Statistical data analysis in the DANSS experiment

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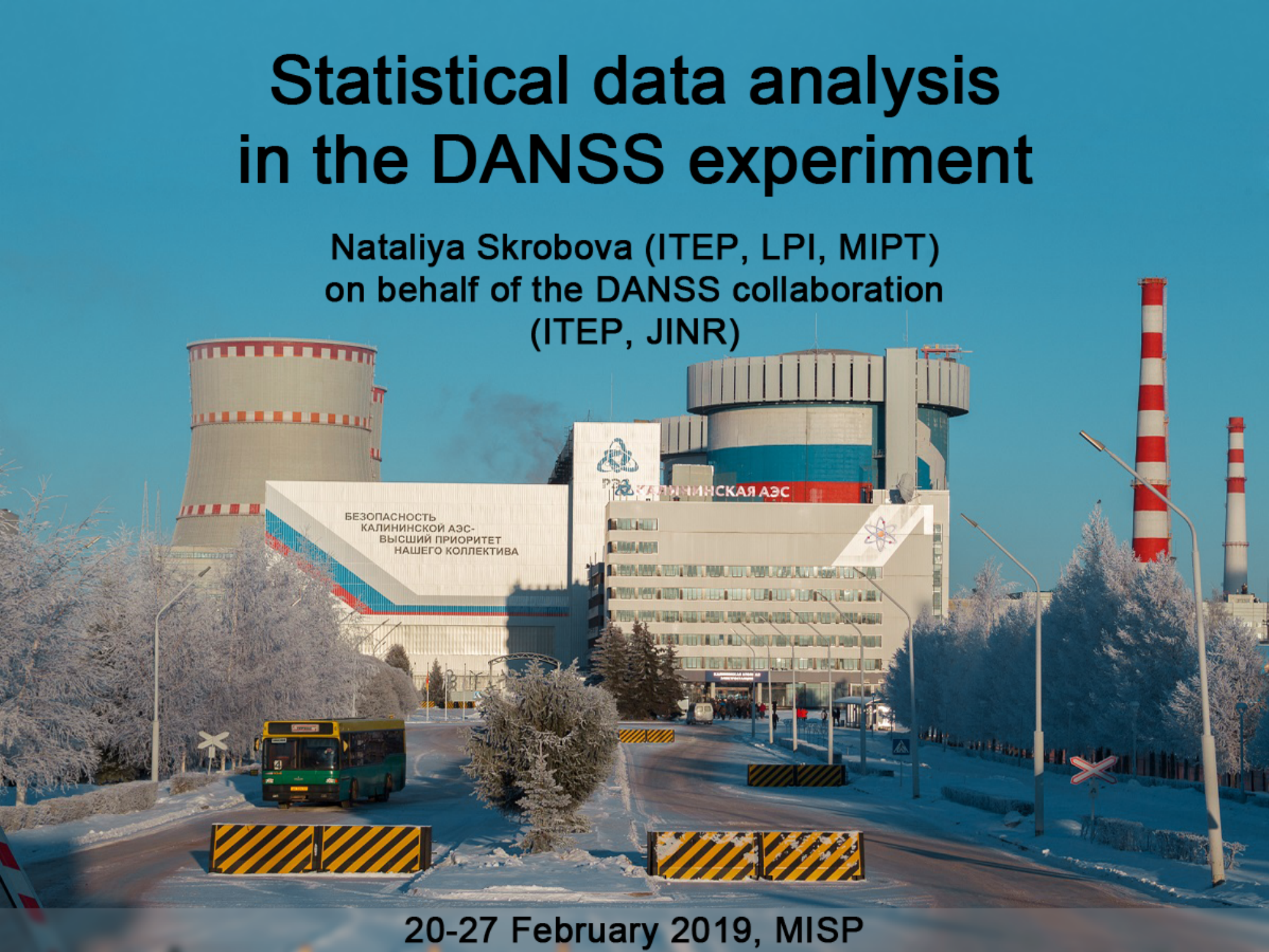
on behalf of the DANSS collaboration
(ITEP, JINR)



20-27 February 2019, MISP

Motivation

There are several indications in favor of existence of the 4th neutrino flavor — "sterile" neutrino

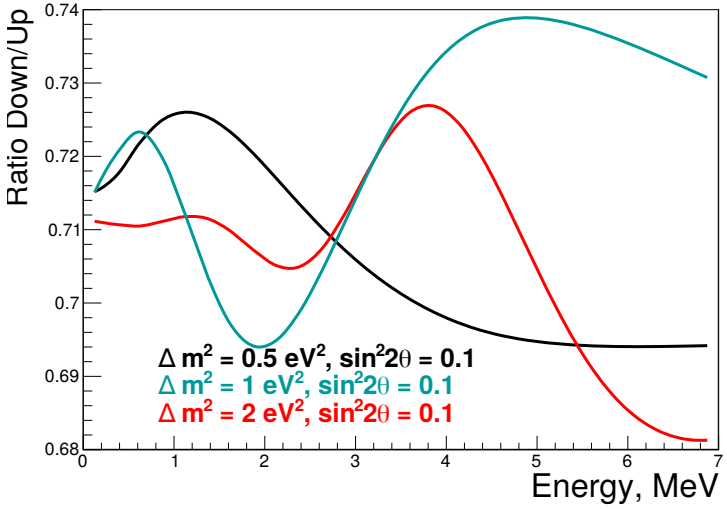
$$P = 1 - \sin^2 2\theta_{14} \sin^2 \left(\frac{1.27 \Delta m^2_{14} [\mathrm{eV}^2] L[\mathrm{m}]}{E_\nu [\mathrm{MeV}]} \right)$$

Expected parameters: (G. Mention et al., arXiv:1101.2755)

$$|\Delta m^2| > 1.5 \mathrm{eV}^2 \text{ and } \sin^2(2\theta) = 0.14 \pm 0.08 \text{ at (95\%CL)}$$

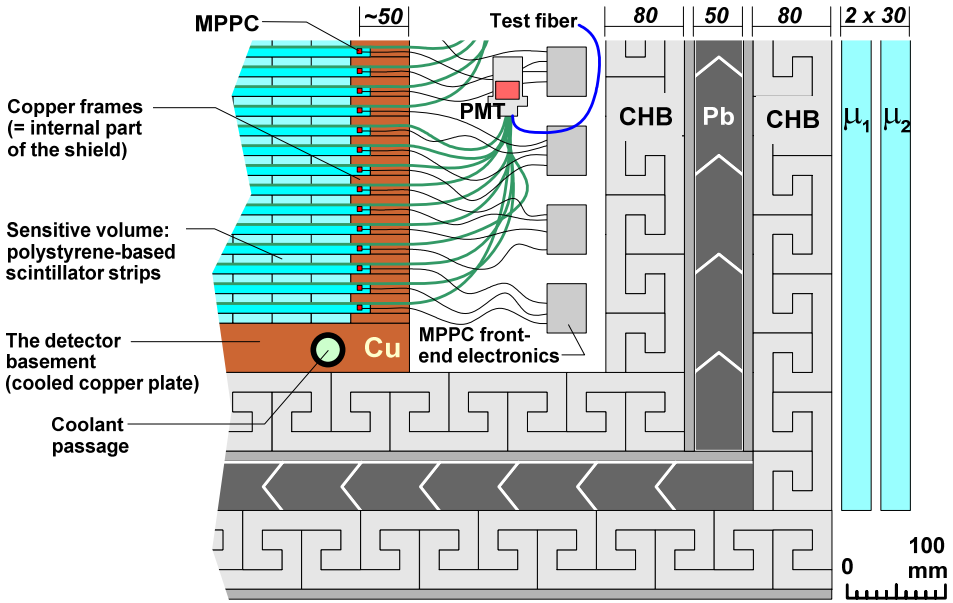
DANSS:

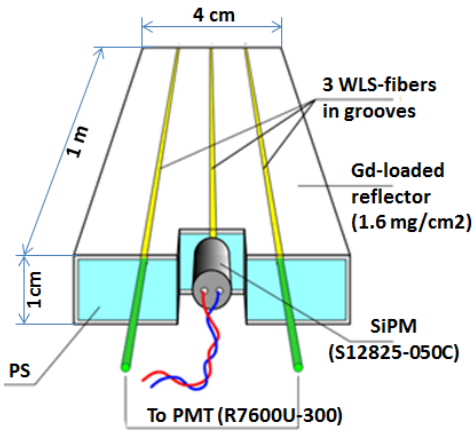
Measure ratio of neutrino spectra at different distance from the reactor core — both spectra are measured in the same experiment with the same detector. No dependence on the theory, absolute detector efficiency or other experiments.



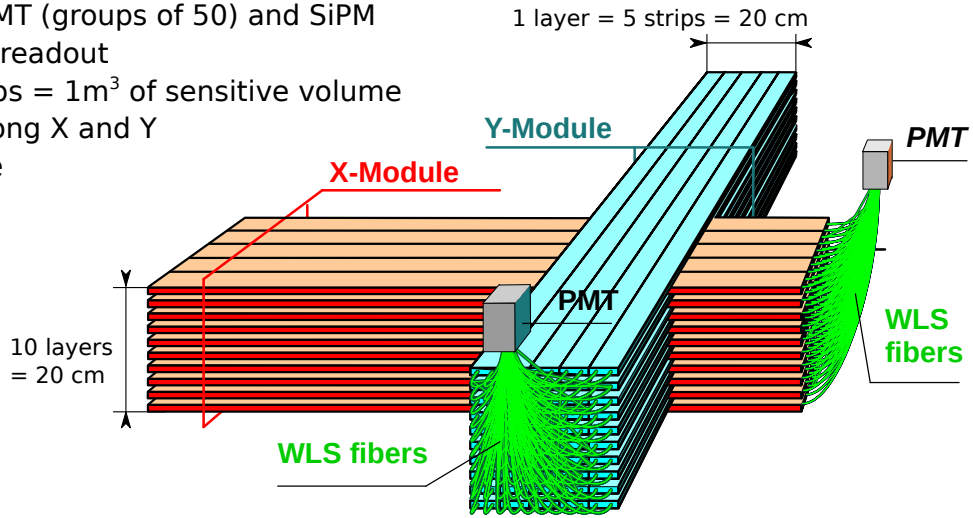
DANSS design [JINST 11 (2016) no.11, P11011]

- Multilayer closed passive shielding: electrolytic copper frame 5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides
- Dedicated WFD-based DAQ system
- Total 46 64-channel 125 MHz 12 bit Waveform Digitisers (WFD)
- System trigger on certain energy deposit in the whole detector (PMT based) or μ-veto signal
- Individual channel selftrigger on SiPM noise (with decimation)





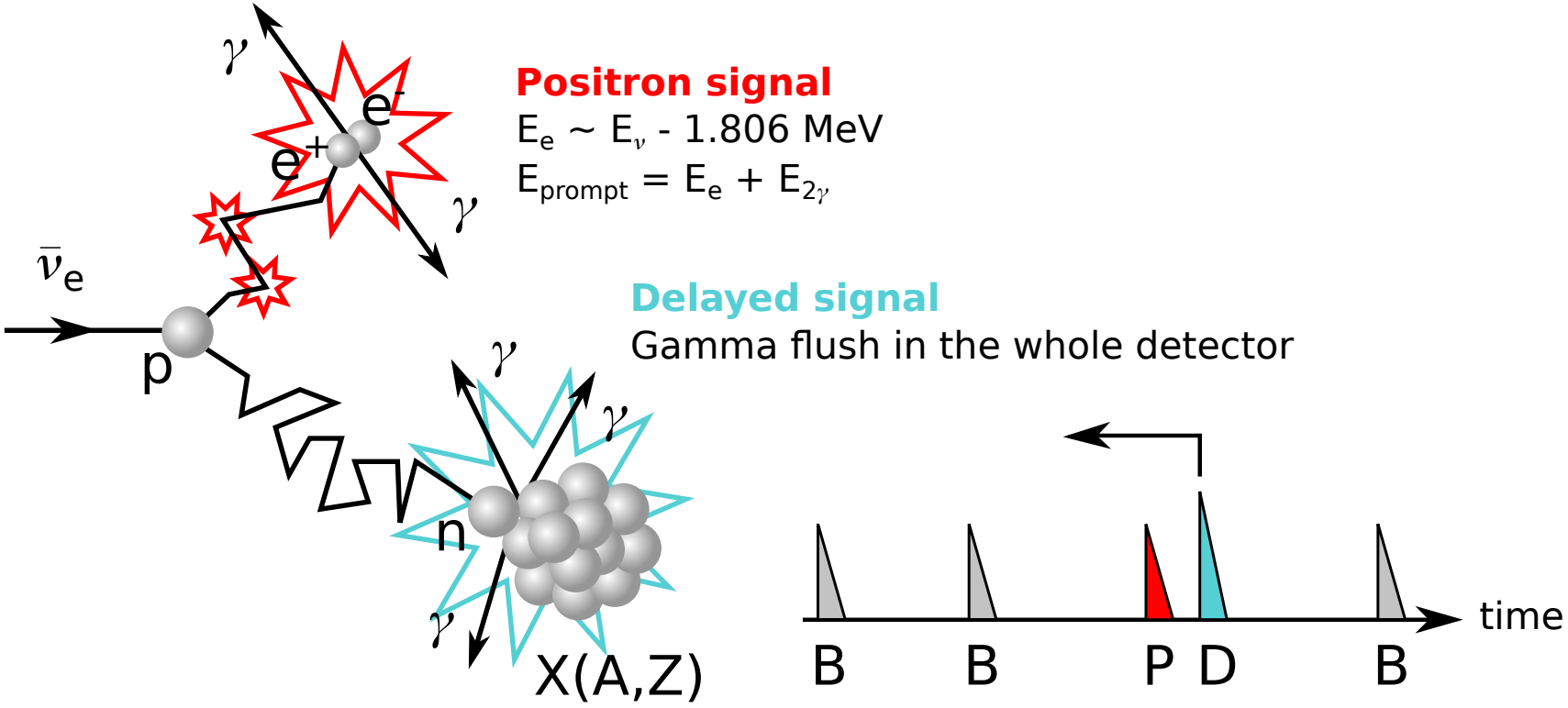
- Double PMT (groups of 50) and SiPM (individual) readout
- 2500 strips = 1m^3 of sensitive volume
- Strips along X and Y
- 3D-picture



Antineutrino registration

Inverse Beta-Decay (IBD) reaction:

$$\tilde{\nu}_e + p \rightarrow n + e^+$$



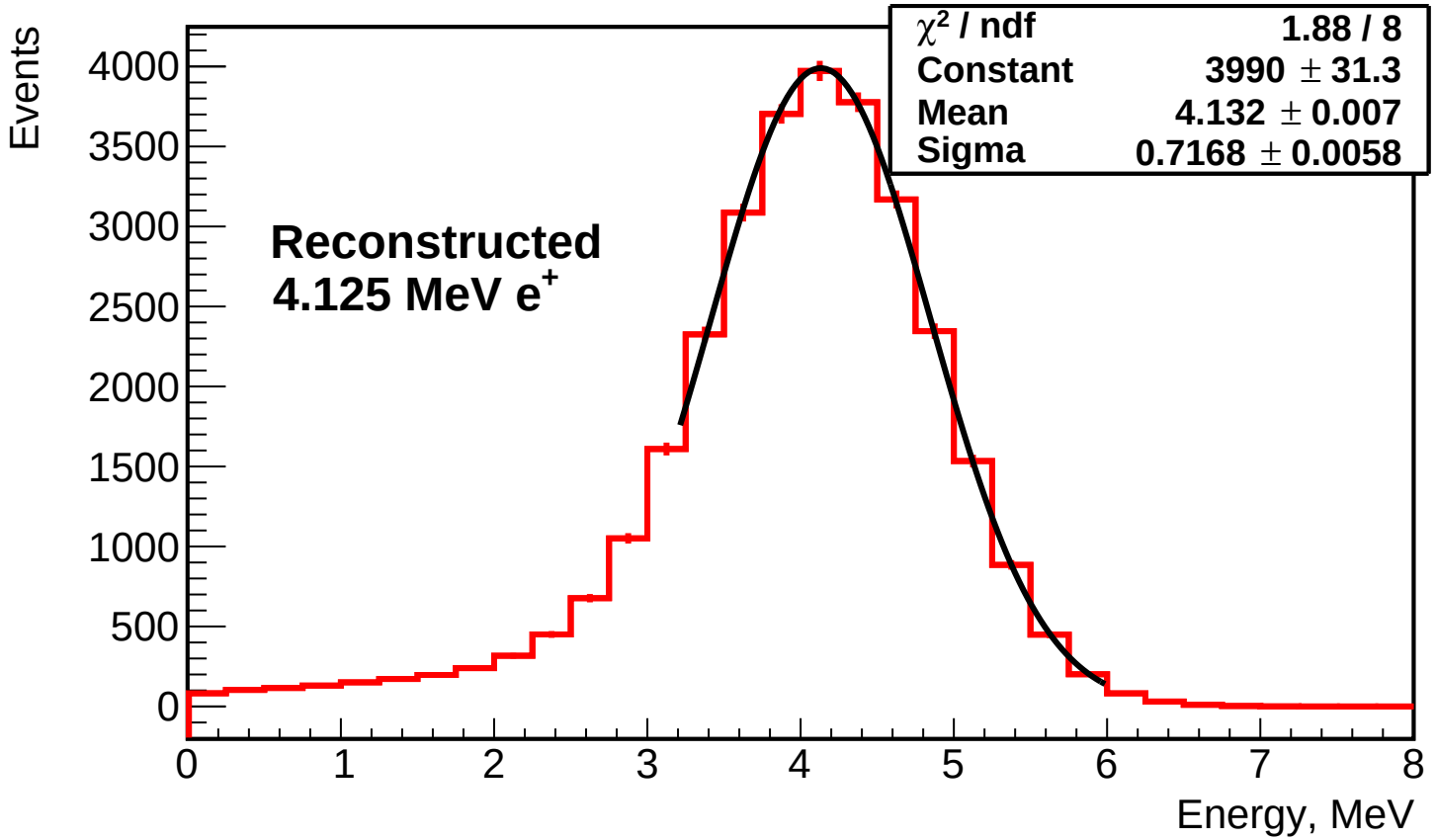
Spectra calculation

For every Δm^2 and $\sin^2(2\theta)$ e^+ spectrum was calculated for Up and Down detector positions taking into account:

- reactor and detector size
- average reactor burning profile
- expected e^+ spectrum (from Huber and Mueller)
  Results don't depend on this choice!
- IBD crossection
- oscillation probability
- detector energy resolution

Detector resolution

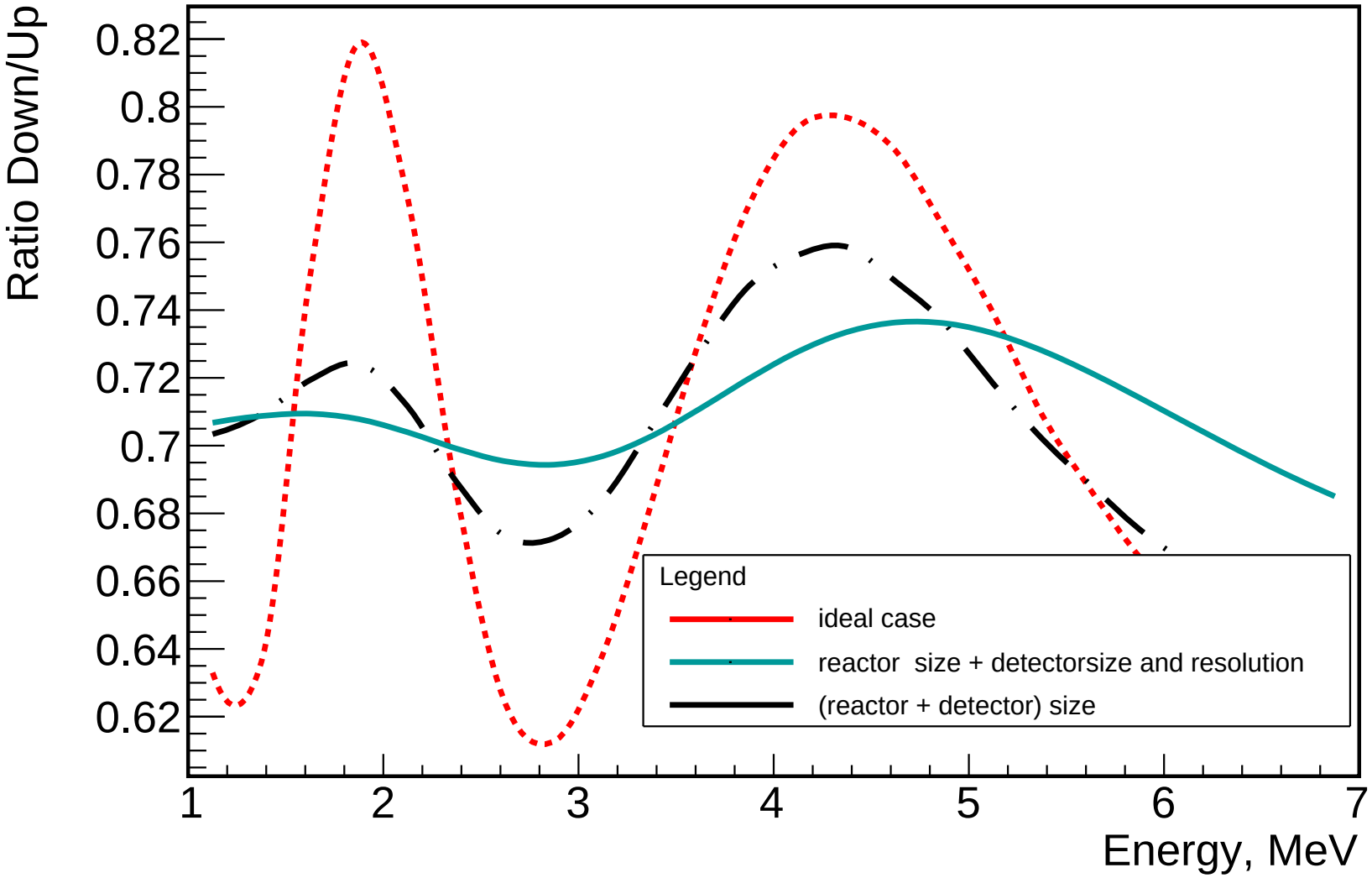
- Monte-Carlo simulation
- The same processing algorithm as for data
- Corrected for dead layers and misidentified γ



Down/Up ratio

Predicted spectra ratio for $\Delta m^2 = 2.32 eV^2$, $\sin^2 2\theta = 0.142$

The large size of the reactor core and modest energy resolution lead to smearing of the oscillation pattern



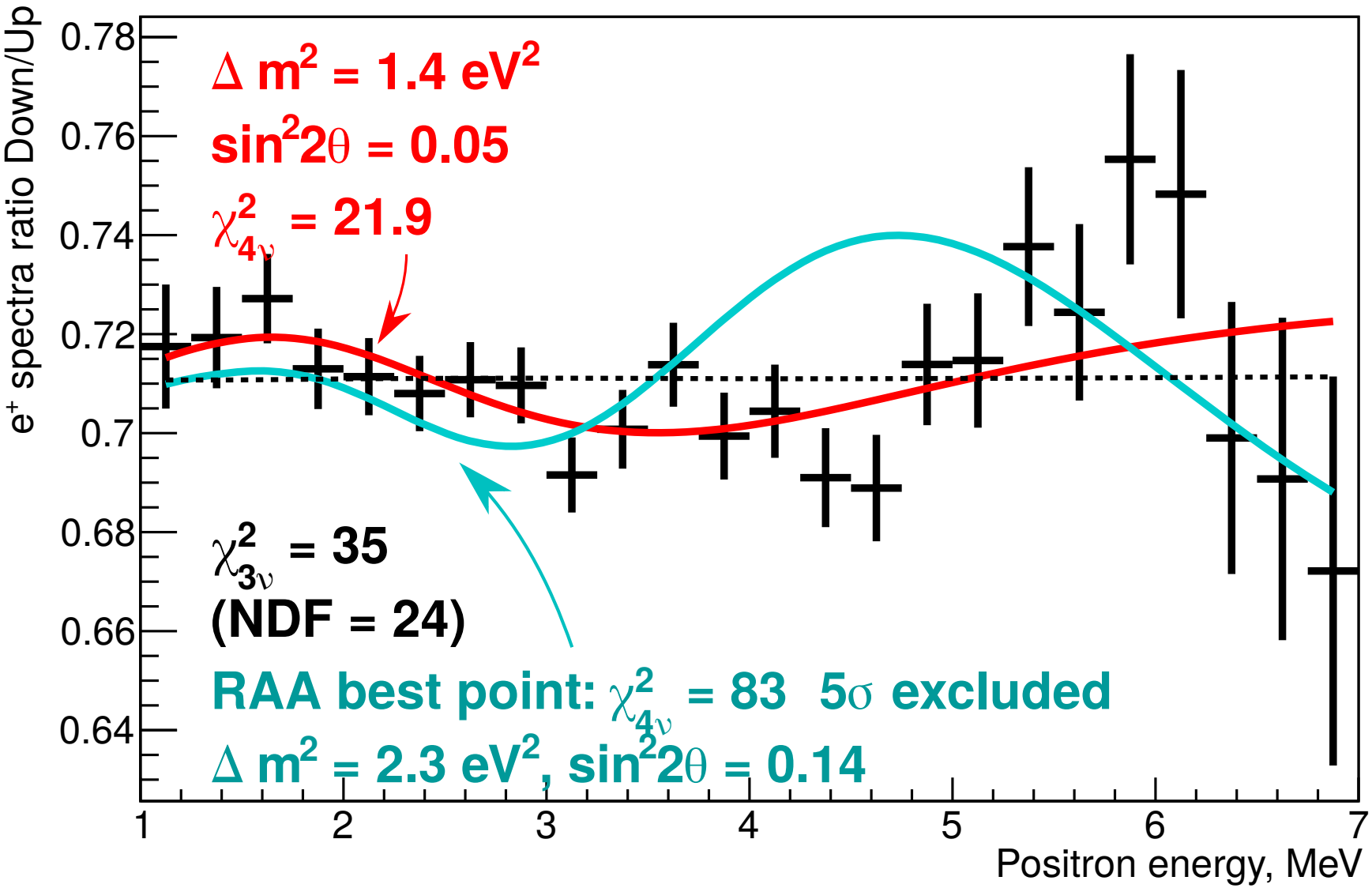
χ^2 statistics

Ratio of Down/Up spectra is and compared with experiment

$$\chi^2 = \sum_{i=1}^{N} (R_i^{\mathrm{obs}} - k \times R_i^{\mathrm{pre}})^2 / \sigma_i^2,$$

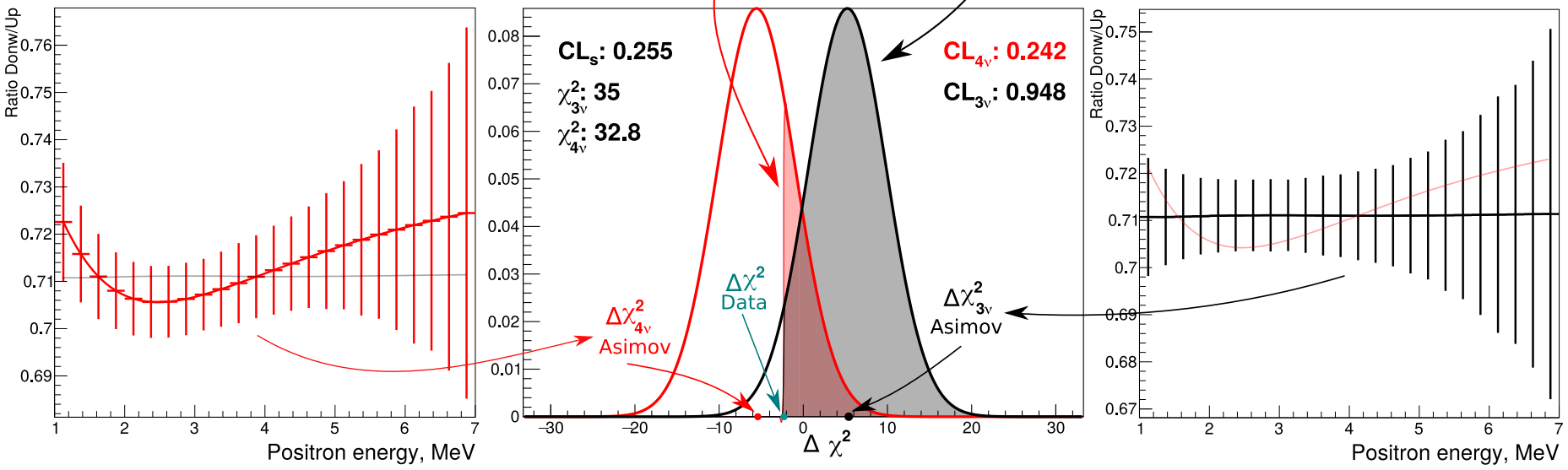
R_i^{obs} (R_i^{pre}) – the observed (predicted) ratio of $\tilde{\nu}_e$ counting rates at the two detector positions
σ_i – statistical standard deviation of R_i^{obs}
k – normalization factor = ratio of the total number of the IBD events per day at the bottom and top detector positions (the total numbers of IBD events per day in MC at the two positions were equal)
i – energy bin
Systematics not included here and will be treated separately

Down/Up ratio



Gaussian CL_s [arXiv:1407.5052v4]

- $\Delta\chi^2 = \chi^2_{4\nu} - \chi^2_{3\nu}$ has Gaussian(μ, σ) distribution
- Parameters (μ, σ) determined from Asimov data set:
  $\mu = \Delta\chi^2 = \chi^2_{4\nu} - \chi^2_{3\nu}$, $\sigma = 2\sqrt{|\Delta\chi^2|}$;
  $\mu_{4\nu} = -\chi^2_{3\nu}$, $\mu_{3\nu} = -\mu_{4\nu}$, $\sigma_{3\nu} = \sigma_{4\nu}$
- Calculate $\Delta\chi^2_{data}$
- $CL_s = \frac{CL_{4\nu}}{CL_{3\nu}}$, where $CL_{4\nu} = \int_{\Delta\chi^2_{data}}^{\infty} G_{4\nu}$, and $CL_{3\nu} = \int_{\Delta\chi^2_{data}}^{\infty} G_{3\nu}$



4ν excluded at 90(95)% if $CL_s < 0.1(0.05)$

Systematics studies

Variations in:

- Energy resolution $\pm 10\%$
- Energy scale $\pm 2\%$
- Level of cosmic background 0.5%
- Energy intervals used in fit (1.5-6)MeV

Analysis repeated with different values of systematics parameters. A point in the Δm^2_{14}, $\sin^2 2\theta_{14}$ plane was included into the final excluded area if it appeared in the excluded areas for all tested variations of the parameters.

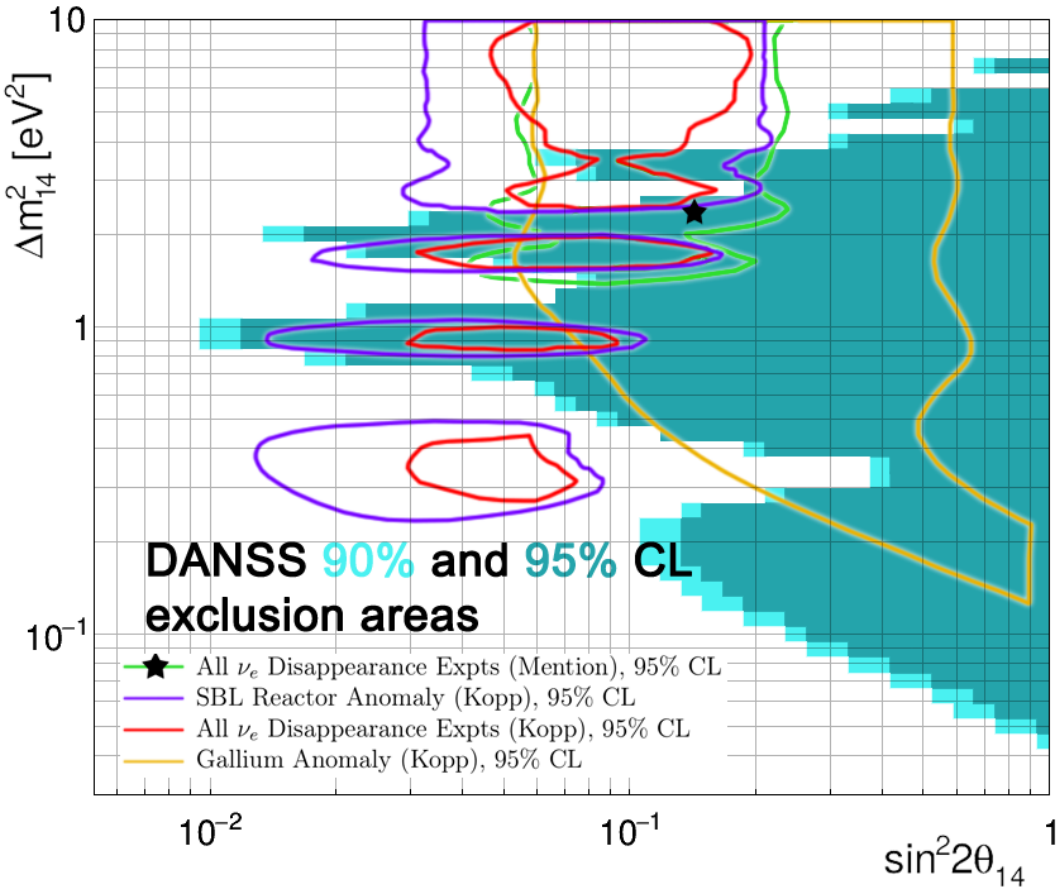
Treating systematics parameters as nuisance parameters in χ^2 provides the same result, but doesn't allow to include variations in fit range.

Results [10.1016/j.physletb.2018.10.038]

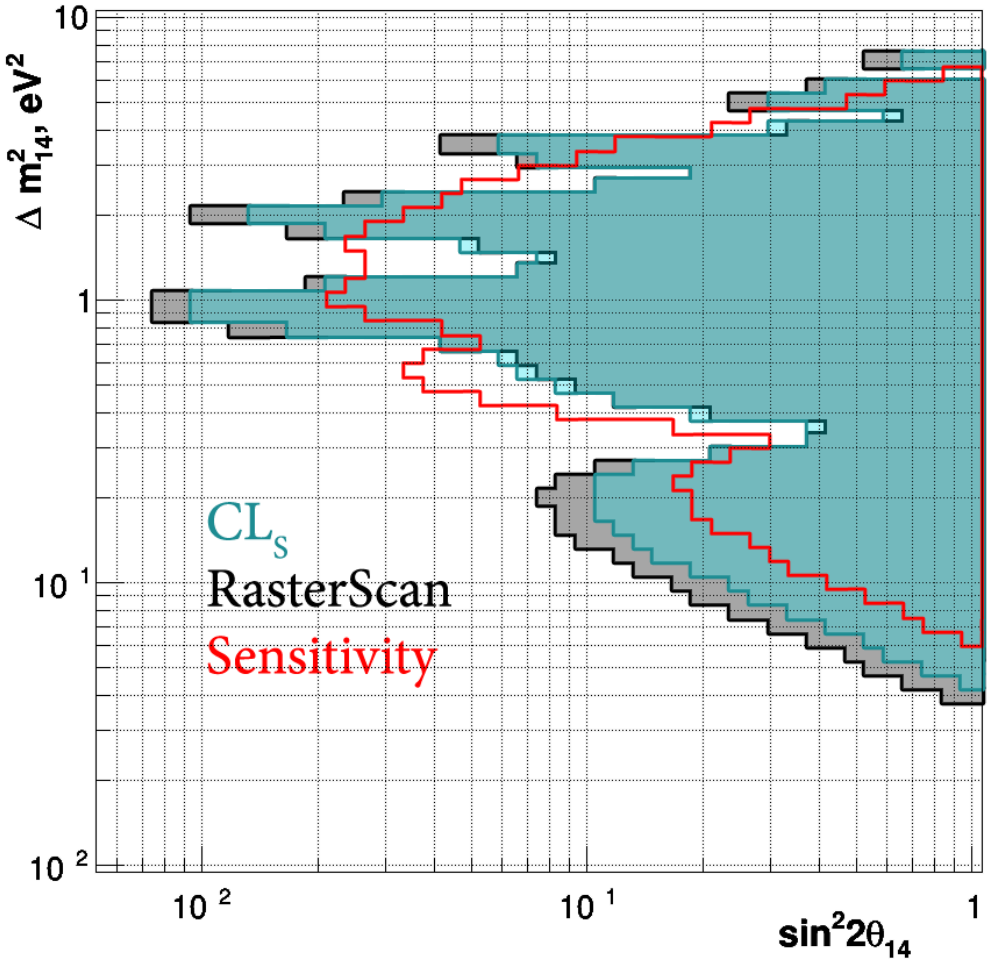
Exclusion region (90%, 95%) calculated using Gaussian CL_s method

A large and important fraction of allowed parameter region is excluded by preliminary DANSS results using only ratio of e^+ spectrum at different L (independent on ν spectrum, detector efficiency,. . .)

- DANSS plans to collect more data and to include into analysis all available data
- Detector calibration and systematics studies will be continued



Raster-Scan vs CL_s



RasterScan

$\Delta\chi^2 = \chi^2_{\Delta m^2,\theta} - \chi^2_{min(\Delta m^2)}$

levels:

$\Delta\chi^2 > 2.71(90\%)$

$\Delta\chi^2 > 3.84(95\%)$

CL_s method is more conservative

Sensitivity contour(90%):

-pseudoexperiments carried out

-level calculated with CL_s method

Summary

- DANSS analysis based on 706 thousand IBD events excludes a large and the most interesting fraction of available parameter space for sterile neutrino
- RAA best fit point is excluded at 5σ level
- In analysis only ratio of e^+ spectra at two distances is used (with no dependence on $\tilde{\nu}_e$ spectrum and detector efficiency!)
- Significance of the best fit point will be evaluated using Feldman-Cousins method and more statistics

We plan to collect more data, to improve MC for perfect description of detector response, to refine detector calibration, to continue systematic studies, to include all available statistics into analysis.

Thank you!

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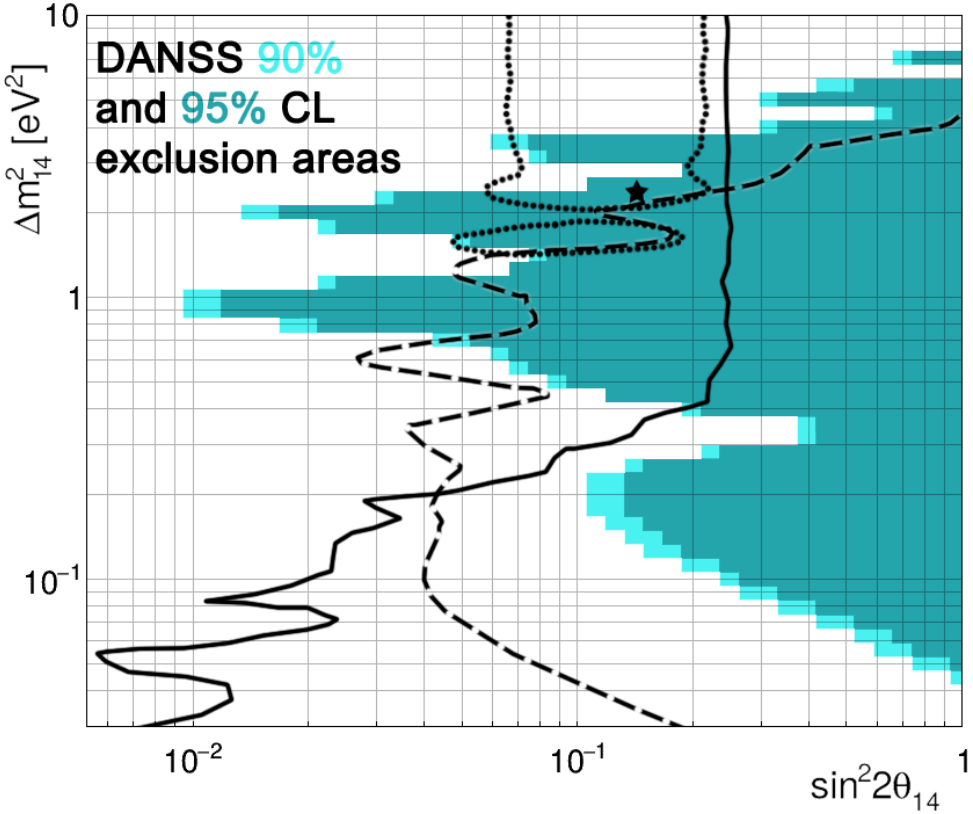
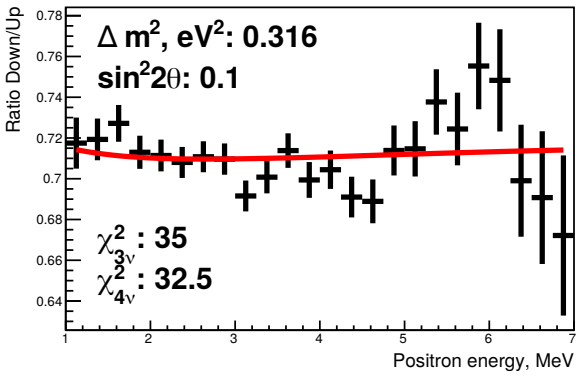
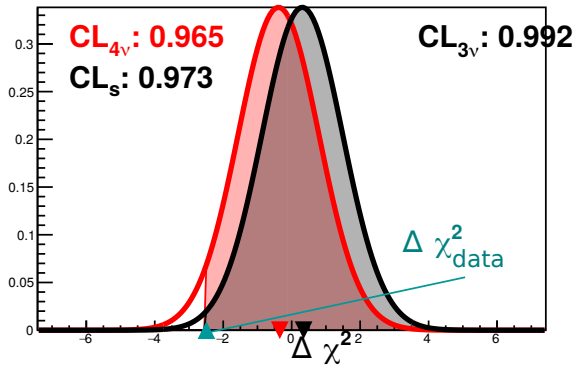
Exclusion regions



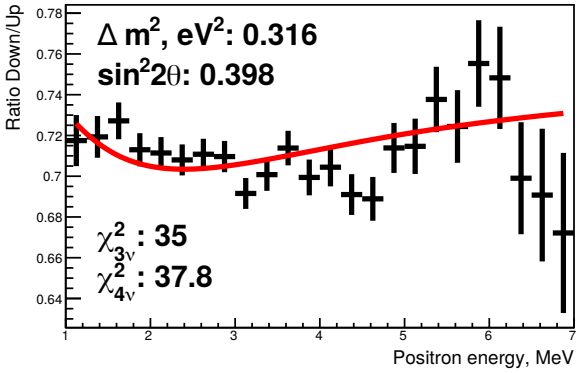
90% CL from:
Daya Bay (solid)
Bugey (dashed)
RAA (dotted)

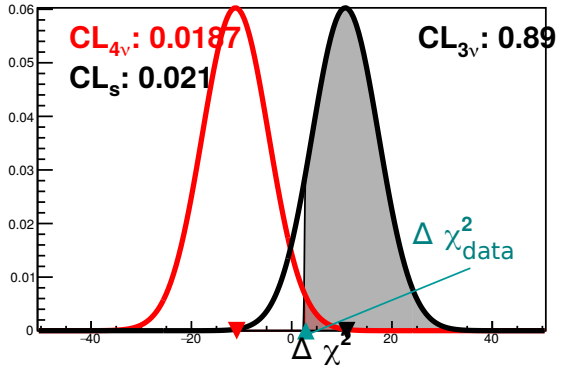
Gaussian CL_s: examples



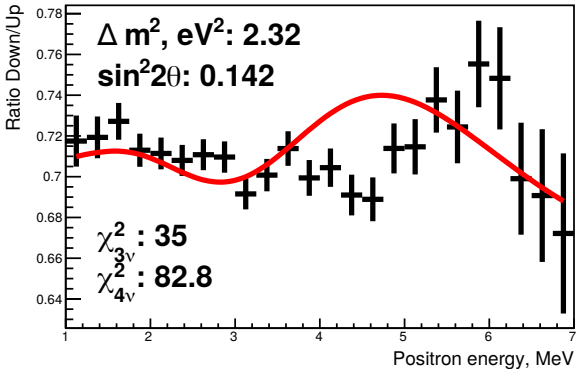


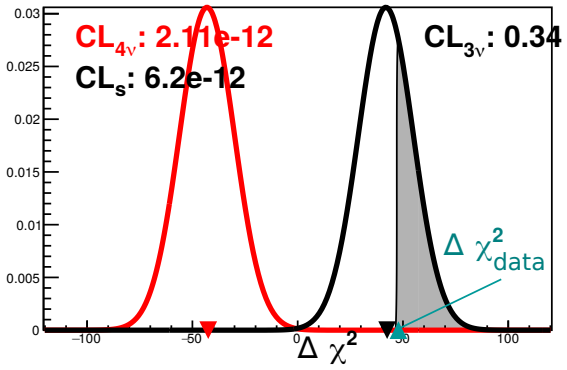
not excluded





$>$ 95% CL excluded

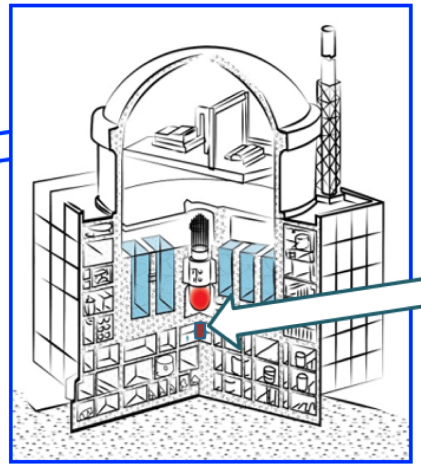




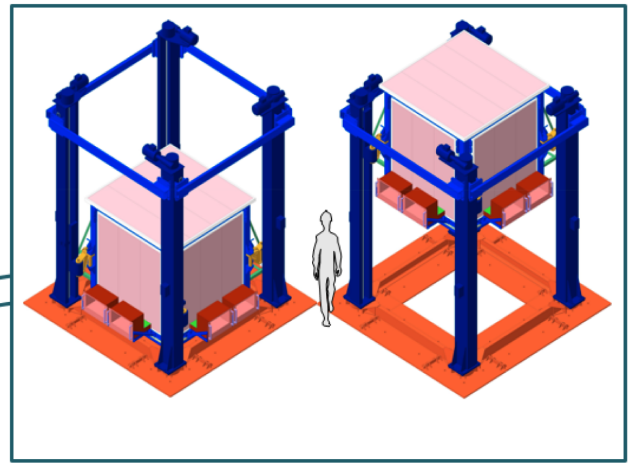
5σ excluded

Detector site

KNPP - Kalinin Nuclear Power Plant, Russia, ~350 km NW from Moscow

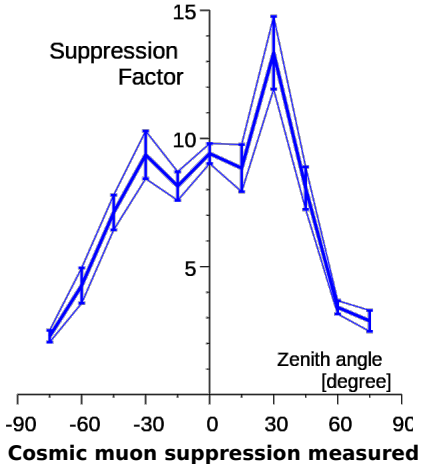


Below 3.1 GW commercial reactor ~ $5 \cdot 10^{13} \nu \cdot cm^{-2} c^{-1}$



DANSS on a lifting platform
A week cycle of up/middle/down position

- No flammable or dangerous materials – can be put just after reactor shielding
- Reactor fuel and body with cooling pond and other reservoirs provide overburden ~50 m w.e. for cosmic background suppression
- Lifting system allows to change the distance between the centers of the detector and of the reactor core from 10.7 to 12.7 m on-line
- The top position corresponds to ~15000 IBD events per day for 100% efficiency



Fuel

	begin 4	end 4	begin 5
^{235}U	63.7%	44.7%	66.1%
^{238}U	6.8%	6.5%	6.7%
^{239}Pu	26.6%	38.9%	24.9%
^{241}Pu	2.8%	8.5%	2.3%

core: h = 3.7 m, d = 3.2 m