Обзор методов анализа данных в физике нейтрино по материалам PHYSTAT-ν 2019

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Семинар ОФВЭ ПИЯФ 19.02.2019

PHYSTAT - серия “рабочих совещаний” по статистическим методам в физике высоких энергий.

https://espace.cern.ch/phystat/_layouts/15/start.aspx#/

Introduction:

PHYSTAT is a workshop series dealing with statistical methods in particle physics. It was founded in 2000 by Louis Lyons. A wide range of topic is covered: frequentist and bayesian inference, parameter estimation, hypothesis testing, Goodness of Fit testing, confidence interval estimation, unfolding, multivariate analysis techniques, systematic uncertainties, data combination and more. The workshop is a unique meeting point of Physicists and Statisticians, where the latest advances in statistical techniques and procedures are exchanged. The workshop consists of a mixture of invited and contributed talks plus panel discussions. The proceedings of the workshop provide a comprehensive reference on statistical issues and state of the art methods used in particle physics and neighbouring fields.

Since beginning of 2018 Olaf Behnke (DESY) is actaing as chair person of PHYSTAT.

Next Events:

- PHYSTAT-LHC 2019 (DESY) Oct. 2019

Please send your suggestion for possible future meetings to olaf.behnke@desy.de,

Links to past events:

- PHYSTAT-nu 2019 (CERN) Jan 22-25
- PHYSTAT-nu 2016 (FNAL) Workshop on Statistical Issues in Experimental Neutrino Physics September 19-21, 2016 Fermilab
- PHYSTAT-nu 2016 (Kavli, Japan)
- PHYSTAT 2011 (CERN) Proceedings *"Statistical issues related to discovery claims in search experiments, concentrating on those at the LHC, + Unfolding workshop"*
- PHYSTAT 2007 (CERN) Link to proceedings *"Statistical issues for LHC physics."*
- PHYSTAT 2005 (Oxford) Proceedings *"Statistical Problems in Particle Physics, Astrophysics and Cosmology"*
- PHYSTAT 2003 (SLAC) *"Statistical Problems in Particle Physics, Astrophysics and Cosmology"*
- PHYSTAT 2002 (Durham) *"Advanced statistical analysis techniques as used in measurements and searches in Particle Physics, including Astroparticle Physics"*
- Workshop on Confidence Limits 2000 (FNAL)
- 1st Workshbop on Confidence Limits 2000 (CERN)

PHYSTAT Committee (2019):

- Olaf Behnke (DESY) [Chair] olaf.behnke@desy.de
- Louis Lyons (Imperial) *louis.lyons@physics.ox.ac.uk*
- Robert Cousins (UCLA) cousins@physics.ucla.edu
- Glen Cowan (RHUL) g.cowan@rhul.ac.uk
- Kyle Cranmer (NYU(kyle.cranmer@cern.ch
- Thomas R. Junk (FNAL) trj@fnal.gov
- Mikael Kuusela (CMU) mikael.kuusela@cern.ch
- NIcholas Wardle (Imperial) *nw709@ic.ac.uk*

Введение

https://indico.cern.ch/event/735431/

PHYSTAT-ν 2019 посвящено методам анализа данных в физике нейтрино.

PHYSTAT-nu 2019

22-25 January 2019
CERN
Europe/Zurich timezone

Search...

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The workshops deals with the statistical issues in the broad range of modern neutrino physics, in particular in view of the increased precision of current and future experiments.Topics to be included are

- Measuring model parameters, choosing between models
- Setting limits, discovery
- Determination of systematic uncertainties
- Unfolding
- Machine learning for event reconstruction and classification

The workshop will be a mixture of invited and contributed talks from physicists and statisticians.

Введение

$\sim$ 100 neutrino physicists
$\sim$ 50 LHC physicists
6 statisticians.

Louis Lyons (Imperial College (GB)). Introductory statistics course, part I.

Why 5σ for Discovery?

Statisticians ridicule our belief in extreme tails (esp. for systematics)

Our reasons:

1) Past history (Many 3σ and 4σ effects have gone away)
2) LEE
3) Worries about underestimated systematics
4) Subconscious Bayes calculation

$$\frac{p(H_1|x)}{p(H_0|x)} = \frac{p(x|H_1)}{p(x|H_0)} * \frac{\pi(H_1)}{\pi(H_0)}$$

Posterior prob — Likelihood ratio — Priors

"Extraordinary claims require extraordinary evidence"

N.B. Points 2), 3) and 4) are experiment-dependent

Alternative suggestion:

L.L. "Discovering the significance of 5σ" http://arxiv.org/abs/1310.1284 67

Почему 5−σ-discovery?

Louis Lyons (Imperial College (GB)). Introductory statistics course, part I.

How many σ's for discovery?

SEARCH	SURPRISE	IMPACT	LEE	SYSTEMATICS	No. σ
Higgs search	Medium	Very high	M	Medium	5
Single top	No	Low	No	No	3
SUSY	Yes	Very high	Very large	Yes	7
B_s oscillations	Medium/Low	Medium	Δm	No	4
Neutrino osc	Medium	High	$\sin^2 2\vartheta$, Δm^2	No	4
$B_s \to \mu\,\mu$	No	Low/Medium	No	Medium	3
Pentaquark	Yes	High/V. high	M, decay mode	Medium	7
$(g-2)_\mu$ anom	Yes	High	No	Yes	4
H spin ≠ 0	Yes	High	No	Medium	5
4^{th} gen q, l, ν	Yes	High	M, mode	No	6
Dark energy	Yes	Very high	Strength	Yes	5
Grav Waves	No	High	Enormous	Yes	8

Suggestions to provoke discussion, rather than `delivered on Mt. Sinai'

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Bob Cousins: "2 independent expts each with 3.5σ better than one expt with 5σ"

Полезные асимптотические формулы

Glen Cowan (Royal Holloway, University of London). Introductory Statistics Course - Part II.

Measure two Poisson distributed values:

$n \sim \text{Poisson}(s+b)$ (primary or "search" measurement)

$m \sim \text{Poisson}(\tau b)$ (control measurement, τ known)

Asymptotic significance

Use profile likelihood ratio for q_0, and then from this get discovery significance using asymptotic approximation (Wilks' theorem):

$$Z = \sqrt{q_0}$$

$$= \left[-2 \left(n \ln \left[\frac{n+m}{(1+\tau)n} \right] + m \ln \left[\frac{\tau(n+m)}{(1+\tau)m} \right] \right) \right]^{1/2}$$

for $n > \hat{b}$ and $Z = 0$ otherwise.

Essentially same as in:

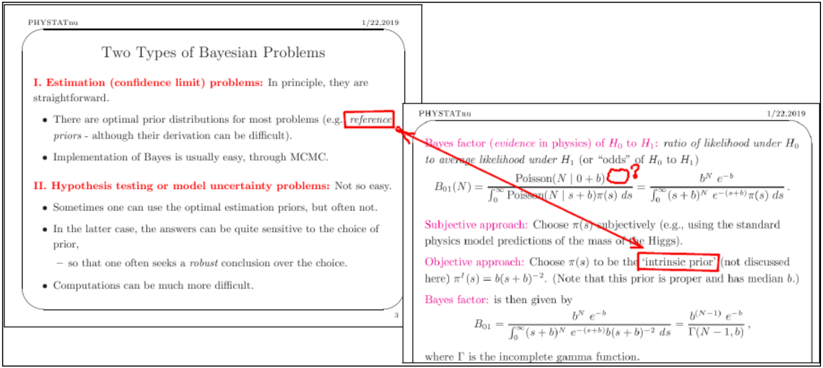
Robert D. Cousins, James T. Linnemann and Jordan Tucker, NIM A 595 (2008) 480–501; arXiv:physics/0702156.

Tipei Li and Yuqian Ma, Astrophysical Journal 272 (1983) 317–324.

G. Cowan PHYSTAT - ν Intro Course II / CERN, 22 Jan 2019 42

Имеется и более простая формула для известной величины b.

James Berger (Duke University). Bayesian techniques.


PHYSTATnu 1/22,2019

Two Types of Bayesian Problems

I. Estimation (confidence limit) problems: In principle, they are straightforward.

- There are optimal prior distributions for most problems (e.g. *reference priors* - although their derivation can be difficult).
- Implementation of Bayes is usually easy, through MCMC.

II. Hypothesis testing or model uncertainty problems: Not so easy.

- Sometimes one can use the optimal estimation priors, but often not.
- In the latter case, the answers can be quite sensitive to the choice of prior,
  - so that one often seeks a *robust* conclusion over the choice.
- Computations can be much more difficult.

3

PHYSTATnu 1/22,2019

Bayes factor (*evidence* in physics) of H_0 to H_1: *ratio of likelihood under* H_0 *to average likelihood under* H_1 (or "odds" of H_0 to H_1)

$$B_{01}(N) = \frac{\text{Poisson}(N \mid 0+b)}{\int_0^\infty \text{Poisson}(N \mid s+b)\pi(s)\,ds} = \frac{b^N\ e^{-b}}{\int_0^\infty (s+b)^N\ e^{-(s+b)}\pi(s)\,ds}.$$

Subjective approach: Choose $\pi(s)$ subjectively (e.g., using the standard physics model predictions of the mass of the Higgs).

Objective approach: Choose $\pi(s)$ to be the 'intrinsic prior' (not discussed here) $\pi^I(s) = b(s+b)^{-2}$. (Note that this prior is proper and has median b.)

Bayes factor: is then given by

$$B_{01} = \frac{b^N\ e^{-b}}{\int_0^\infty (s+b)^N\ e^{-(s+b)} b(s+b)^{-2}\,ds} = \frac{b^{(N-1)}\ e^{-b}}{\Gamma(N-1,b)},$$

where Γ is the incomplete gamma function.

Референсные априорные обычно не интегрируемы (improper)!
Это не проблема для формулы Байеса (произвольная константа сокращается).

Статус физики нейтрино

Alain Blondel (Universite de Geneve (CH)).

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

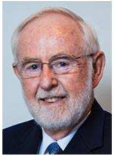


Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

A massless particle cannot be seen to transform $\tau_{lab} = \tau_{particle} * E/m \rightarrow \infty$

Статус физики нейтрино

Alain Blondel (Universite de Geneve (CH)).

neutrino definitions

the electron neutrino is present in association with an electron (e.g. beta decay)

the muon neutrino is present in association with a muon (pion decay)

the tau neutrino is present in association with a tau ($W \to \tau\nu$ decay)

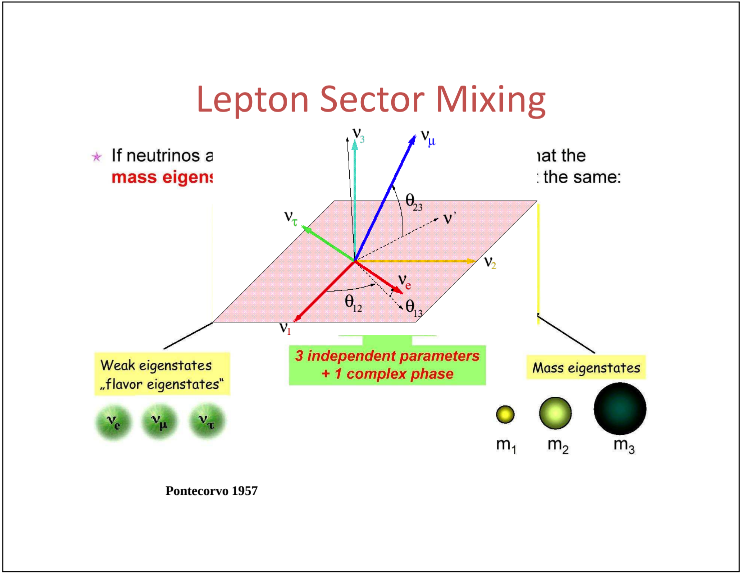
these flavor-neutrinos are not (as we know now) quantum states of well defined mass (neutrino mixing)

the mass-neutrino with the highest electron neutrino content is called ν_1

the mass-neutrino with the next-to-highest electron neutrino content is ν_2

the mass-neutrino with the smallest electron neutrino content is called ν_3

Alain Blondel (Universite de Geneve (CH)).



Статус физики нейтрино

Alain Blondel (Universite de Geneve (CH)).

General framework and status:

1. **We know that there are three families of active, light neutrinos *(LEP)***
2. **Solar neutrino oscillations are established *(Homestake+Gallium+Kam+SK+SNO)***
3. **Atmospheric neutrino (ν_μ –>) oscillations are established *(IMB+Kam+SK+ K2K)***
4. **At that frequency, (ν_μ –> ν_e) oscillations, small (5%) have been observed (T2K, NOvA) and ν_e disappearance has been measured (Daya Bay, Reno, Double Chooz)**

This allows a consistent picture with 3-family oscillations preferred:
LMA: θ_{12} ~30^0 Δm_{12}^2~8 10^{-5}eV^2 , θ_{23} ~45^0 $\Delta m_{23}{}^2$~ ±2.5 10^{-3}eV^2, θ_{13} <~ 9^0
with several unknown parameters though 2018 revealed hints of CPV and NH.
=> an exciting experimental program for at least 20 years *)
including leptonic CP & T violations.

5. **There are unexplained phenomena interpreted as possible higher frequency oscillation (LSND miniBooNe, reactors) but they are inconsistent with excellent disappearance experiments (MINOS, MINOS+, ICECUBE and DayaBay) so sterile neutrino explanation is ruled out, but further investigation will be performed with time-sensitive experiments (SBN,**

***)to set the scale: CP violation in quarks was discovered in 1964**
and there is still an important program (K0pi0, B-factories, Neutron EDM, BTeV, LHCb..) to go on for 10 years…i.e. a total of ~50 yrs.
and we have not discovered leptonic CP yet!

Статус физики нейтрино

Particle Data Group, 2018.

Neutrino Properties

See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m < 2$ eV (tritium decay)
Mean life/mass, $\tau/m > 300$ s/eV, CL = 90% (reactor)
Mean life/mass, $\tau/m > 7 \times 10^9$ s/eV (solar)
Mean life/mass, $\tau/m > 15.4$ s/eV, CL = 90% (accelerator)
Magnetic moment $\mu < 0.29 \times 10^{-10}\ \mu_B$, CL = 90% (reactor)

Number of Neutrino Types

Number $N = 2.984 \pm 0.008$ (Standard Model fits to LEP-SLC data)
Number $N = 2.92 \pm 0.05$ (S = 1.2) (Direct measurement of invisible Z width)

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Mass, Mixing, and Oscillations" by K. Nakamura and S.T. Petcov in this *Review*.

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23}) = 0.421^{+0.033}_{-0.025}$ (S = 1.3) (Inverted order, quad. I)
$\sin^2(\theta_{23}) = 0.592^{+0.023}_{-0.030}$ (S = 1.1) (Inverted order, quad. II)
$\sin^2(\theta_{23}) = 0.417^{+0.025}_{-0.028}$ (S = 1.2) (Normal order, quad. I)
$\sin^2(\theta_{23}) = 0.597^{+0.024}_{-0.030}$ (S = 1.2) (Normal order, quad. II)
$\Delta m^2_{32} = (-2.56 \pm 0.04) \times 10^{-3}$ eV^2 (Inverted order)
$\Delta m^2_{32} = (2.51 \pm 0.05) \times 10^{-3}$ eV^2 (S = 1.1) (Normal order)
$\sin^2(\theta_{13}) = (2.12 \pm 0.08) \times 10^{-2}$

Физика нейтрино и статистика

Yoshi Uchida (Imperial College London)

Three-Neutrino Oscillations

$$U_{ij} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix}$$

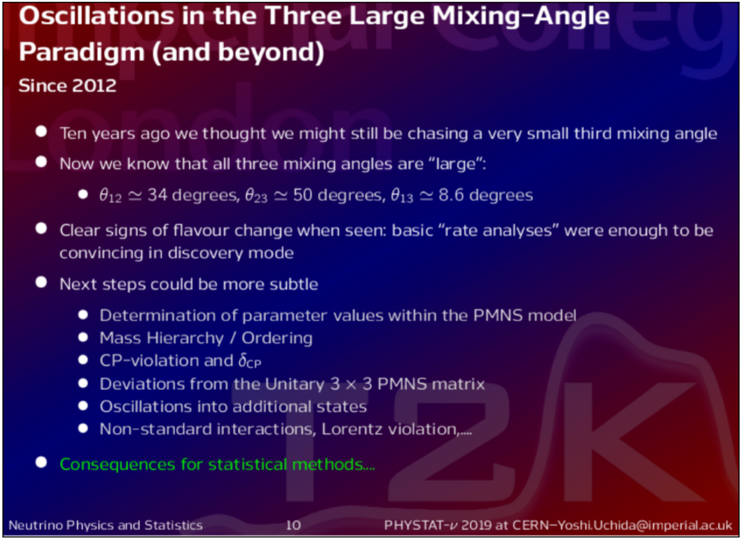
$$\times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Previous oscillations correspond to the “1–2” and “2–3” parameters
- The third type of oscillation would correspond to “1–3”
- Zero or very small θ_{13} combined with very different Δm^2 values for the two existing oscillations implies strong decoupling between them (Two-neutrino oscillations)
- Finite θ_{13} means two of the three Δm^2 values are very similar and oscillation effects become complicated

  $\Rightarrow$ Three-neutrino mixing

Физика нейтрино и статистика

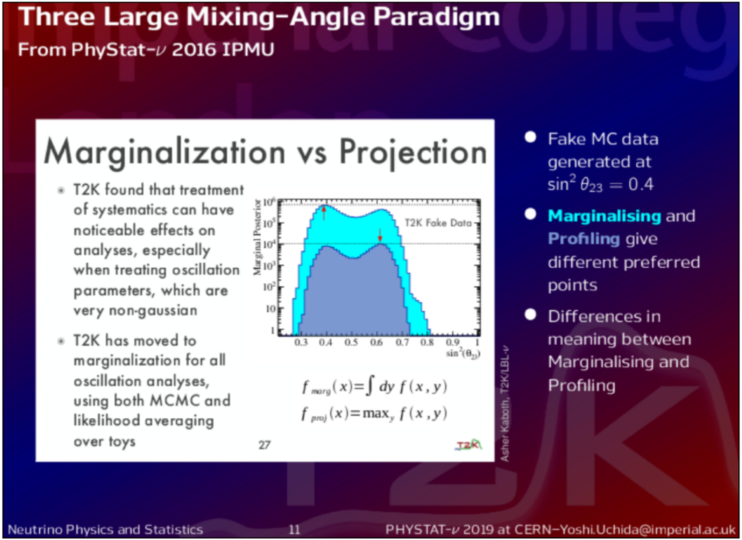
Yoshi Uchida (Imperial College London)



PMNS matrix: the Pontecorvo–Maki–Nakagawa–Sakata matrix, see previous slide.

Физика нейтрино и статистика

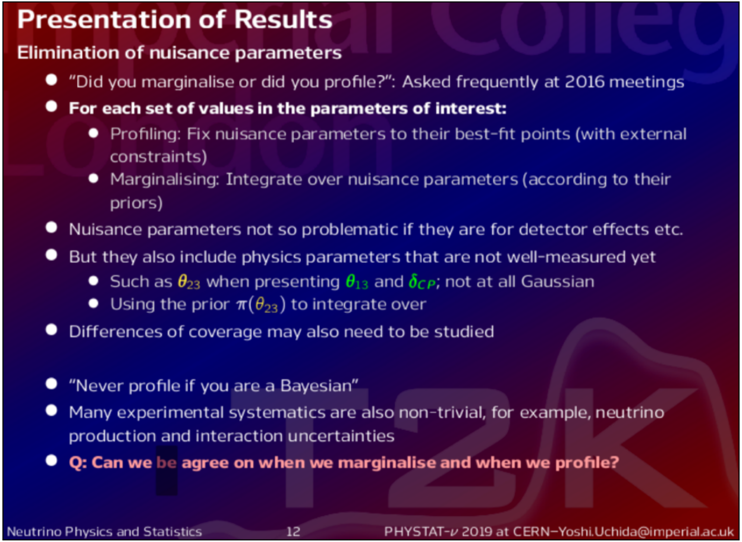
Yoshi Uchida (Imperial College London)



Множество важных деталей не объясняется. Есть сообщения о других методах в этой коллаборации.

Физика нейтрино и статистика

Yoshi Uchida (Imperial College London)



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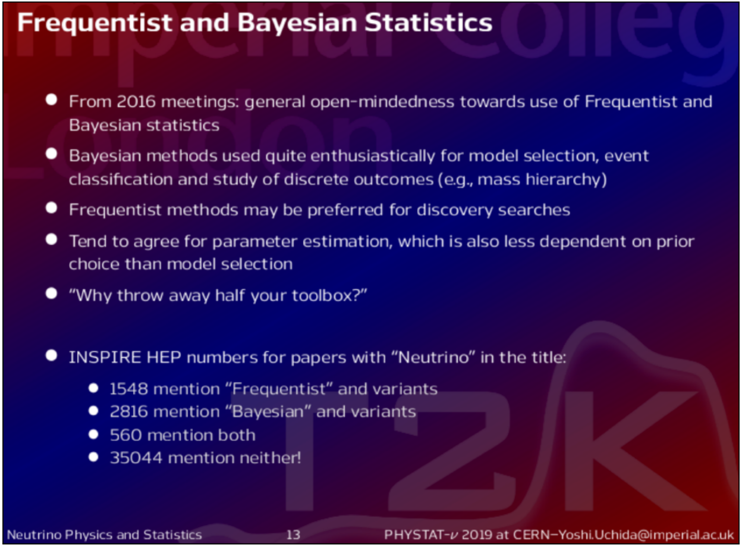

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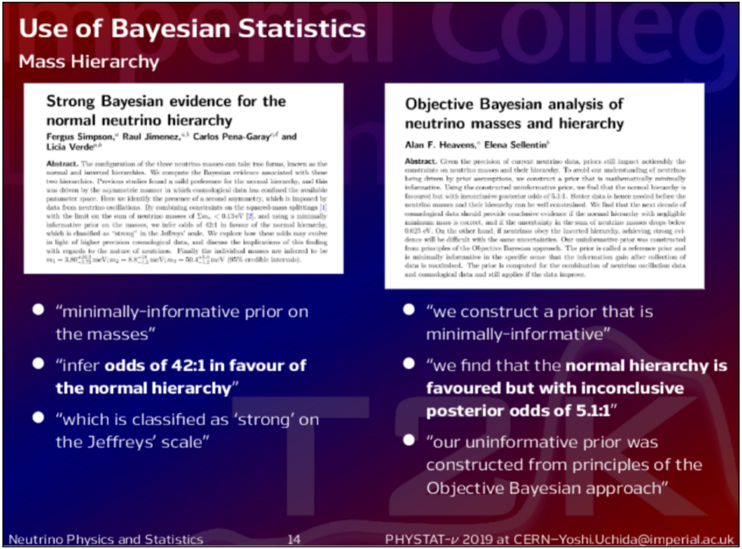
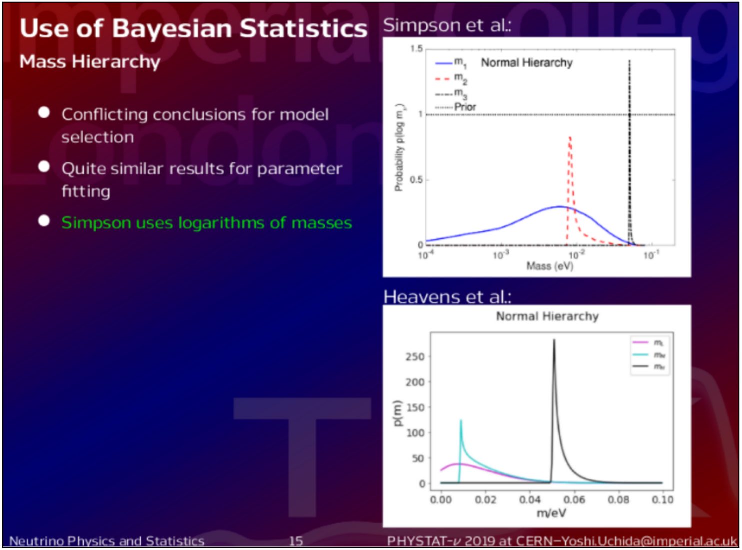


1. Hyperprior (a family of priors) for $ln(m)$.
2. Uniform prior for difference of squares of m.

Физика нейтрино и статистика

Yoshi Uchida (Imperial College London)



Последние оценки иерархии масс

Stefano Gariazzo (IFIC-CSIC/University of Valencia)

Can current data tell us the neutrino mass ordering?

1. [Hannestad, Schwetz, 2016]: extremely weak (2:1, 3:2) preference for NO (cosmology + [Bergstrom et al., 2015] neutrino oscillation fit) Bayesian approach;
2. [Gerbino et al, 2016]: extremely weak (up to 3:2) preference for NO (cosmology only), Bayesian approach;
3. [Simpson et al., 2017]: strong preference for NO (cosmological limits on $\sum m_\nu$ + constraints on Δm^2_{21} and $|\Delta m^2_{31}|$) Bayesian approach;
4. [Schwetz et al., 2017], "Comment on ..."[Simpson et al., 2017]: effect of prior?
5. [Capozzi et al., 2017]: 2σ preference for NO (cosmology + [Capozzi et al., 2016, updated 2017] neutrino oscillation fit) frequentist approach;
6. [Caldwell et al., 2017] very mild indication for NO (cosmology + neutrinoless double-beta decay + [Esteban et al., 2016] readapted oscillation results) Bayesian approach;
7. [Wang, Xia, 2017]: Bayes factor NO vs IO is not informative (cosmology only).

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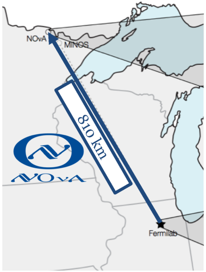
S. Gariazzo "Fits to large and combined data sets" PHYSTAT-nu, 23/01/2019 16/25

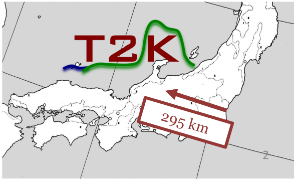
Эксперименты с “длинной базой”

Alexander Himmel (Fermilab)

What is a Long-Baseline Neutrino Experiment?

- A beam of neutrinos (primarily ν_μ) is produced by an accelerator.
- The neutrinos are allowed to travel and oscillate over a long distance.
- Detectors at the near and far end observe the neutrinos before and after oscillations.
- While energy and distance vary, the ratio of L/E is chosen to maximize “atmospheric” oscillations.

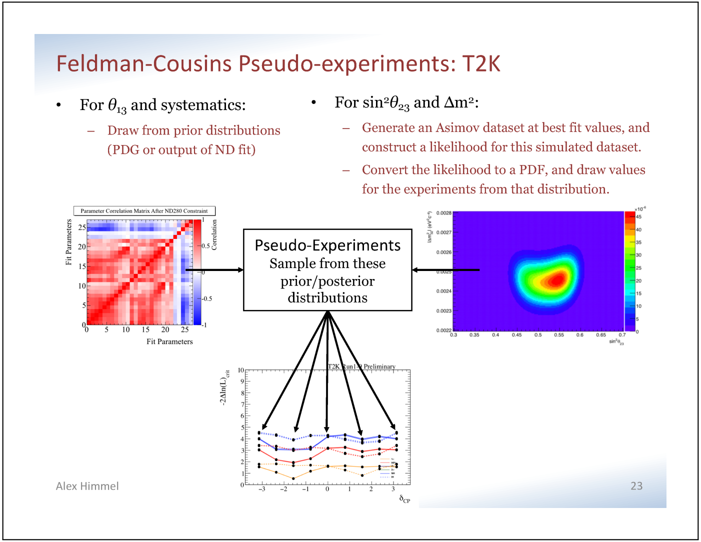




Alex Himmel 2

Эксперименты с “длинной базой”

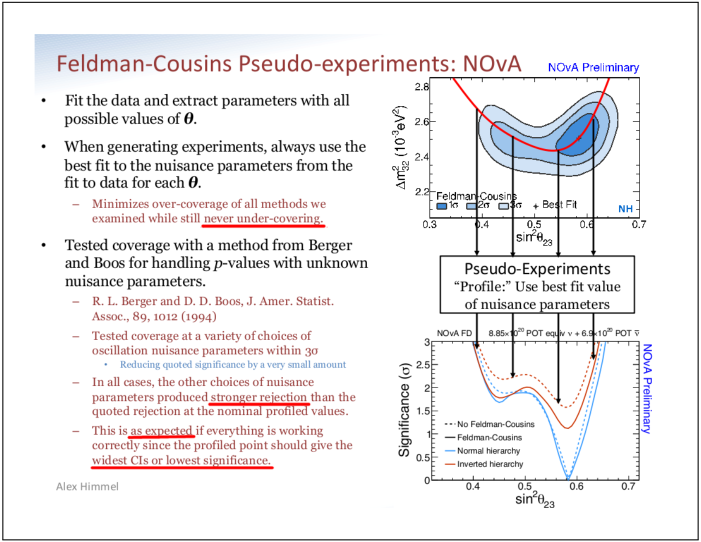
Alexander Himmel (Fermilab)



Процедура сильно отличается от стандартной.

Эксперименты с “длинной базой”

Alexander Himmel (Fermilab)



Underlines are mine.

В частном случае подчеркнутое может быть верно. В общем случае подчеркнутое неверно!

Слайд из моего доклада от 10.01.2017

Выбор p-величины

- Максимизация p-величины подбором мешающих параметров:
  1) Дает консервативную оценку, но насколько консерватизм оправдан?
  2) Нетривиальные максимумы существуют не для всех тестовых статистик и выборок.
  3) Существование таких тестовых статистик и выборок не доказано для произвольной задачи.
  4) В некоторых случаях выбранные мешающие параметры несовместимы с измерениями.
  5) Установление ограничений при подборе приводит к зависимости от (произвольных) ограничений.
- Максимизация p-величины подбором мешающих параметров на доверительном множестве: [R. L. Berger, D. D. Boos, J.Am.Stat.Ass., 89 (1994) 1012] “Valid p-value”: $P(\rho \leq \alpha) \leq \alpha$ для любого $\alpha \in [0, 1]$.
  Пусть C_β есть доверительное множество соотв. $1 - \beta$ для θ, если H_0 — истинна. $\rho_\beta = \sup_{\theta \in C_\beta}\{\rho(\theta)\} + \beta$, ρ_β заменяется на $\min\{\rho_\beta, 1\}$, и этот минимум — “valid p-value”.
  Устраняет (формально) проблему 4), но только её.

Christophe Bronner (University of Tokyo)

Mass hierarchy significance
Super-K results

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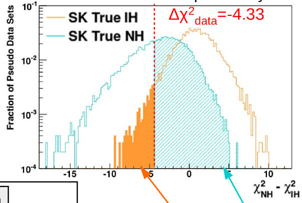
- Used CLs to report significance: not truly frequentist, but conservative
- Computed p-values and CLs for lower/upper edges of the 90% CL intervals for $\sin^2(\theta_{23})$ and δ
- Quoted a range of CLs-based significance in the paper

Plot for SK atmospheric only



P-values and CLs for IH exclusion

P-values	Lower	Best fit	Upper
SK only	0.012	0.027	0.020
SK+T2K model	0.004	0.023	0.024

CLs	Lower	Best fit	Upper
SK only	0.181	0.070	0.033
SK+T2K model	0.081	0.075	0.056

$$\mathrm{CL}_s = \frac{p_0(IH)}{1 - p_0(NH)}$$

PRD 97, 072001 (2018)

Формула в дискретном случае не верна!

Проблема моделирования реакторных антинейтрино

Emilio Ciuffoli (IMP, CAS)

Reactor Neutrino Spectrum

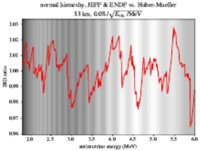
Theoretical model for reactor neutrino fluxes:

- *Ab initio* approach: calculate spectrum branch-by-branch (however, problematic for the large number of isotopes, $\simeq 10^3$, and branching ratio, $\simeq 10^4$)
- Conversion method: measure the beta spectrum directly and then convert to $\bar{\nu}_e$

In the last years with the measurement of the "5 MeV bump" it became clear that the current models for reactor neutrinos are not very reliable. Moreover, only available measurements of reactor neutrino spectrum with low energy resolution ($\simeq 6\%/\sqrt{E}$; for MH $3\%/\sqrt{E}$ needed).

A fine structure ("sawtooth-like features') is most likely present (showed also in "ab initio" calculations) and currently undetected; it could be a problem for the MH determination

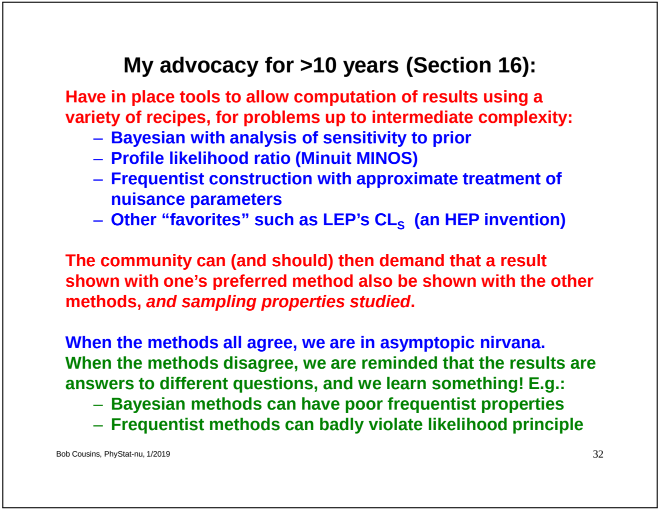
See also D. Forero, R. Hawkins, P. Huber, arXiv:1710.07378, and Danielson *et al*, arXiv:1808:03276



Danielson *et al*, arXiv:1808:03276

Uncertainty in the Reactor Neutrino Spectrum and MHD

Robert Cousins Jr (University of California Los Angeles (US)),



Другие доклады

Ещё около 20 докладов, в том числе по unfolding и deep neural networks.

Заключение

На совещании PHYSTAT-ν 2019 обсуждены

- основные методы статистического анализа данных,
- некоторые другие методы анализа,
- статус нейтринных экспериментов и перспективы на будущее.

Спасибо за внимание!