どれが好き?



を見るスー



大気・加速器ニュートリノ 同時解析に向けた π運動量系統誤差の 導入と適合度検定

L. Berns, C. Bronner^A, M. Guigue^B, M. Kuze, B. Quilain ^C, R. Wendell ^D, C. Wret ^E, J. Xia ^F, Super-Kamiokande Collaboration, T2K Collaboration

Tokyo Institute of Technology, Kamioka Observatory ICRR^A, LPNHE Paris^B, Laboratoire Leprince-Ringuet^C, Kyoto University^D, University of Rochester E, ICRR University of Tokyo F

ニュートリノ新学術研究会, 2022-03-08

Comic © Higgstan

Bac Kibb II cum marizes the racional error on the period number of SK events using a 1σ variation flux, cross-section, and far detector uncertainties.

NEUTRINOS FROM

COSMIC RADIATION

COSMIC RADIATION

sienelternsolest ha

de antineutrino

int option

a thaxing the second second

ratantineerine

Hairsbeites

arameters. The

Fating over the

- Joint fit of atrhosoner of sk costs using a 14 variation with MOU signed between SK/T2K from what w
- Expect increased in [1]. As described in Sec. I the three dependent parameters sin (θ_{23}) and $\Delta \pi \pi_{32}^2$ which $\delta_{\rm CP}$, mass or dependent parameters sin (θ_{23}) and $\Delta \pi \pi_{32}^2$ which beyond stats the transformed of the parameters in the second state to the parameters in the parameters is the contract of the parameters in the paramet

For this talk focusing of an initial interest of the manuaceus of an initial set is contribution neutrino cross-static and an initial and an initial and an initial set of the antiperiod of the

- 1. Overlap in energy range means and interset correlating systematic analysis essential for the second interset method with the second interset intersection of the second intersection of the second intersection of the second intersection of the second intersection intersection of the second intersection of
- 2. SK atm. will) be an area of the second pair of xsec constraints by **T2K** on ear area ected

osc musattie comotified of with prior provability densities params $\mathcal{F}(\mathbf{f})$, giving a likelihood as the provability densities vant oscillation params $\mathcal{F}(\mathbf{f})$ (1)



Provide and an anti-constructed energy distribution of the 135 far detector v_{μ} =CCQE candidate events (1917) and 66 \overline{v}_{μ} =CCQE candidate events (right), with predicted spectra for best fit finismotion and each applied in the spectra for best fit finismotion and each applied in the spectra for best fit finismotion and each applied with and those obtained using the Feldman-Cousins [40] method was found to be small. For the Feldman-Cousins method, the critical chi-square fiscillation produced by it and those obtained using the Feldman-Cousins [40] method was found to be small. For the Feldman-Cousins [40] method was found to be small. For the Feldman-Cousins [40] method was found to be small. For the Feldman-Cousins [40] method, the critical chi-square stallactor parameter space.

The reconstructed energy spectra of the events observed during neutrino and antineutrino running modes are shown in Figure 1. These are overlaid with the predictions for the best fit values of the oscillation parameters assumption of the best fit values of the oscillation parameters



Back table if communicates the racional error on the set of six events using a 1σ variation flux, cross-section, and far detector uncertainties.

- Joint fit of atrices between SK/T2K from what w
- sented in [1]. As described in Sec. I the three **Expect in Case Sec** scillation of all the is extended to include dependent parameters sin (θ_{23}) and Δm_{32}^2 whice $\delta_{\rm CP}$, mass or defined by the model brief of the second states in the second states in the second states in the second states in the second states of the parameters in the second states in the second states of the second state

ens have) a non-she than the rimpast on the mise as and the second secon

NEUTRINOS FROM

COSMIC RADIATION

COSMIC RADIATION

For this talk focus of the second antifut in the background sum neutrino cross-states and the second antifut in the second second second antifut in the second seco

- 1. Overlap in energy property interview reconstructed energy spectra correlating systematic participation of the setting of th
- 2. SK atm. wil) ber every store of the part of promotion of the store of the store
 - osc $\pi(\mathbf{f})$, giving a likelihood so the plot of the



Provide and a set of the set of

The reconstructed energy spectra of the events observed during neutrino and antineutrino running modes are shown in Figure 1: These are overlaid with the predictions for the best fit values of the oscillation parameters assume inconstructed anongy appearts of the forents; it as es the fractional error on the events using a 1σ variation d far detector uncertainties. es the fractional error on

NEUTRINOS FROM

COSMIC

RADIATION

events using a 1 variation d far detector uncertainties.

d here follows from what w scribed in Sec. I the three scillation analysis rmansm is extended to incl s sin² (Brath and A To a synder dilacia followsy from renate to gezihad an Sea A zzza zhad malism is vestlendind Enclied **F** 🔊 ĢÌ 勴

iesthe laskesting. Miel conte Stevent consective of the la eksintigalan the background sung= olepanical and the size of the



tes the fractional error on the events using a 1σ variation d far detector uncertainties.

NEUTRINOS FROM COSMIC RADIATION

COSMIC

RADIATION

events using a 1 σ variation scillation analysis d far detector uncertainties.

d here follows from what w scribed in Sec. I the three scillation sectorided to incl s sin² (Cratherended to incl s sin²

icsTh2.1aSysath3. Mill bong Greshift (Opsediated ingthe lo Rekainsteal on the backgrowing sum= blaining to the speaker of



zes the fractional error on the events using a 1σ variation d far detector uncertainties.

NEUTRINOS FROM

COSMIC

RADIATION

es the fractional error on events using a 1 variation d far detector uncertainties.

d here follows from what w scribed in Sec. I the three scillation analysis rmansm is extended to incl s sin² (Brath anth A TO a synhol dilacia followsy from relace to scould san a san a third izealism Svetlended tocing f swends donnidaen desynden side the sease of the second blerin past ond hermseasoned icsthe laskestis. Miel conte drevant consedictod in at her la ekandies on the backsigning sugg olepanical and the size of the





T2K ND \rightarrow atm?

quasi-elastic

resonant

- Would like to apply xsec constraint from T2K ND to Sub-GeV atmospheric samples. Dominant interaction: quasi-elastic, next is resonant single pion production.
- Both T2K ND and SK atmospheric samples only fit in lepton kinematics (momentum and direction) and do not directly use pion kinematics.
- However, samples are separated by number of pions, with
 - T2K ND: combines multiple pion tags
 - \rightarrow insensitive to p_{π}
 - SK atm: only uses decay-e tag for "invisible" pions
 - \rightarrow selects low- p_{π} pions







T2K ND \rightarrow atm?



resonant

- Would like to apply xsec constraint from T2K ND to Sub-GeV atmospheric samples. Dominant interaction: quasi-elastic, next is resonant single pion production.
- Both T2K ND and SK atmospheric samples only fit in lepton kinematics (momentum and direction) and do not directly use pion kinematics.
- However, samples are separated by number of pions, with
 - T2K ND: combines multiple pion tags
 - \rightarrow insensitive to p_{π}
 - SK atm: only uses decay-e tag for "invisible" pions
 - \rightarrow selects low- p_{π} pions



- The cross section model used in ND280 fits does not have systematics affecting the pion momentum distribution, and we do not believe the MC has this distribution correct (e.g. nuclear effects)
- In order to apply existing T2K ND constraint to SK atmospheric, want to develop a systematic uncertainty to change the pion momentum distribution while keeping the lepton kinematics the same, since these are well measured.

Trick to achieve goal: (idea by C. Wret)

- 1. lepton kinematics only depends on the kinematics of the resonance
- 2. so in the resonance rest frame, we can change the angular distribution of pion emission ("Adler angle") without affecting the lepton kinematics
- 3. since the resonance is boosted, a pion emitted along the boost direction will end up with a larger momentum etc.





changes

Trick to achieve goal: (idea by C. Wret)

- 1. lepton kinematics only depends on the kinematics of the resonance
- 2. so in the resonance rest frame, we can change the angular distribution of pion emission ("Adler angle") without affecting the lepton kinematics
- since the resonance is boosted, a pion emitted along the boost direction will end up with a larger momentum etc.

 \mathcal{U}

11

• Using the Adler angle $x = \cos \theta$, simply weight events with

$$\frac{1}{\operatorname{norm}(\alpha)} (1 + \alpha x)^n \quad (-1 \le \alpha \le + 1),$$







not bother)

Trick to achieve goal: (idea by C. Wret)

- 1. lepton kinematics only depends on the kinematics of the resonance
- 2. so in the resonance rest frame, we can change the angular distribution of pion emission ("Adler angle") without affecting the lepton kinematics
- since the resonance is boosted, a pion emitted along the boost direction will end up with a larger momentum etc.

 \mathcal{U}

12

• Using the Adler angle $x = \cos \theta$, simply weight events with

 $\frac{1}{\operatorname{norm}(\alpha)} (1 + \alpha x)^n \quad (-1 \le \alpha \le +1),$

we pick n = 3 (up to sextupole weights)

- norm(α) is *n*-polynomial of α chosen to exactly preserve the total event rate prior to event selections (MC dependent, and tuned against atm MC)
- No physical justification, just a phenomenological way to generate large shifts in pion momentum while leaving lepton kinematics mostly invariant. Intending to use flat prior in parameter domain [-1, +1].

(Will try to explore more physically motivated uncertainty in future.)



do not bother)

Trick to achieve goal: (idea by C. Wret)

- 1. lepton kinematics only depends on the kinematics of the resonance
- 2. so in the resonance rest frame, we can change the angular distribution of pion emission ("Adler angle") without affecting the lepton kinematics
- 3. since the resonance is boosted, a pion emitted along the boost direction will end up with a larger momentum etc.

 \mathcal{U}

250

 $\underline{\times}10^3$

• Using the Adler angle $x = \cos \theta$, simply weight events with

$$\frac{1}{\operatorname{norm}(\alpha)} (1 + \alpha x)^n \quad (-1 \le \alpha \le + 1),$$

we pick n = 3 (up to sextupo

- norm(α) is *n*-polynomial of α preserve the total event rate p (MC dependent, and tuned ac
- No physical justification, just : generate large shifts in pion rr $\overset{200}{}$ $\overset{200}{}$ $\overset{---\alpha}{} = 0$ lepton kinematics mostly inva $\overset{---\alpha}{} = 0.33$ prior in parameter domain $\begin{bmatrix} -& 0 & 150 \\ -& -& \alpha & = 1 \\ 0 & 150 \\ -& -& \alpha & = 1 \\ 13 \end{bmatrix}$ (Will try to explore more physically metivated uncertainty in future.)



- Use maximum distortion of new pion momentum systematic and fit without it to see potential impact
- Here, using down-going atm. samples to study systematic model without "unblinding" effect on oscillation parameters (this is still MC, not data)
- Metric: goodness-of-fit (GOF) Good GOF is essentiat for reliable oscillation parameter constraints. Note: impact on osc. params also estimated, hopefully can share in near future.

Does pion momentum distribution matter?



Without ND constraint, other parameters can absorb effect

SK+T2K Work in Progress	Pearson GOF CC1π	Parameter GOF CC1 π vs. other	Combined p-value
w/o ND	+0.2σ	+0.6σ	0.11
With ND	+1.6σ	+2.0σ	0.001 🔨

- In this case, fitting with new pion momentum systematic will perfectly absorb the effect, because that's how it was generated
- In practice, dependence of pion momentum distribution on neutrino energy / flavor etc. may be different from this systematic. Similar GOF on actual data should help in deciding whether systematic necessary / good enough or not.
- This was only using down-going part, for full atm. samples expect even stronger impact

With ND constraint, pion / momentum shift cannot be absorbed by other parameters → poor GOF

- Expected increase in value of statistic estimated using Asimov fits
- These are converted to p-values using statistic distribution estimated by fitting toy experiments
- The individual statistic p-values were converted to a +Xσ value using the standard normal quantile function

- Use maximum distortion of new pion momentum systematic and fit without it to see potential impact
- Here, using down-going atm. samples to study systematic model without "unblinding" effect on oscillation parameters (this is still MC, not data)
- Metric: goodness-of-fit (GOF) Good GOF is essential for reliable oscillation parameter constraints.

Note: impact on osc. params also estimated, hopefully can share in near future.

- In this case, fitting with new pion momentum systematic will perfectly absorb the effect, because that's how it was generated
- In practice, dependence of pion momentum distribution on neutrino energy / flavor etc. may be different from this systematic. Similar GOF on actual data should help in deciding whether systematic necessary / good enough or not.
- This was only using down-going part, for full atm. samples expect even stronger impact

Does pion momentum distribution matter?

Parameter GOF

Without ND constraint, other parameters can absorb effect

Combined

With ND constraint, pion momentum shift cannot be absorbed by other parameters → poor GOF

- Expected increase in value of statistic estimated using Asimov fits
- These are converted to p-values using statistic distribution estimated by fitting toy experiments
- The individual statistic p-values were converted to a +Xσ value using the standard normal quantile function

SK+T2K Work in Progress	CC1π	$CC1\pi$ vs. other	p-value	
w/o ND	+0.2σ	+0.6σ	0.11	
With ND	+1.6σ	+2.0σ	0.001	

Pearson GOF

- Use maximum distortion of new pion momentum systematic and fit without it to see potential impact
- Here, using down-going atm. samples to study systematic model without "unblinding" effect on oscillation parameters (this is still MC, not data)
- Metric: goodness-of-fit (GOF) Good GOF is essential for reliable oscillation parameter constraints.

Note: impact on osc. params also estimated, hopefully can share in near future.

- In this case, fitting with new pion momentum systematic will perfectly absorb the effect, because that's how it was generated
- In practice, dependence of pion momentum distribution on neutrino energy / flavor etc. may be different from this systematic. Similar GOF on actual data should help in deciding whether systematic necessary / good enough or not.
- This was only using down-going part, for full atm. samples expect even stronger impact

Does pion momentum distribution matter?

Without ND constraint, other parameters can absorb effect

With ND constraint, pion momentum shift cannot be absorbed by other parameters → poor GOF

- Expected increase in value of statistic estimated using Asimov fits
- These are converted to p-values using statistic distribution estimated by fitting toy experiments
- The individual statistic p-values were converted to a +Xσ value using the standard normal quantile function

) iable	SK+T2K Work in Progress	Pearson GOF CC1π	Parameter GOF CC1 π vs. other	Combined p-value	
ints.	w/o ND	+0.2σ	+0.6σ	0.11	
-	With ND	+1.6σ	+2.0σ	0.001 🚽	

÷

- Use maximum distortion of new pion momentum systematic and fit without it to see potential impact
- Here, using down-going atm. samples to study systematic model without "unblinding" effect on oscillation parameters (this is still MC, not data)
- Metric: goodness-of-fit (GOF) Good GOF is essential for reliable oscillation parameter constraints.

Note: impact on osc. params also estimated, hopefully can share in near future.

- For fit of SK atm. *with* ND,
 - having this kind of pion momentum systematic may be essential for good fit.
 - - 17

w/o ND

With ND

Does pion momentum distribution matter?

Parameter GOF

 $CC1\pi$ vs. other

 $+0.6\sigma$

 $+2.0\sigma$

Without ND constraint, other parameters can absorb effect

Combined

p-value

0.11

0.00'

with ND constraint, pion 🧳
momentum shift cannot be
absorbed by other parameters
→ poor GOF



Pearson GOF

CC1π

 $+0.2\sigma$

 $+1.6\sigma$

- Use maximum distortion of new pion momentum systematic and fit without it to see potential impact
- Here, using down-going atm. samples to study systematic model without "unblinding" effect on oscillation parameters (this is still MC, not data)
- Metric: goodness-of-fit (GOF) Good GOF is essential for reliable oscillation parameter constraints. -

Note: impact on osc. params also estimated, hopefully can share in near future.

- In this case, fitting with new pion momentum systematic will perfectly absorb the effect, because that's how it was generated
- In practice, dependence of pion momentum distribution on neutrino energy / flavor etc. may be different from this systematic. Similar GOF on actual data should help in deciding whether systematic necessary / good enough or not.
- This was only using down-going part, for full atm. samples expect even stronger impact

Does pion momentum distribution matter?

Parameter GOF

 $CC1\pi$ vs. other

 $+0.6\sigma$

 $+2.0\sigma$

Pearson GOF

CC1π

 $+0.2\sigma$

 $+1.6\sigma$

Without ND constraint, other parameters can absorb effect

Combined

p-value

0.11

0.001

With ND constraint, pion / momentum shift cannot be absorbed by other parameters → poor GOF

- Expected increase in value of statistic estimated using Asimov fits
- These are converted to p-values using statistic distribution estimated by fitting toy experiments
- The individual statistic p-values were converted to a +Xσ value using the standard normal quantile function

w/o ND

With ND

Summary

- Joint fit of atmospheric and accelerator neutrinos from SK+T2K ongoing
- Presented one of the ongoing works toward a coherent systematics model: an uncertainty to vary pion momentum distribution
 - By reweighting angular distribution in resonance rest-frame, was able to shifts pion momentum distribution *without* altering lepton kinematics
 - Confirmed to be an essential addition for correlating Sub-GeV interaction models of SK and T2K due to different pion momentum dependence of pion selection efficiency at T2K ND and SK atm.
 - Down-going events already sensitive to these kinds of mis-modeling effects with various goodness-of-fit metrics
- Various other studies of cross section and detector systematics ongoing, expect first oscillation parameter sensitivity studies soon.

backup

CP violation sensitivity

-Atmospheric



- Complicated pattern in appearance prob.
- Due to detector resolution, sensitivity mostly from #events in sub-GeV region.
 - → $\cos(\delta_{CP} \phi_0)$ sensitivity with different phase offset ϕ_0 than accelerator
- $\nu, \bar{\nu}$ separation difficult but ν has larger flux and xsec.

-Accelerator



- Anti-correlated change of $\nu_e, \bar{\nu}_e$ appearance probability
- Since T2K only sees first oscillation maximum, mostly a change in # of e-like events
 - → sensitive to $sin(\delta_{CP})$



True neutrino energies of various μ -like atm. samples



Cross section model strategy

- T2K beam samples (3 types of samples)
 - precision study of a narrow flux at $E_{\nu} \lesssim 1 \, \text{GeV}$
 - dominated by simple quasi-elastic scattering
 - strong constraint from near detector (ND280)



• SK atmospheric samples (18 samples)

0.1

_____0.1

i<u>≌</u> 0.1

<u>5</u> 0.12

0.08

0.06

0.04

0.02

23

- many types of samples including ones with tagged pions which ND280 constraint is not targeted for
- some range up to very high energies with very inelastic interactions (many pions)

GeV samples: egion ←))280 constraint ystematics to cover degrees sured by ND280

quasi-elastic

)les:

G True E_v (GeV)

ut ND280 constraint

Charged pions

what is visible in water Cherenkov detectors





Goodness of fit

- Pearson GOF, i.e. $\chi^2_{\text{Pearson}} := \min_{\alpha} \chi^2(\theta)$ Simple, but good Pearson GOF can still be a poor fit because $\chi^2_{\text{Pearson}} \sim \chi^2_k$ with $k = N_{\text{bins}} - N_{\text{free}}$ and $N_{\rm free}$ the number of unconstrained parameters.
 - If e.g. we mis-model a sub-dominant interaction mode for which the control sample has small number of bins, the large variation of χ_k^2 can hide this poor fit
- Parameter GOF [1], check the agreement of two independent data sets A,B:

 $\chi^2_{\text{PGOF}} := \min_{\theta} \left[\chi^2_A(\theta) + \chi^2_B(\theta) \right] - \min_{\theta'} \chi^2_A(\theta') - \min_{\theta''} \chi^2_B(\theta'')$ asymptotically related to the number of common parameters (not bins) and independent from A-only and Bonly χ^2_{Pearson} .

 We extended the PGOF formalism to work with data sets that are correlated through common prior constraints.



Goodness of fit

• Pearson GOF, i.e. $\chi^2_{\text{Pearson}} := \min_{\alpha} \chi^2(\theta)$ Simple, but good Pearson GOF can still be a poor fit because $\chi^2_{\text{Pearson}} \sim \chi^2_k$ with $k = N_{\text{bins}} - N_{\text{free}}$ and $N_{\rm free}$ the number of unconstrained parameters.

If e.g. we mis-model a sub-dominant interaction mode for which the control sample has small number of bins, the large variation of χ_k^2 can hide this poor fit

• Parameter GOF ^[1], check the agreement of two independent data sets A,B:

 $\chi^2_{\text{PGOF}} := \min_{\theta} \left[\chi^2_A(\theta) + \chi^2_B(\theta) \right] - \min_{\theta'} \chi^2_A(\theta') - \min_{\theta''} \chi^2_B(\theta'')$ asymptotically related to the number of common parameters (not bins) and independent from A-only and Bonly χ^2_{Pearson} .

 We extended the PGOF formalism to work with data sets that are correlated through common prior constraints.

QJ X Std Der [min x (0) Ø AB at Pearson x² level a very <<u>−2</u>∂ 21000 good fit $\chi^2_B(\theta)$ ≈10 UR at parameter level ≈ 20 , barely acceptable Seuc. trie

Goodness of fit

• Pearson GOF, i.e. $\chi^2_{\text{Pearson}} := \min_{\alpha} \chi^2(\theta)$ Simple, but good Pearson GOF can still be a poor fit because $\chi^2_{\text{Pearson}} \sim \chi^2_k$ with $k = N_{\text{bins}} - N_{\text{free}}$ and $N_{\rm free}$ the number of unconstrained parameters.

If e.g. we mis-model a sub-dominant interaction mode for which the control sample has small number of bins, the large variation of χ_k^2 can hide this poor fit

• Parameter GOF [1], check the agreement of two independent data sets A,B:

 $\chi^2_{\text{PGOF}} := \min_{\boldsymbol{\theta}} \left[\chi^2_{\boldsymbol{\theta}}(\boldsymbol{\theta}) + \chi^2_{\boldsymbol{\theta}}(\boldsymbol{\theta}) \right] - \min_{\boldsymbol{\theta}'} \chi^2_{\boldsymbol{\theta}}(\boldsymbol{\theta}') - \min_{\boldsymbol{\theta}''} \chi^2_{\boldsymbol{\theta}}(\boldsymbol{\theta}'')$ asymptotically related to the number of common parameters (not bins) and independent from A-only and Bonly χ^2_{Pearson} .

 We extended the PGOF formalism to work with data sets that are correlated through common prior constraints.

Goodness-of-fit

Under null hypothesis (nominal MC)

		DG	DG not $CC1\pi^+$	DG CC1 π^+	DG CC1 π^+ vs. other		
Prior	Adler syst	$\mathbb{E}[\chi^2_{\rm min}]$	$\mathbb{E}[\chi^2_{ ext{min}}]$	$\mathbb{E}[\chi^2_{ m min}]$	$\mathbb{E}[\chi^2_{\mathrm{PGOF}}]$	$\mathrm{SD}[\chi^2_\mathrm{PGOF}]$	
Pre-ND	\checkmark	83.7	77.4	4.5	14.4	4.5	
Pre-ND		86.4	77.7	7.0	15.7	5.0	
Post-ND	\checkmark	85.1	78.9	5.1	12.6	5.1	
Post-ND		86.7	79.7	5.9	13.0	4.1	

Under maximal distortion of Adler angle distribution $\left(lpha = -1 ight)$

		DG		DG not C	$C1\pi^+$	DG CC	$1\pi^+$	DG CC1 π^+	vs. other
Prior	Adler syst	$\Delta \mathbb{E}[\chi^2_{\rm min}]$	p	$\Delta \mathbb{E}[\chi^2_{\rm min}]$	p	$\Delta \mathbb{E}[\chi^2_{\rm min}]$	p	$\Delta \mathbb{E}[\chi^2_{\rm PGOF}]$	p
Pre-ND	\checkmark	0	0.48	0	0.48	0	0.48	0	0.46
Pre-ND		0.7	0.46	0	0.48	0.2	0.41	1.0	0.28
Post-ND	\checkmark	0	0.48	0	0.48	0	0.42	0	0.62
Post-ND		13.8	0.15	0.04	0.48	6.3	0.055	11.8	0.022