Years of PC Overview

31/May–1/June/2018

M. Komatsu

Thanks to

Stefano Dusini

and

Andrea Longhin

Since July 2012

Mandate started from Sep. 2012 at Alushta, since July as an interim PC with Stefano.

- Meetings : 50 PC and 22 CM
  - 2012 : 4 PC + 3 CM (since July)
  - 2013 : 10 PC + 7 CM
  - 2014 : 10 PC + 4 CM
  - 2015 : 8 PC + 4 CM
  - 2016 : 8 PC + 2 CM
  - 2017 : 8 PC + 1 CM
  - 2018 : 2 PC + 1 CM (Today)

Alushta meeting, Sep. 2012
Photo taken at Yalta

Years of overview : 2012-14

- Major objective was to renew efficiency and BG with full chain.
  - Ever since OPERA proposal, efficiencies and BGs were patched here and there, but not fully renewed.
- As a result of renewal, we could deliver these papers.
  - Electron neutrino : JHEP 1307 (2013) 004
  - Second tau paper : JHEP 1311 (2013) 036
  - Third tau paper : Phys.Rev. D89 (2014) no.5, 051102 (3.4σ)
  - Charm paper : Eur.Phys.J. C74 (2014) no.8, 2986
- New normalization based on located events
  - To cope with three different strategy (2008-9,2010,2011)

Normalization on the located

To normalize signal and background to the located events we have to express the "exposure" Mass × Pot in term of 0mu or 1mu located events

$$N_{obs}^{0\mu} = N_{obs}^{0\mu}(CC) + N_{obs}^{0\mu}(NC) = MPN_A \int \phi(E)\left(\sigma_{\nu_\mu CC}\,\varepsilon_{CC}^{0\mu} + \sigma_{\nu_\mu NC}\,\varepsilon_{NC}^{0\mu}\right) dE =$$

$$= MPN_A \int \phi(E)\,\sigma_{\nu_\mu CC}\left(\varepsilon_{CC}^{0\mu} + \frac{\sigma_{\nu_\mu NC}}{\sigma_{\nu_\mu CC}}\,\varepsilon_{NC}^{0\mu}\right) dE$$

$$= MPN_A\left(\int \phi\,\sigma_{\nu_\mu CC}\,\varepsilon_{CC}^{0\mu}\, dE + \int \phi(E)\,\sigma_{\nu_\mu NC}\,\varepsilon_{NC}^{0\mu}\, dE\right) = MPN_A\left(\langle \varepsilon_{CC}^{0\mu}\rangle N^0_{\nu_\mu CC} + \langle \varepsilon_{NC}^{0\mu}\rangle N^0_{\nu_\mu NC}\right)$$

$$= MPN_A\, N^0_{\nu_\mu CC}\left(\langle \varepsilon_{CC}^{0\mu}\rangle + \alpha \langle \varepsilon_{NC}^{0\mu}\rangle\right) \quad \text{where} \quad \alpha = \frac{N^0_{\nu_\mu NC}}{N^0_{\nu_\mu CC}} \sim 0.276\,; \quad N_i^0 = \int \phi\,\sigma_i\, dE$$

$$N^0_{\nu_\mu CC} = 647/_{kton/10^{19}pot}$$

$$MPN_A = \frac{N_{obs}^{0\mu}}{N^0_{\nu_\mu CC}\left(\langle \varepsilon_{CC}^{0\mu}\rangle + \alpha \langle \varepsilon_{NC}^{0\mu}\rangle\right)}$$

$$N_{exp}^{\tau(0\mu)} = \frac{N_{obs}^{0\mu}}{N^0_{\nu_\mu CC}\left(\langle \varepsilon_{CC}^{0\mu}\rangle + \alpha \langle \varepsilon_{NC}^{0\mu}\rangle\right)} \langle \varepsilon \rangle\, N_\tau^0$$

The background is normalized in a similar way

2008/2009

- $Dm2 = 2.32\ 10^{-3}\ eV^2$
- Data: 0mu = 417; 1mu = 2445;

2008 - 2009

Channel	Signal	Background			
		Total	Charm	Had.	Large Mu. Scat.
$\tau \to 1h$	0.136134	0.0125561	0.00486342	0.00769269	0
$\tau \to 3h$	0.191512	0.0504833	0.0494448	0.00103851	0
$\tau \to \mu$	0.208728	0.00772924	0.00151072	0	0.00621852
$\tau \to e$	0.20341	0.00891628	0.00891628	0	0
Total	0.739784	0.079685	0.0647352	0.00873121	0.00621852

- 2008/2009 Data: $5.3\ 10^{19}$ pot
- The located events are the 92% of the 2008/2009 data
- The 1mu events are 18% of the nominal table while the 0mu are the 15%
- Taking into account the dead material and the bad quality films
- (5.3/22.5) x 0.92 x (1-0.078) x (1 - 0.06) = 19%
- We are missing some 0mu events or there is some extra inefficiency not accounted

2010/2011

- Dm2 = 2.32 10^{-3} eV^2
- 2010 Data: 0mu = 218; 1mu = 927;
- 2011 Data: 0mu = 225; 1mu = 0;

2010

Channel	Signal	Background			
		Total	Charm	Had.	Large Mu. Scat.
$\tau \to 1h$	0.0831574	0.00702292	0.00308023	0.00394269	0
$\tau \to 3h$	0.115653	0.0325666	0.0320344	0.000532263	0
$\tau \to \mu$	0.139893	0.00430653	0.000852638	0	0.0034539
$\tau \to e$	0.127643	0.00554441	0.00554441	0	0
Total	0.466347	0.0494405	0.0415116	0.00447495	0.0034539

2011

Channel	Signal	Background			
		Total	Charm	Had.	Large Mu. Scat.
$\tau \to 1h$	0.0858276	0.00724842	0.00317913	0.00406929	0
$\tau \to 3h$	0.119367	0.0336123	0.033063	0.000549354	0
$\tau \to \mu$	0	0	0	0	0
$\tau \to e$	0.131742	0.00572244	0.00572244	0	0
Total	0.336936	0.0465832	0.0419646	0.00461864	0

Years of overview : 2014-16

- To achieve 5 sigma discovery
  - With a limited mass and limited PoT, what we can do?
  - Further improvements of efficiency and reduction of BG.
  - With a great effort also on scanning coordination.
- As a result, we could deliver these papers.
  - Fourth tau : PTEP 2014 (2014) no.10, 101C01 (4.2σ)
  - Sterile paper : JHEP 1506 (2015) 069
  - Fifth tau : Phys.Rev.Lett. 115 (2015) no.12, 121802 (5.1σ)
    - More than 100 citations today
    - We could deliver this result before Nobel Prize 2015
- Thanks to big progress on scanning and analysis

Scientific Background on the Nobel Prize in Physics 2015

NEUTRINO OSCILLATIONS

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

Super-Kamiokande's oscillation results were later confirmed by the detectors MACRO [55] and Soudan [56], the long-baseline accelerator experiments K2K [57], MINOS [58] and T2K [59] and more recently also by the large neutrino telescopes ANTARES [60] and IceCube [61]. Appearance of tau-neutrinos in a muon-neutrino beam has been demonstrated on an event-by-event basis by the OPERA experiment in Gran Sasso, with a neutrino beam from CERN [62].

Phys.Rev.Lett. 115 (2015) no.12, 121802

Dating back to '97

LNGS-LOI 8/97
September 8, 1997

LETTER OF INTENT

The OPERA emulsion detector for a long-baseline neutrino-oscillation experiment

ABSTRACT

We present a new detector concept (OPERA), a massive iron/emulsion target for a long-baseline neutrino-oscillation search. The experiment can perform an appearance search for $\nu_\mu - \nu_\tau$ oscillation in the parameter region indicated by the atmospheric neutrino anomaly. It exploits nuclear emulsion for the unambiguous detection of the decay of the τ produced in ν_τ charged current interactions and features a detector target with relatively small mass (200 ton) and dimensions. The very low background is an essential ingredient to its high discovery potential and promises a unique role in the clarification of the experimental scenario. OPERA can run in the Gran Sasso Laboratory in the proposed neutrino beam from CERN.

An appearance experiment to search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in the CNGS beam

CERN/SPSC 2000-028
SPSC/P318
LNGS P25/2000
July 10, 2000

ABSTRACT

The OPERA[4] experiment is proposed for an appearance search of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in the parameter region indicated by Super-Kamiokande as the explanation of the zenith dependence of the atmospheric neutrino deficit. OPERA is a long baseline experiment to be located at the Gran Sasso Laboratory in the CNGS[5] neutrino beam from the CERN SPS. The detector design is based on a massive lead/nuclear emulsion target. Nuclear emulsions are used as high resolution tracking devices, for the direct observation of the decay of the τ leptons produced in ν_τ charged current interactions. Electronic detectors locate the events in the emulsions. Magnetised iron spectrometers measure charge and momentum of muons. The discovery potential of OPERA originates from the observation of a ν_τ signal with very low background level. The direct observation of $\nu_\mu \leftrightarrow \nu_\tau$ appearance will constitute a milestone in the study of neutrino oscillations.

The number of observed events allowing for a claim of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation discovery at the 4σ level is defined by the $1.0 - (6.3 \times 10^{-5})$ CL upper limit of the Poisson distribution with a mean value corresponding to the expected number of background events. For a 4σ discovery claim, about 5 events are required. More generally, Fig. 143 gives the statistical significance (expressed in terms of equivalent σ for a Gaussian distribution) as a function of the number of events observed.

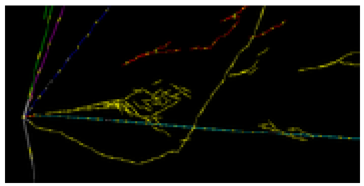
Years of overview : 2016-18

- Major objectives
  - For nue : Fully updated efficiency evaluation and with full data.
  - For tau : New strategy with looser cut using multivariate analysis with full statistics
- We delivered
  - New nue : Submitted to JHEP on 30th/Apr. (arXiv:1803.11400)
  - Final tau : Phys.Rev.Lett. 120 (2018) no.21, 211801 (6.1σ)
  - Charge multiplicity : Eur.Phys.J. C78 (2018) no.1, 62
- Also, many other papers are published since 2012
  - Neutrino velocity (2012data) : JHEP 1301 (2013) 153
  - AMM paper : JINST 11 (2016) no.07, P07022
  - Muon charge ratio : Eur.Phys.J. C74 (2014) 2933

PHYSICAL REVIEW LETTERS
moving physics forward

Dear Sir or Madam,

We are pleased to inform you that the Letter



Final results of the OPERA experiment on ν_τ appearance in the CNGS neutrino beam

N. Agafonova *et al.* (OPERA Collaboration)
Phys. Rev. Lett. **120**, 211801 (2018)

Published 22 May 2018

has been highlighted by the editors as an Editors' Suggestion. Publication of a Letter is already a considerable achievement, as *Physical Review Letters* accepts fewer than 1/4 of submissions, and is ranked first among physics and mathematics journals by the Google Scholar five-year h-index. A highlighted Letter has additional significance, because only about one Letter in six is highlighted as a Suggestion due to its particular importance, innovation, and broad appeal. Suggestions are downloaded twice as often as the average Letter, and are covered in the press substantially more often. If Suggestions were a separate publication, they would have an Impact Factor of 14. More information about our journal and its history can be found on our webpage prl.aps.org.

Appreciation to young people

(some of them are not young anymore)

- Those who worked for event analysis
  - Event location, decay search, cross check, dedicated special event analysis, track follow down, muon charge determination
- Those who worked for MC chain (OpEmuRec)
  - Code development, event production, efficiency and background evaluation
- Those who worked for background reduction and understanding
  - Hadron interaction test experiment, muon LAS evaluation, charm detection efficiency

- Without these young people’s contribution, we could not achieve our goal.

PC meetings since last CM

- We had seven PC meetings since March 2017 CM on Video
- PC meeting 18/5/2017
  - https://indico.cern.ch/event/639378/
  - Double vertex event, marginal event, numu disappearance, Open Data viewer, nue paper status, strategy for nutau and nue combined analysis and electron search in ECC.
- PC meeting 13/6/2017
  - https://indico.cern.ch/event/644952/
  - Numu disappearance, marginal event analysis, combined analysis, nue internal note and Open Data.
- PC meeting 14/7/2017
  - https://indico.cern.ch/event/652139/
  - Nue paper editor's propposal, marginal event toward paper, numu disappearance, combined analysis, cosmic ray annual modulation and nue search in ECC.
- PC meeting 5/9/2017
  - https://indico.cern.ch/event/661676/
  - As same as above

PC meetings since last CM

- We had seven PC meetings since March 2017 CM on Video
- PC meeting 24/11/2017
  - https://indico.cern.ch/event/681726/
  - Nue paper draft status, cosmic ray annual modulation toward paper, marginal event paper and double vertex event paper.
- PC meeting 26/04/2018
  - https://indico.cern.ch/event/724114/
  - Cosmic ray annual modulation, non-standard interaction, CERN Open Data
- PC meeting 17/05/2018
  - https://indico.cern.ch/event/728948/
  - Combined analysis, numu disappearance, Slides for the seminar at LNGS on May 22nd.

Since last CM (March 2017)

HIGHLIGHTED OVERVIEW

Matteo @ 5 Sep. 2017

Combined analysis status

M. Tenti

05 September 2017

Matteo @ 5 Sep. 2017

Configuration

- Std. Osc. Model
- Matter effects (constant density)
- Parameters of interest:
  - θ_{23}, θ_{13}
- Nuisance parameters:
  - δ_{CP}, θ_{12}
- Constants
  - $\Delta m^2_{21} = 7.37 \times 10^{-5}$ eV^2

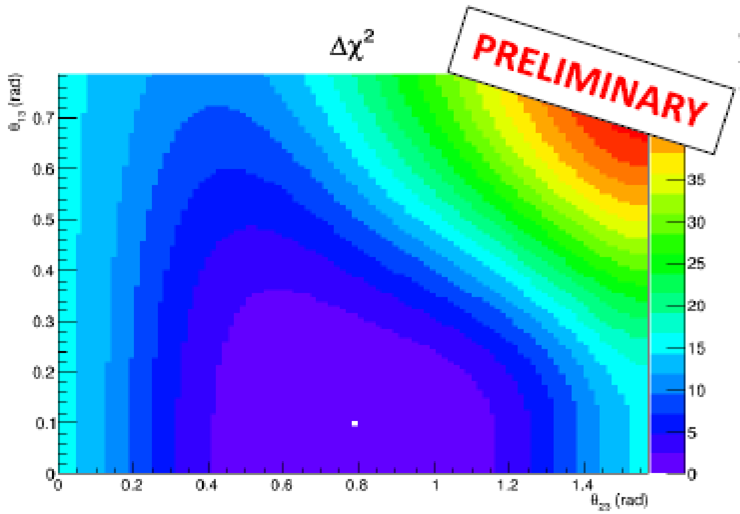
- Priors
  - Gaussian on Δm^2_{31} $(2.54 \pm 0.05) \times 10^{-3}$ eV^2
- Likelihood:
  - $L = L_e + L_\tau$ + Prior
  - L_e, L_τ poissonian: $L = \prod_i \frac{\lambda_i^{n_i} \cdot e^{-\lambda_i}}{n_i!}$
- Test statistic: profile likelihood ratio

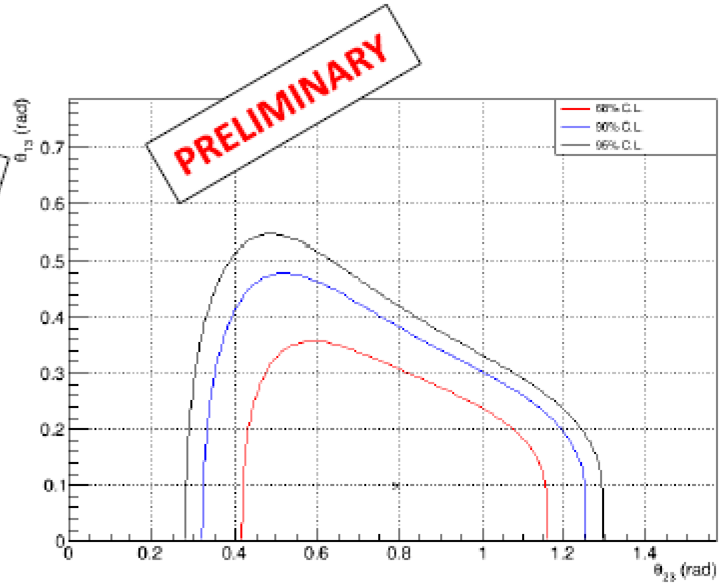
05/09/2017 M. Tenti - PC 2

Matteo @ 5 Sep. 2017

$\Delta\chi^2$ & Allowed region

θ_{23} vs θ_{13}





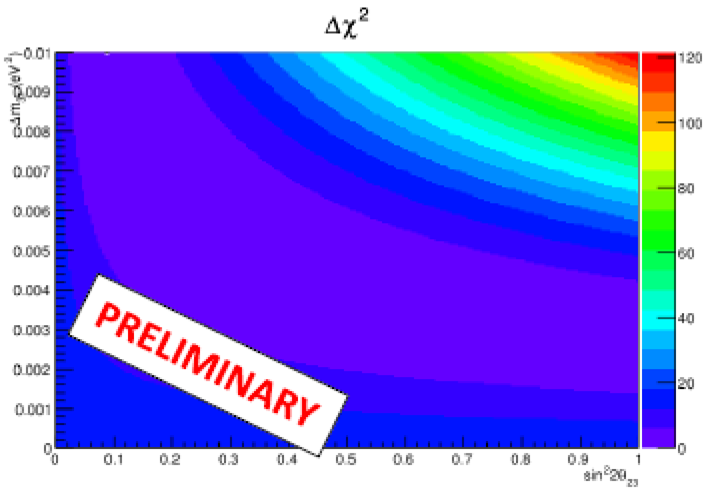
Best fit: $(\theta_{23}, \theta_{13}) = (0.79, 0.098)$ [rad]

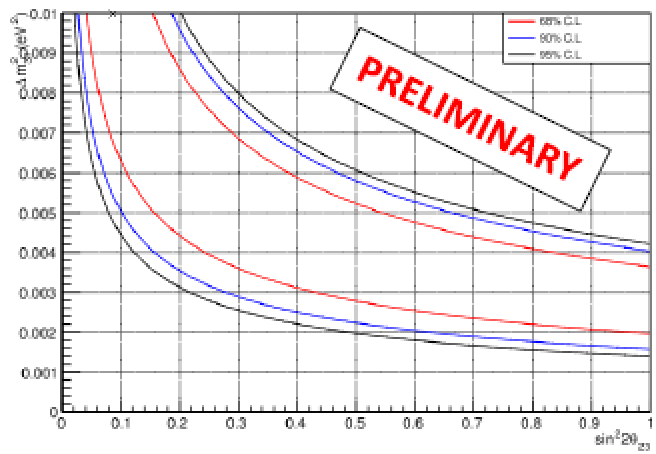
05/09/2017 M. Tenti - PC 6

Matteo @ 5 Sep. 2017

$\Delta\chi^2$ & Allowed region

$\sin^2 2\theta_{23}$ vs Δm^2_{31}

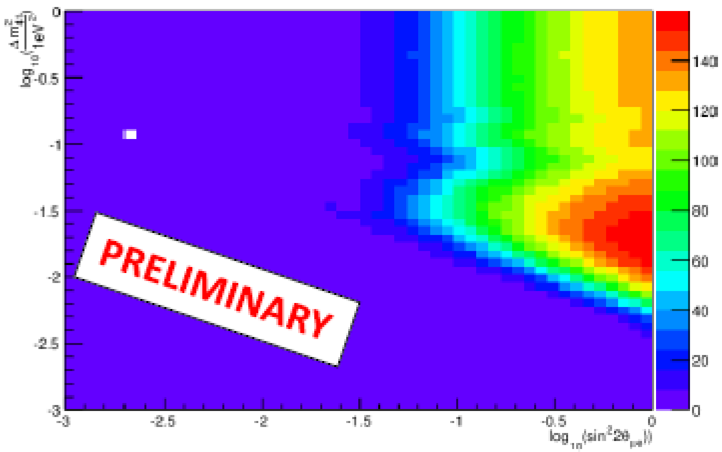


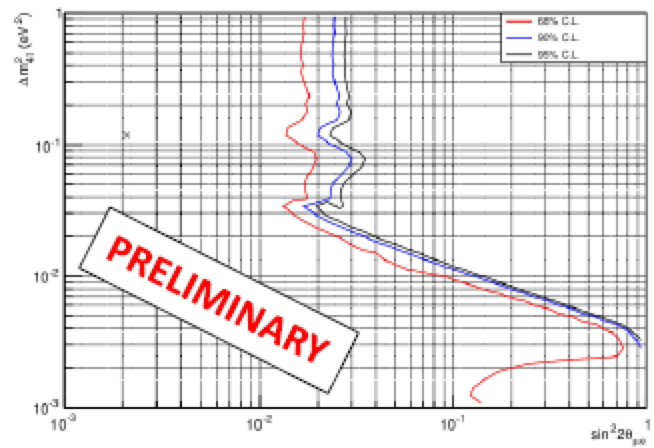


Matteo @ 5 Sep. 2017

$\Delta\chi^2$ & Allowed region

$\sin^2 2\theta_{\mu e}$ vs Δm^2_{41}

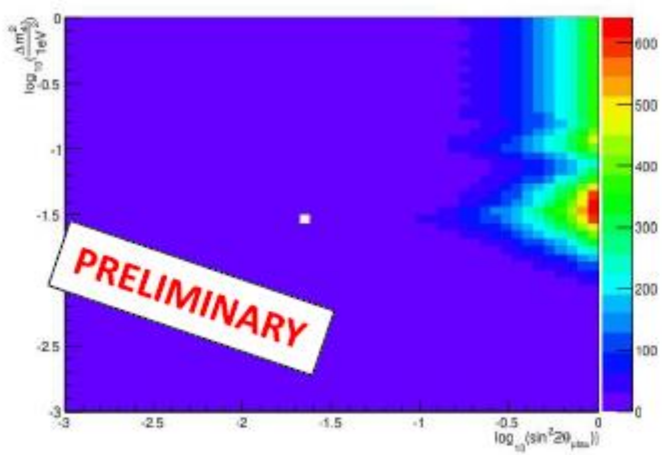


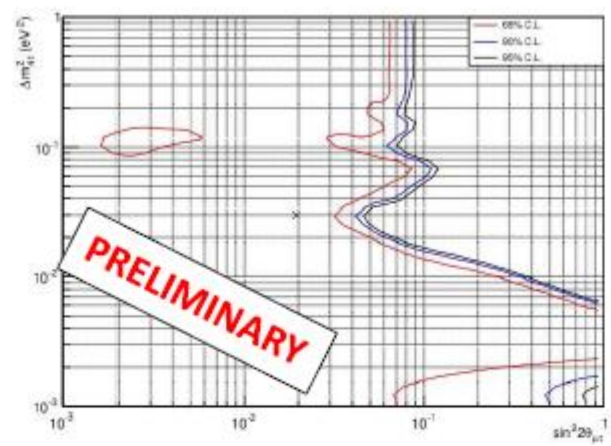


Matteo @ 5 Sep. 2017

$\Delta\chi^2$ & Allowed region

$\sin^2 2\theta_{\mu\tau}$ vs Δm^2_{41}





05/09/2017 M. Tenti - PC 16

Gabriele @ 24 Nov. 2017

Istituto Nazionale di Fisica Nucleare

Tau Charm Neutrino Analysis Report

Marco Roda, Chiara Sirignano, Gabriele Sirri

OPERA PC Meeting
2017.11.24

Tau Charm Paper

Gabriele @ 24 Nov. 2017

- Analysis closed and presented at Nagoya Meeting: March 2016
- Internal note: March 2016
- Draft paper public reading: April 2017
- Comments on the draft paper
  - Most of the suggestions were implemented
- Additional clarification about the robustness of the significance given at PC Meeting: 18th May 2017
  - Addressed points were:
    1. additional channel for unaccounted topologies
    2. non-extended likelihood (contribution of the shape)
    3. classifiers other than NN

Interpretation

Gabriele @ 24 Nov. 2017

The significance level (size of the test) is the result of a frequentist hypothesis test.

Changing the PDF means testing different hypotheses.

1. Poissonian term included

   "The background only can give one event that looks like the observed event"

   vs

   "The background + signal can give one event that looks like the observed event"

2. No Poissonian term

   "A single background event looks like the observed event"

   vs

   "A single background or signal event looks like the observed event"

Gabriele @ 24 Nov. 2017

Updated Results

- The old simulation was re-tested
  - We found a small bug which was changing the significance
    - Double counting of 1 PDF in the global likelihood
  - The new result is: 4.0 sigma (+/- 0.2)

- As requested we computed the significance without Poissonian term
  - The result is: 2.8 sigma (+/- 0.04)

- These results were obtained by sampling the test statistic using an Bayes-Frequentist calculation, marginalizing nuisance parameters
  - Cousins, Highland, NIM A320 (1992) 331

Objectives for 2018

- Combined analysis paper
  - We can explore all oscillations from ν_μ.
    - $\nu_\mu \rightarrow \nu_\tau$ appearance
    - $\nu_\mu \rightarrow \nu_e$ appearance
    - $\nu_\mu \rightarrow \nu_\mu$ disappearance
- Cosmic ray annual modulation paper
  - Already sent to internal referees
- Double vertex paper
  - Contents are approved in PC meeting, only editorial work.
- NSI (Non Standard Interaction) and LIV (Lorentz Invariance Violation)
- Data and Software preservation
- Additional physics outputs

Agenda

- Data related
  - Data and Software preservation : Cristiano
  - CERN Open Data Portal : Sergey
- Papers in preparation and running analysis
  - nutau and nue combined analysis : Matteo
  - numu disappearance analysis : Budimir
  - cosmic annual modulation : Alessandro
  - Double vertex paper status : Chiara, Gabriele
- Analysis for future papers
  - nue analysis in ECC : Hayakawa
  - Charm analysis : Mustafa
  - Non-Standard interaction and Lorentz Invariance Violation : Alessandro

20 years of dream has accomplished