Accelerator Neutrino Experiment

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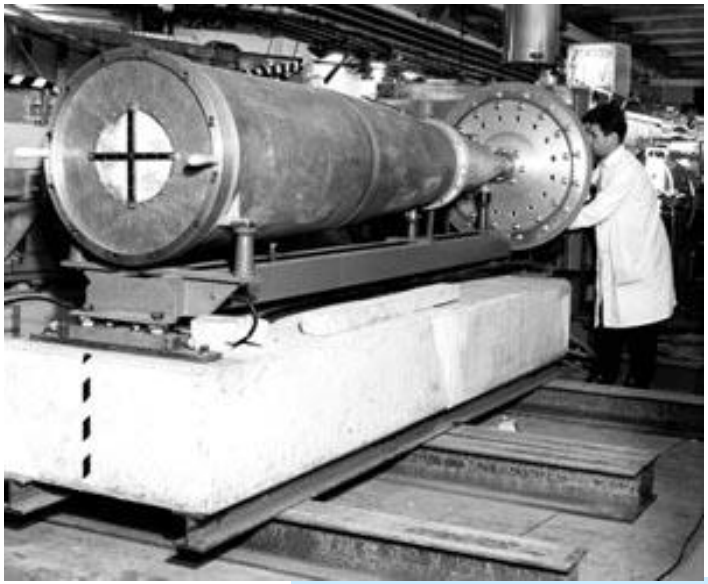
中微子束流

- 莱德曼：1956年检验宇称不守恒：400MeV质子打碳靶，π→μ+ν，利用缪子衰变的不对称，设计了一个检验实验，3天就得到了确定的结果。
- 五十年代末，蓬泰科尔沃与施瓦茨独立地提出了一种产生几乎纯净中微子束流的方法。施瓦茨随即加入了莱德曼、斯坦伯格、以及其他人组成的小组，将这个想法付诸实施。
- 1961年，Van der Meer在CERN研制出第一个 Horn
- 1962年，莱德曼、舒瓦茨、施坦博格产生 μ 中微子束流，发现第二种中微子—— μ中微子（1988年诺贝尔奖）



中微子束流

VOLUME 9, NUMBER 1 PHYSICAL REVIEW LETTERS JULY 1, 1962

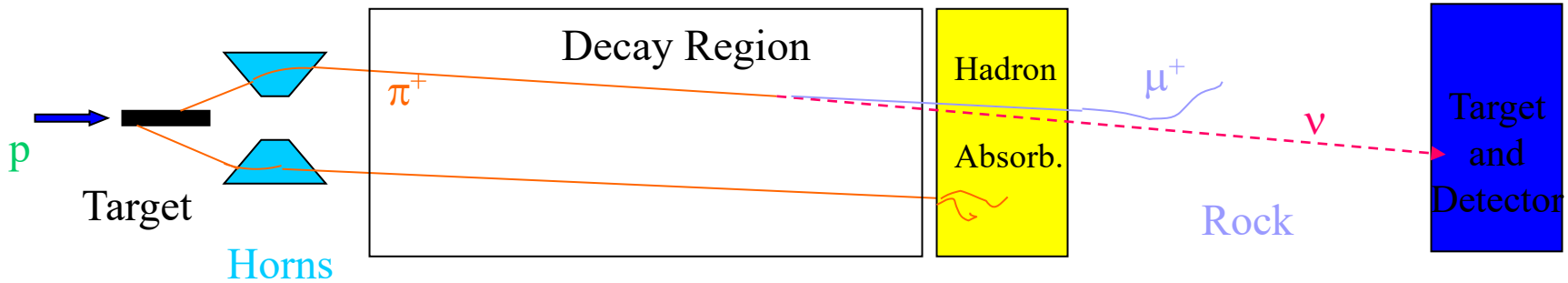
莱德曼、舒瓦茨、施坦博格发现第二种中微子—— μ中微子

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)



- **Proton on target**
- **Pion decays**

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\downarrow$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

长基线加速器中微子实验

- 日本
  - ⇨ **K2K, T2K, Hyper-K**
- 美国
  - ⇨ **MINOS, Nova, DUNE**
  - ⇨ **MiniBooNE, MicroBooNE, …**
- 欧洲
  - ⇨ **ICRUS, OPERA, LBNO, ESS-nu**

$$\nu_\mu \to \nu_\mu$$

$$\nu_\mu \to \nu_e$$

$$\nu_\mu \to \nu_\tau$$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c^2_{13}s^2_{13}s^2_{23} \sin^2 \Delta_{31} \\ & + 8c^2_{13}s_{13}s_{23}c_{23}s_{12}c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21} \\ & - 8c^2_{13}s^2_{13}s^2_{23}s^2_{12} \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\ & + 4c^2_{13}s^2_{12}[c^2_{12}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13} \cos \delta] \sin^2 \Delta_{21} \\ & - 8c^2_{13}s^2_{13}s^2_{23}(1 - 2s^2_{13}) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[\cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

Leading Term

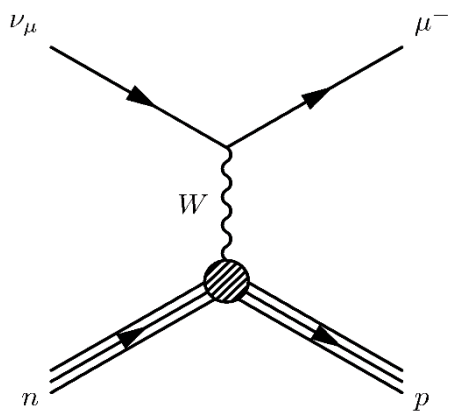
CPV Term

Solar Term

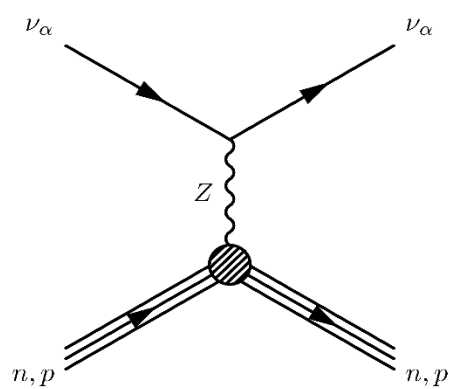
Matter Term

Detection

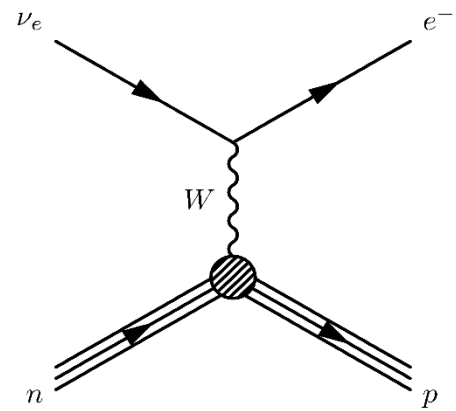
ν_μ CC Event



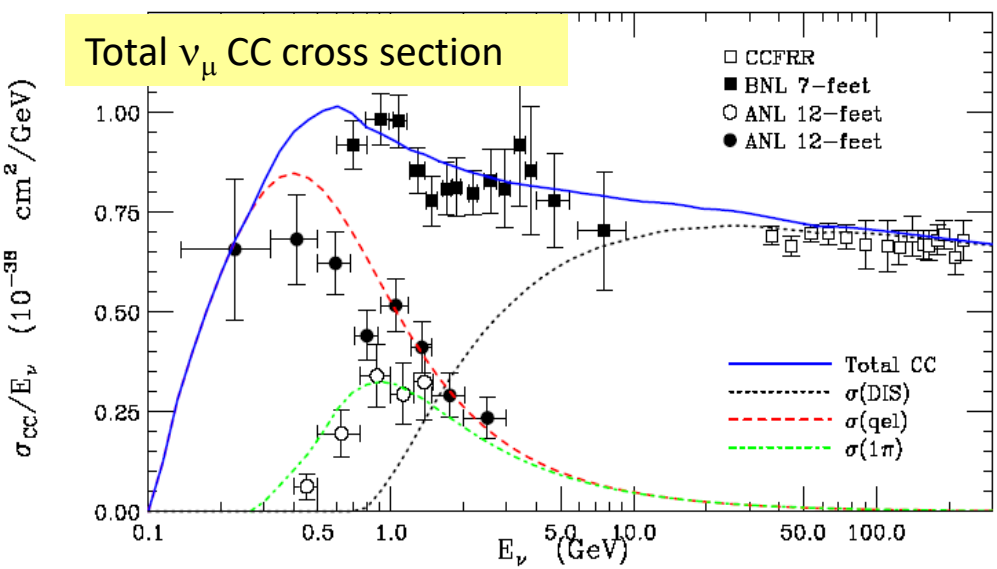
NC Event

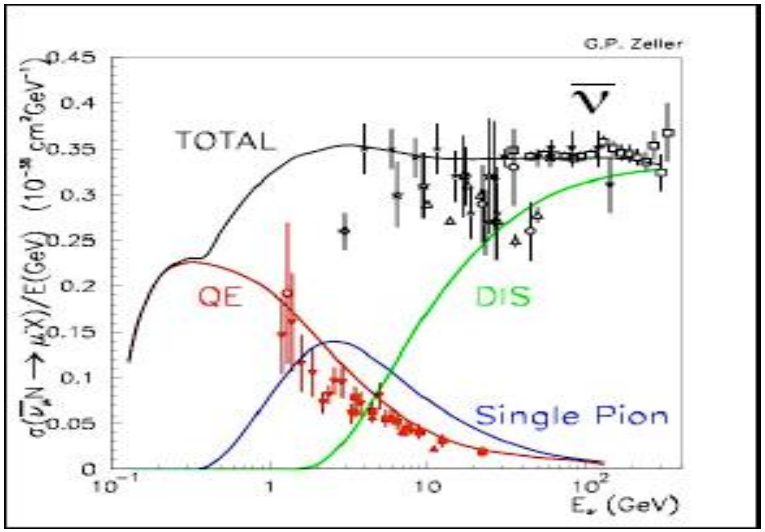


ν_e CC Event



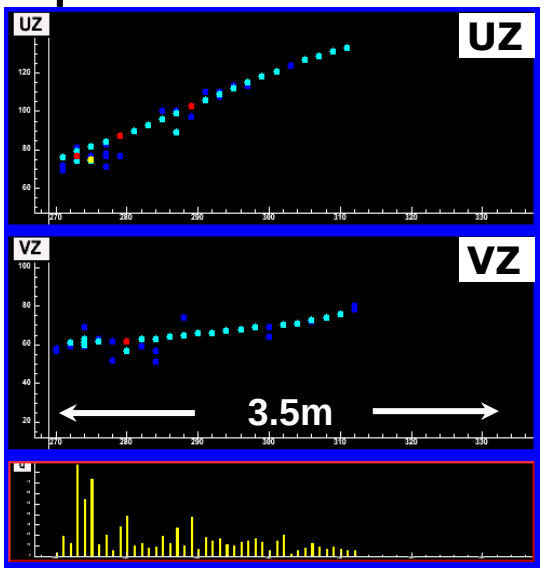
Total ν_μ CC cross section





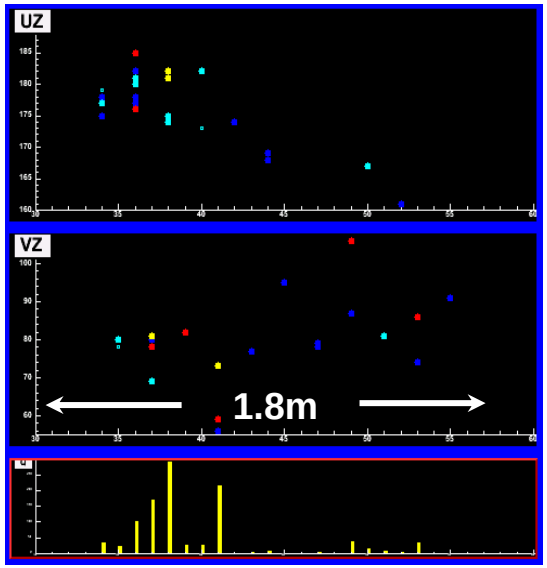
Event Topologies

ν_μ CC Event



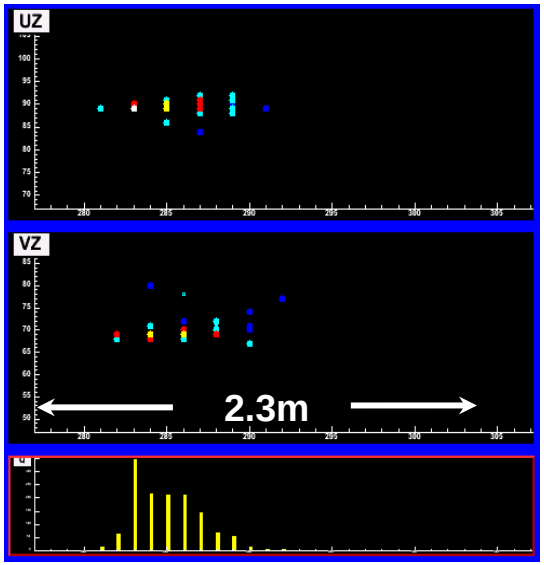
long μ track & hadronic activity at vertex

NC Event

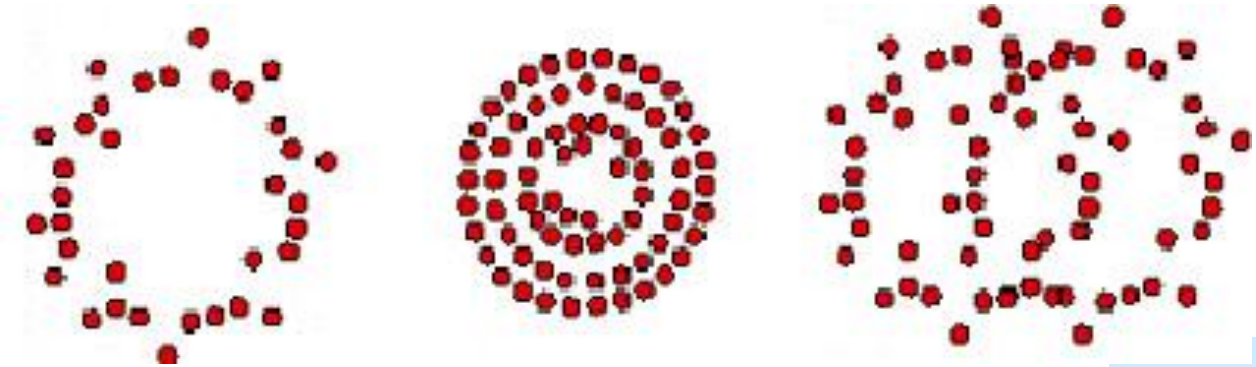


short event, often diffuse

ν_e CC Event

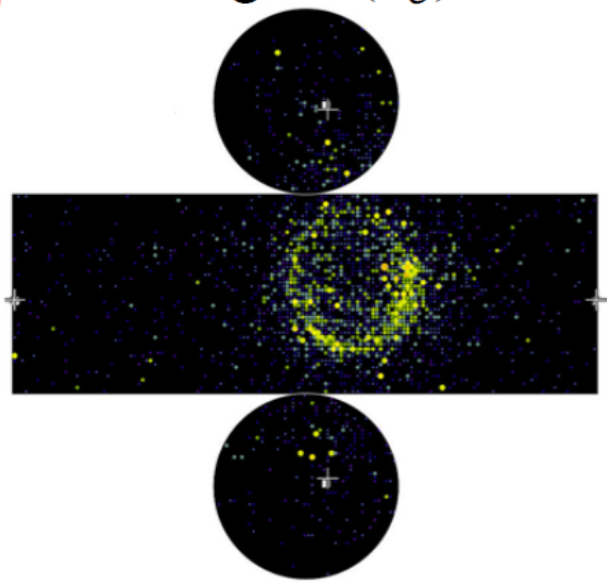


short, with typical EM shower profile

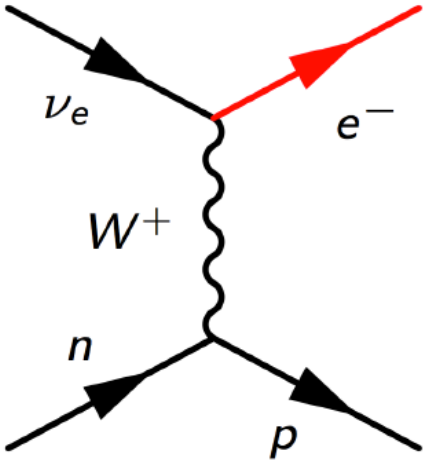


Neutrino Detection at SK Far Detector

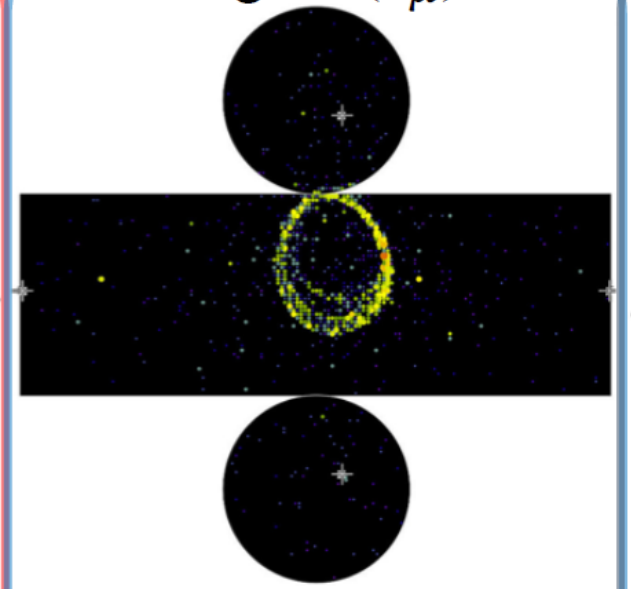
Signal (ν_e)



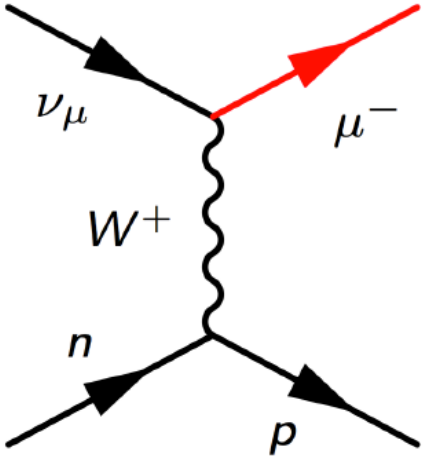
ν_e CCQE



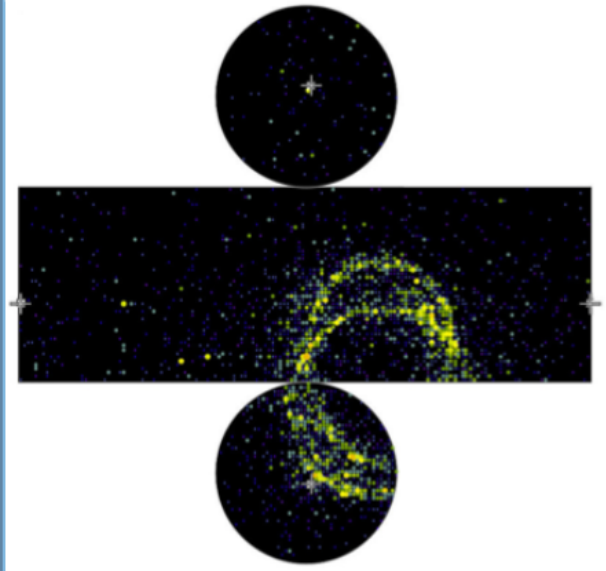
Signal (ν_μ)



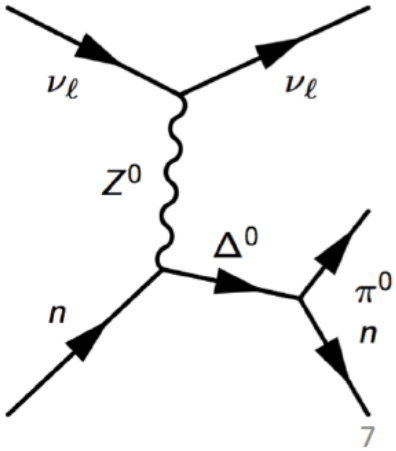
ν_μ CCQE



Background

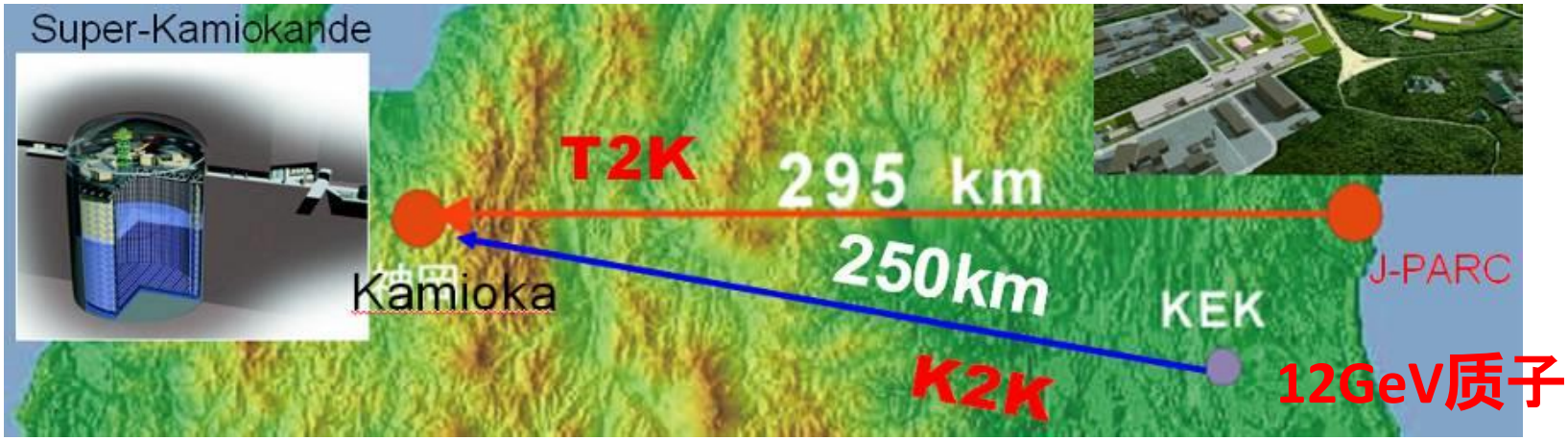


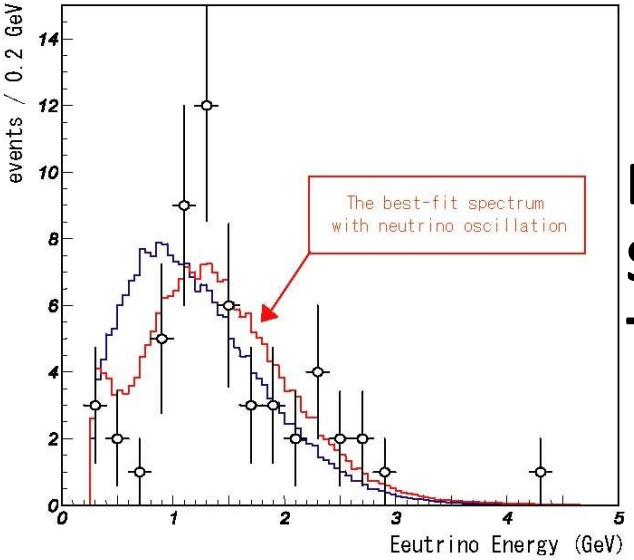
ν_ℓ NC1π^0



K2K

- 2003年日本的K2K实验用加速器验证了大气中微子振荡。第一个长基线加速器中微子实验。





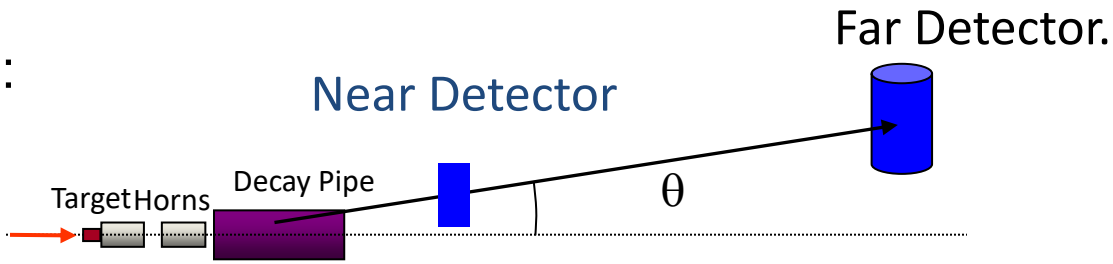
Event rate: 2.9σ

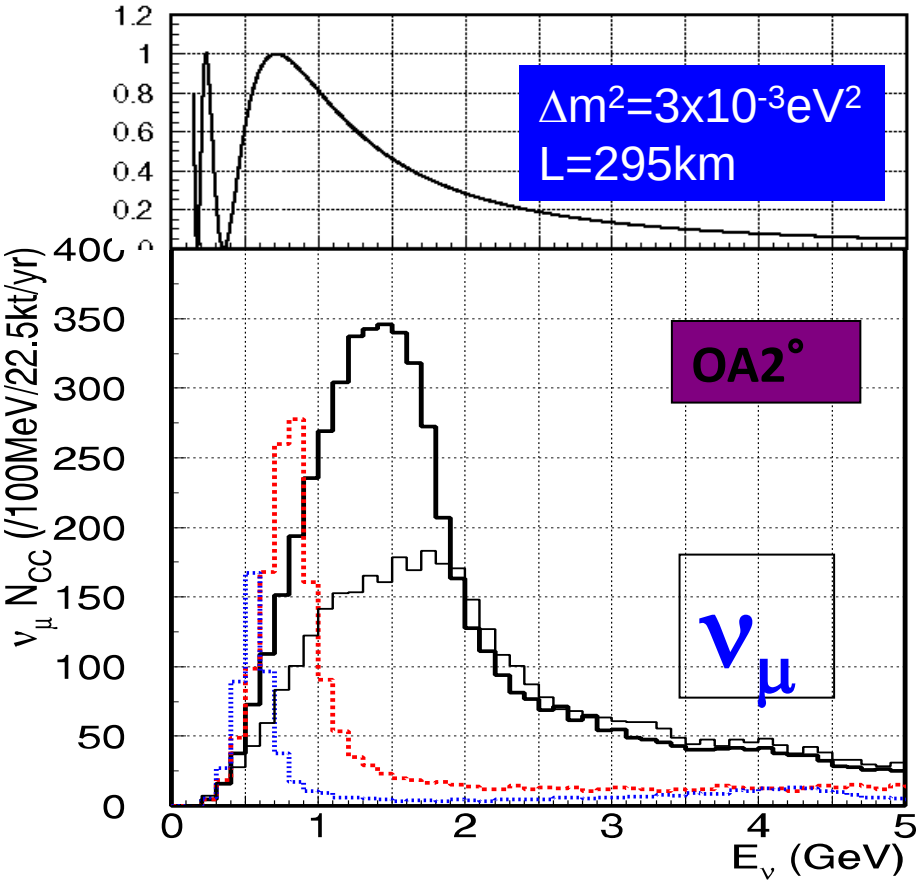
Spectrum: 2.5 σ

Total: 3.9 σ

Neutrino beam: Off-Axis

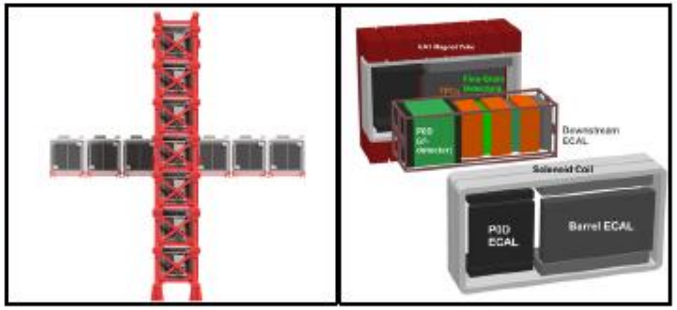
an Idea from BNL (TRIUMF):
T2K, NOvA

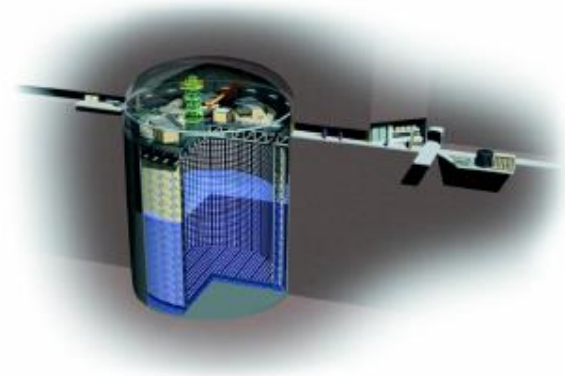


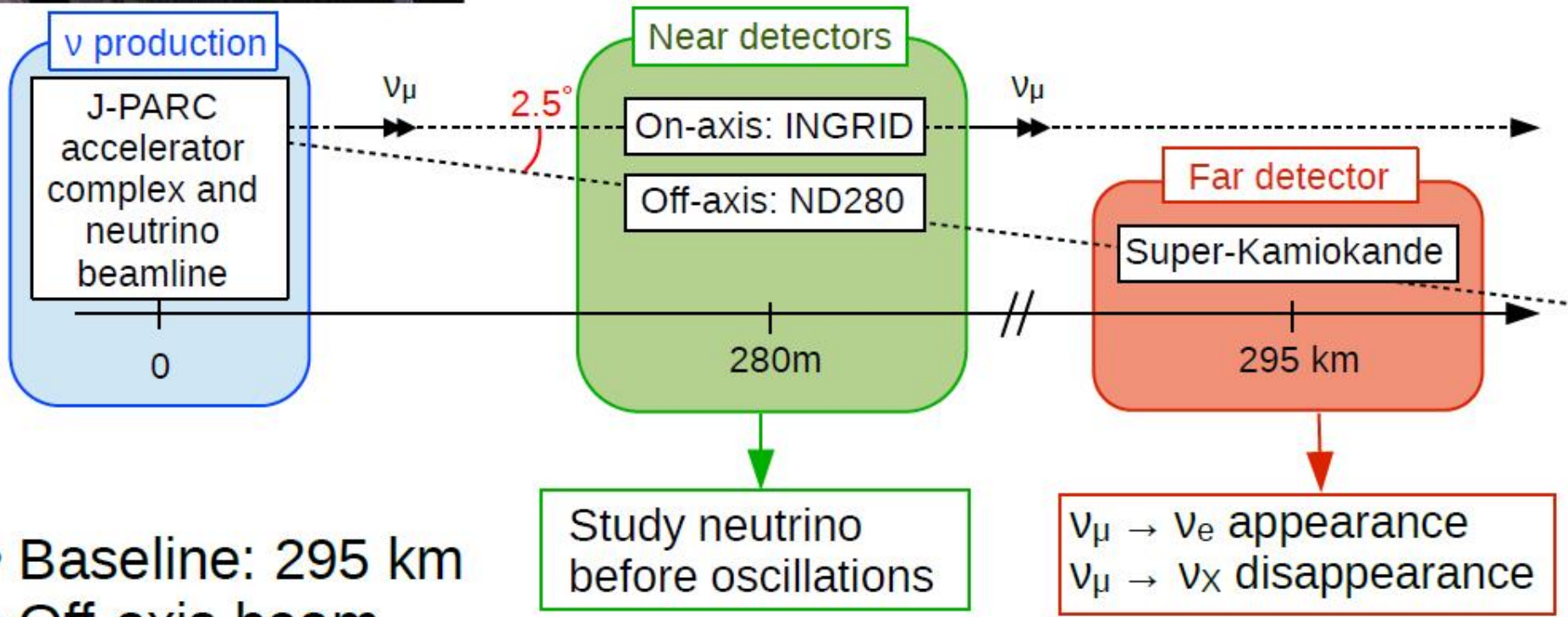


- ***Pros –***
  - ⇨ ***Increases flux on osc. max.***
  - ⇨ ***Reduces high-E tail, and thus NC backgrounds***
  - ⇨ ***Reduces ν_e contamination from K and μ decay***
- ***Cons –***
  - ⇨ ***Complicates disappearance measurement***
  - ⇨ ***Increases near/far differences***
  - ⇨ ***Have to know angle!***

T2K Experiment

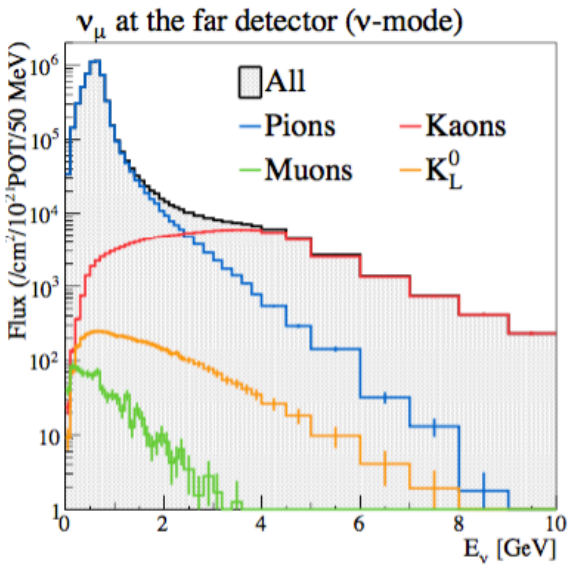


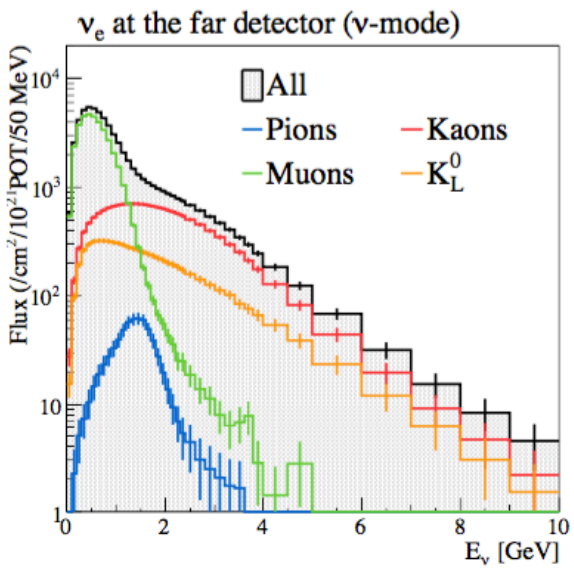




- Baseline: 295 km
- Off-axis beam

Intrinsic ν_e Background / Xsec



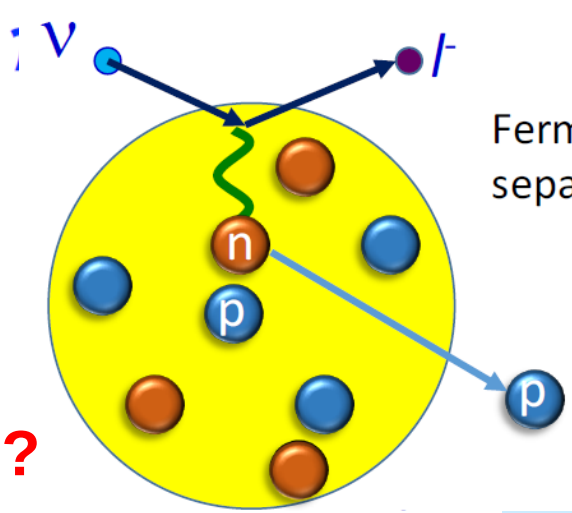


ν_μ (anti-ν_μ) : pions at low E_ν, kaons at large E_ν

ν_e : muons at at low E_ν, kaons at high E_ν
anti-ν_e : kaons for all E_ν

ν_μ parents:

1. π
2. K^+

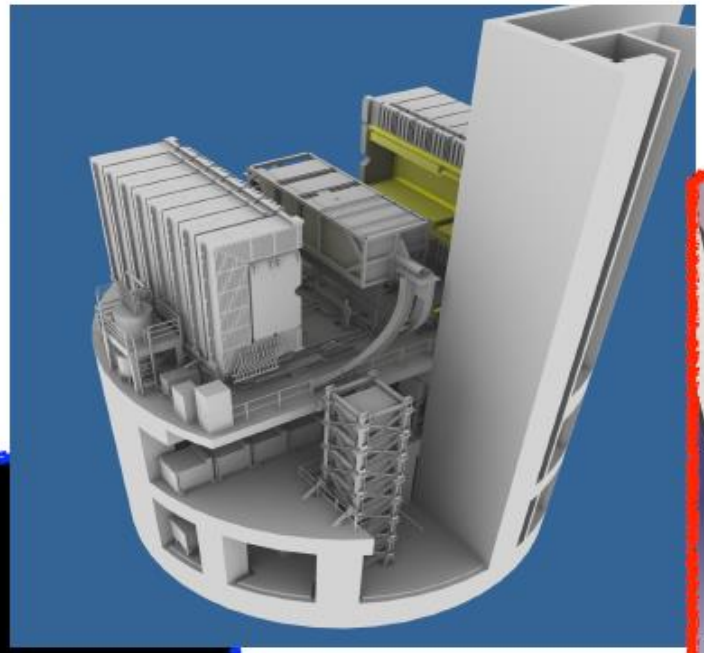


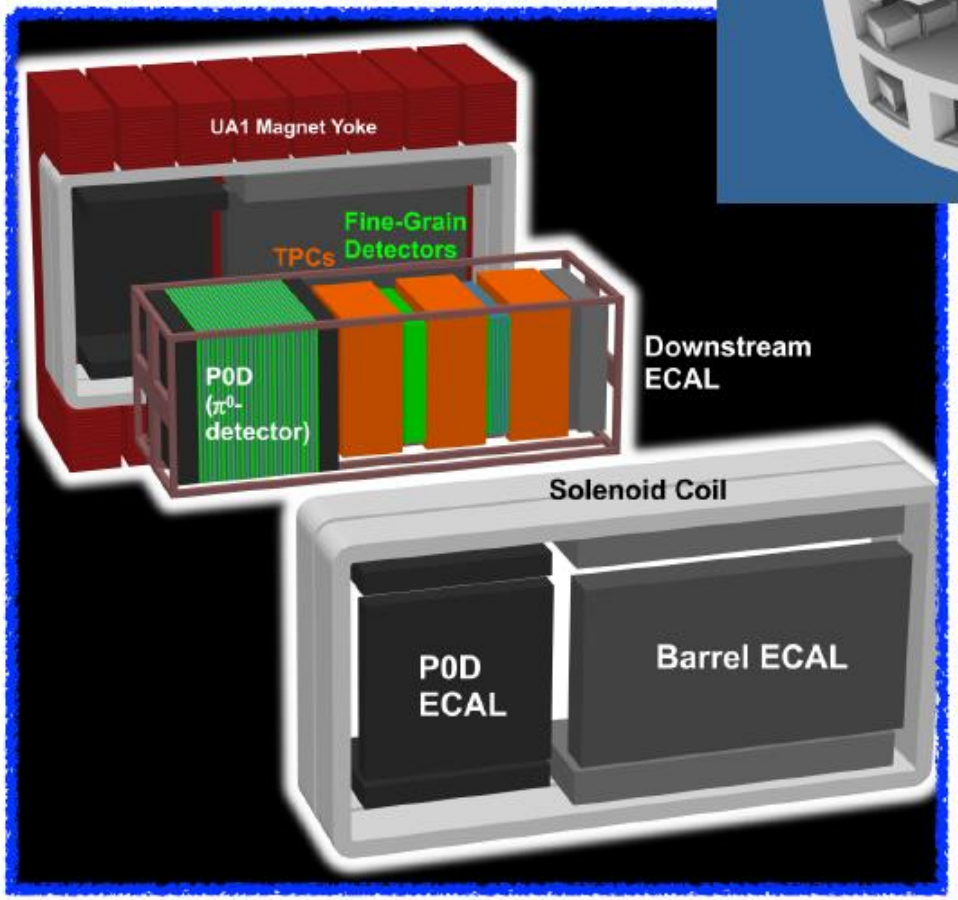
Fermi motion, separation energy etc..

Neutrino Cross section?

ND280

Near Detector @ 280m from the target



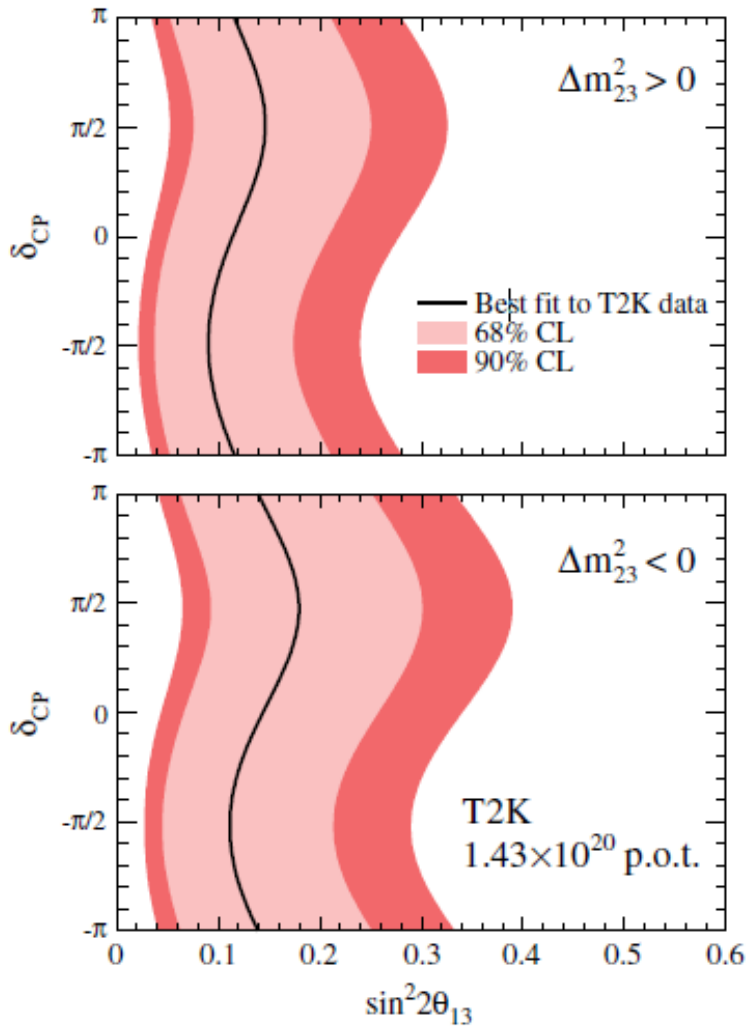


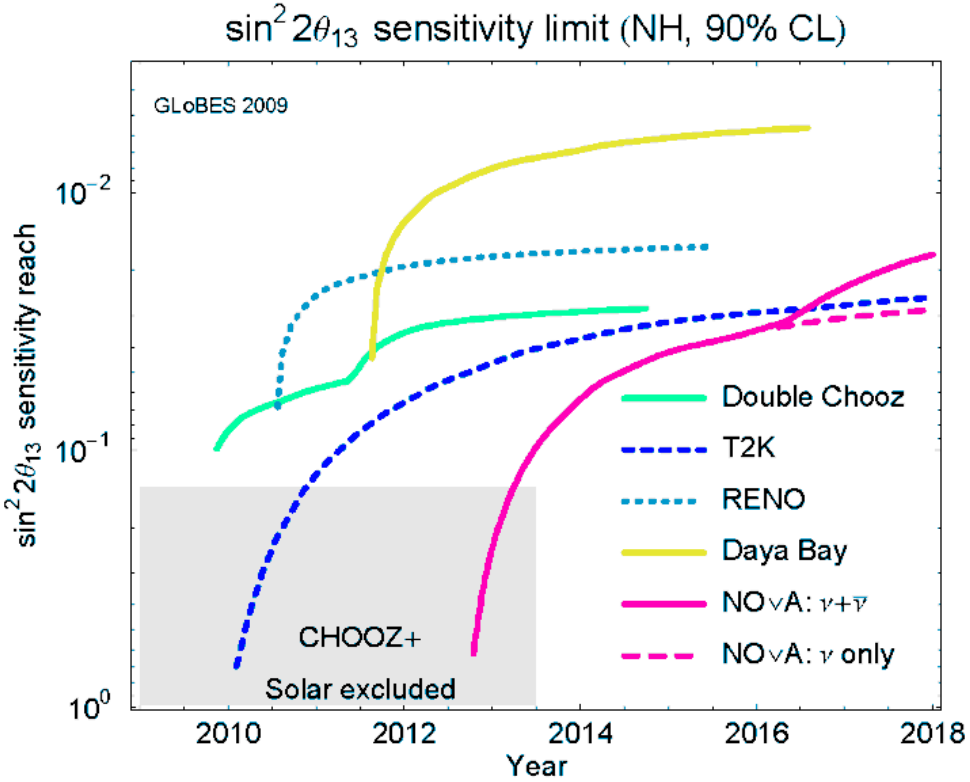
- **INGRID** @ on-axis (0 degree)
  - ν beam monitor [rate, direction, and stability]

- **ND280** @ 2.5 degree off-axis
  - Normalization of Neutrino Flux
  - Measurement of neutrino cross sections.
    - Dipole magnet w/ 0.2T
    - **P0D**: π^0 Detector
    - **FGD+TPC**: Target + Particle tracking
    - **EM calorimeter**
    - **Side-Muon-Range Detector**

T2K发现theta13非零迹象

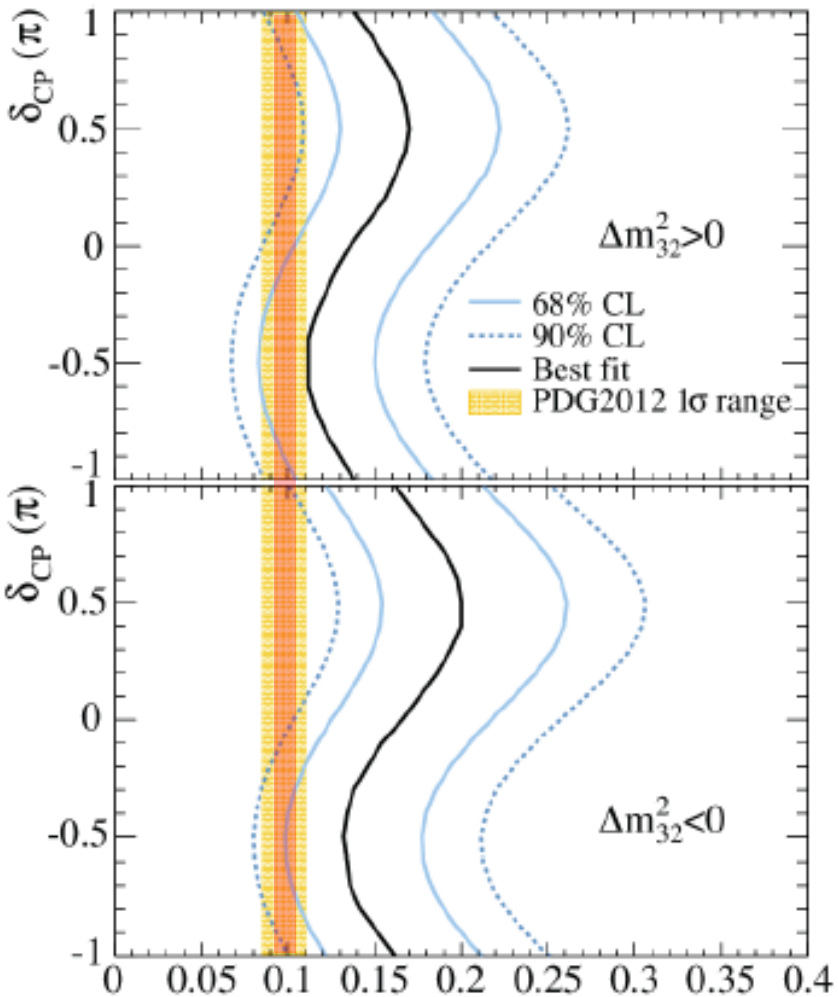
- 2011年6月15日，日本T2K实验宣布探测到6个电子中微子
- 2011年3月11日福岛地震





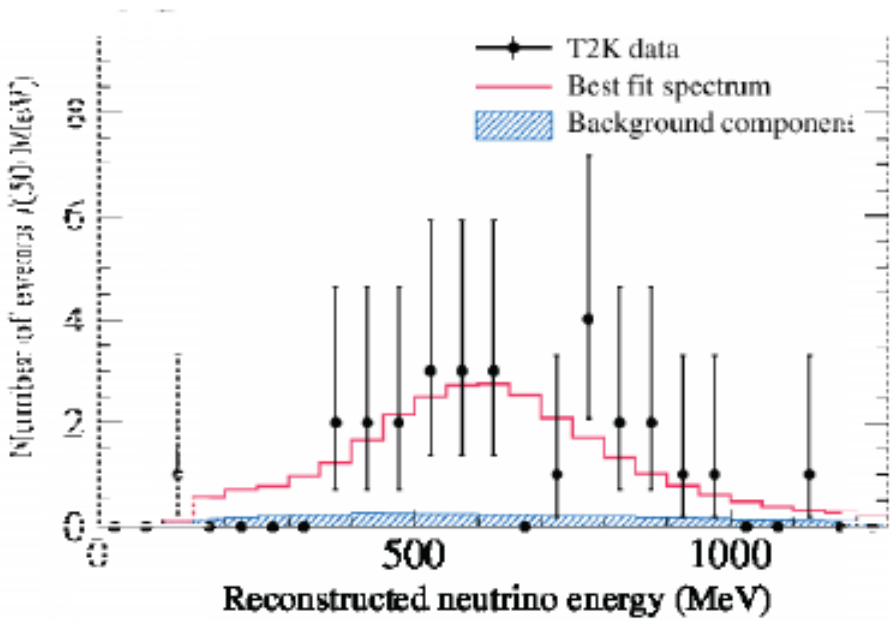
T2K与反应堆测量的 θ_{13} 结合 →

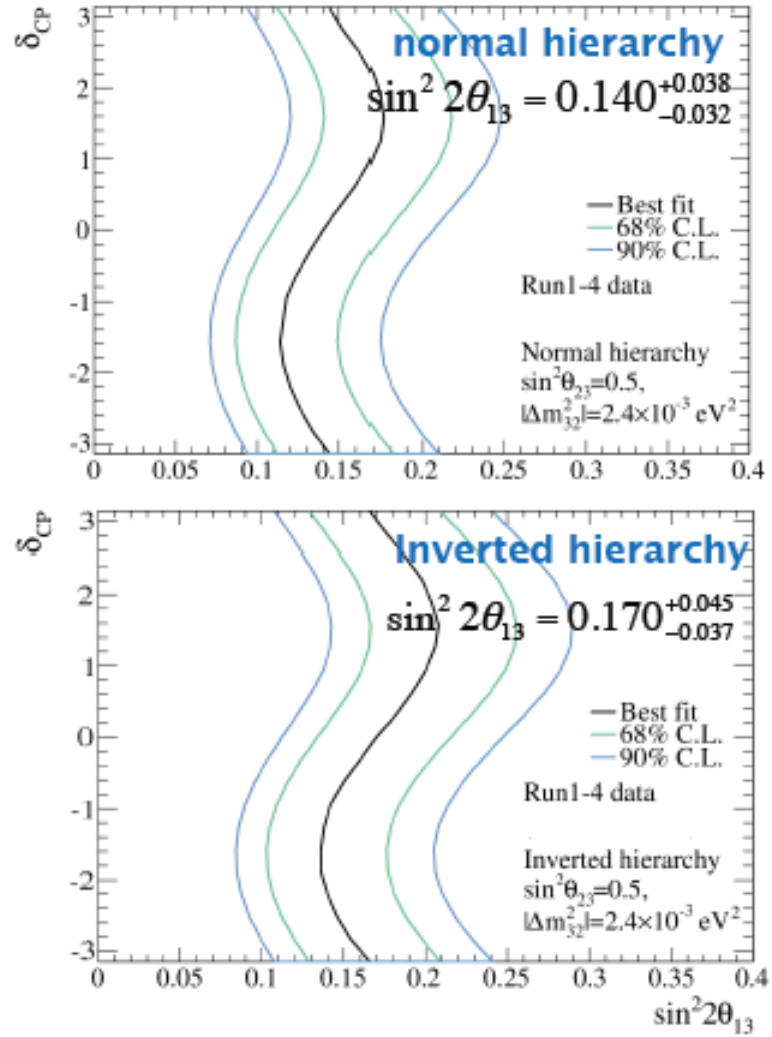
- Comparing with the external reactor constraint the best overlap is for the normal hierarchy with $\delta_{cp}=-\pi/2$.
- This is a **lucky point**!
- You also need to increase the θ_{23} mixing angle to account for the number of observed events.



Phys. Rev. Lett. 112, 061802 (2014)

T2K observation of ν_e Appearance





4.92 ± 0.55 events expected background

28 events observed

21.6 events expected @ $\sin^2 2\theta_{13} = 0.1$

$\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

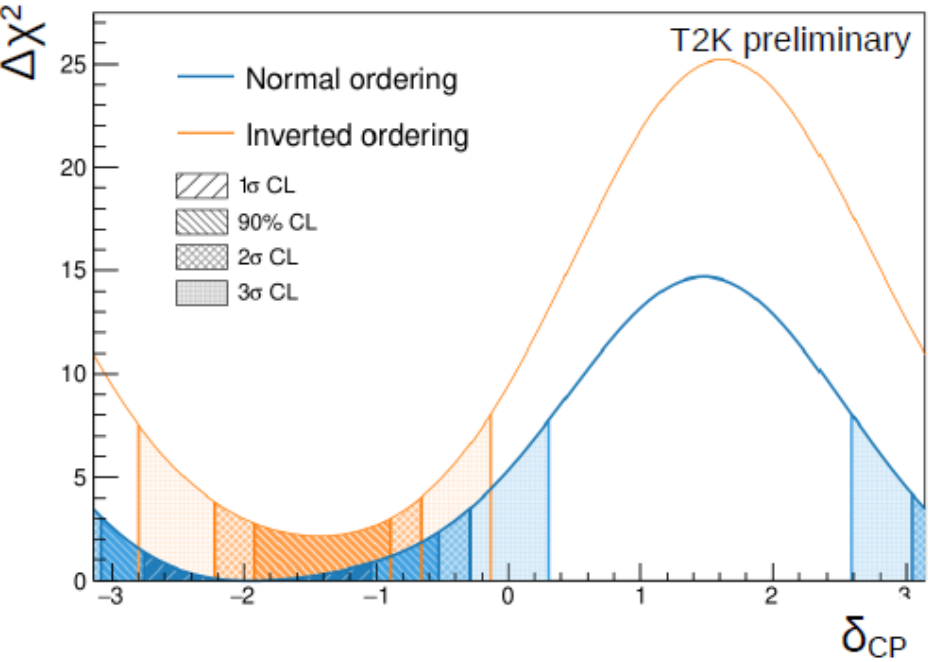
7.3 σ significance for non-zero θ_{13}

First ever observation (>5σ) of an explicit ν appearance channel

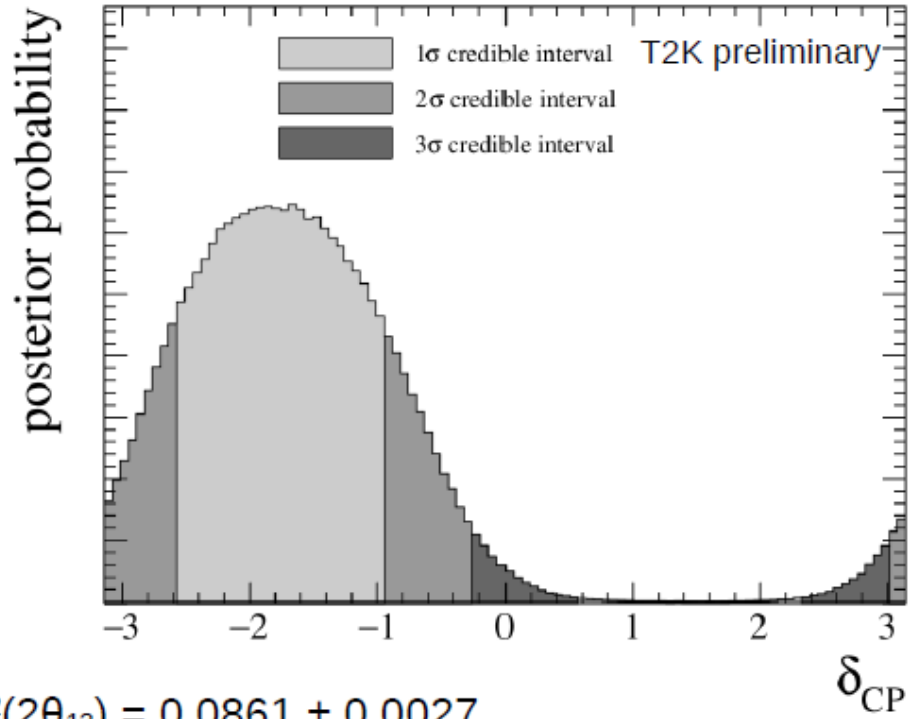
T2K最近CP测量结果

- CP-conserving values of δ=0 and δ=π outside of 90% CL intervals
- Tested effect of alternative interaction model, did not find biases that would change this conclusion

Frequentist results
(Feldman-Cousins method)



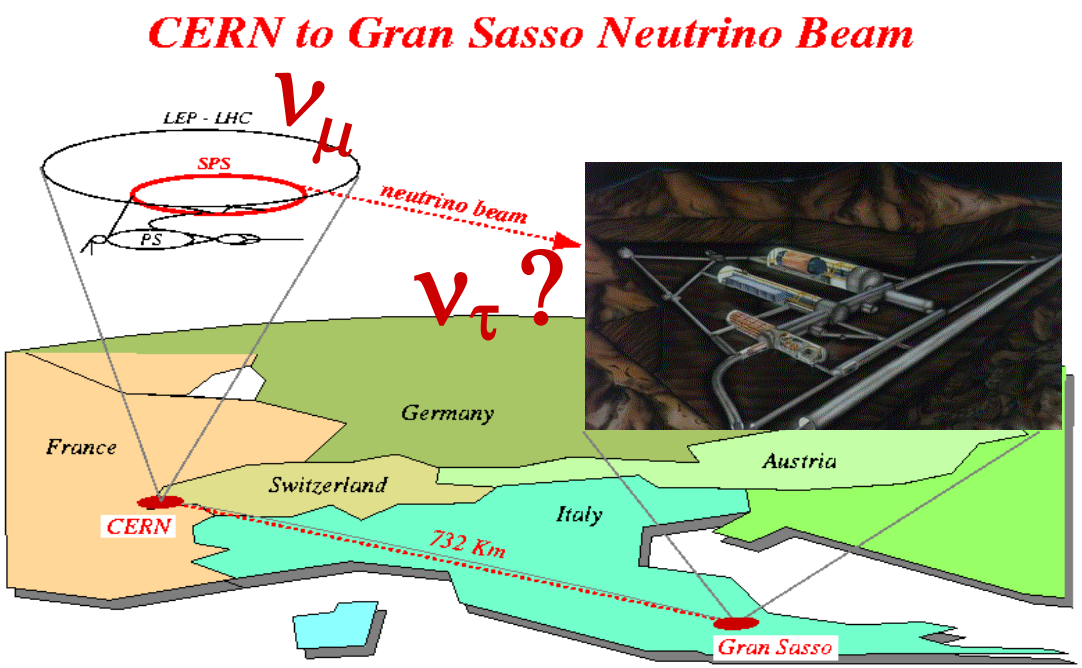
Bayesian results
(marginalized over MO)



Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

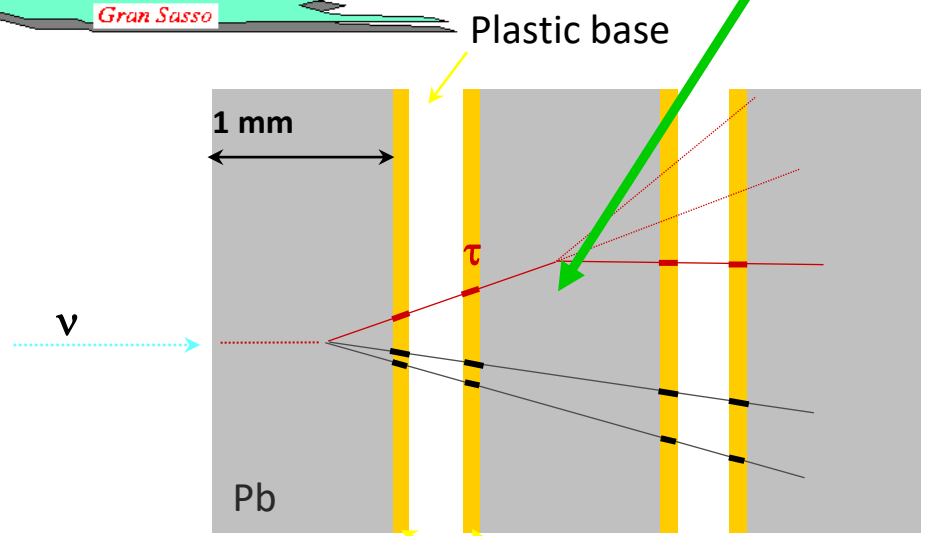
- **提升加速器功率，运行至HK建成，有望CP~3σ**

CNGS and OPERA



Direct approval of $\nu_\mu \rightarrow \nu_\tau$ oscillation

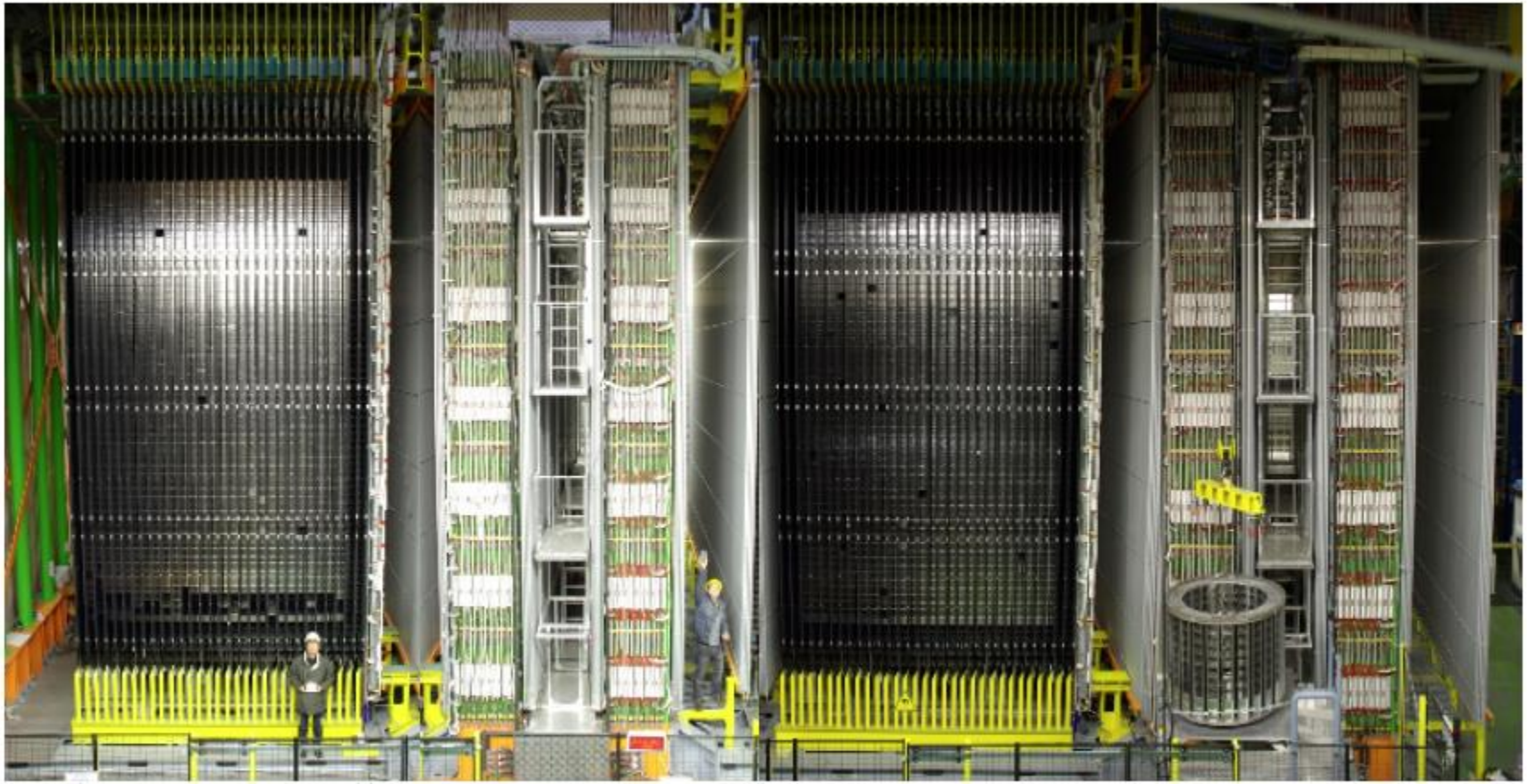
Signature of τ appearance



OPERA 探测器

OPERA detector 150,000 ECC 1.25kton target

~3'100 m.w.e. overburden, ~1 cosmic μ / m^2 x hour

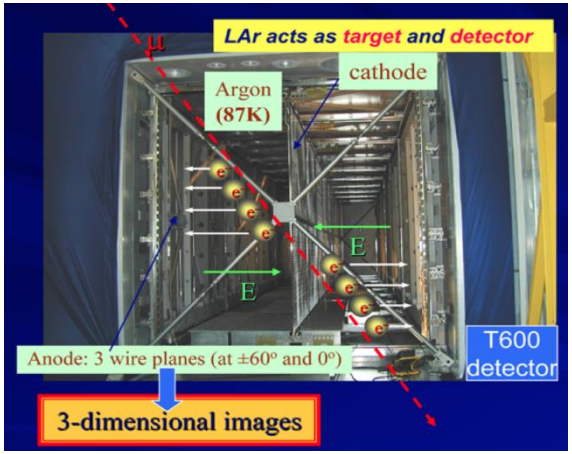


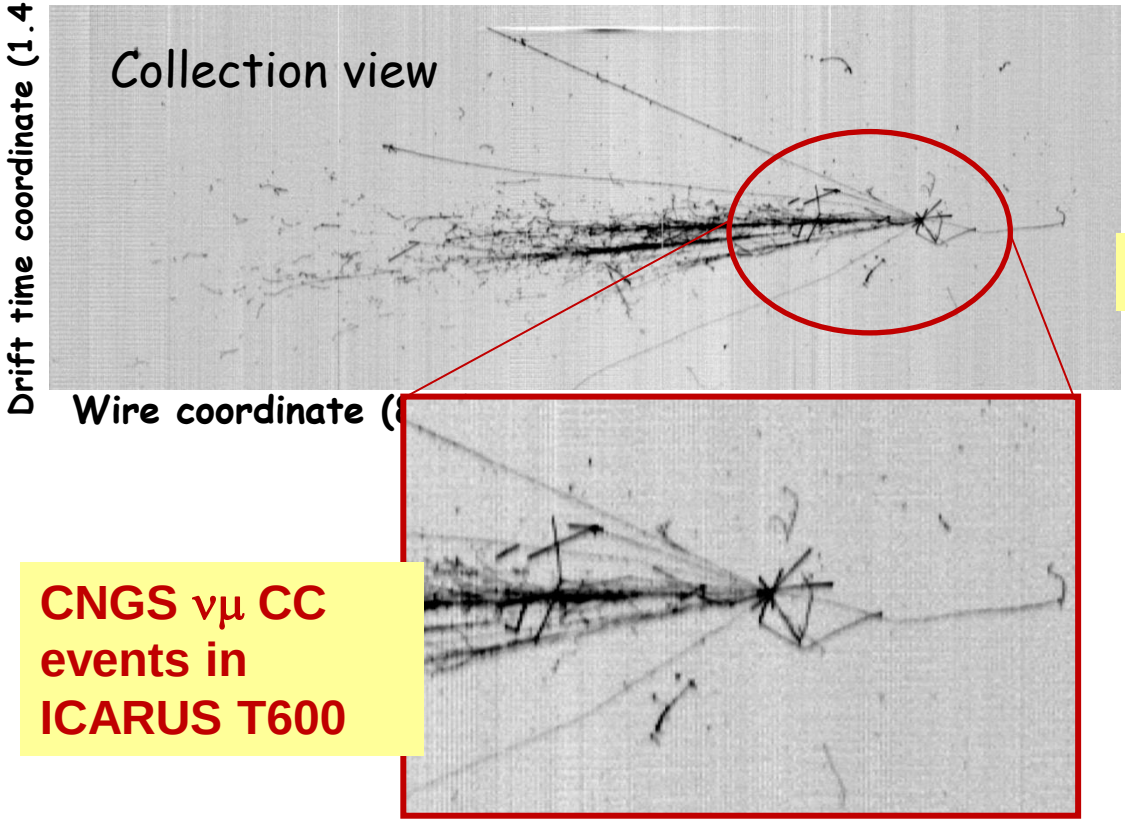
Target area

Muon spectrometer

ICARUS

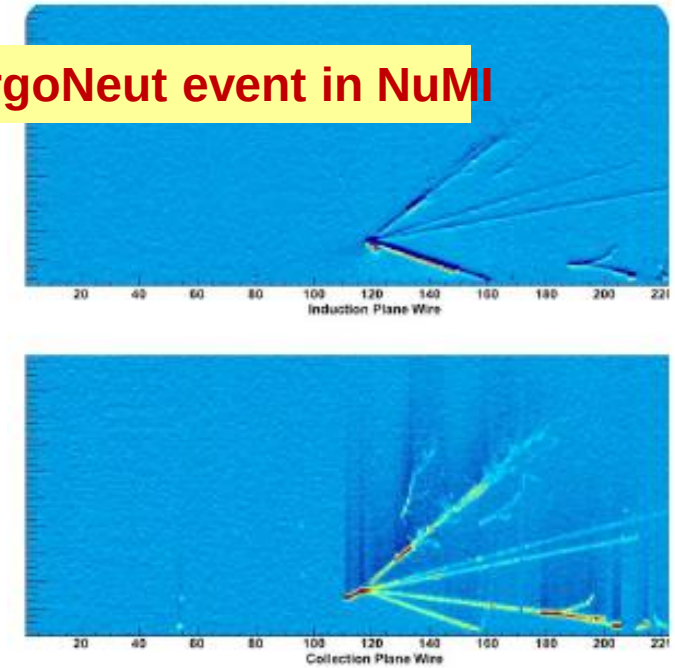
- ICARUS: Gran Sasso Lab
- 液氩TPC: Time Projection Chamber (时间投影室)，3D成像
- Successful After 20 years R&D



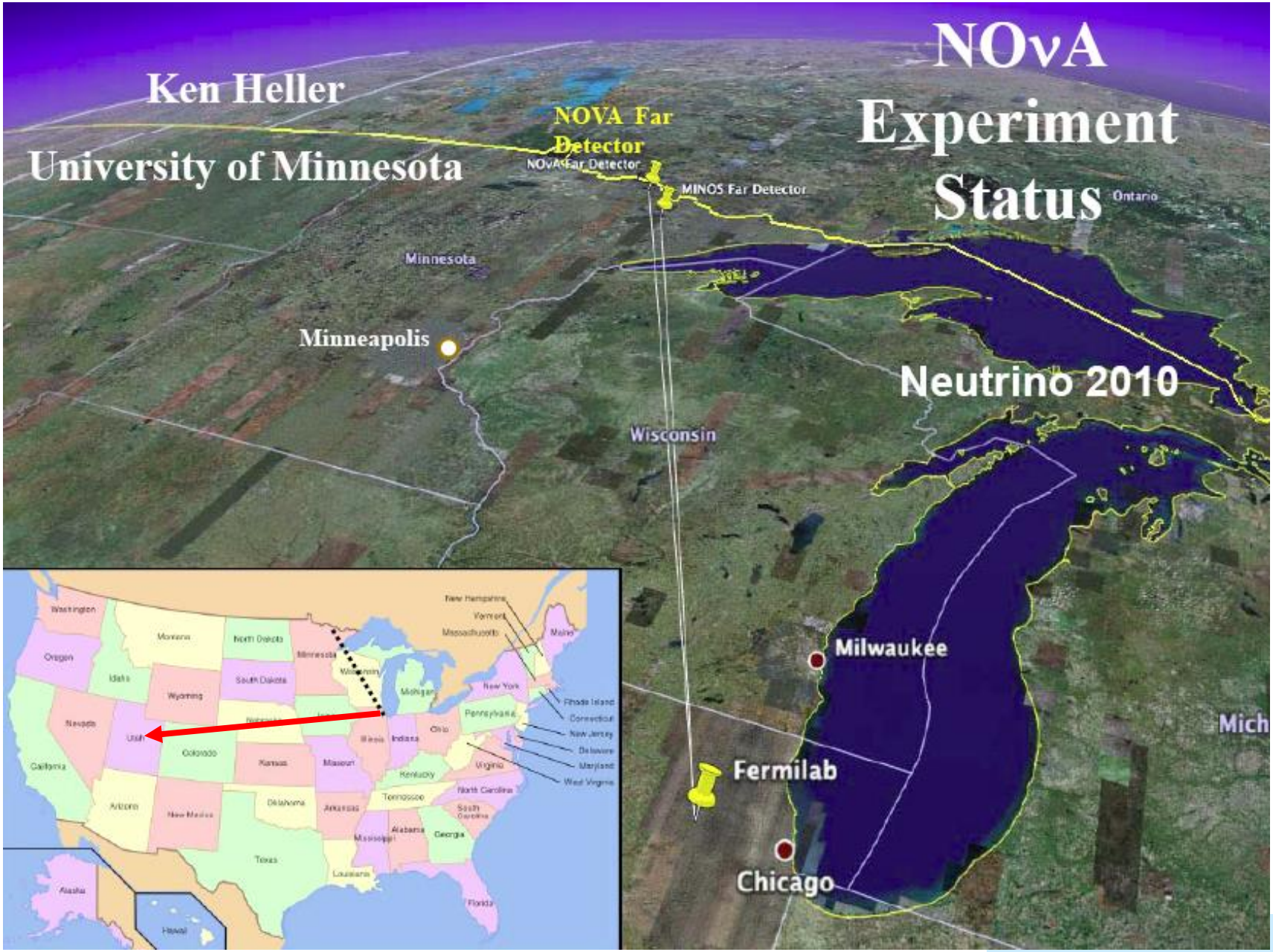


CNGS νμ CC events in ICARUS T600

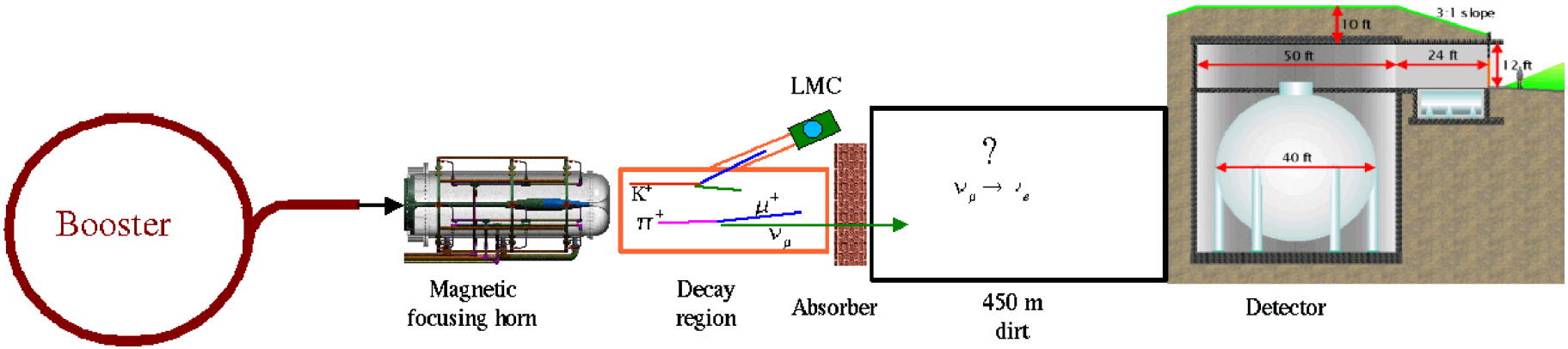
ArgoNeut event in NuMI



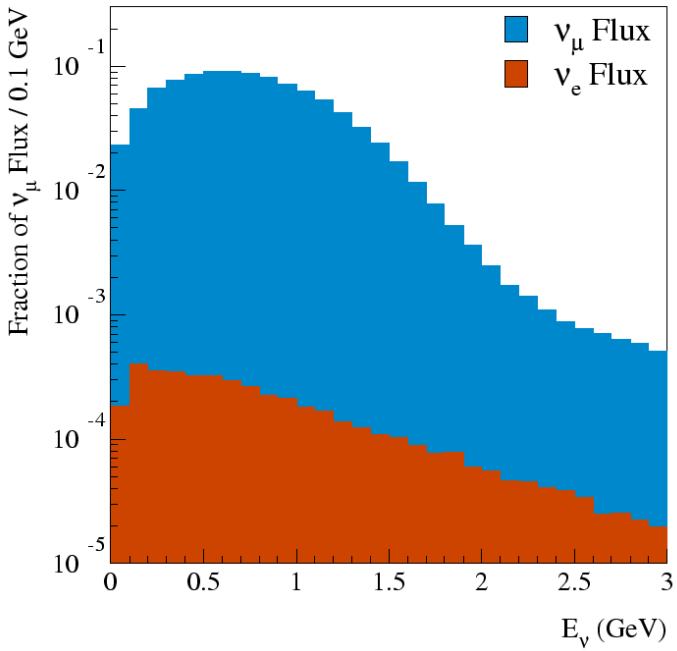
美国费米实验室的中微子束流



MiniBooNE

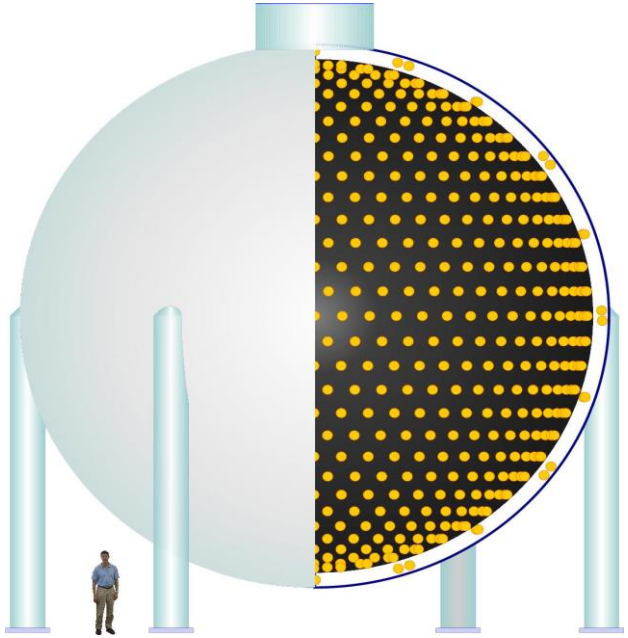


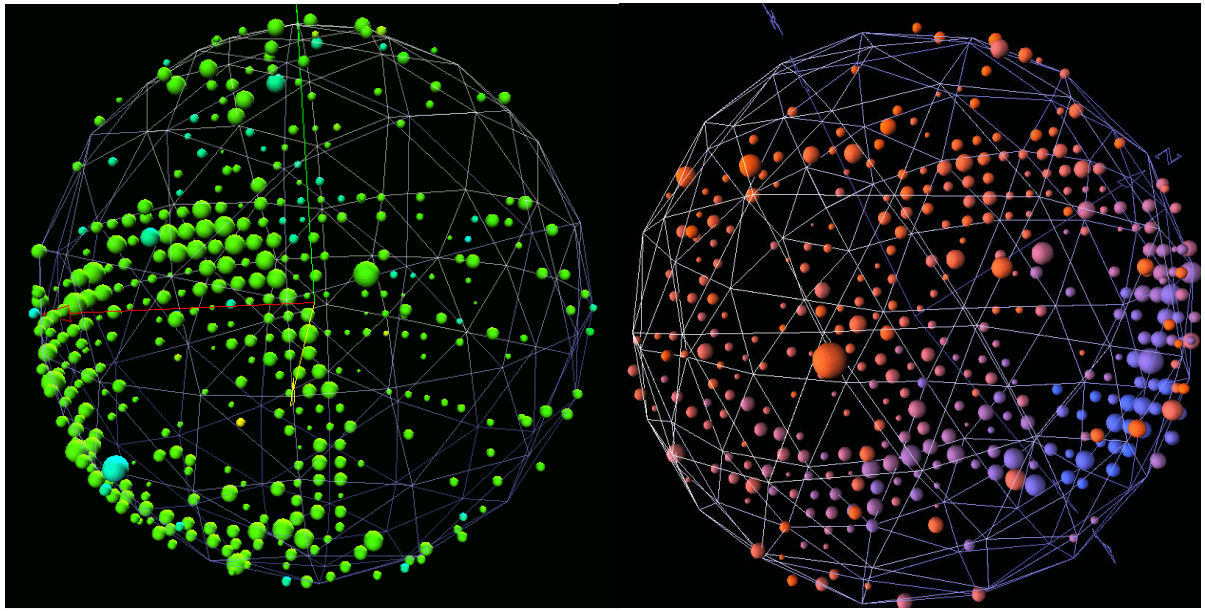
- LSND
- Primary Beam: 8 GeV proton
- Beryllium target produce π^+ and κ^+ in range of 1-4 GeV
- Produced mesons are focused by horn.
- Mesons decay to secondary beam ν_μ and intrinsic background ν_e



MiniBooNE Detector

- 12 m in diameter.
- Filled with mineral oil.
- 1280 PMTs in tank region, 10% coverage with 8in PMTs.
- 240 PMTs in veto region.



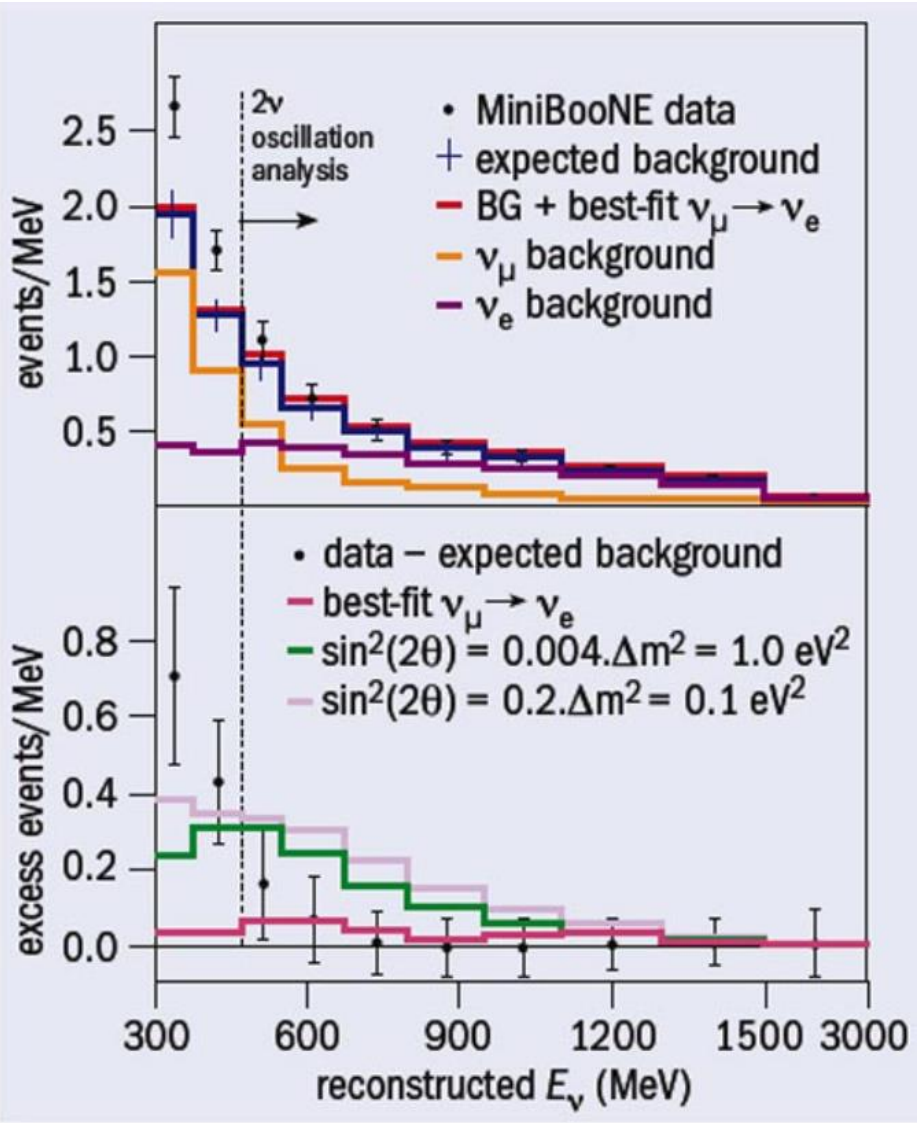


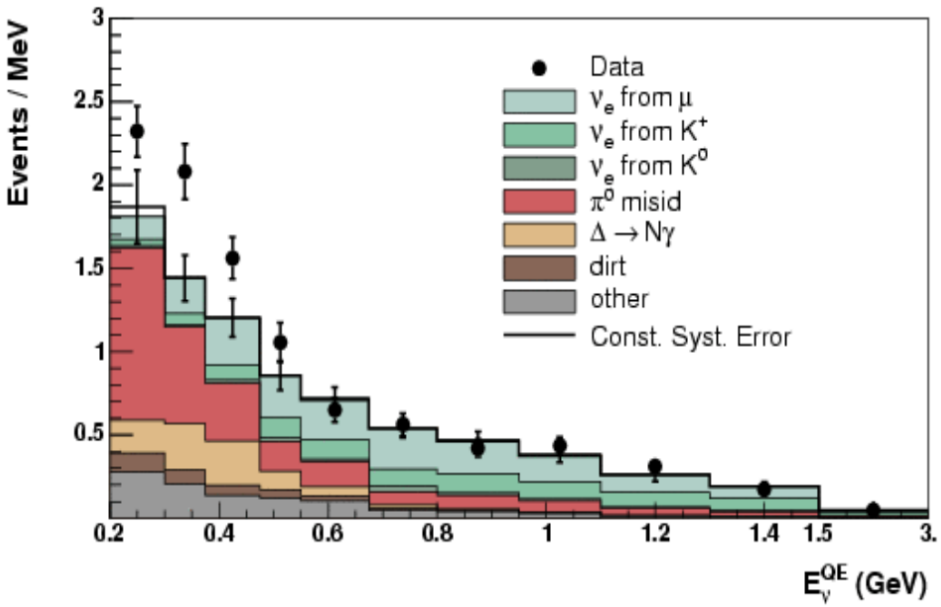
Left picture shows event display of a comic muon

Right one is a candidate of π^0

MiniBooNE结果

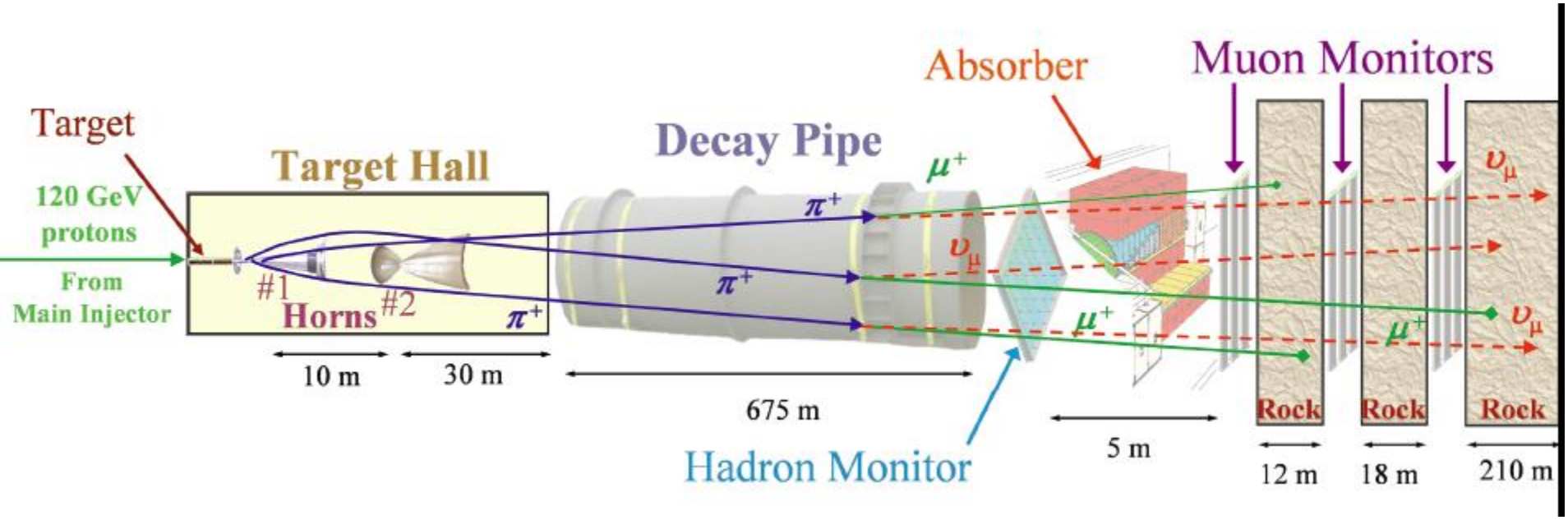
- CERN Courier: MiniBooNE solves neutrino mystery (30 April 2007)



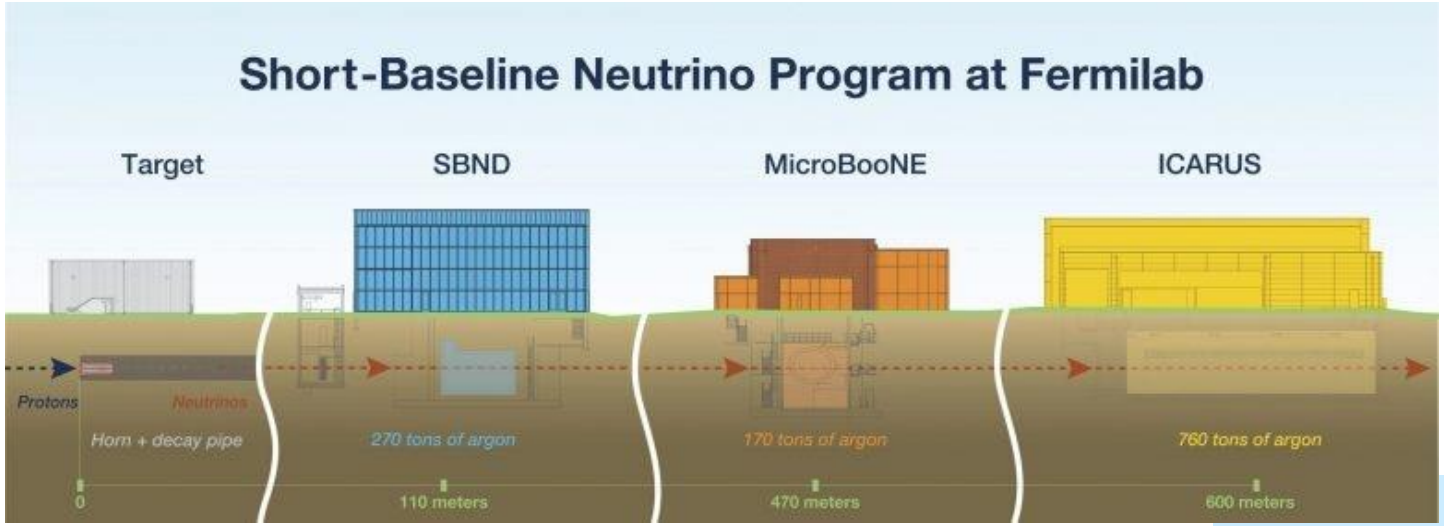


→ MicroBooNE

Neutrinos at the Main Injector(NUMI)



120 GeV proton beam from the main Injector on graphite target

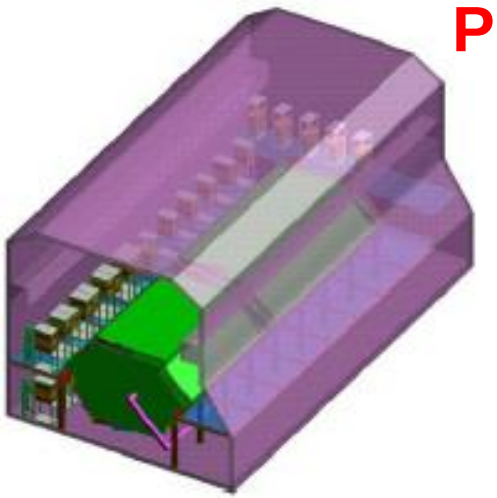


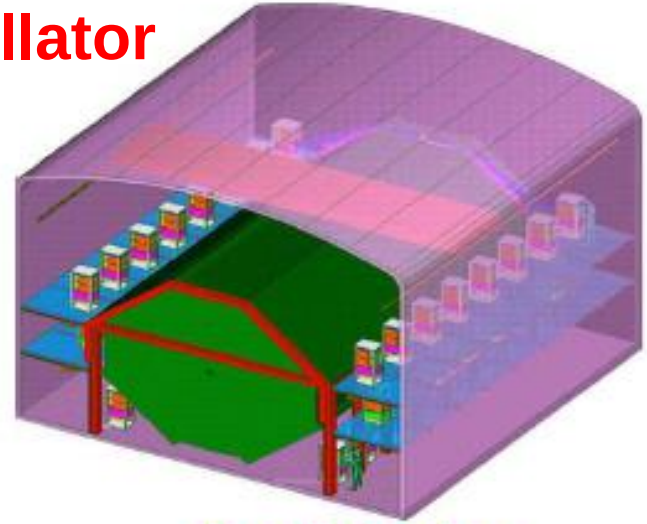
MINOS Detectors

Magnetized Steel and Scintillator Tracking Calorimeter

- 2.5cm thick Magnetized steel planes: B~1.3T
- 1cm thickx4.1cm width plastic scintillator strips arranged orthogonal orientation on alternate planes

Plastic Scintillator





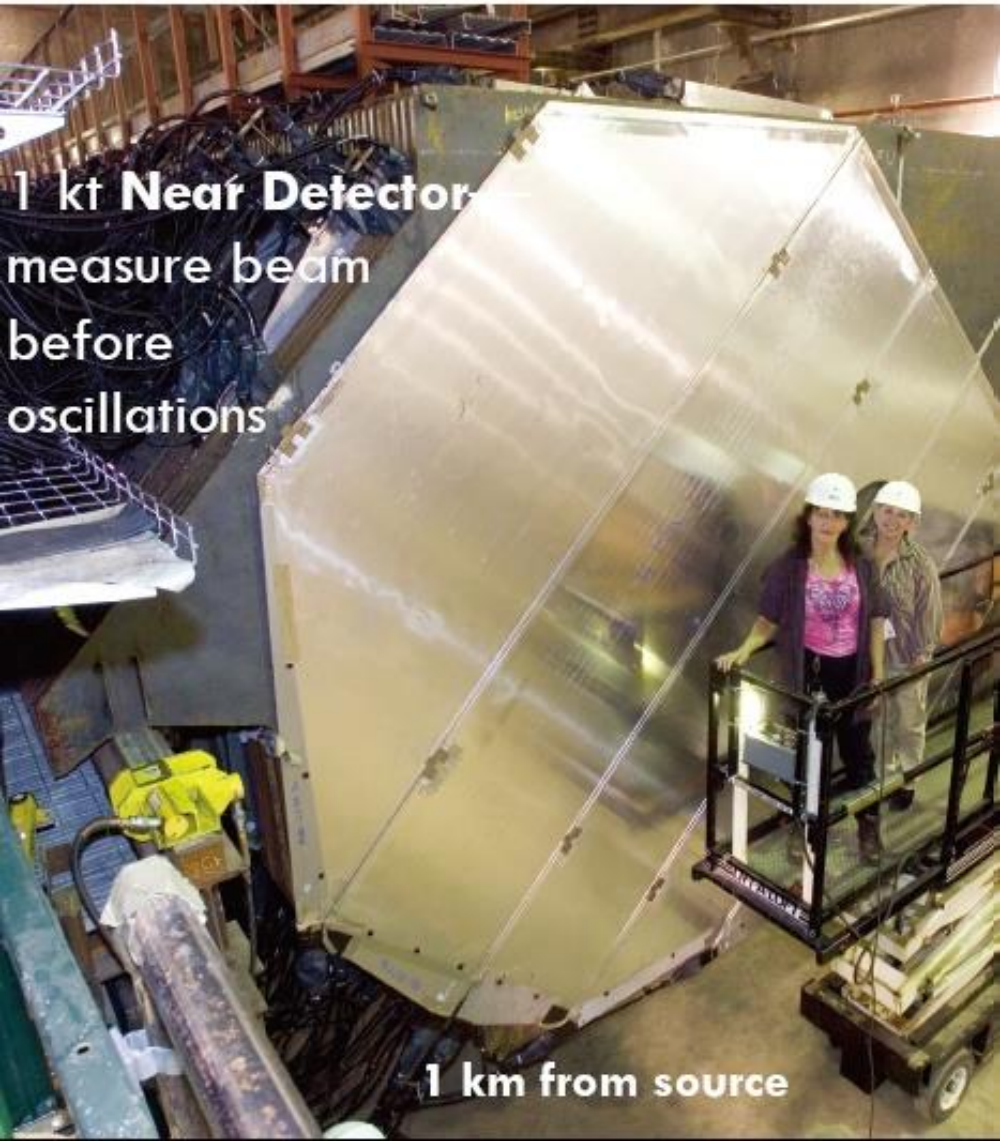
Near Detector

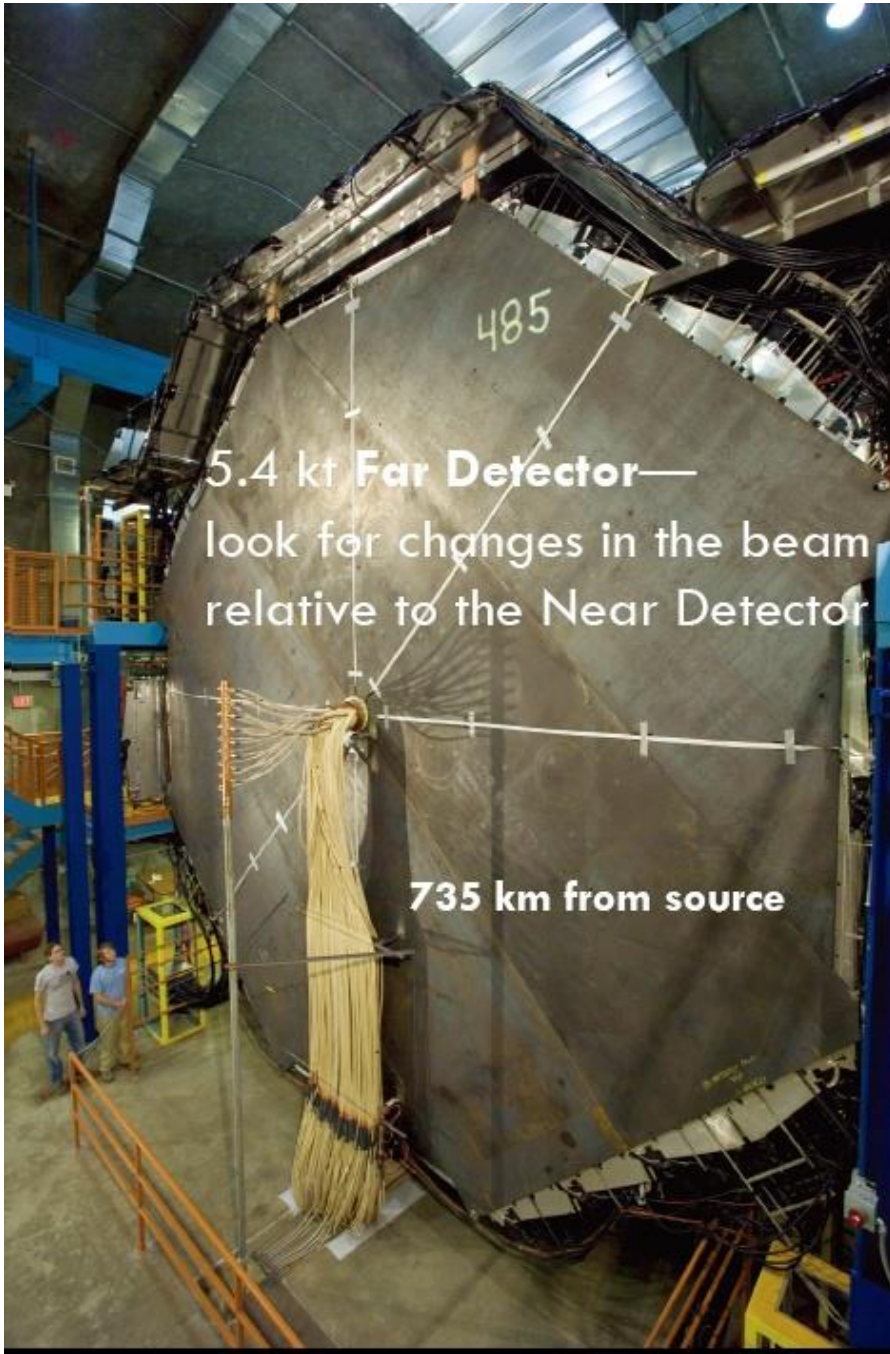
- 1kton mass (3.8x4.8x17m^3)
- 44ton fiducial mass
- 282 steel and 153 scintillator planes

Far Detector

- 5.4kton mass (8x8x30m^3)
- 3.9kton fiducial mass
- 484 steel and scintillator planes

Magnetized, tracking calorimeters





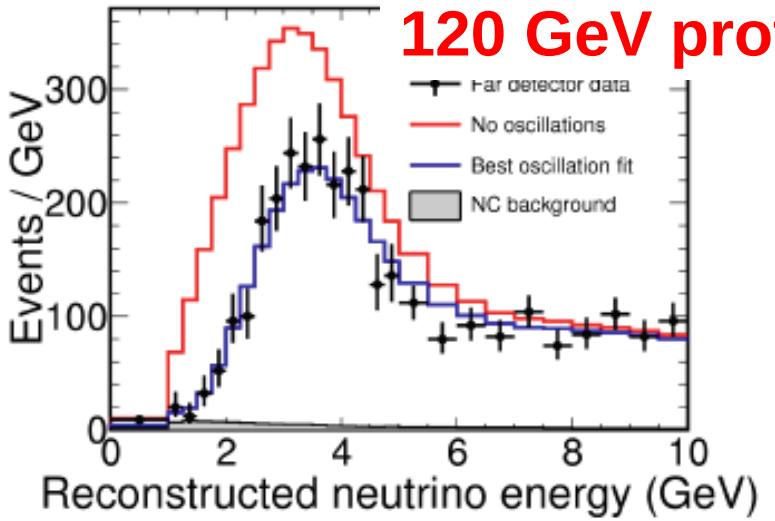
MINOS charged current disappearance results (arXiv:1103.0340)

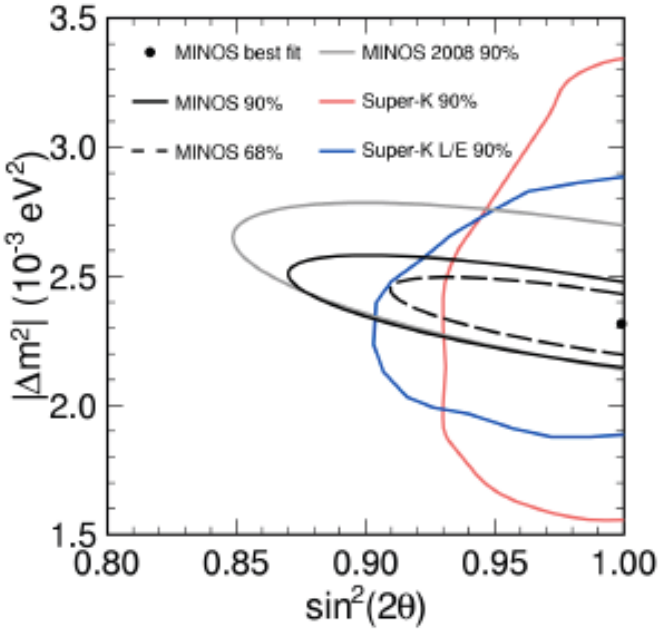
April 2011

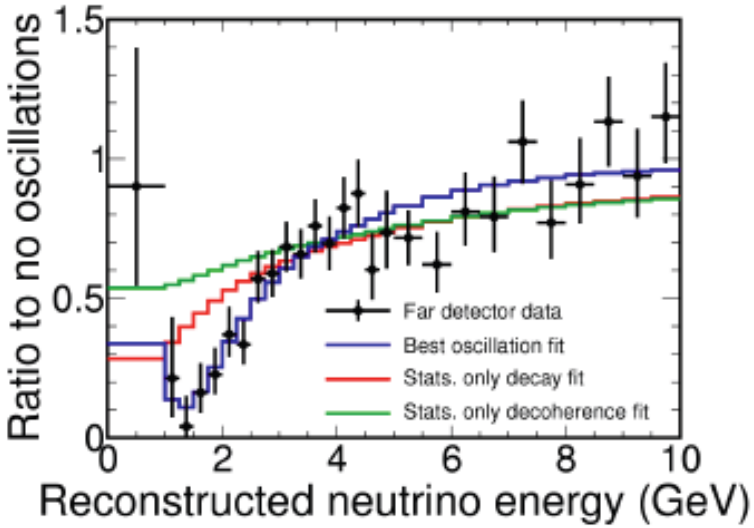
Best fit: $\left|\Delta m^2\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$

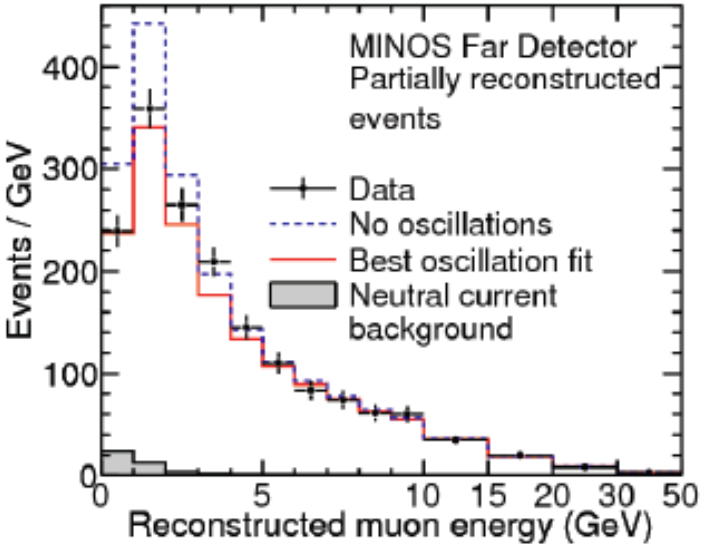
$\sin^2(2\theta) > 0.90$ (90% C.L.)

120 GeV proton



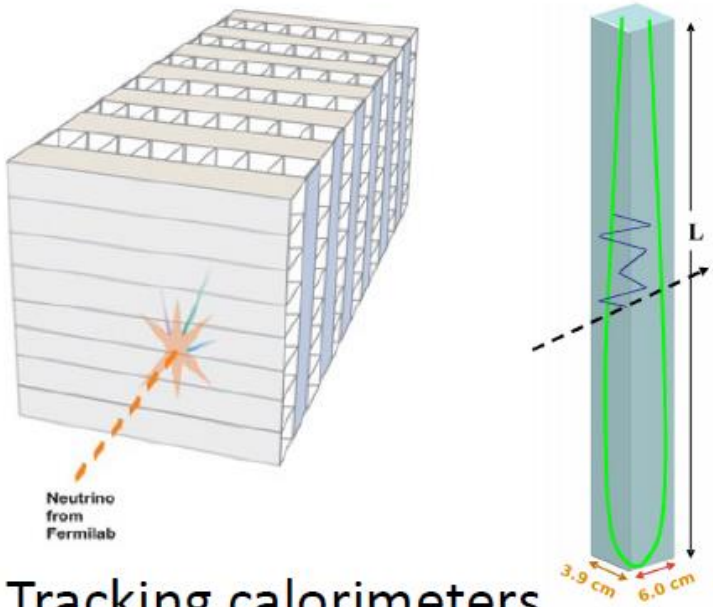




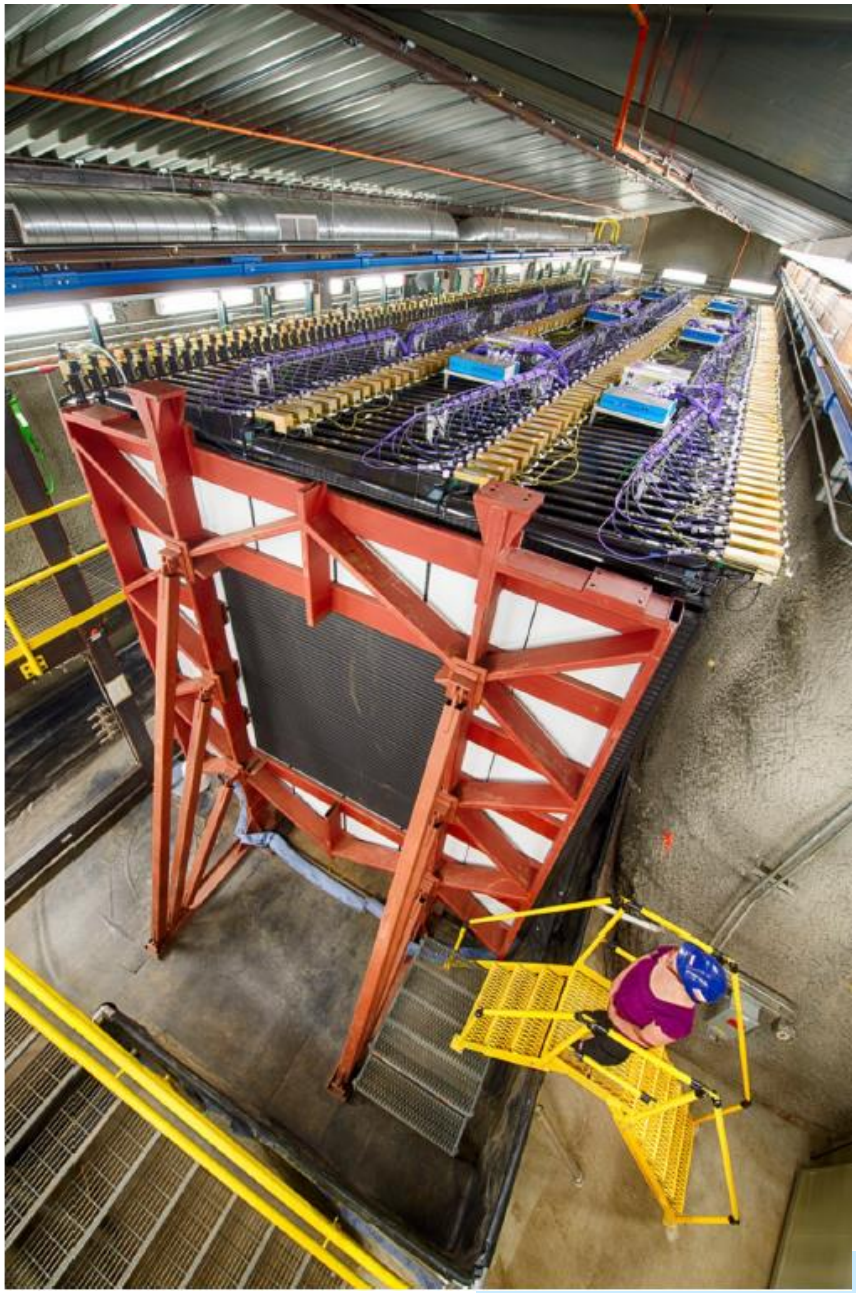


NOvA (off-axis)

NOvA Detectors



- Tracking calorimeters
- Extruded plastic cells, filled with liquid scintillator
- 0.17 X_0 per layer
- Near Detector
  - 300 tons, 1 km from target
  - Huge statistics: >1M ν_μ CC selected events



NOvA结果与计划

Best Fit

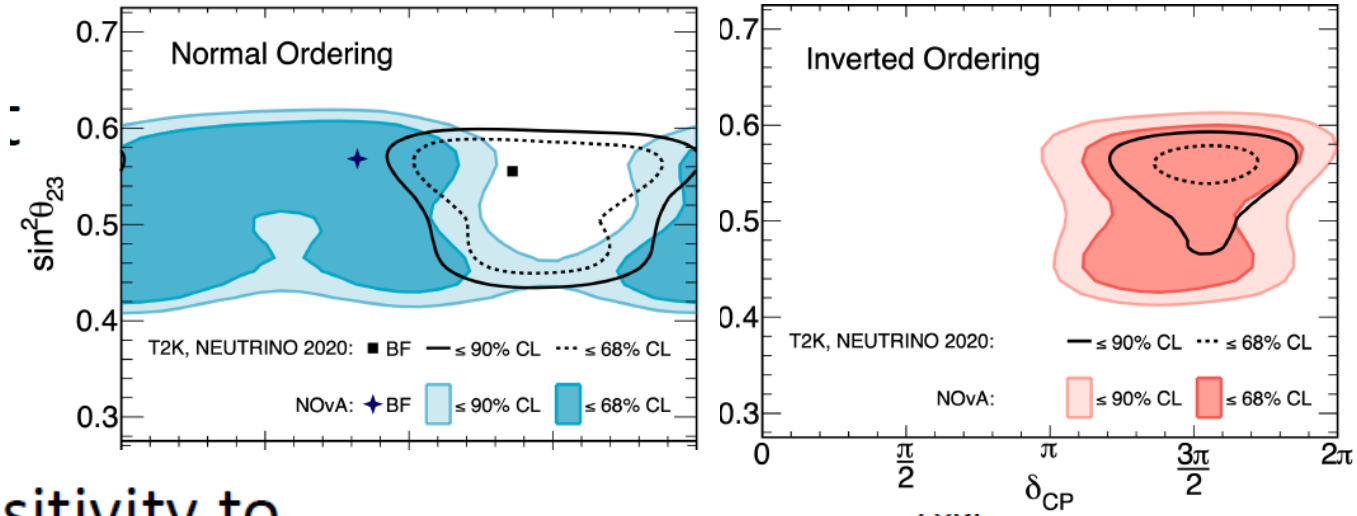
Normal hierarchy

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ eV^2$

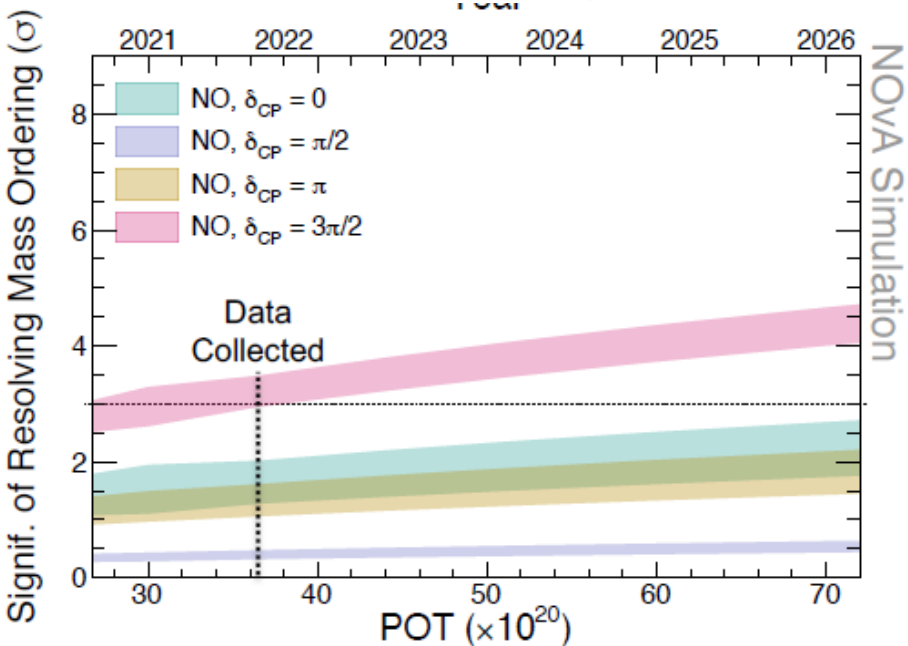
$\sin^2\vartheta_{23} = 0.57^{+0.04}_{-0.03}$

$\delta = 0.82\pi$

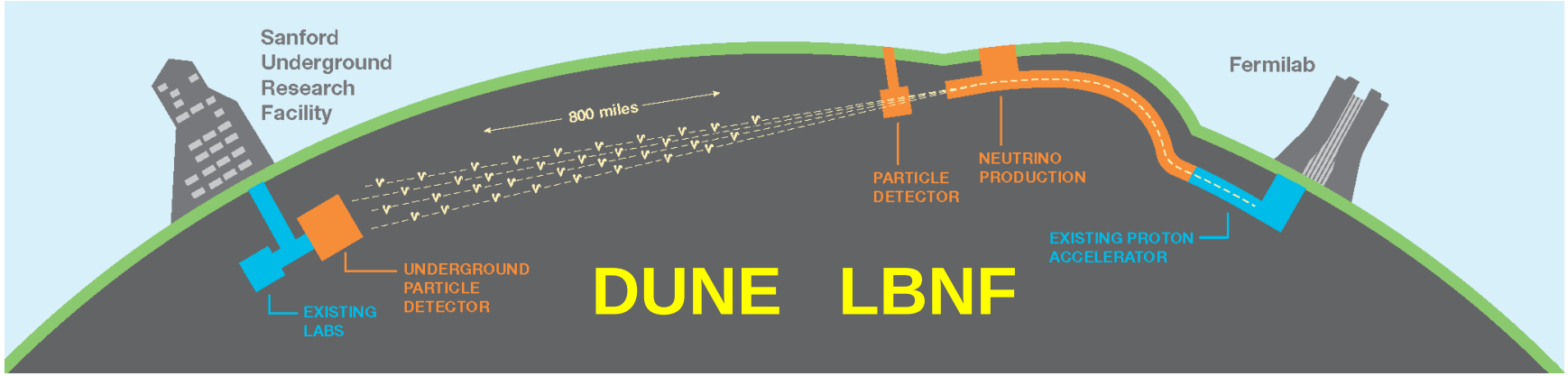
2020 data set: https://arxiv.org/abs/2108.08219



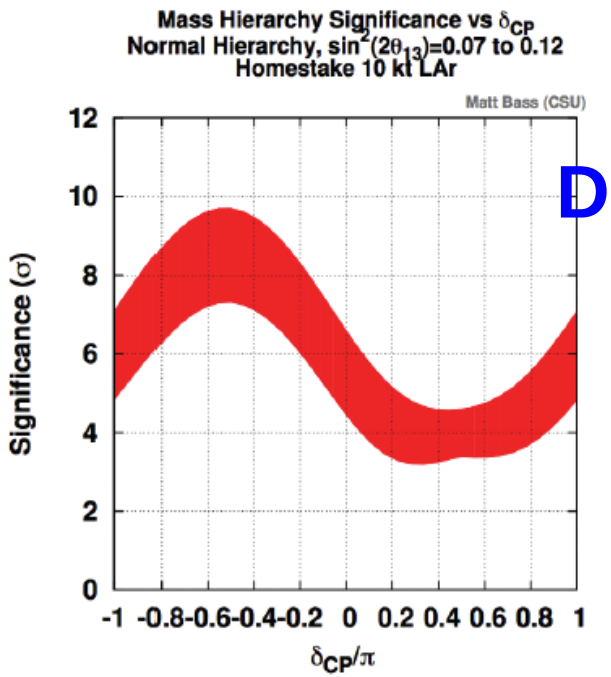
- Increasing sensitivity to mass ordering to come
  - Will more than double data set in both beams
  - >3σ mass ordering sensitivity for 30-40% of δ-values
  - By run end, statistical errors still significantly larger than current systematics on ν_e

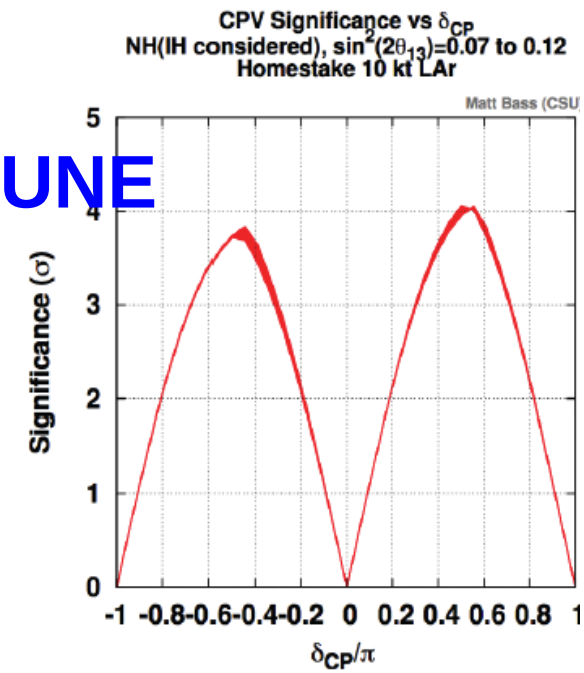


Future Accelerator nu Experiment

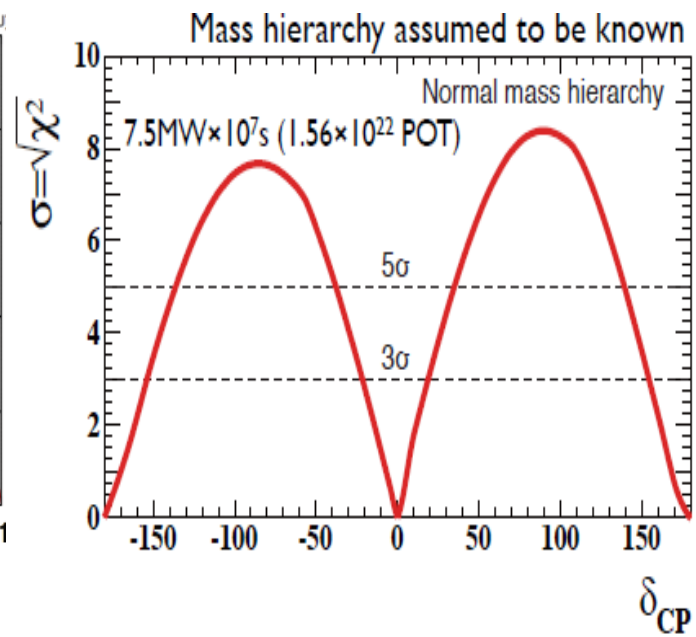


DUNE



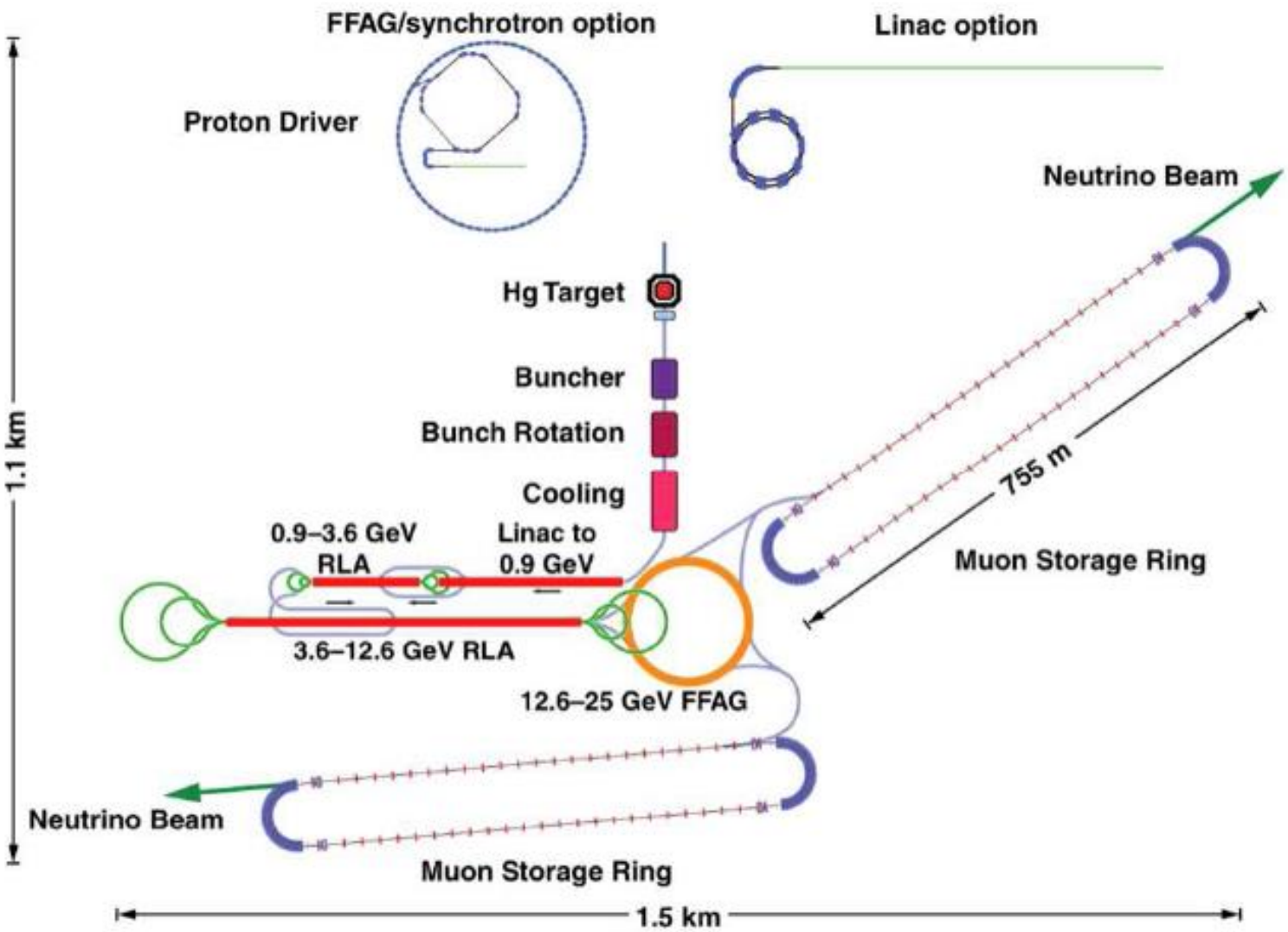


Hyper-K



Neutrino Factory

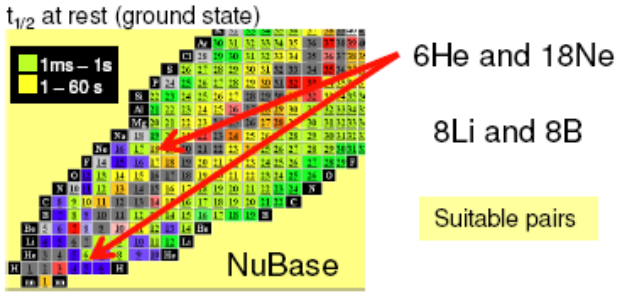
- 缪子冷却、再加速，存储，产生单能缪中微子

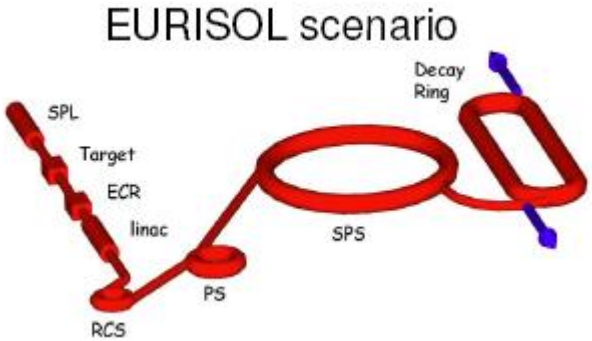


IDS-NF Baseline 2007/1.0

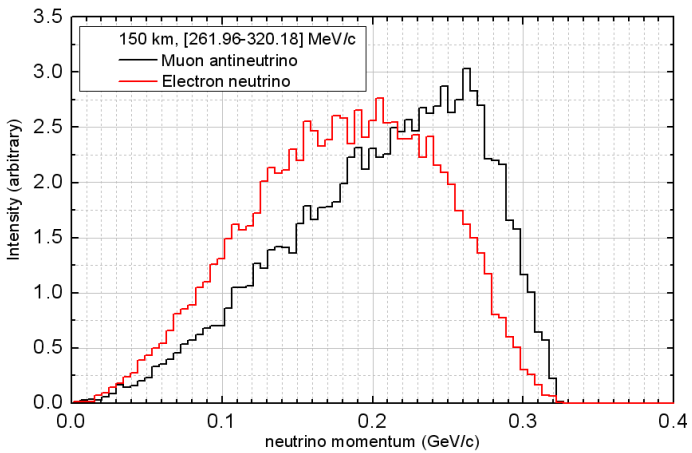
Beta 束流

- Similar to neutrino factory, but replace muon by a beta-emitter
- Choice of isotopes:
  - ⇨ Beta-active: production rate, safety, …
  - ⇨ Reasonable lifetime: ~ seconds
  - ⇨ Low Z prefered: accelerator, ν/ion=1
- CERN-based option:
  - ⇨ 150 GeV(^{6}He) or 250 GeV(^{18}Ne)
  - ⇨ 2.9*10^{18} ne from ^{6}He
  - ⇨ 1.1*10^{18} ne from ^{18}Ne
  - ⇨ Mton water detector
- Physics reach: worse than the neutrino factory by a factor of 10





MOMENT: A New Idea on ν Beam



High-power proton linac（15MW，1.5GeV）

ADS type (~300m)

Pion target

Dump

Pion collection section

Pion decay section (~25m)

Muon phase rotation section(~5m)

Bending section(~20m)

$\bar{\nu}_\mu$ / ν_e or ν_μ / $\bar{\nu}_e$

To detector (~150km)

μ decay channel (~300m)

(SC solenoids or quads)

- Neutrinos from muon decay
- Proton LINAC for ADS ~15 MW
- Energy: 300 MeV/150 km
- Phys. Rev. STAB **17**, 090101 (2014)

Neutrinos after the target/ collection/decay similar to NuFact: ~ 10^{21} ν/year