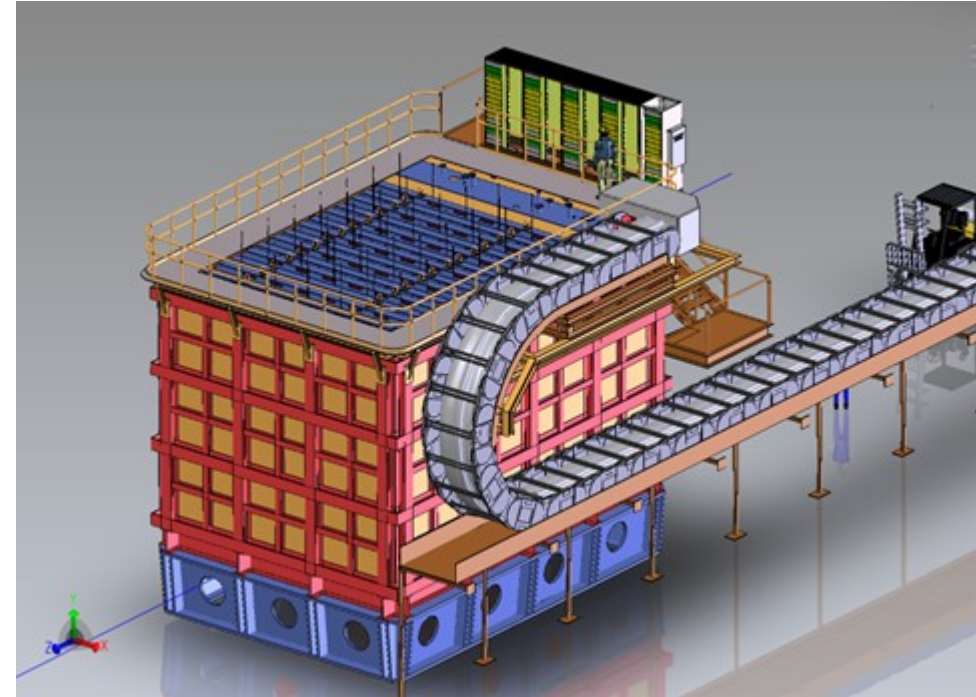
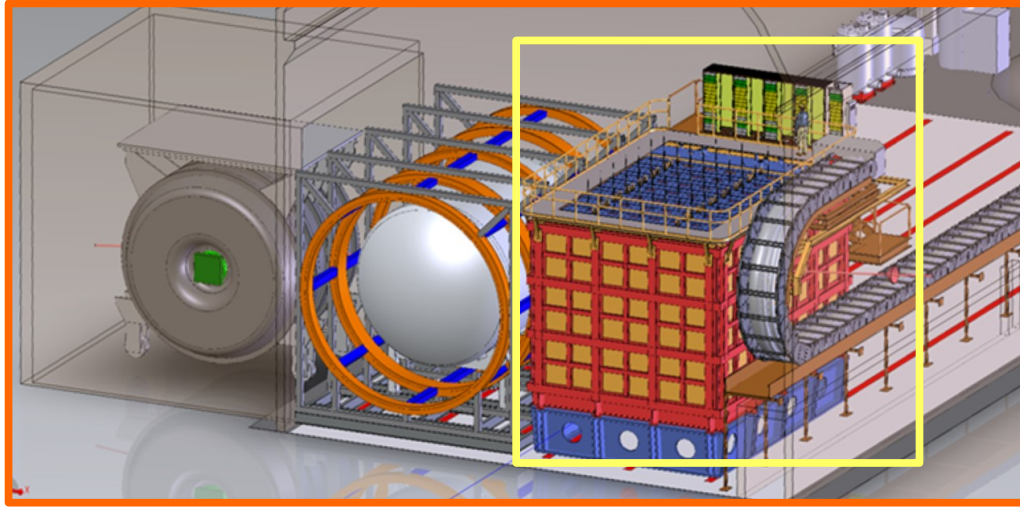
PRISM concept (Precision Reaction Independent Spectrum Measurement)

- Detector movable to **different off-axis angles** → **simultaneous flux constraint**



DUNE

– Near detector



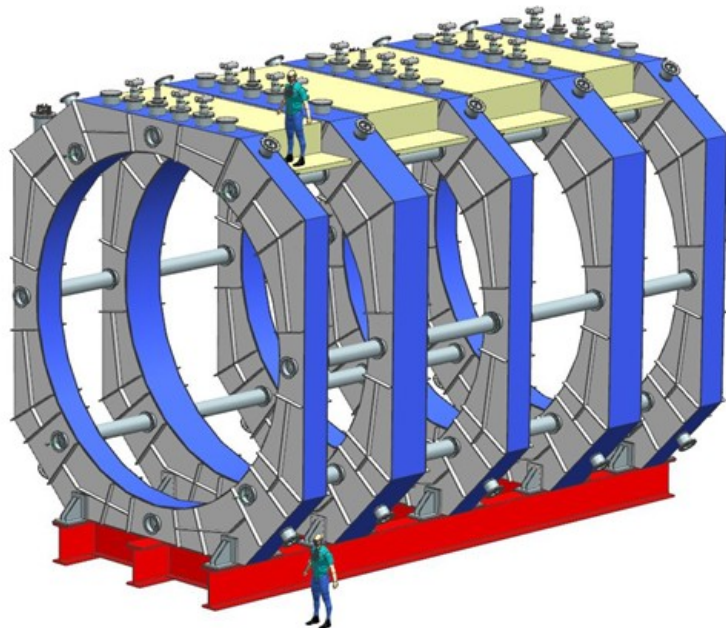
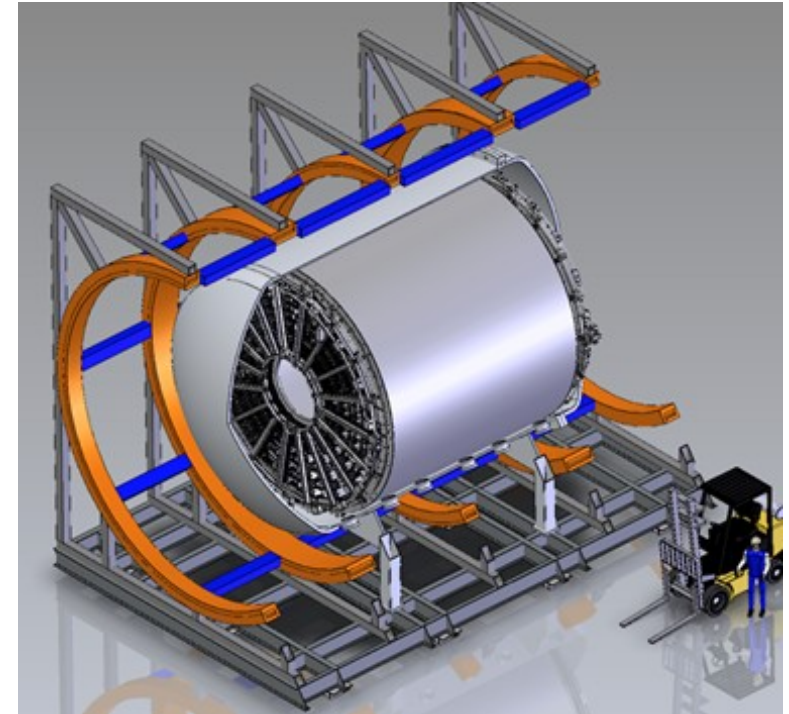
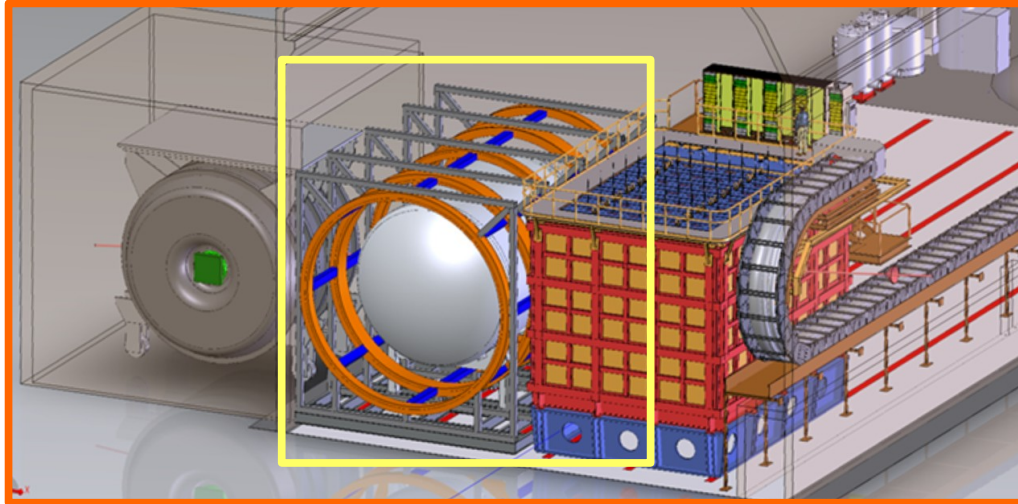
2×2 prototype in Bern, to be placed in the NuMI beam MINOS ND Hall

ArgonCube

- 35 LAr modules, pixelated readout (**~2 billion voxels**)
→ same target as Far Detector

DUNE

– Near detector

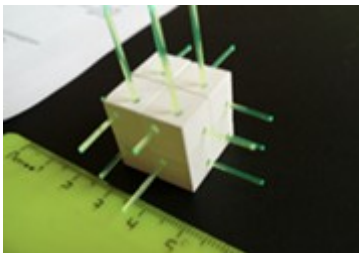
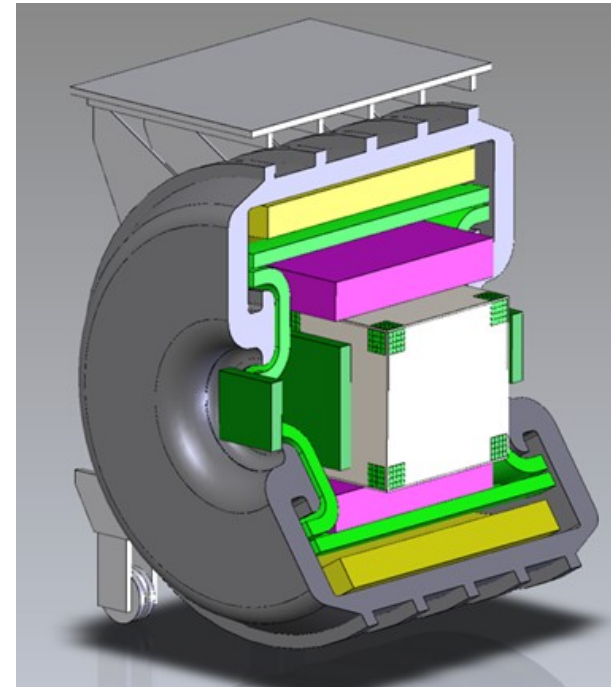
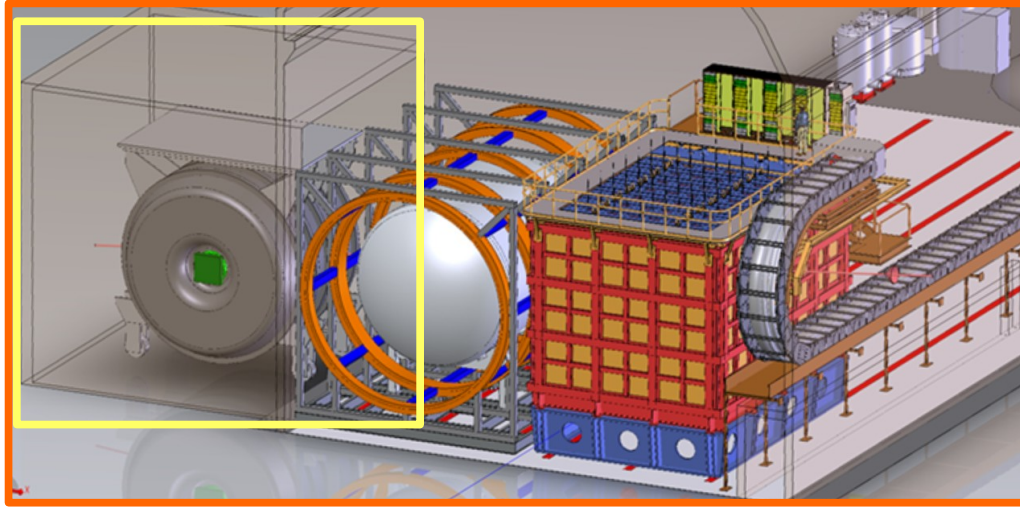


MPD (Multi-Purpose Detector)

- Super-conducting magnet 0.5 T, **3.5 m inner radius** (could contain the ALICE TPC)
 - charge selection
- High pressure gaseous TPC (10 bar)
 - low threshold, full acceptance
- ECal (not shown)
 - neutral particle containment

DUNE

– Near detector



3DST-KS (3D scintillator tracker – KLOE spectrometer)

- On-axis flux monitoring
- neutron detection

- Active target (**8 t of 1 cm³ plastic cubes**)
- KLOE spectrometer (tracker + KLOE Ecal&magnet SC 0.6T)

Summary

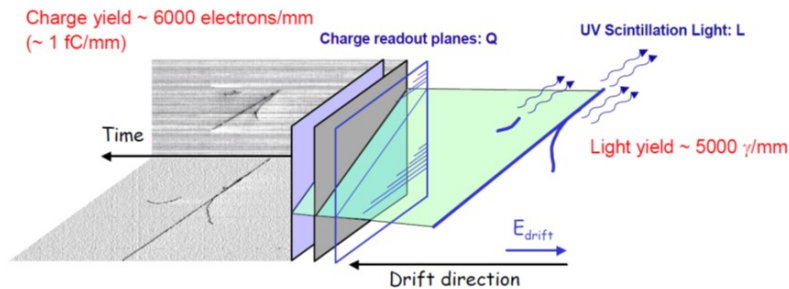
- CP violation *uniquely* probed by accelerator neutrinos
 - ✓ Powerful controlled source of both neutrinos and antineutrinos
 - ✓ Global-scale projects, challenging and ambitious
- **CP violation seems real!**
 - ✓ T2K reports 3σ measurement of δ_{CP}
- **DUNE is (more) real!**
 - ✓ 2017: start of construction at SURF
 - ✓ 2018: operation of two large-scale prototypes at CERN
 - ✓ 2019: International approval of DUNE funding matrix (**> 3σ !**)
 - 2021: start of installation of first 17-kt far detector module
 - 2024: start of operation of 17-kt far detector module
 - 2026: start of beam operation (1.2 MW) with two 17-kt FD modules
- **Exciting time for HK, stay tuned!**

Thank you!

BACKUP

protoDUNE

– DUNE far detector prototypes at CERN

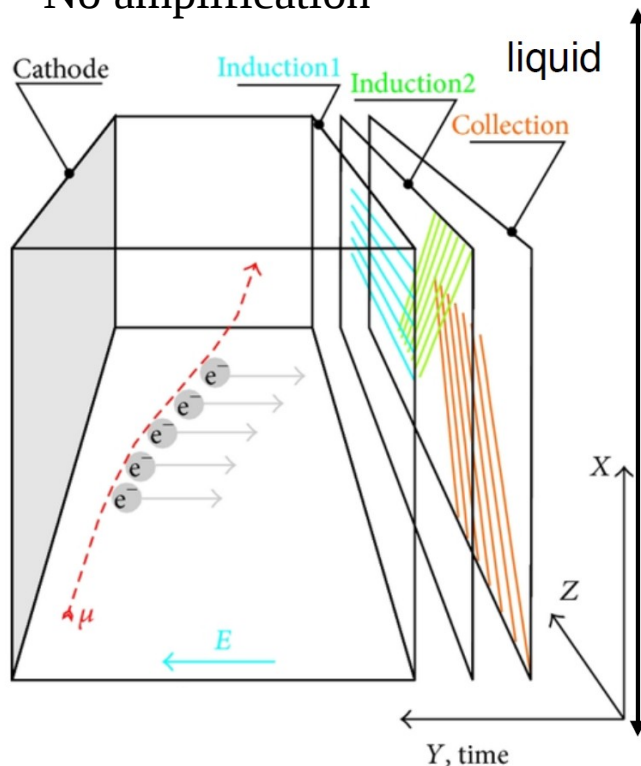


LAr TPC

- 3-dimensional track reconstruction with both ionization and scintillation
- **Superb imaging quality**

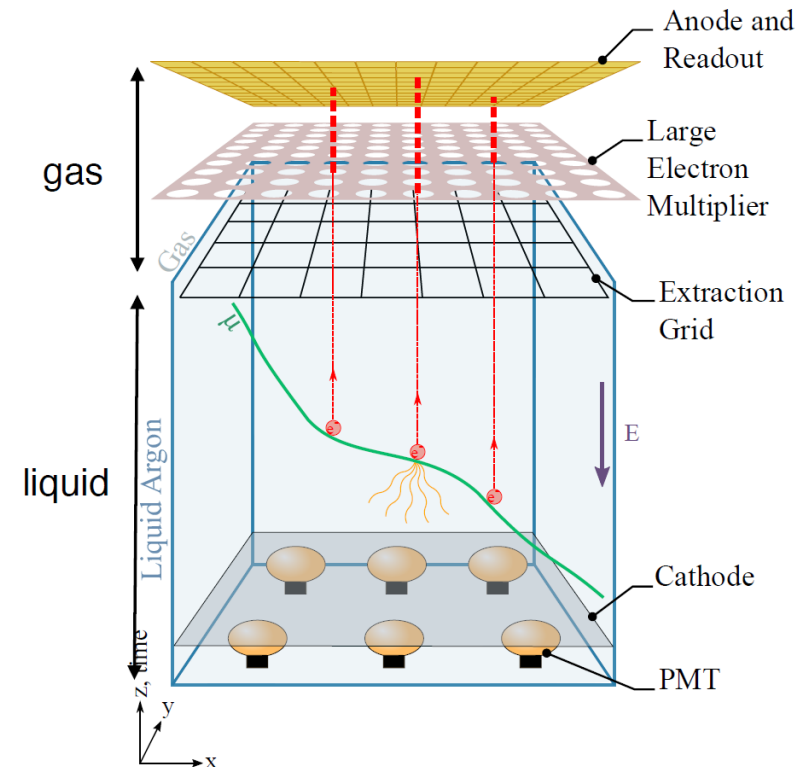
Single phase

- Horizontal drift, wire readout (photon detector in APA)
- No amplification



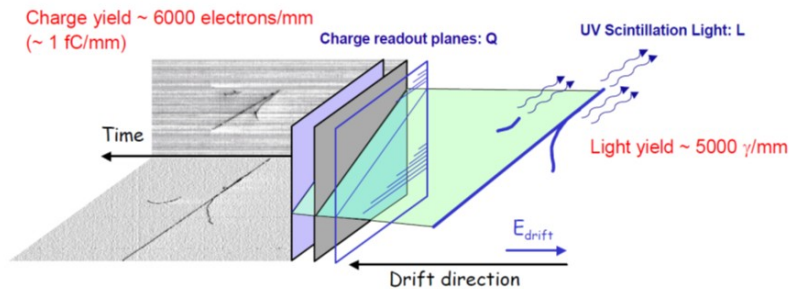
Dual phase

- Vertical drift, PCB readout
- Tunable gain (signal amp. in gas)



protoDUNE

– DUNE far detector prototypes at CERN

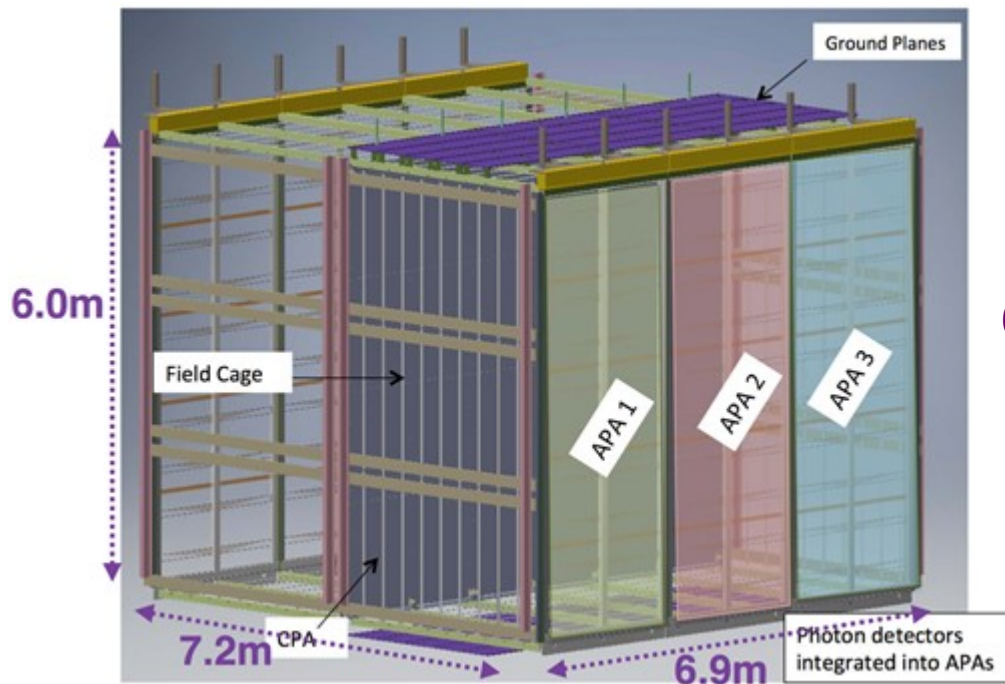


LAr TPC

- 3-dimensional track reconstruction with both ionization and scintillation
- **Superb imaging quality**

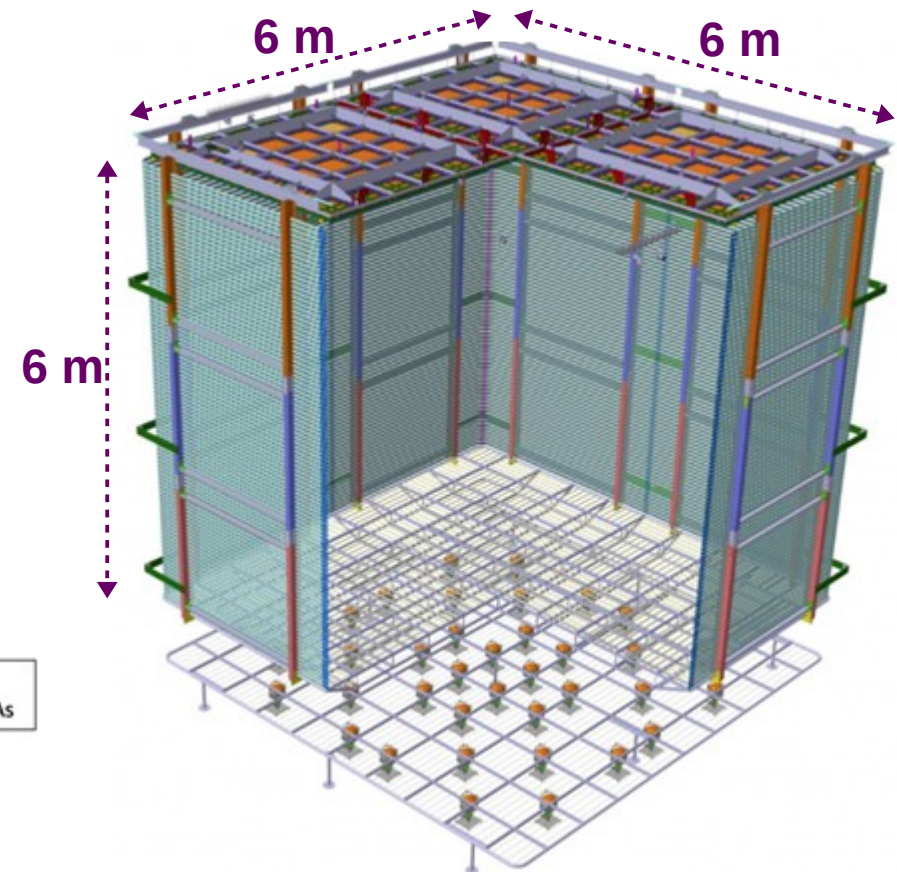
Single phase

- 3.6 m horizontal drift

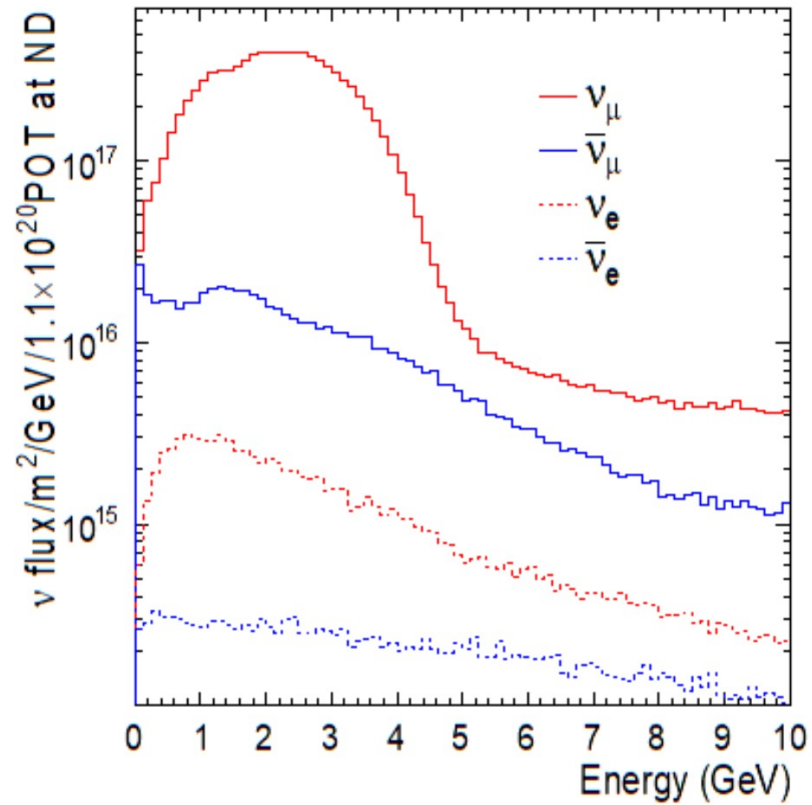


Dual phase

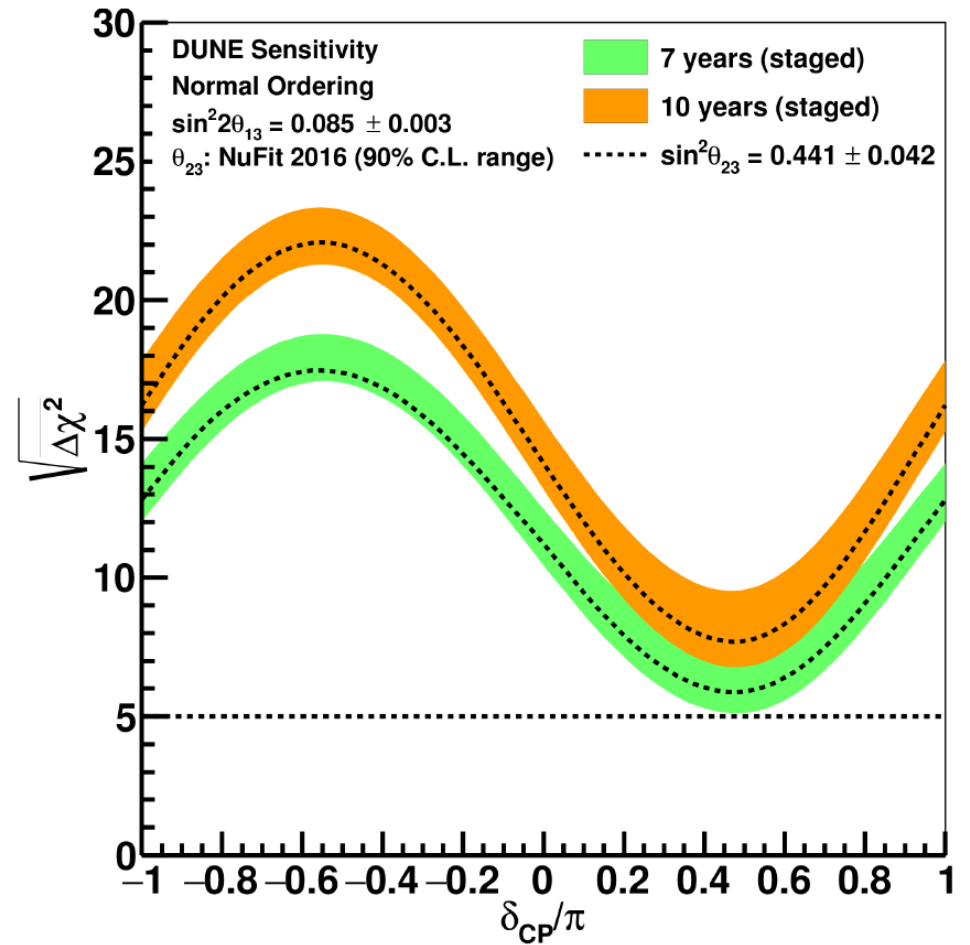
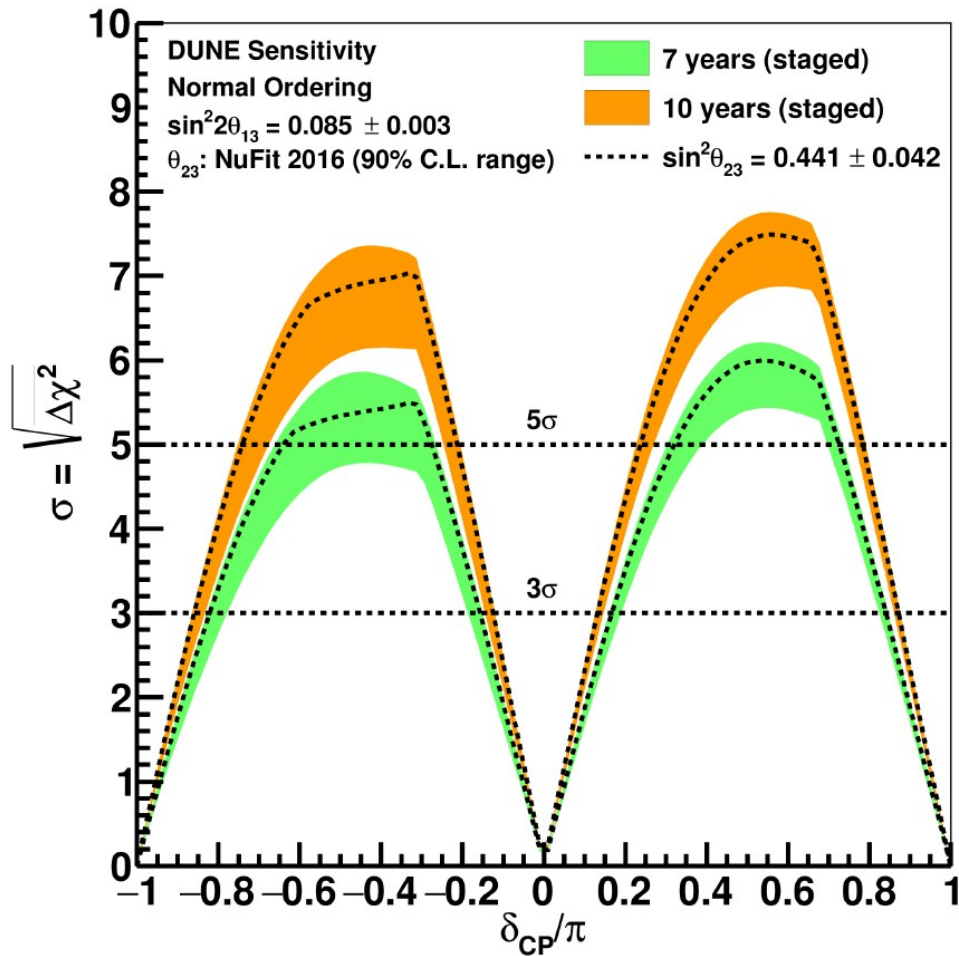
- 6 m vertical drift



Optimized CPV tune
FHC On-axis
1.25 MW



Detector	Target (Fid. mass t)	# ν_μ CC ($\times 10^6$)
LAr	Ar (50)	80
HPgTPC	Ar (1)	1.5
3DST-KS	CH (8)	12



Worcester, Elizabeth. (2018, June). DUNE: Status and Science. Zenodo.
<http://doi.org/10.5281/zenodo.1286764>

END