ν_μ disappearance

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OPERA Collaboration meeting
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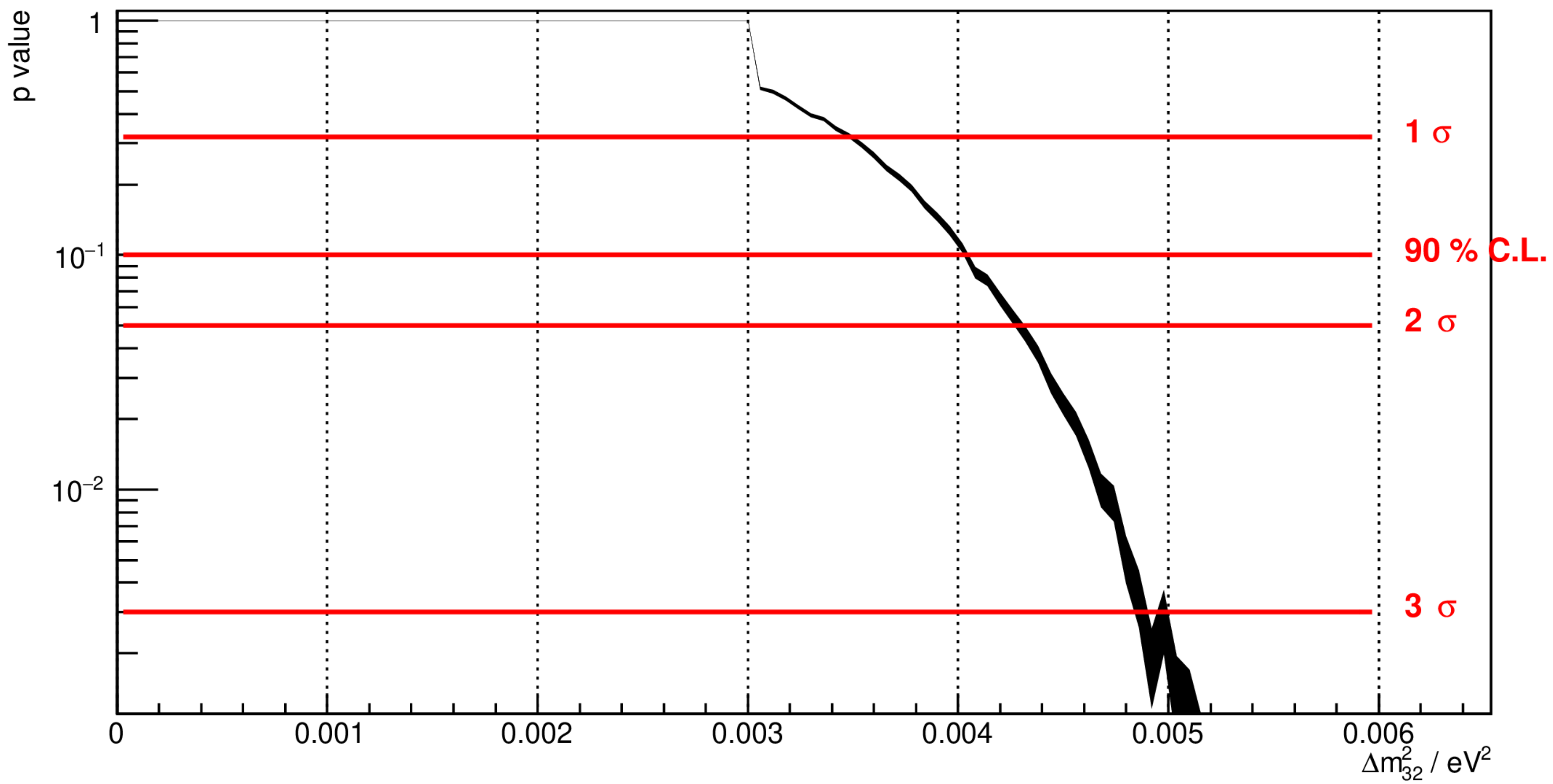
The result



$$\left|\Delta m^2_{32}\right| < 4.1 \cdot 10^{-3}\ \mathrm{eV}^2\ @\ 90\%\ \mathrm{C.L.}$$

Monte Carlo

Monte Carlo

- A new full simulation of neutrino interactions in OPERA and surrounding material was created
- Separate beamfiles for three categories of materials
  - Lead
  - Iron
  - ISO
    - all other materials
    - C12 target was used to produce ISO beamfiles

Beamfiles

- A set of beamfiles was produced using Genie 2.8.6
- All CNGS prompt flux components
  - NC interactions included here
- ν_μ appearance fluxe
  - $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$
  - all other appearance fluxes proved to be negligible
- 6 flux components in total, 3 materials – 18 different beamfiles

Flux	ν flavour	Number of events			Oscillation channel
		LEAD	IRON	ISO	
ν_μ	ν_μ	10^6	10^6	$3 \cdot 10^6$	$\nu_\mu \rightarrow \nu_\mu$
	ν_e	10^6	10^6	10^6	$\nu_\mu \rightarrow \nu_e$
	ν_τ	10^6	10^6	10^6	$\nu_\mu \rightarrow \nu_\tau$
$\overline{\nu}_\mu$	$\overline{\nu}_\mu$	10^6	10^6	10^6	$\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$
ν_e	ν_e	10^6	10^6	10^6	$\nu_e \rightarrow \nu_e$
$\overline{\nu}_e$	$\overline{\nu}_e$	10^6	10^6	10^6	$\overline{\nu}_e \rightarrow \overline{\nu}_e$

OPERA geometry sub-volumes

- Seven sub-volumes were defined, according to materials and expected number of triggered events
  - opdy_lead – all lead in OPERA detector
  - opdy_iron – all iron in OPERA detector
  - opdy_iso – volume containing all other materials in OPERA
  - borexino – Borexino and its infrastructure
  - front_rock – rock in front
  - below_hallc – rock below
  - side_and_above_hallc – shield and rock around Hall C, except the one below
- A single MC run is defined by a sub-volume and flux component

Interaction vertex selection

- Neutrino interaction vertices were chosen according to the interaction probability
  - extension to OpSim
  - trivial for subvolumes containing only one material, not trivial for others

Event weights

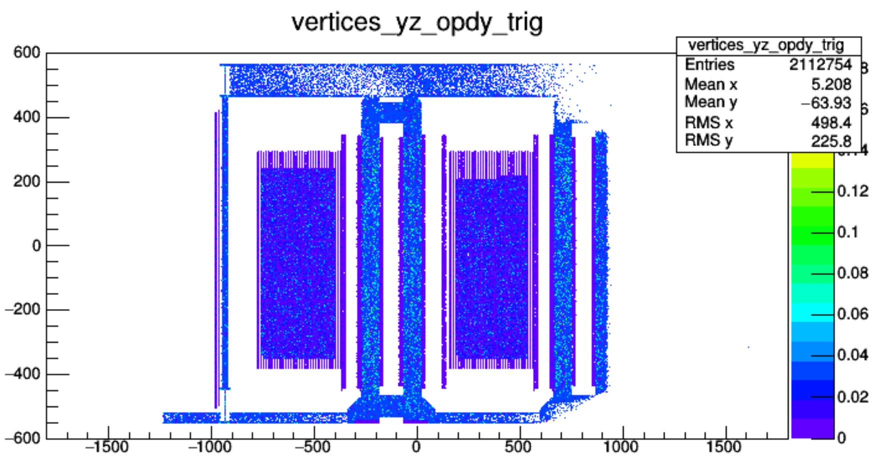
- Events are re-weighted such that the total sum of all event weights equals the number of expected CNGS neutrino interactions for 1.82e20 p.o.t

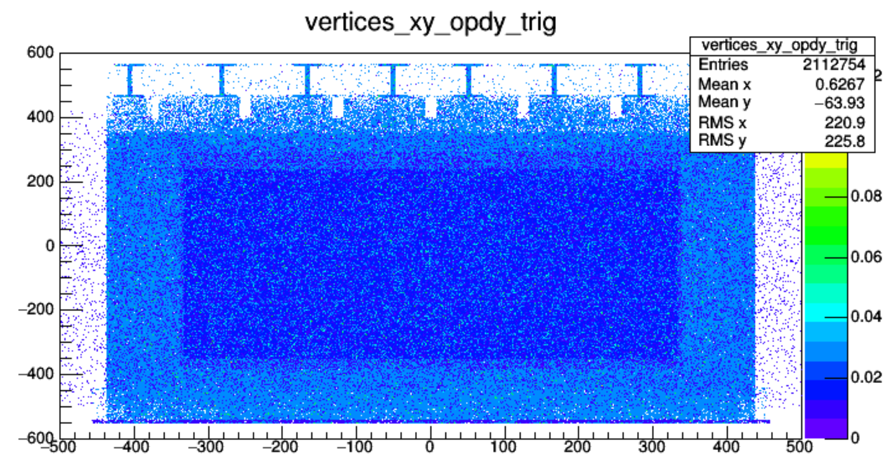
- *unoscillated weight* – weight of appearance events before oscillation probability is applied

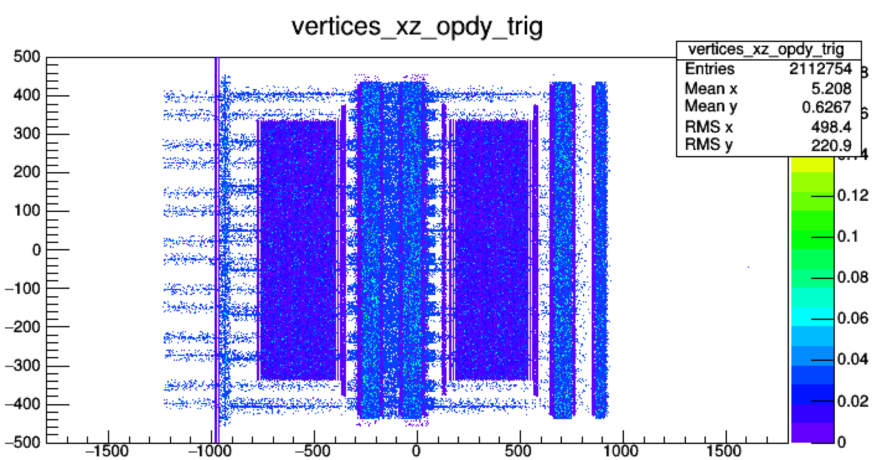
Trigger

- Trigger components:
  - TT_trigger - two consecutive TT planes with more than 1 pe in either horizontal or vetical direction or a single plane with more than 500 ADC
  - RPC_trigger – at least 3 planes in a single spectrometer fired
  - ndigits – number of RPC+TT digits
- Total trigger
  - (TT_trigger **OR** RPC_trigger) **AND** ndigits>10
- This trigger was applied both to MC and DATA events
  - it’s slightly stricter than the actual ELEDET event trigger

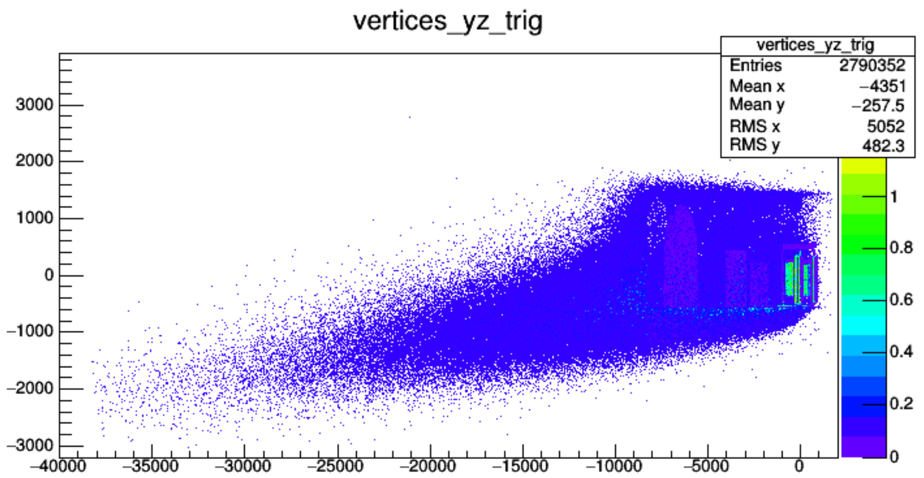
Distribution of vertices in detecctor of triggered ν_μ events

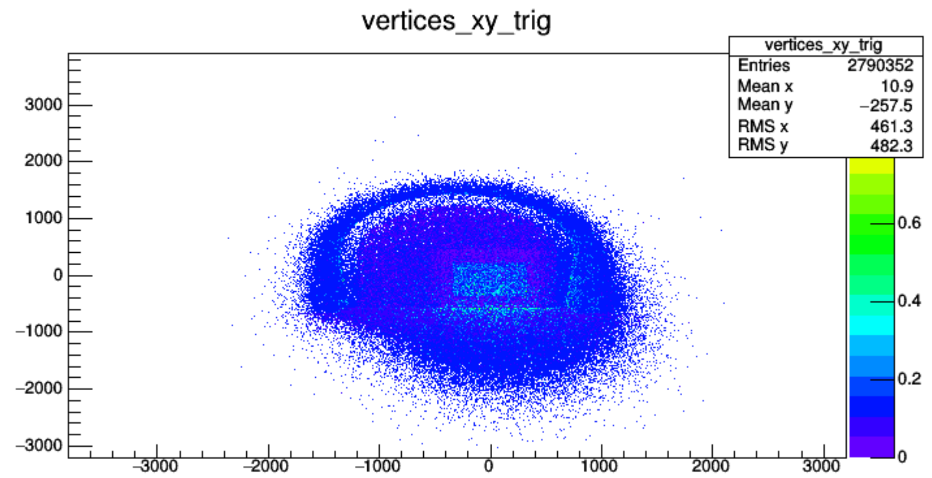


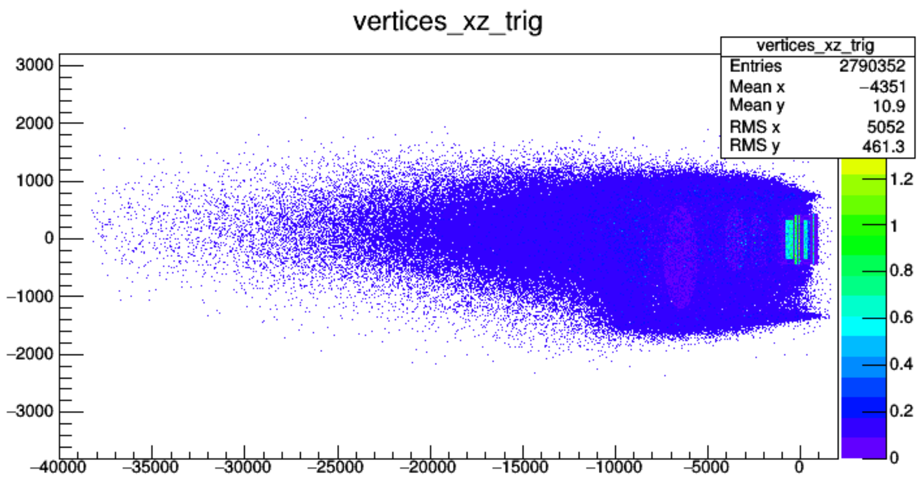




Distribution of vertices of triggered events for all ν_μ simulated events







Total production

Subvolume	Flux component	N_{prod}	w_{unosc}	N_{trig}	$w^{(\mathrm{trig})}_{\mathrm{unosc}}$	$w^{(\mathrm{trig})}_{\mathrm{noosc}}$	$w^{(\mathrm{trig})}_{\mathrm{osc}}$
opdy_lead	$\nu_\mu \to \nu_\mu$	1000000	16862.4	969237	15199.6	15199.6	14947.6
	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	47500	350.3	45084	309.2	309.2	304.9
	$\nu_e \to \nu_e$	20000	151.9	19510	137.8	137.8	137.6
	$\overline{\nu}_e \to \overline{\nu}_e$	4000	8.8	3834	7.9	7.9	7.9
	$\nu_\mu \to \nu_e$	10000	12942.6	9993	12028.2	0.0	10.7
	$\nu_\mu \to \nu_\tau$	10000	5962.4	9940	5511.7	0.0	69.1
opdy_iso	$\nu_\mu \to \nu_\mu$	500000	3300.6	443080	2844.1	2844.1	2798.2
	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	10000	75.8	8722	64.3	64.3	63.4
	$\nu_e \to \nu_e$	5000	29.7	4438	25.6	25.6	25.6
	$\overline{\nu}_e \to \overline{\nu}_e$	1000	1.9	861	1.6	1.6	1.6
	$\nu_\mu \to \nu_\tau$	2000	1136.6	1798	992.2	0.0	11.9
	$\nu_\mu \to \nu_e$	2000	2497.9	1801	2185.8	0.0	1.9
opdy_iron	$\nu_\mu \to \nu_\mu$	1000000	31247.1	533960	16684.7	16684.7	16418.3
	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	100000	693.6	51430	356.7	356.7	352.2
	$\nu_e \to \nu_e$	30000	281.4	15201	142.6	142.6	142.5
	$\overline{\nu}_e \to \overline{\nu}_e$	2000	17.5	959	8.4	8.4	8.4
	$\nu_\mu \to \nu_\tau$	20000	10861.6	10536	5721.9	0.0	59.9
	$\nu_\mu \to \nu_e$	20000	23767.5	9356	11118.5	0.0	7.4
borexino	$\nu_\mu \to \nu_\mu$	1000000	67165.1	152361	10233.3	10233.3	10092.8
	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	150000	1541.4	29150	299.5	299.5	296.7
	$\nu_e \to \nu_e$	150001	604.5	14091	56.8	56.8	56.8
	$\overline{\nu}_e \to \overline{\nu}_e$	4000	38.9	351	3.4	3.4	3.4
front_rock	$\nu_\mu \to \nu_\mu$	385000000	43672826.8	186425	21147.3	21147.3	21048.4
	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	10000000	1003565.8	11700	1174.2	1174.2	1171.1
	$\nu_e \to \nu_e$	4400000	393057.6	20	1.8	1.8	1.8
below_hallc	$\nu_\mu \to \nu_\mu$	2500000	2530974.2	18396	18623.9	18623.9	18410.4
	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	1000000	58159.7	10957	637.3	637.3	633.2
	$\nu_e \to \nu_e$	300000	22778.9	431	32.7	32.7	32.7
side_and_above_hallc	$\nu_\mu \to \nu_\mu$	3990000	4147610.0	8780	9126.8	9126.8	8999.6
	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	1000000	95308.7	1654	157.6	157.6	155.7
Total	-	412 277 501	52 103 821.2	2 574 056	134 835.6	97 277.3	96 271.6

Total number of triggered events

- MC expectancy
  - no oscillations – 97277 events
  - std. oscillations – 96272 events
- DATA – 93458 events
- Well within 15% beam uncertainty

Neutrino oscillation parametrization

Standard 3-generation neutrino model

- Used by PDG and recommended by the Giunti book

$$|\nu_\alpha\rangle = U^*_{\alpha k}\,|\nu_k\rangle$$

$$U = U_{23}U_{13}U_{12}$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

$$A^{\alpha\beta}_{ij} \equiv U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}$$

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij}}{2}\frac{L}{E}$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left(A^{\alpha\beta}_{ij}\right)\sin^2\frac{\phi_{ij}}{2} \pm 2\sum_{i>j}\mathrm{Im}\left(A^{\alpha\beta}_{ij}\right)\sin\phi_{ij}$$

$\Delta m^2_{21} = 0$ approximation

We can use this approximation because are working below the first oscillation maximum

From PDG: $\left(\frac{\Delta m^2_{21}}{\Delta m^2_{32}}\right)^2 \approx 10^{-3}$

we are left with two mixing angles and a single mass splitting, 3 parameters in total

$$P_{\alpha\to\beta;\alpha\neq\beta} = 4\left|U^*_{\alpha 3}U_{\beta 3}\right|^2 \sin^2\frac{\Delta m^2_{32}}{4}\frac{L}{E}$$

$$P_{\alpha\to\alpha} = 1 - 4\left|U_{\alpha 3}\right|^2\left(1-\left|U_{\alpha 3}\right|^2\right)\sin^2\frac{\Delta m^2_{32}}{4}\frac{L}{E}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{cp}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{cp}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{cp}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{cp}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{cp}} & c_{23}c_{13} \end{pmatrix} \begin{matrix} e \\ \mu \\ \tau \end{matrix}$$

1 2 3

Parametrization used in the analysis

$$P_{e\to e} = M_{ee}\sin^2\left(C\frac{\Delta m^2_{32}}{E}\right)$$

$$P_{\mu\to e} = M_{\mu e}\sin^2\left(C\frac{\Delta m^2_{32}}{E}\right)$$

$$P_{\mu\to \mu} = (1 - M_{\mu\mu})\sin^2\left(C\frac{\Delta m^2_{32}}{E}\right)$$

$$P_{\mu\to \tau} = (M_{\mu\mu} - M_{\mu e})\sin^2\left(C\frac{\Delta m^2_{32}}{E}\right)$$

$$C = 928.908\frac{\mathrm{GeV}}{\mathrm{eV}^2}$$

$$M_{\mu\tau} = M_{\mu\mu} - M_{\mu e}$$

$$P_{\alpha\to\beta} = P_{\beta\to\alpha} = P_{\overline{\alpha}\to\overline{\beta}} = P_{\overline{\beta}\to\overline{\alpha}}$$

because $\Delta m^2_{21} = 0$

Fit parameter

- the only free parameter in this analysis is Δm^2_{32} and all the other parameters are assumed to be known a priori
- the values of oscillation parameters used in this analysis are:

$$\Delta m^2_{21} = 0$$
$$\sin^2\theta_{13} = 0.0210$$
$$\sin^2\theta_{23} = 0.51$$

→

$$M_{ee} = 0.08168$$
$$M_{\mu e} = 0.03645$$
$$M_{\mu\mu} = 0.98410$$
$$M_{\mu\tau} = 0.94765$$

Analysis

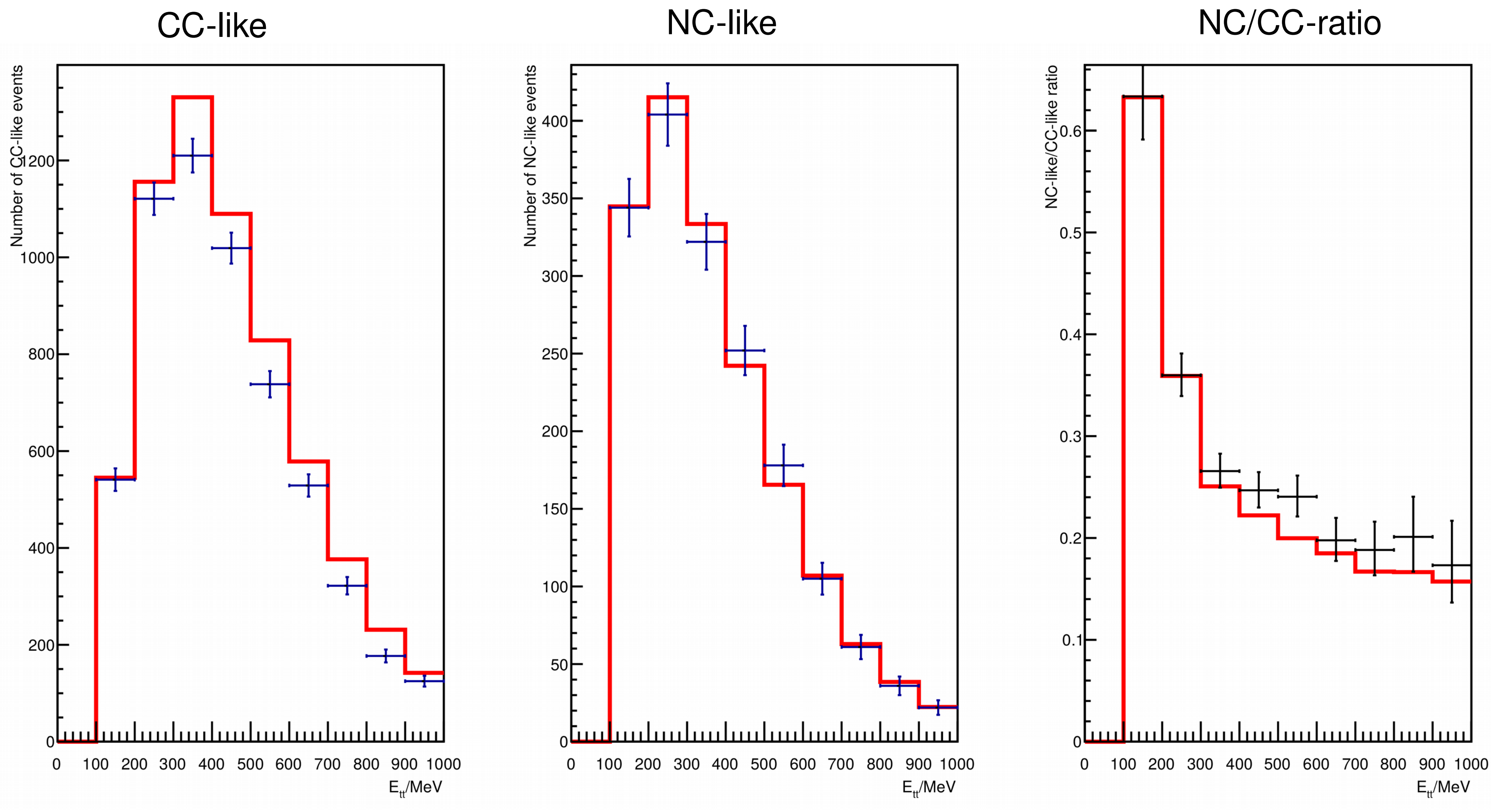
Main ideas

- Use NC/CC ratio vs. E_tt to reduce the CNGS flux uncertainty
- Compare data to MC oscillated by different values of Δm^2_{32}
  - oscillated MC is obtained by multiplying event weights with appropriate oscillation probability
- Use p-value formalism to reject Δm^2_{32} for which MC is incompatible with data

Data selection

- CC selection
  - good muon track exists
  - bending topology - at least one digit in each of the arms of at least one spectrometer
  - reconstructed muon charge negative
- NC selection
  - no muon tracks at all
  - no bending topology
- Global selection
  - passed the trigger
  - CONTAINED
  - BF ok
  - more 600 p.e. in TT's
  - BF first brick in first 20 walls
  - is classified as either NC or CC

Data selection



Data selection

Selection efficiency calculated from MC

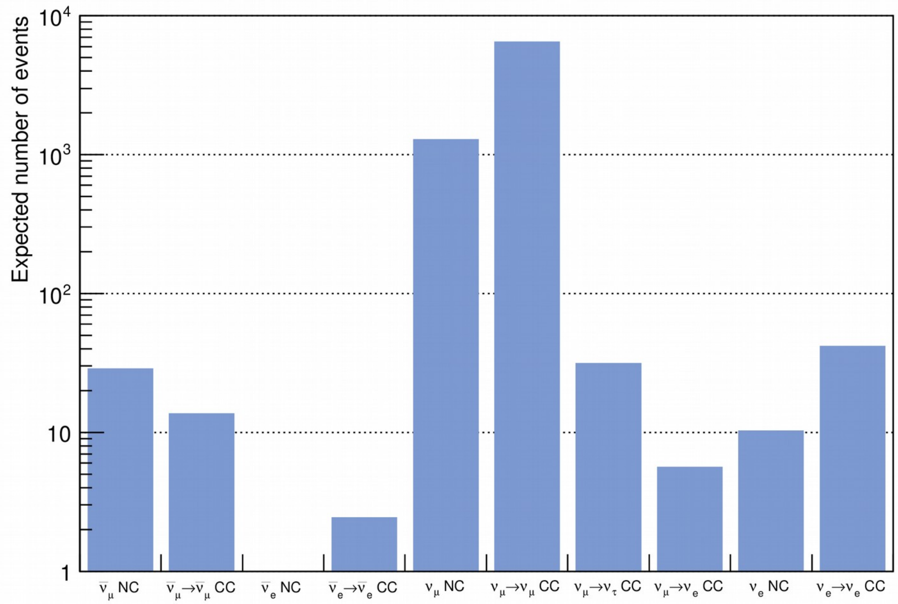
	Efficiency (%)
Target	44.3
Internal	0.2
External	0.06

Interaction types under standard oscillations

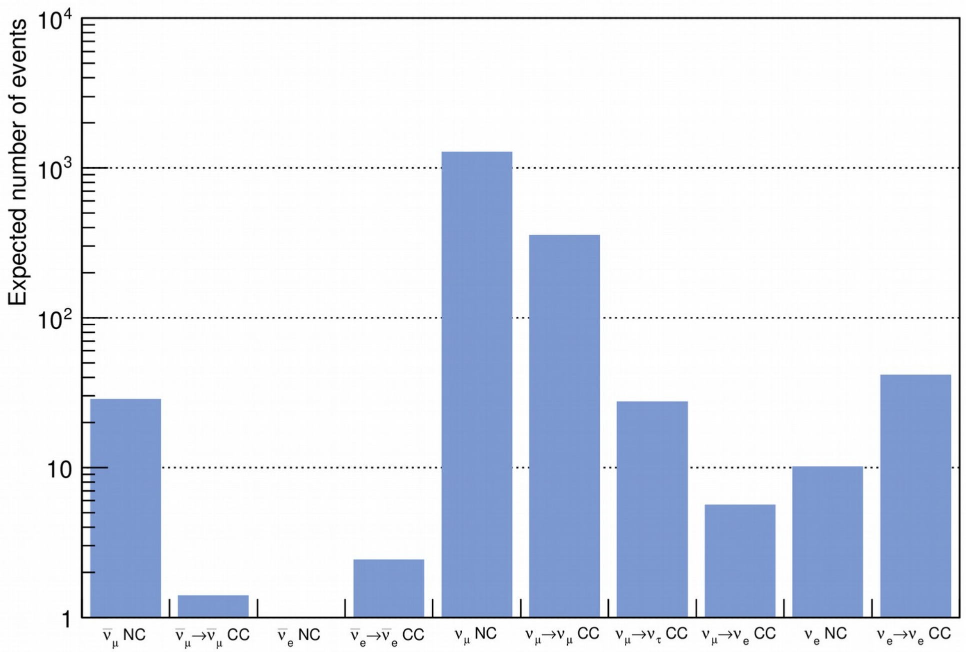
Selection	Proportion of events (%)		
	ν_μ CC	ν and $\overline{\nu}$ NC	Other CC
Global	82.0	16.8	1.2
CC-like	99.5	0.2	0.3
NC-like	20.2	75.3	4.5

Data selection

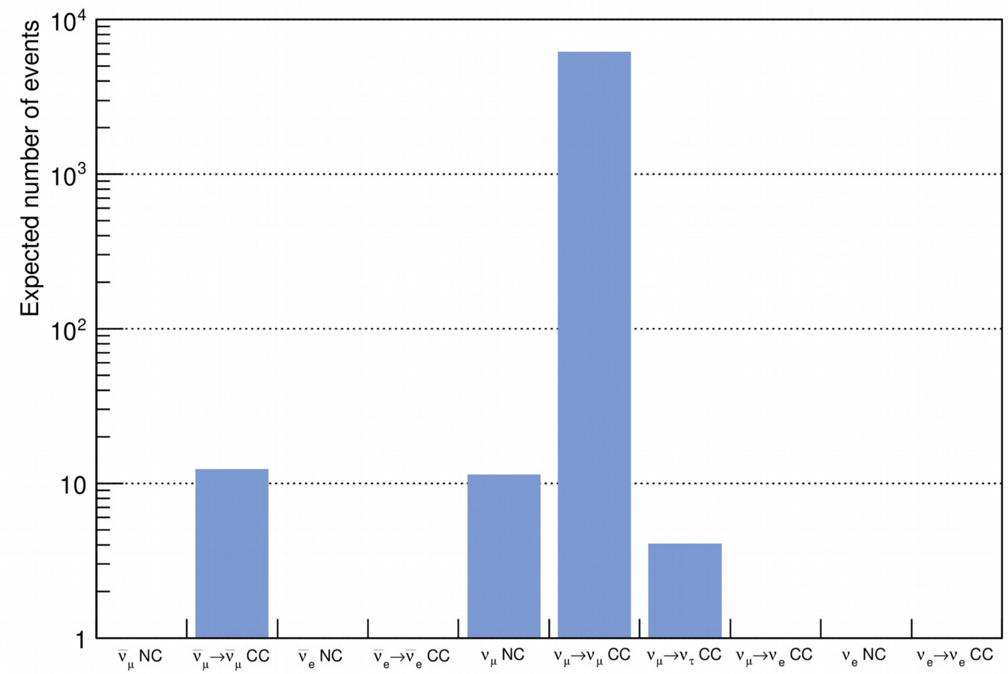
Global selection flux components



NC-like selection flux components



CC-like selection flux components



Statistics

- Consider two Poisson distributions with expectation values λ_l and λ_k.
- Suppose we measure a random variable from each of these two distributions and get l and k, respectively
- Bayesian probability distribution that $\lambda_l / \lambda_k = x$, given measurements l and k, and with a flat prior on λ_l and λ_k is given by the formula:

$$P_{l/k}(x) = \frac{(k+l+1)!}{k!\; l!} \frac{x^l}{(1+x)^{k+l+2}}$$

This formula was checked by a toy MC and is very precise

Likelihood

- For the analysis I create three histograms
  1) Number of measured NC events vs. E_tt (data)
  2) Number of measured CC events vs. E_tt (data)
  3) NC/CC ratio predicted by MC vs E_tt (MC)
     - this depends on oscillation parameters
- All histograms have *N* bins and equal E_tt range
- I construct a likelihood function using the formula

$$L(\Delta m^2_{32}) = \prod_{i=1}^{N} P_{NC_i/CC_i}\left(R_i(\Delta m^2_{32})\right)$$

NC-histogram bin value

bin index

CC-histogram bin value

MC histogram bin value, dependent on oscillations

Profile likelihood

assumed value of Δm^2_{32}
(our null-hypothesis)

likelihood function
given data for assumed Δm^2_{32}

$$\lambda(\Delta m^2; \mathrm{data}) = \frac{L(\Delta m^2; \mathrm{data})}{L(\widehat{\Delta m^2}; \mathrm{data})} \equiv \frac{L(\Delta m^2; \mathrm{data})}{\hat{L}(\mathrm{data})}$$

value of Δm^2_{32} that
maximizes likelihood

maximum possible
likelihood given data

Data is a random variable of a distribution which has a true Δm^2_{32} as a parameter
- in each (pseudo)experiment we get different data set due to statistical fluctuations

Test statistics (two different ones)

- we use two different test statistics:
  - "standard"

    $$t_{\Delta m^2} = -2\ln\lambda(\Delta m^2)$$

    - equivalent to F&C
  - upper limit

    $$q_{\Delta m^2} = \begin{cases} -2\ln\lambda(\Delta m^2) & \widehat{\Delta m^2} \leq \Delta m^2 \\ 0 & \widehat{\Delta m^2} > \Delta m^2 \end{cases}$$

- for each Δm^2_{32}, these are random variables (since they depend on data, which is a random variable), and therefore they have distributions

p-values

- given the distribution of test statistics and our measurement, we can extract p-value for a given Δm^2_{32}
  - if a p-value is smaller than predefined threshold, we exclude that specific Δm^2_{32}
- distributions can be found using pseudo-experiments
- p-value is then:

$$p_{t_\mu}(\Delta m^2_{32}) = \int_{t_{\mu;\mathrm{obs}}}^{\infty} f_{t_\mu}(t_\mu|\Delta m^2_{32})dt_\mu$$

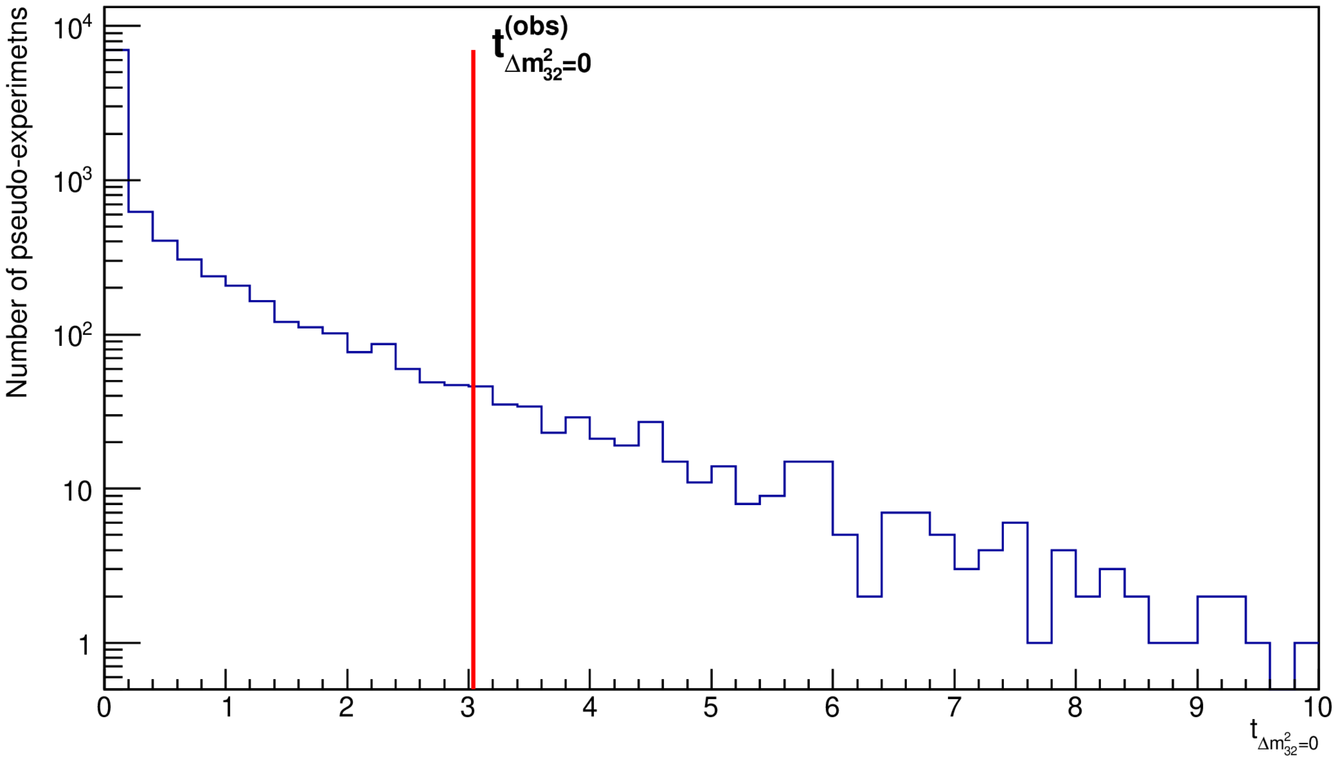
p-value as a function of Δm^2_{32}

observed (measured) value of test statistic

distribution of a test statistic given Δm^2_{32}

$$p_{q_\mu}(\Delta m^2_{32}) = \int_{q_{\mu;\mathrm{obs}}}^{\infty} f_{q_\mu}(q_\mu|\Delta m^2_{32})dq_\mu$$

p-values

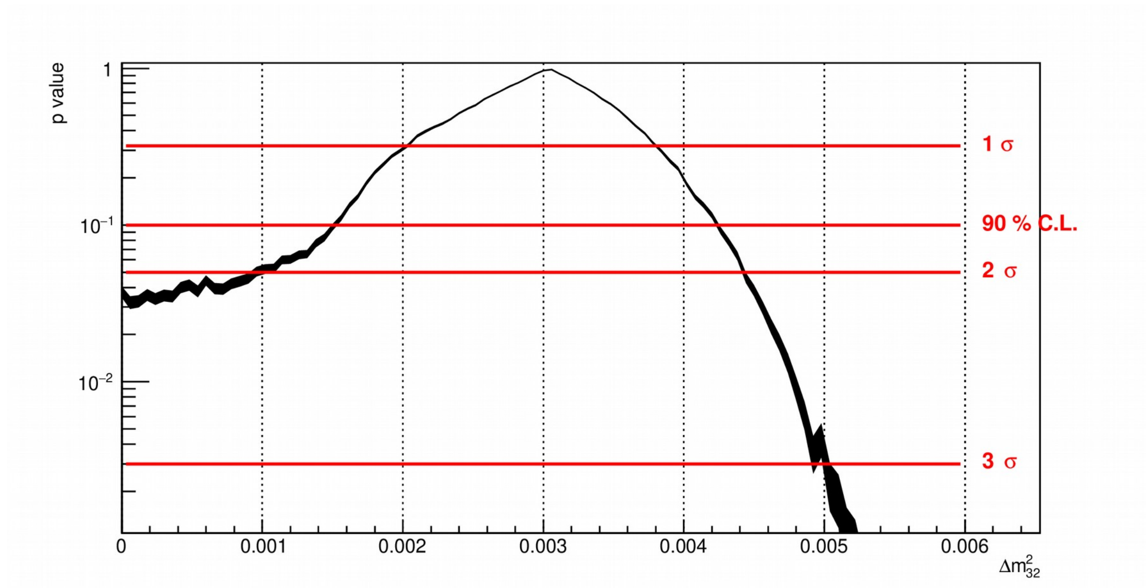


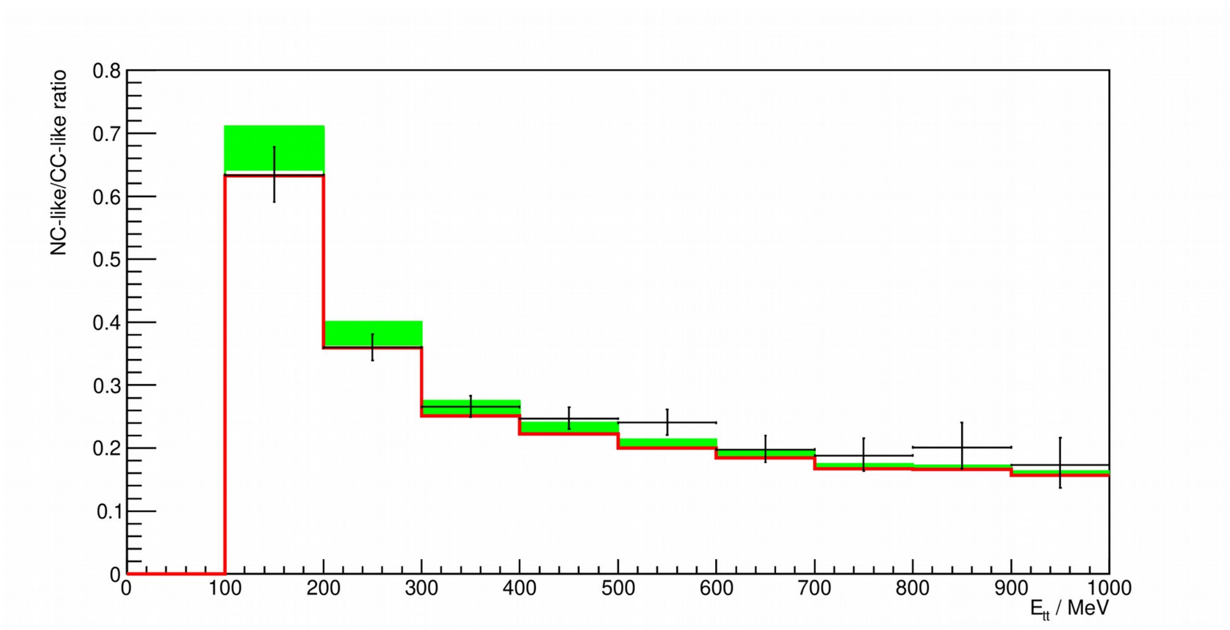
Number of pseudo-experimetns
10^4
10^3
10^2
10
1
$t^{(obs)}_{\Delta m^2_{32}=0}$
0
1
2
3
4
5
6
7
8
9
10
$t_{\Delta m^2_{32}=0}$

Δm^2_{32} measurements

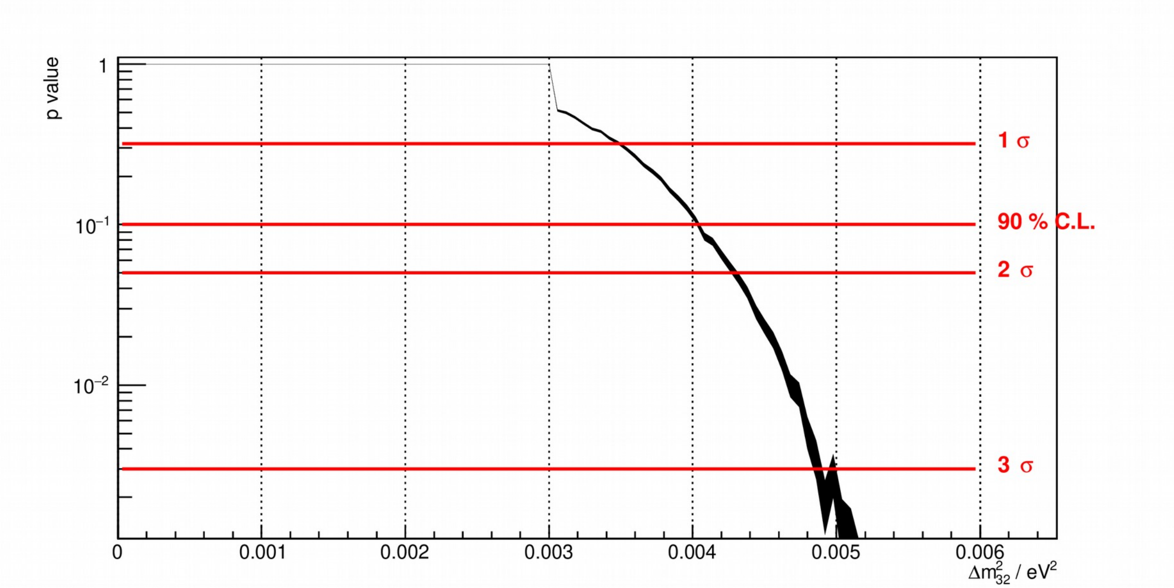
- p-values calculated for Δm^2_{32} in range [0.0,6.0]e-3 eV^2, with step 0.06e-3 eV^2
- for each Δm^2_{32} value 10000 pseudoexperiments were produced to obtain test statistic distribution

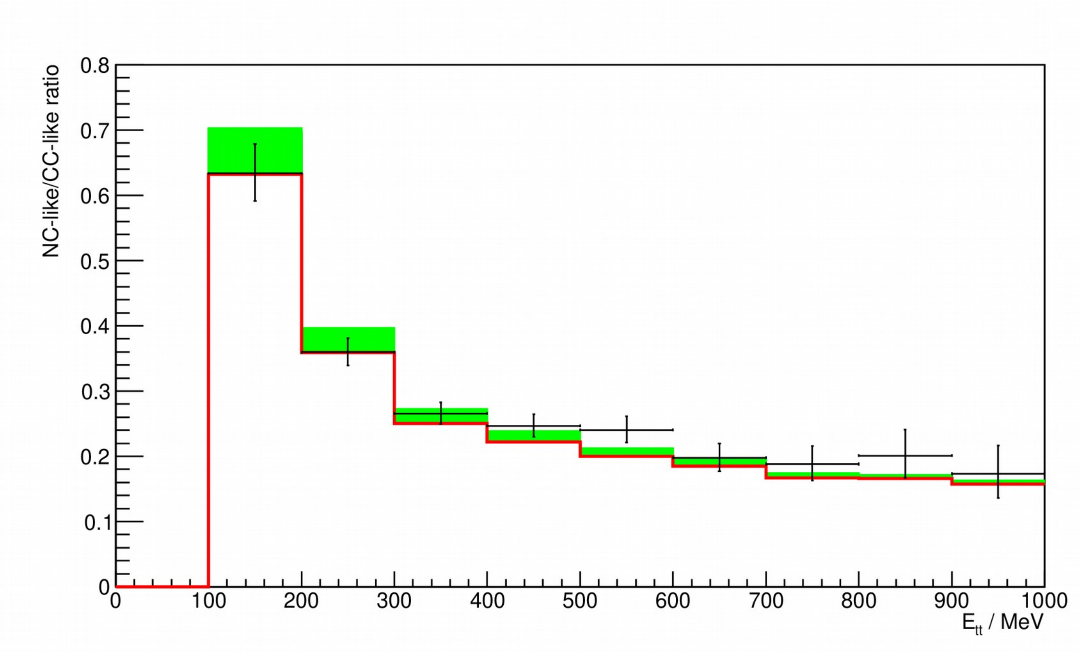
Standard test statistic



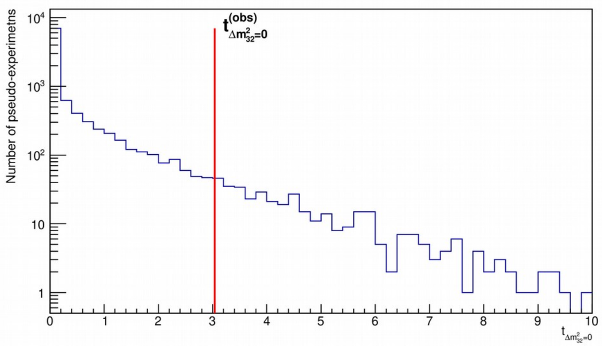


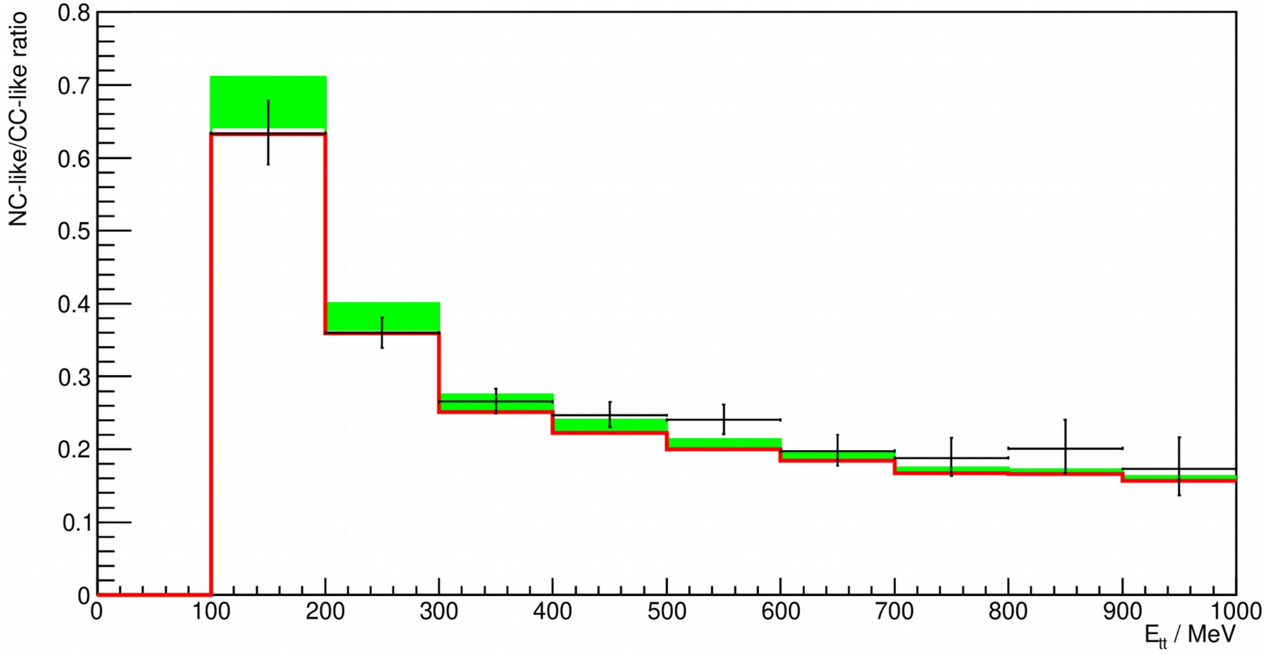
Upper limit test statistic

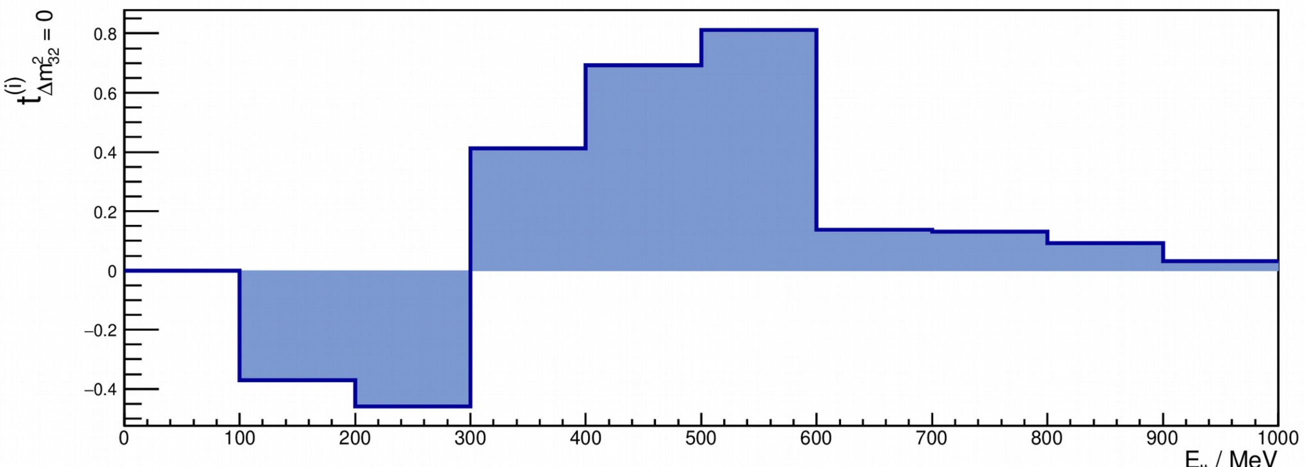




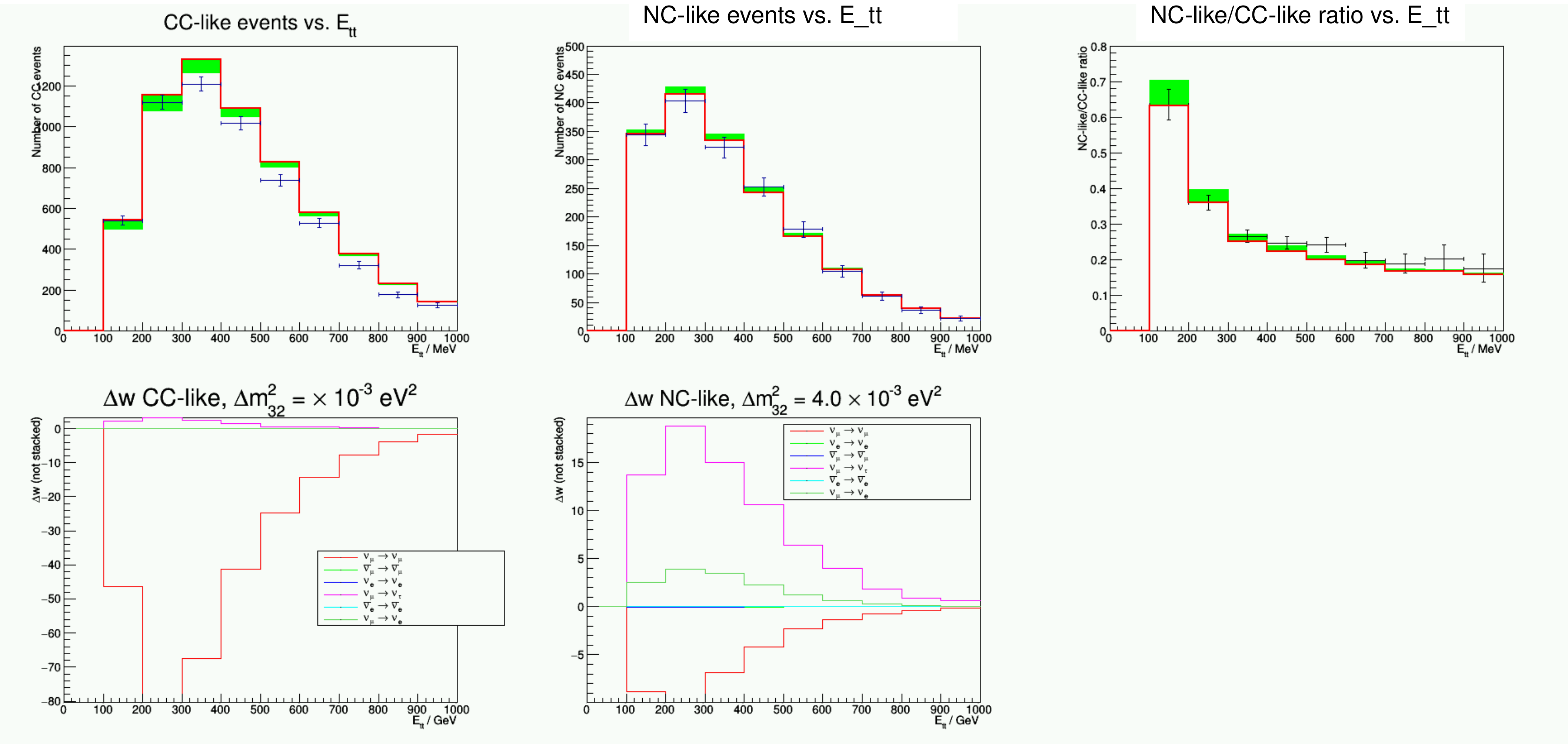
Lower limit systematics







Appearance components



Beam uncertainty

- The beam smearing has been implemented to investigate the effects of beam uncertainty
- Smearing algorithm
  - Neutrino events were sorted in 10 GeV bins of true neutrino energy
  - A random number was generated for each bin
  - Gaussian with mean 1.0 and standard deviation 0.15
  - Each event weight in the each bin was multiplied by the random number generated for this bin
- 1000 smeared fluxes were generated

Beam uncertainty

- Likelihood function was defined as

$$L(\Delta m_{32}^2) = \prod_{i=1}^{N} \left(\frac{1}{M} \sum_{j=1}^{M} P_{\mathrm{NC}_i/\mathrm{CC}_i} \left(R_i^{(j)} (\Delta m_{32}^2) \right) \right)$$

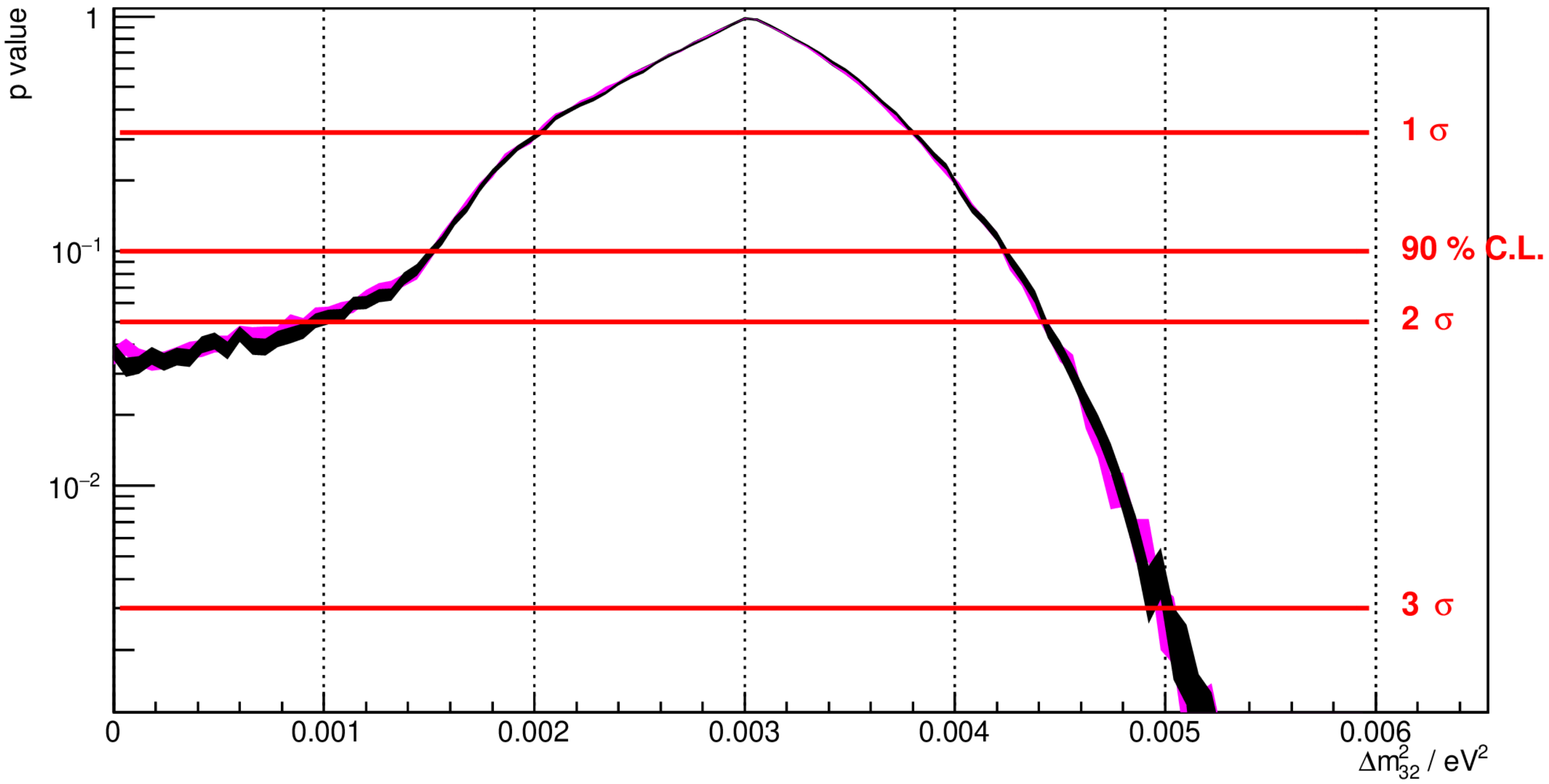
Number of smeared fluxes

NC-like/CC-like expectation for *j*-th smeared flux in *i*-th bin

index *i* runs over E_tt bins

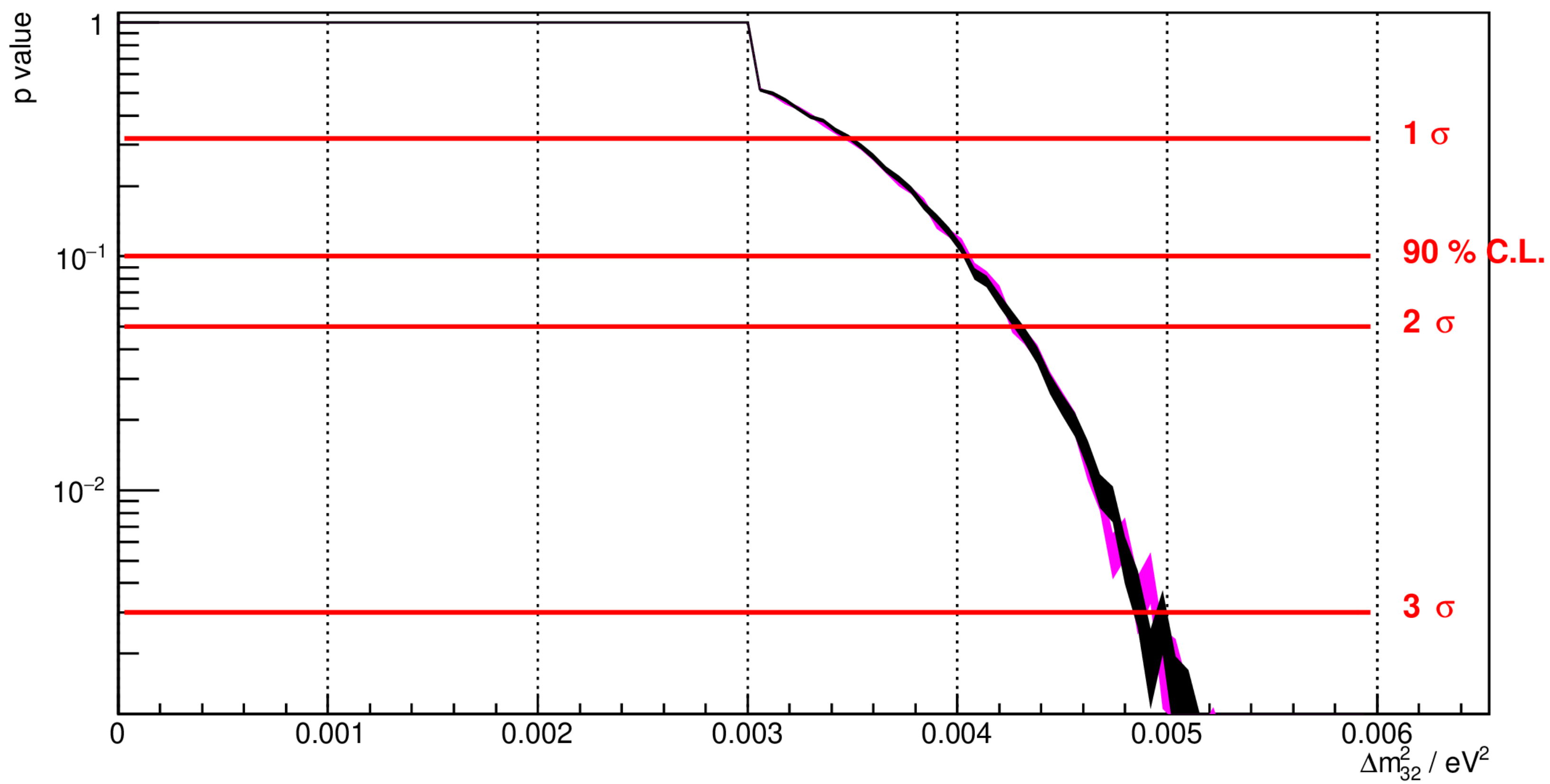
index *j* runs over smeared fluxes

Standard test statistic



black – not smeared
pink - smeared

Upper limit test statistic



black – not smeared
pink - smeared

Conclusions

- An analysis of oscillation parameters using ELDET data was performed
- A new MC simulation of interactions in OPERA and the surrounding materials have been produced both for appearance and disappearance oscillation channels
- Since we have no near detector, NC-like/CC-like ratio was used to normalize the beam
- A an upper limit on Δm^2_{32} has been obtained, assuming $\Delta m^2_{21}=0$ and PDG mixing angles, in the analysis dominated by muon neutrino disappearance
  - a lower limit proved to be unreliable
- The result of this analysis is an reliable upper limit on Δm^2_{32}

$$\left|\Delta m^2_{32}\right| < 4.1 \cdot 10^{-3}\ \mathrm{eV}^2\ @\ 90\%\ \mathrm{C.L.}$$