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(Accelerator-based) Long baseline neutrino experiments

Takashi Kobayashi KEK

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Neutrino physics

- Great progress in last decade
 - Exhibit first violation of standard "SM": Non-zero mass
 - Surprisingly large mixing unlike quarks
- Yet unknowns & puzzles (>40yrs behind quark)
 - Flavor mixing
 - Standard 3 x 3 PMNS mixing picture is correct?
 - All three flavors participate mixing? $(\theta_{13}?)$
 - Why so different from quark mixing?
 - CP is violated?
 - * Mass
 - Absolute mass
 - "Unexplained lightness of the existence"
 - Mass ordering (hierarchy)
 - Any additional neutrino??
- Unraveling mysteries of neutrino is expected to shed light on fundamental questions in particle physics
 - High energy scale physics
 - Matter dominated universe



Knowledge before Summer 2011





Only upper bound on θ₁₃
No measurement of Δm₁₃
θ₂₃ maximal?
Mass hierarchy (sign of Δm₃₁²)
No hint on CPV
(Absolute mass) 5

Long baseline oscillation experiments

- Optimized for $\Delta m^2 = 4Ev/L = 2 \sim 3x 10^{-3} eV^2$
- v_{μ} beam of 1~10GeV from pion decay
 - ♦ → Baseline ~ several 100km
- Physics
 - * v_{μ} disappearance $(\theta_{23}, \Delta m_{23})$: θ_{23} really maximal (45deg)??
 - * v_{τ} appearance (θ_{23} , Δm_{23}): Definite check. Consistent w/ disappearance?
 - * v_e appearance $(\theta_{13}, \Delta m_{13})$: Last key to realize CPV search
 - Sterile neutrino search
 - Something new!
- Players
 - 1. Confirmation of SK atm v results (90s, 2000s-)
 - K2K(1999~2004), MINOS(2005~2012), CNGS(2008~)
 - 2. Discovery of nue appearance (Starting ~2010s)
 - T2K(2009~), NOvA (2013~)
 - 3. CPV and mass hierary (20XX~)



Sensitive to

CPV ∝ sin δ · s₁₂ · s₂₃ · s₁₃
sign of Δm₁₃ (Mass hierarchy) thru Matter effect

Existence of ν_e appearance
→Non-zero (reasonable size) θ₁₃
→CPV term can exist

Chance to detect CPV in the future!





MINOS (2005~2012)

- ~3GeV vµ beam from FNAL 120GeV MI
 ~350kW operation achieved
- (magnetized)Iron-scintillator tracker at 735km (5.4kt) and near (980t)
- Physics goals
 - ♦ (Anti-)vµ disappearance
 - ve appearance
 - Also measure atmospheric neutrino
- Finished data taking on Apr.30, 2012
 - * 10.7x10²⁰POT for v_{μ}
 - * 3.4×10^{20} POT for anti- v_{μ}



CERN neutrino to Gran Sasso (CNGS)

- Wide band v_{μ} beam of 10~30GeV from CERN 400GeV SPS
- Detectors at Gran Sasso ✤ 732km from CERN
- v_{τ} appearance (+ v_e appearance) First beam May 2006

 $P_{osc}^* \sigma_{\tau cc}$ (arbitrary units)

x 10⁵

OPERA (2008~)

- τ ID by decay topology (kink)
- **Emulsion-Counter Hybrid**
- 150k ECC blocks ~1.25kt
- Accumulated 1.4×10^{20} pot by 2011
 - (~1.8e20, 84% of requested in 2012)

ICARUS(Oct.2010~):



T2K experiment



- Off-axis v_{μ} beam @ ~600MeV from J-PARC 30GeV MR
 - ✤ 200kW achieved (>100T p/pulse)
- Super-Kamiokande @ 295km
- Main physics goals
 - ve appearance
 - v_{μ} disappearance

- Started data taking in Jan 2010
- First physics results w/ full data bfr the EQ $(1.43 \times 10^{20} \text{pot})$ in June 2011
- Resumed data taking in Mar. 2012
- New results w/ data until June 9, 2012 (**3.01x10²⁰ pot**) released (18% increase from Nu2012)

K.Sakashita



Data for today's talk (full data set up to now) = 3.01×10^{20} p.o.t. (18% of increase from Neutrino2012)

Important issues in LBL experiments (Integrated) Beam power (& detector mass)

- Understanding of
 - Beam
 - Neutrino interaction
 - Detector (efficiency)
 - for better syst. precision

Typical basic principle of experiment



Measure neutrino at near site







compare

• Cross sections not well measured in 1 - 10 GeV rangeR.Snider@ICHEP

 $N_{far}(E) = P_{osc} \cdot \Phi_{far} \cdot \sigma_{far} \cdot \varepsilon_{far}$





J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales", to be published in Rev. Mod. Phys., 2012.

Understanding beam



Understanding cross sections Many efforts:T2K-ND, SciBooNE, MiniBooNE, MINERvA, ...

T2K-ND CC (M.R.Salzgeber@ICHEP)



MINERvA: σ dedicated expt @FNAL-NuMI





CCqe tent ion btw MiniBooNE & high energy data



New Results

T2K v_e appearance results

- T2K reported the first indication of v_e appearance (=non-zero θ_{13}) on June 15th, 2011 w/ all data, 1.43x10²⁰POT taken before the earthquake
 - ✤ PRL107,041801,2011
- At Nu2012, updated results w/ data taken in 2012
- Here, further updated results w/ full data taken so far, 3.01x10²⁰POT presented (18% increase from Nu2012)
 - * See K.Sakashita's parallel talk for detail



Released	Data (POT)	ν _e cand	BG	p-value	Osc. Ana
June 15, 2011	1.43x10 ²⁰ (~Mar11,2011)	6	1.5 ± 0.3	0.7% (2.5σ)	# of evts
Nu2012(June)	2.56x10 ²⁰ (~May15,2012)	10	2.73 ± 0.37	0.08% (3.2σ)	# of evts
ICHEP2012	3.01x10²⁰ (~Jun9,2012)	11	3.22 ± 0.43	0.08% (3.2σ)	Shape

Measurements by T2K Near detectors



dav

Glenn Lopez and Melody Ravonel, on behalf of the T2K collaboration

T2K analysis and results

Signal: single ring electron

v_µ---→ v_e ---→

- Signal:v_eCCqe v_e+n→p+e⁻
 Selection
 - ✤ 1 e-like ring (>100MeV)
 - * No decay-e
 - Inv. mass of 1st ring and forcedfound 2nd ring <105MeV (remove remaining p0)
 - ✤ Rec. Ev <1250MeV</p>

Background: intrinsic v_e in beam π^o from NC interaction



e-like (showering) ring







K.Sakashita

Invariant mass cut $(M_{inv} < 105 \text{ MeV/c}^2)$





Good rejection of v_{μ} events

T2K: 11 candidate events

K.Sakashita



T2K v_e appearance results

K.Sakashita

Results

Allowed region of sin^22 θ_{13} for each value of δ_{CP}

best fit w/ 68% CL error @δ_{CP}=0 normal hierarchy:

 $\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$

inverted hierarchy:

 $\sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049}$

This result is consistent with rate+shape (rec. E_{ν}) method and rate only method

c.f 2011 result for normal (inverted) hierarchy $\sin^2 2\theta_{13} = 0.11^{+0.10}_{-0.06} \ (0.14^{+0.12}_{-0.07})$



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Attempts for detecting v_e appearance







Expected : oscillated nue 1.5, beam neBG 19.2. Observed nue: 19 events After low-energy selection (Ev<20GeV) Expected events: oscillated 1.1, beam nue BG 3.7 Observed nue: 4 events.



T2K v_{μ} disappearance



- Data bfr EQ: 1.43e20pot (2% of approved amount)
- Signal: $\nu_{\mu}CCQE: \nu_{\mu}+\nu \rightarrow \mu+p$
- 1ring μ -like, 0 or 1 decay-e, p_{μ} >200MeV/c
- ♦ 31 events remain

Best fit: $(\sin^2 2\theta_{23}, \Delta m_{23}^2) = (0.98, 2.65 \text{ x}10^{-3} \text{ eV}^2)$

90% CL region $\sin^2 2\theta_{23} > 0.84$ $\Delta m_{23}^2 = 2.2 \sim 3.1 \times 10^{-3} \text{eV}^2$

Phys. Rev. D 85, 031103(R) (2012)



Constraint on osc. params



$\begin{array}{c} \text{Parallel talk by Marilisa De Serio} \\ \textbf{OPERA} \ \nu_{\tau} \ appearance \end{array}$

Status of the analysis

- 2 candidate events so far (expected 2.1 with 0.2 background events)
- A few more events are under study.
- Progress in estimating detection efficiency and BG.

Years	Status	# of events for Decay search	Expected ν_{τ} (Prelimin ary)	Observed v_{τ} Candidat e Events	Expected BG for ^ν τ (Prelimi nary)
2008- 2009	Finished	2783		1	
2010- 2011	In analysis	1343		1	
2012	Started				
Total		4126	2.1	2	0.2

First cand. ($\tau \rightarrow$ 1had kink) reported in 2010



2nd Cand ($\tau \rightarrow$ 3h) reported in June 2012

v_{τ} appearance from SK atm v

Y.Hayato

Search for the signature of v_{τ} in SK ~ appearance ~ (arXiv:1206.0328 [hep-ex], submitted to PRL) Used data set SK-I: 1489 Days, SK-II: 799 Days and SK-III: 518 Days (previous analysis : Only SK-I = statistics almost doubled) $Data = \alpha \times bkg + \beta \times signal$ $\beta = 1.42 \pm 0.35_{(stat)}^{+0.14} - 0.12(svs)$ 300 Shaded region τ contribution 300 Estimated # of v_{τ} events 200 Events 200 $170.8 \pm 44.3_{(stat)}^{+17.8}_{-15.2(sys)}$ 100 100 lp-aoina Tau Like 500 3.8 σ deviation from 600 400 "no v_{τ} appearance" St 300 400 200 200 100 Non-tau Like Down-aoina -0.5 0.5 0.8 0.2 0.4 0.6 $\cos(\theta)$ NN output

Speed of neutrino

S.Bertolucci @ Nu2012

After the OPERA result in September 2011

All the big experiments al Gran Sasso set up a campaign to repeat the measurement with:

- Improved timing resolution
- Reduction of systematics
- Real time monitoring of the time stamp
- Redundant systems
- Independent clock synchronization and geodesy
- Better structure of the CNGS beam

All consistent w/ c

MINOS measurement (Giles Barr)

 15 ± 11 (stat.) ± 29 (syst.) ns

which is consistent with v=c

To summarize

S.Bertolucci @ Nu2012

- All experiments consistent with no measurable deviation from the speed of light for neutrinos:
 - Borexino: δt = 2.7 ± 1.2 (stat) ± 3(sys) ns
 - ICARUS: δt = 5.1 ± 1.1(stat) ± 5.5(sys) ns
 - LVD: δt = 2.9 ± 0.6(stat) ± 3(sys) ns
 - OPERA: δt = 1.6 ± 1.1(stat) [+ 6.1, -3.7](sys) ns
- Very preliminary analyses, more refinements to be expected soon
- A paradigmatic example of collaboration and competition!



NOvA (2013~)

- Optimized experiment for v_e appearance
- FNAL NuMI off-axis beam
- Power upgrade $320 \text{kW} \rightarrow 700 \text{kW}$

 - ★ Rep cycle 2.2s → 1.33s
- New 14kton liquid scintillator fine grained detector @810km
- Construction for power upgrade and detector on-going
 - Plan to start meas. from May 2013
- First trial of hierarchy determination







Toward CPV&Mass hierarchy

- Large θ_{13} opened possibility of CPV search (& mass hierarchy determination)
 - * BUT, not necessarily means EASY (Relative CPV effect $\propto 1/\sin \theta_{13}$)
 - * Expected CP effect ~ 20% at $\sin^2 2 \theta_{13} \& \sin \delta = 1$ (~2% @ $\sin \delta = 0.1$) at 1st osc. max.
- Order of magnitude higher statistics from present generation experiments
 - High intensity beam (~MW or higher)
 - High sensitivity huge detector
 - Should also capable for proton decay detection
- Requirement on systematic uncertainty becomes severe
 - Hadron prodcution
 - ✤ Xsec meas.
 - Good near detector as far as possible
- Matter effect is larger at larger L (E)
- → Experiment to determine Mass hierarchy could be realized earlier w/ very long baseline (>1000km)



Asymmetry btw app. prob. for v and anti-v

World efforts to formulate future direction

• US: LBNE

- Reconfigured to phased approach:10kt on surface first → DOE CD-1 review in fall 2012
 - Go underground if enough additional fund become available
- ◆ EU
 - EoI of LBNO, CERN-SPSC-2012-021 (SPSC-EOI-007), is submitted to/received by CERN SPSC (June 2012)
 - Excellent sensitivity on hierarchy
- Japan: Two options w/ J-PARC





Summary

- v_e appearance
 - Evidence obtained by T2K
 - P-value $0.7\%(2.5\sigma)$ (2011) $\rightarrow 0.08\%(3.2\sigma)$ (2012)
 - Opened possibility of CPV/Hierarchy meas.
 - * 2σ level from MINOS
- v_{τ} appearance
 - ✤ 2 signal candidates w/ 0.2 BG in OPERA
 - * 3.8 σ level excess in SK atm v_{τ} enhanced analysis
- v_{μ} disappearance
 - θ_{23} most constrained by SK atm v: $\sin^2 2\theta_{23} > 0.93 \sim 0.95$ (@90%CL)
 - * Δm_{23}^2 by MINOS (2.39+0.09-0.11)x10⁻³eV² (4% meas)
- Speed of neutrino consistent w/ light
- Future
 - ★ Near: Improve v_e appearance significance → precision measurements of v_e appearance & v_u disappearance
 - Hint on CPV and/or Mass hierarchy
 - Future experiments for CPV&Mass hierarchy are being discussed & proposed (LoI, EoI, ..)