Combined analysis status

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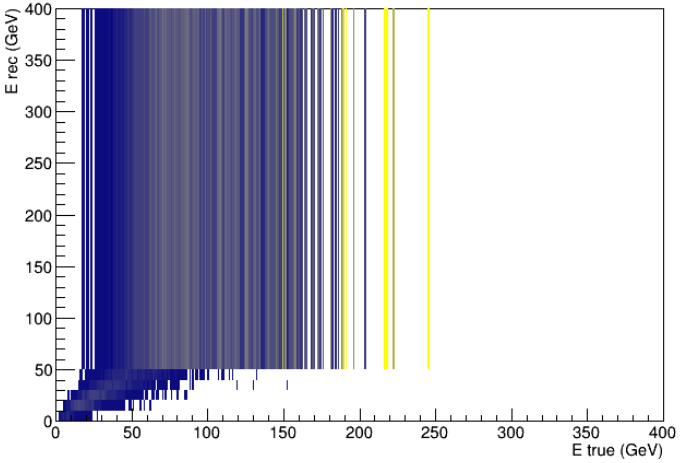
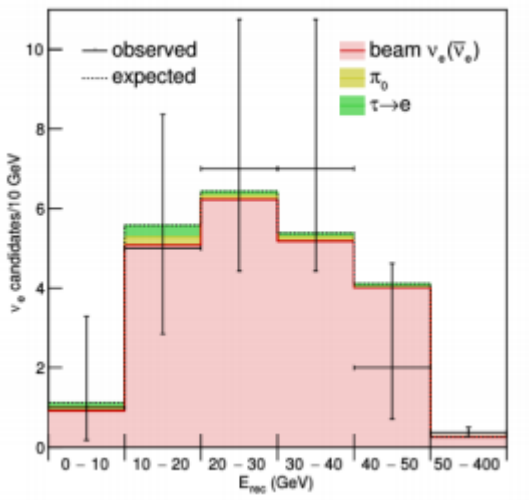
05/31/2018
Villa Orlandi, Anacapri (NA)

ν_e channel (1/2)

- Selection: ν_e candidate
- Observable:
  - reconstructed energy
  - binnig:
    0,10,20,30,40,50,400 (GeV)
- Energy sampling:
  - 400 points [0 - 400 GeV]
- Observation (n_i):
  - 1,5,7,7,2,13
- Normalization:
  - 30.7 w/o ν oscillations

Smearing Matrix





ν_e channel (2/2)

- Signal (s_i):
  - $\boldsymbol{\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e}$
  - $\boldsymbol{\nu_e \rightarrow \nu_e, \bar{\nu}_e \rightarrow \bar{\nu}_e}$
- Background (not osc) (b_i):
  - $\boldsymbol{NC, \tau \rightarrow e}$
  - 0.25, 0.66, 0.19, 0.11, 0.07, 0.1
- Syst. uncertainties (σ_j):
  - 20% E_ν < 10 GeV; 10% E_ν > 10 GeV
  - 45% on not. osc. background

Expected background	Expected νe
1.2 ± 0.54	30.7 ± 3.1

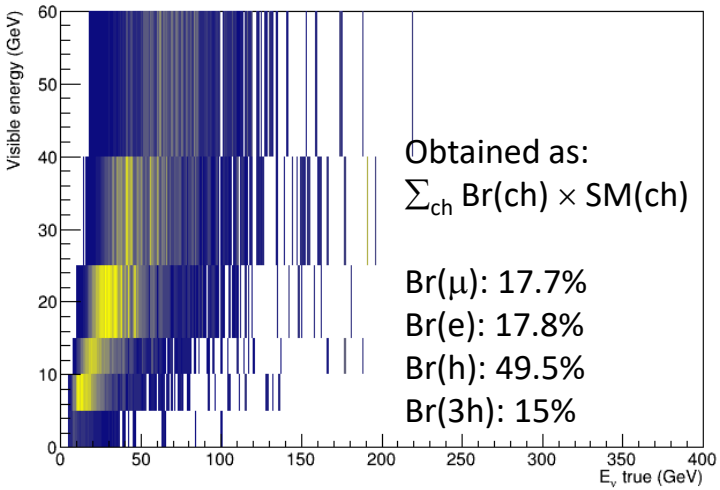
- Likelihood:
  - s_i = signal
  - b_i = not osc. bkg.
  - μ_i = expectation
    - $\mu_i = s_i(1 + k_j) + b_i(1 + k_3)$
    - j = 1, if i = 1
    - j = 2, otherwise
  - n_i = observation
  - σ_j = syst. uncertainties

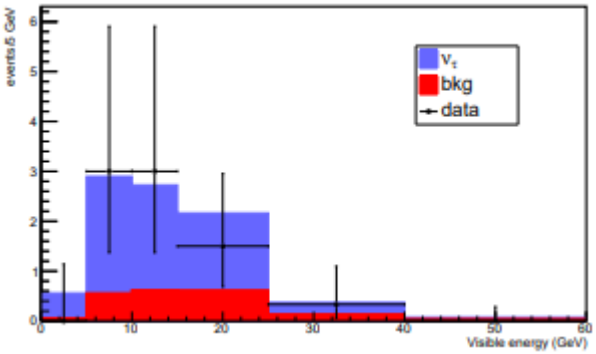
$$-2 \ln L_e = -2 \sum_{i=1}^{N} (n_i \ln \mu_i - N\mu_i) + \sum_{j=1}^{3} \frac{k_j^2}{\sigma_j^2}$$

ν_τ channel (1/2)

- Selection: ν_τ candidate
  [looser selection]
- Observable:
  - visible energy
  - binnig:
    0,5,10,15,25,40,60 (GeV)
- Energy sampling:
  - 400 points [0 - 400 GeV]
- Observation (n_i):
  - 0,3,3,3,1,0
- Normalization:
  - 6.8
    - 2 flavours
    - maximal mixing
    - $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

Smearing Matrix





ν_τ channel (2/2)

- Signal (s_i):
  - $\boldsymbol{\nu_\mu \rightarrow \nu_\tau}$
- Background (not osc) (b_i):
  - ***charm, LAS, had. reint.***
  - 0.0633, 0.552, 0.622, 0.608, 0.131, 0.033
- Syst. uncertainties (σ_j):
  - 11% on signal
  - 20% on not. osc. background

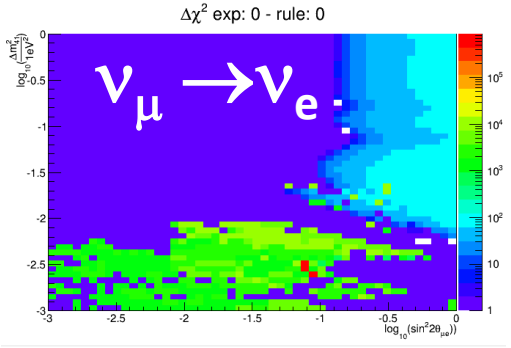
Expected background	Expected $\nu\tau$
2.0 ± 0.4	6.8 ± 0.75

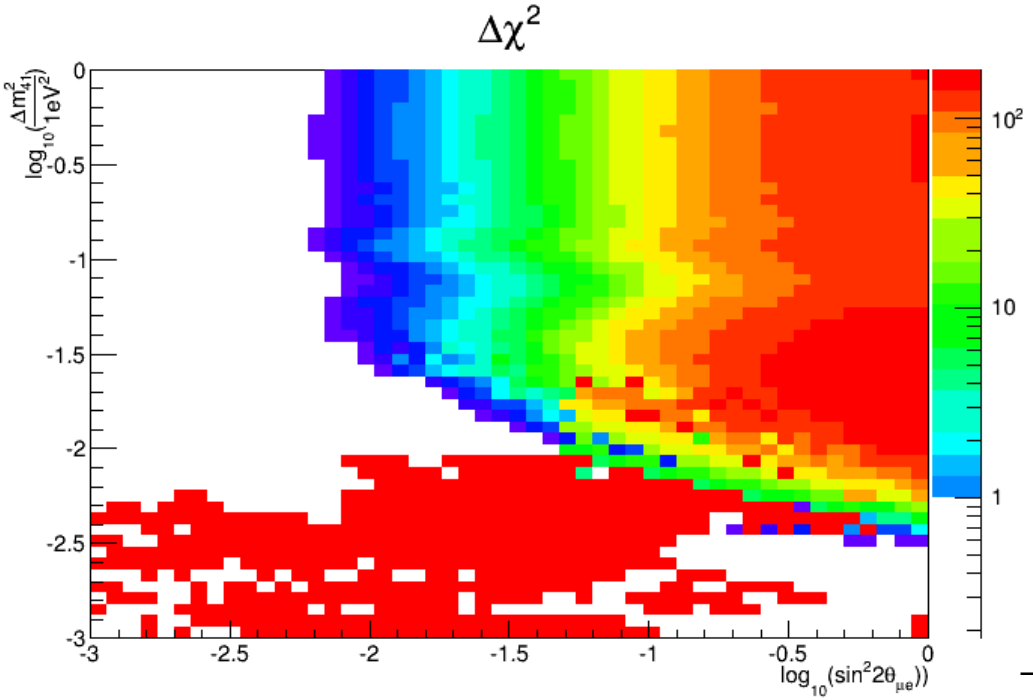
- Likelihood:
  - s_i = signal
  - b_i = not osc. bkg.
  - μ_i = expectation
    - $\mu_i = s_i(1 + k_1) + b_i(1 + k_2)$
  - n_i = observation
  - σ_j = syst. uncertainties

$$-2 \ln L_\tau = -2 \sum_{i=1}^{N} (n_i \ln \mu_i - N\mu_i) + \sum_{j=1}^{2} \frac{k_j^2}{\sigma_j^2}$$

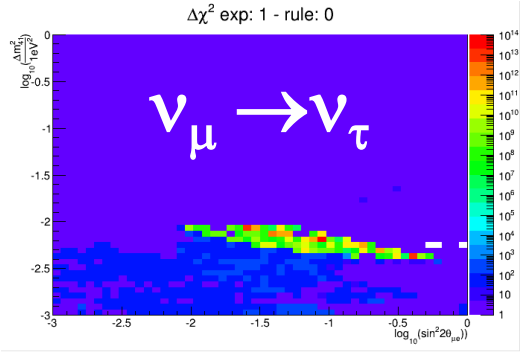
Bug

These are the results of the last run





$$-2\ln L_e = -2\sum_{i=1}^{N}(n_i \ln \mu_i - N\mu_i) + \sum_{j=1}^{3}\frac{k_j^2}{\sigma_j^2}$$



$$-2\ln L_\tau = -2\sum_{i=1}^{N}(n_i \ln \mu_i - N\mu_i) + \sum_{j=1}^{2}\frac{k_j^2}{\sigma_j^2}$$

$L = L_e + L_\tau + \text{Prior}$

Bug: penalty term for systematics was not present

Statistical analysis

- Priors
  - Gaussian on Δm^2_{31}
    $(2.56 \pm 0.05) \times 10^{-3}$ eV^2
    [http://pdg.lbl.gov/2017/reviews/rpp2017-rev-neutrino-mixing.pdf]
- Likelihood:
  - $L = L_e + L_\tau$ + Prior
- Test statistic:
  profile likelihood ratio
- Wilks' theorem
  - To extract limits and confidence/exclusion regions

Parameter	best-fit
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)
$\sin^2\theta_{12}$	0.297
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216
δ/π	1.38 (1.31)

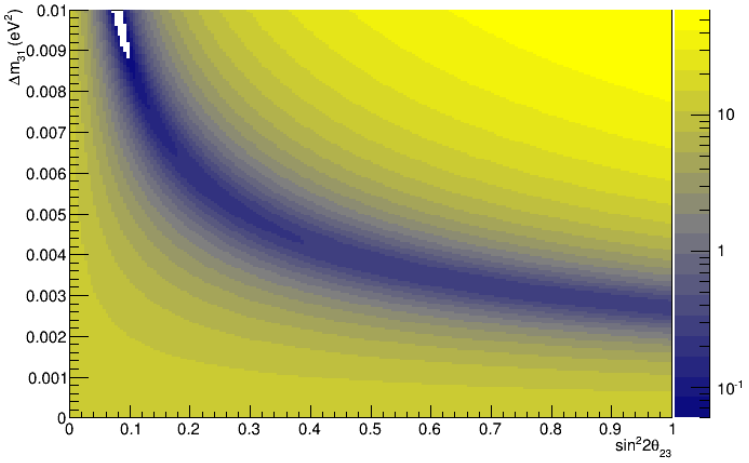
Oscillation model & Mixing matrix representation

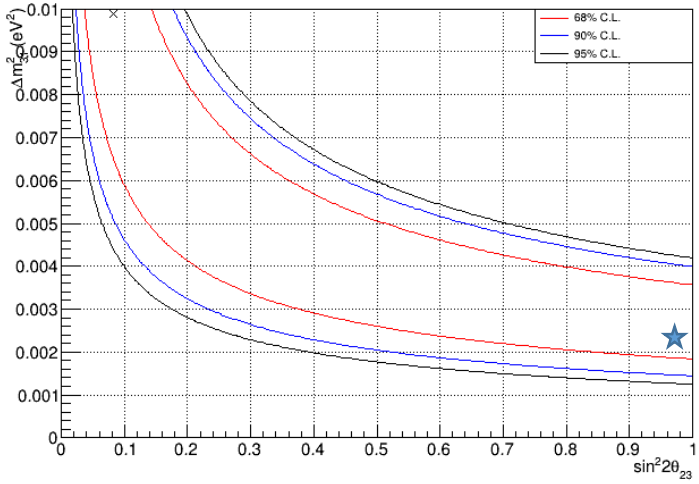
- 3 flavours model
  - $U = R(\theta_{23})\, R(\theta_{13}, \delta_{CP})\, R(\theta_{12})$
- Matter effects (constant density)
- NH

Δm^2_{31} VS θ_{23}

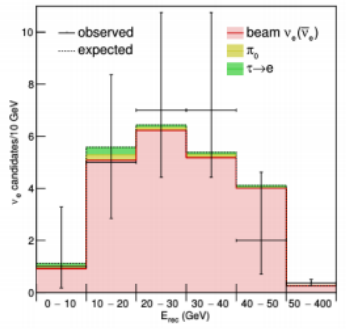
POI and nuisance params

- Parameters of interest:
  - θ_{23}, Δm^2_{31} (prior removed)
- Nuisance parameters:
  - θ_{12}, θ_{13}, δ_{CP}
- Constants
  - $\Delta m^2_{21} = 7.37 \times 10^{-5}$ eV^2

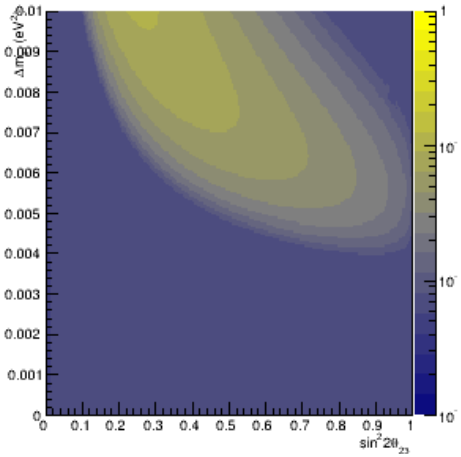




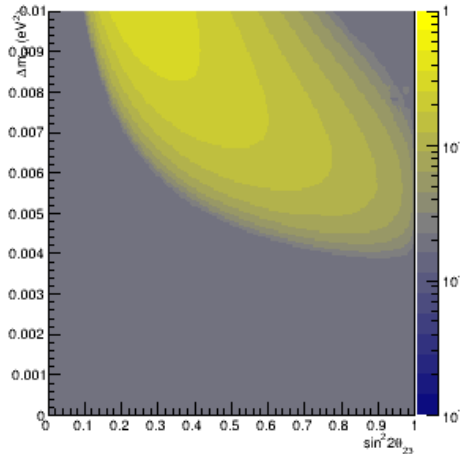
Bin contribution (ν_e channel)



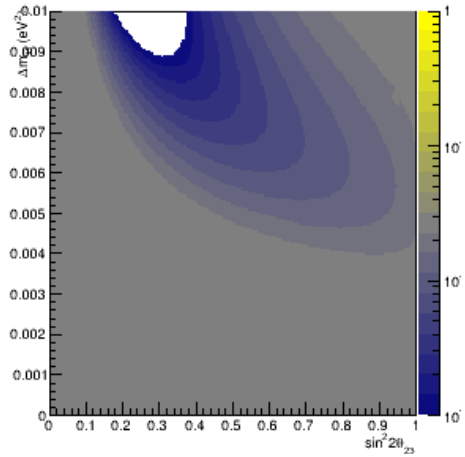
Bin: 1



Bin: 2

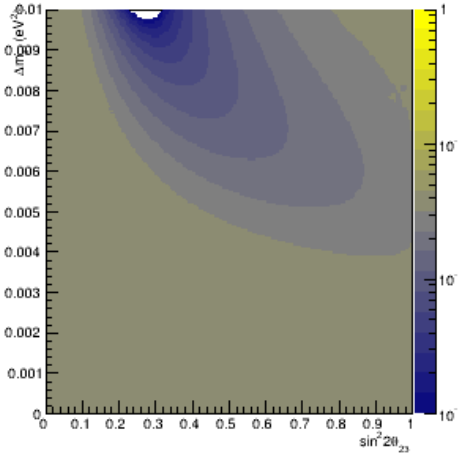


Bin: 3

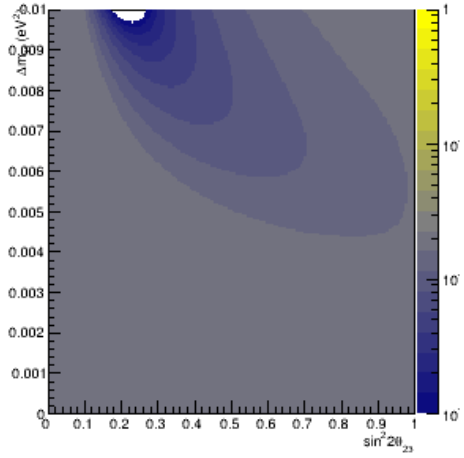


Z axis range: [0 - 1]

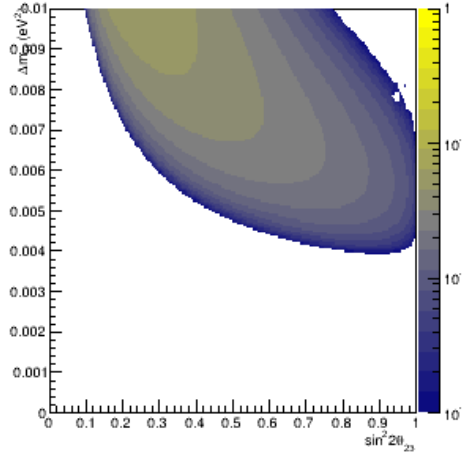
Bin: 4



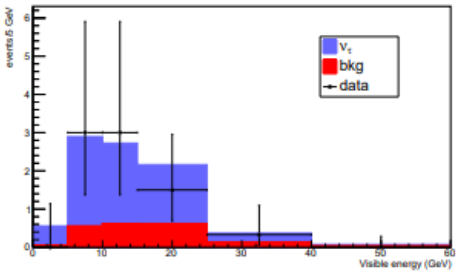
Bin: 5



Bin: 6

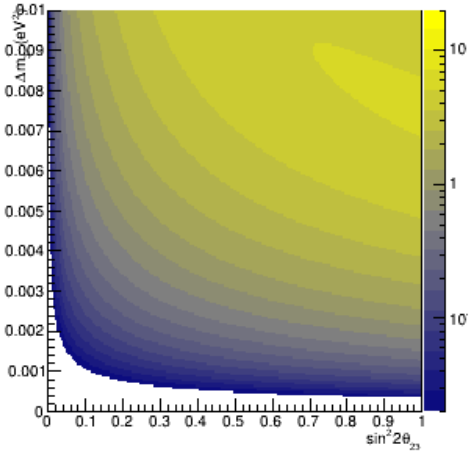


Bin contribution (ν_τ channel)

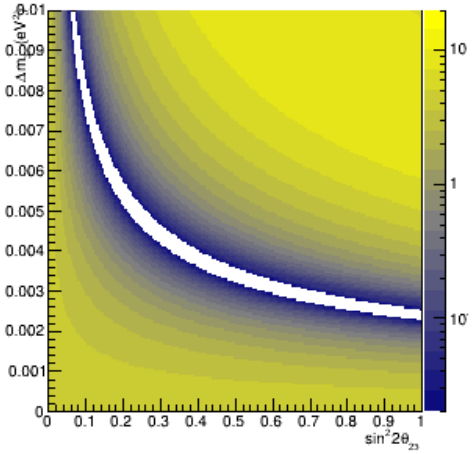


Z axis range: [0 - 20]

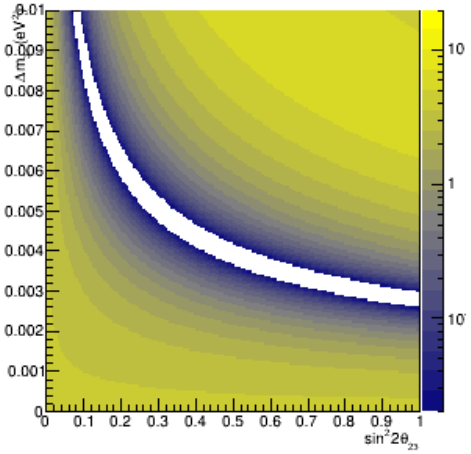
Bin: 1



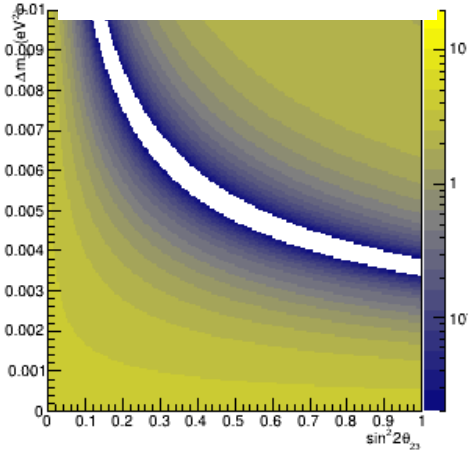
Bin: 2



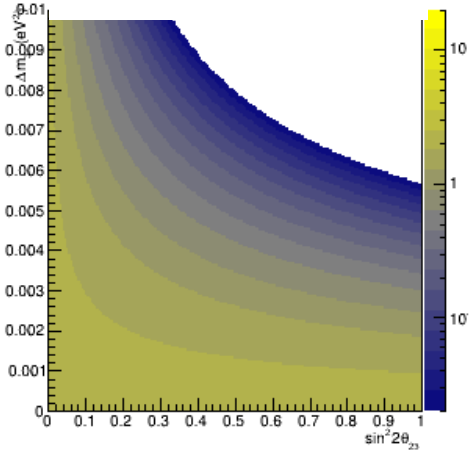
Bin: 3



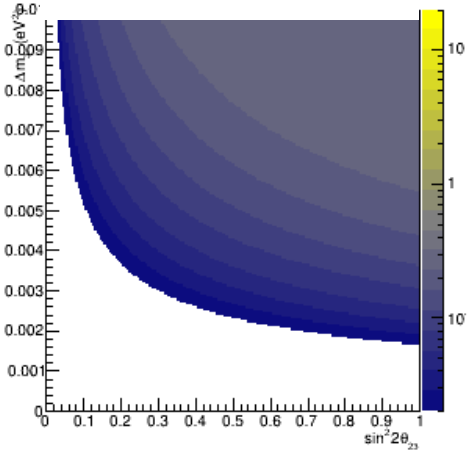
Bin: 4



Bin: 5



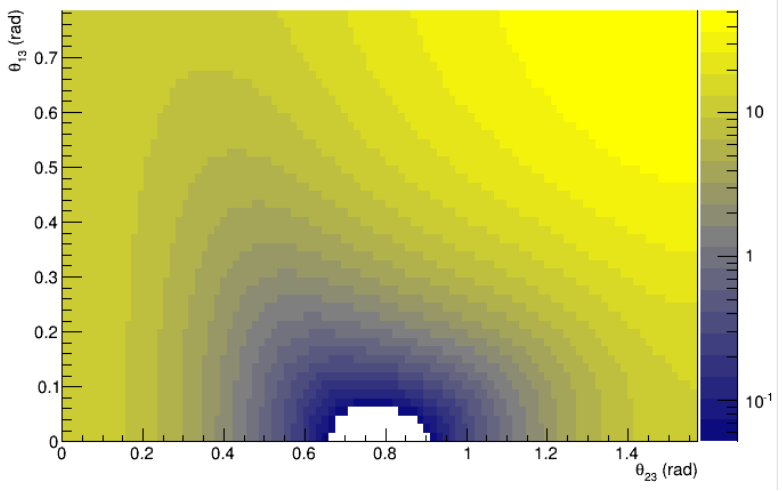
Bin: 6

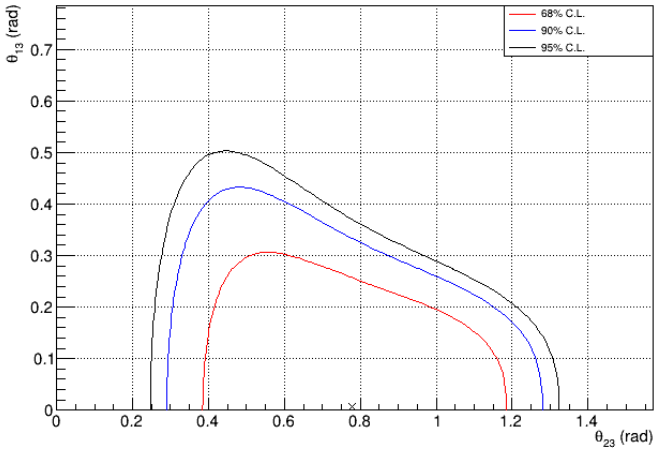


θ_{13} VS θ_{23}

POI and nuisance params

- Parameters of interest:
  - θ_{23}, θ_{13}
- Nuisance parameters:
  - θ_{12}, δ_{CP}, Δm^2_{31}
- Constants
  - $\Delta m^2_{21} = 7.37 \times 10^{-5}$ eV^2

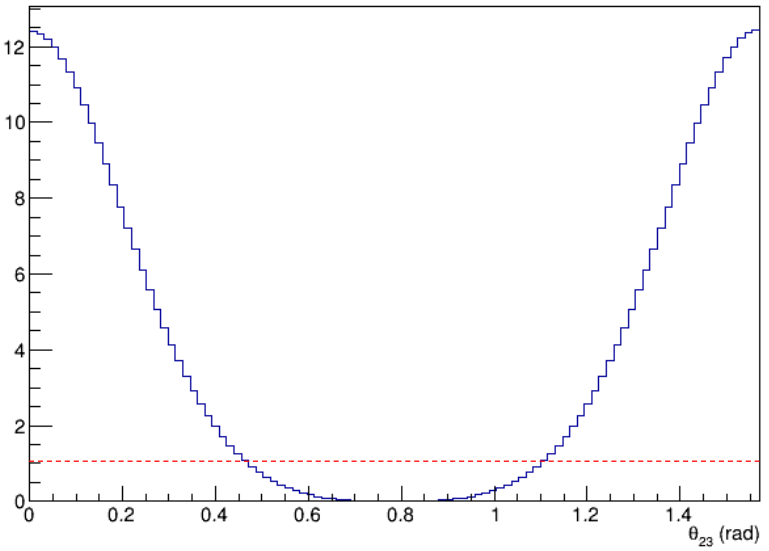


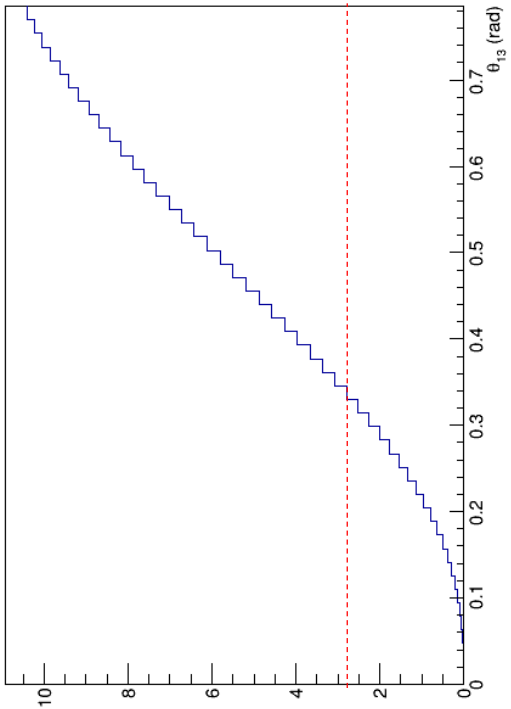


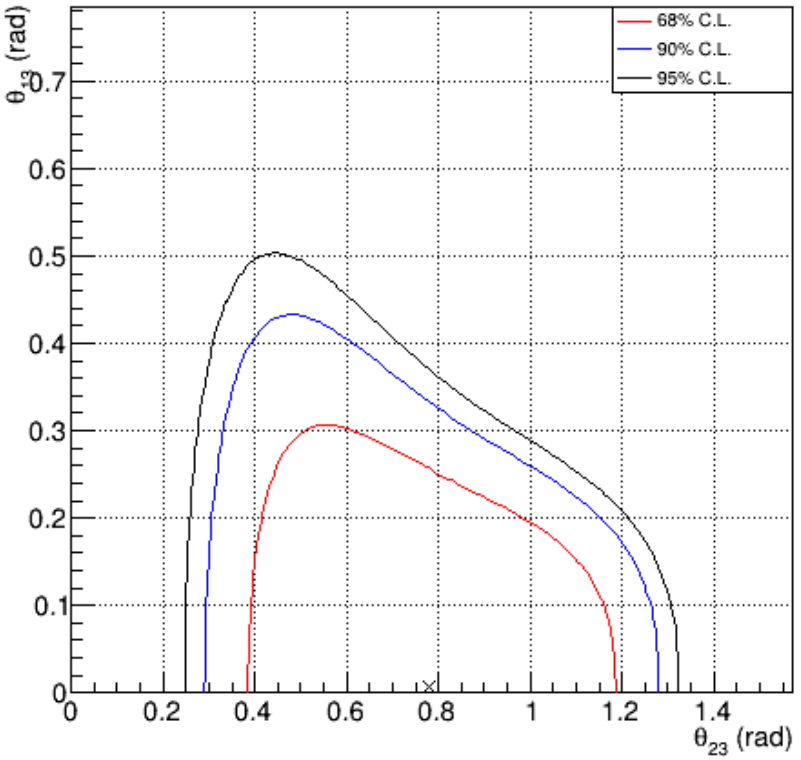
Profiling

θ_{23} = [0.47 – 1.10] @ 68% C.L.

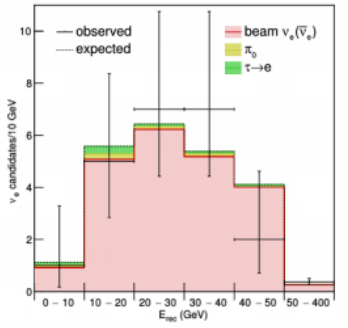
θ_{13} < 0.33 @ 90% C.L.



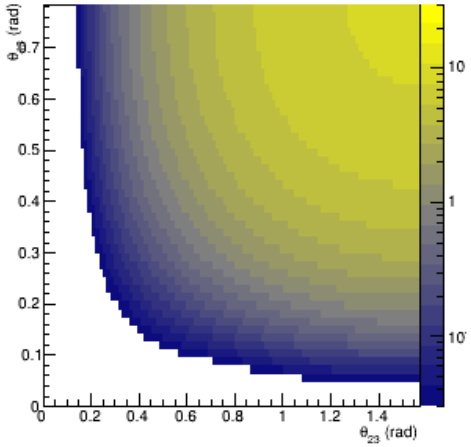




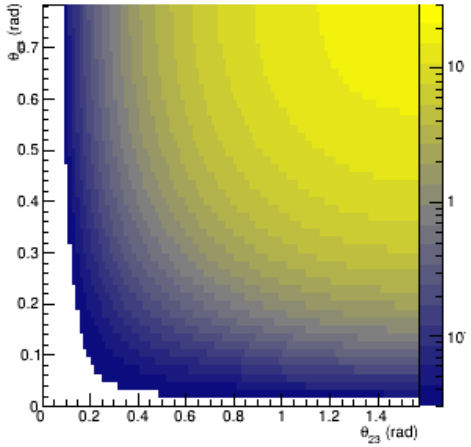
Bin contribution (ν_e channel)



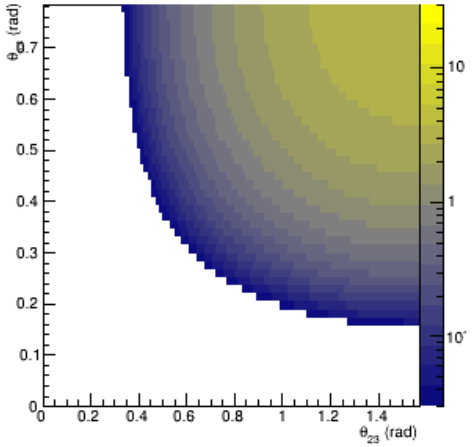
Bin: 1



Bin: 2

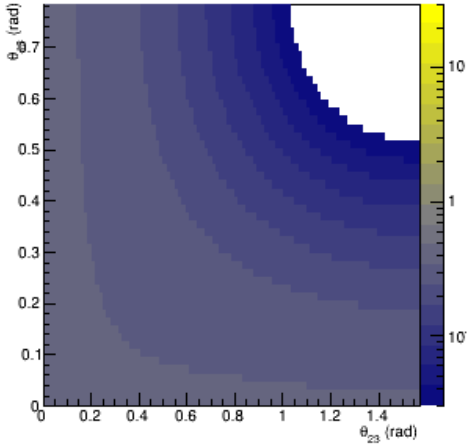


Bin: 3

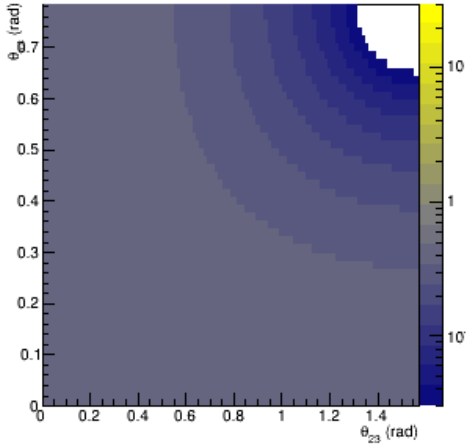


Z axis range: [0 - 30]

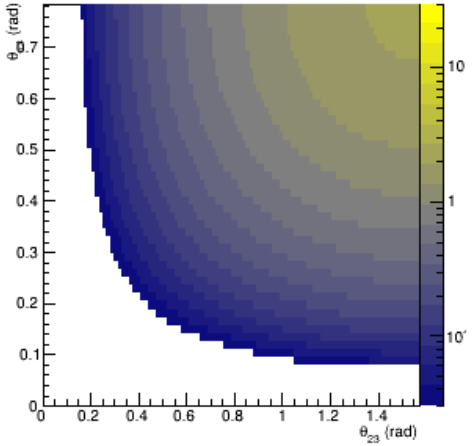
Bin: 4



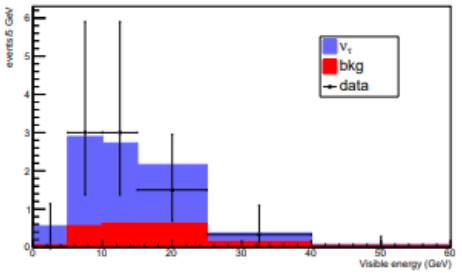
Bin: 5



Bin: 6

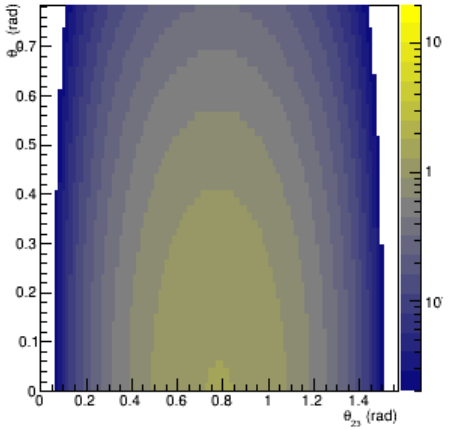


Bin contribution (ν_τ channel)

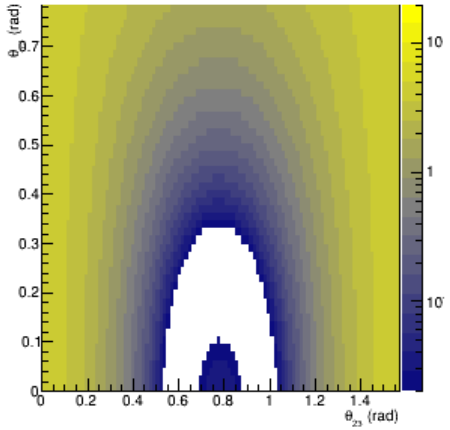


Z axis range: [0 - 20]

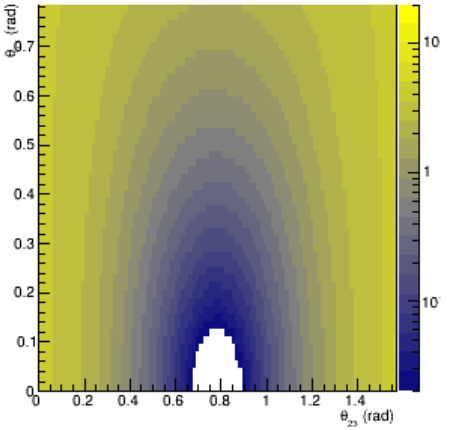
Bin: 1



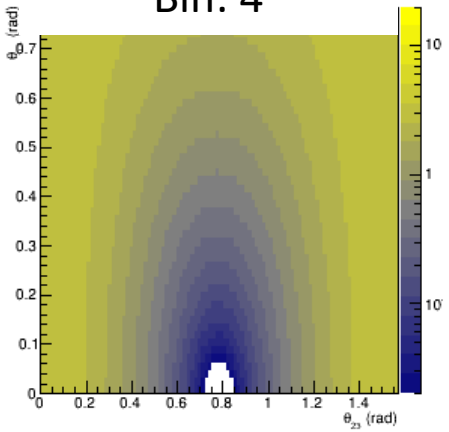
Bin: 2



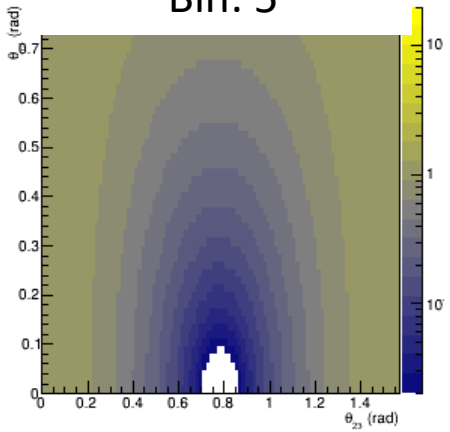
Bin: 3



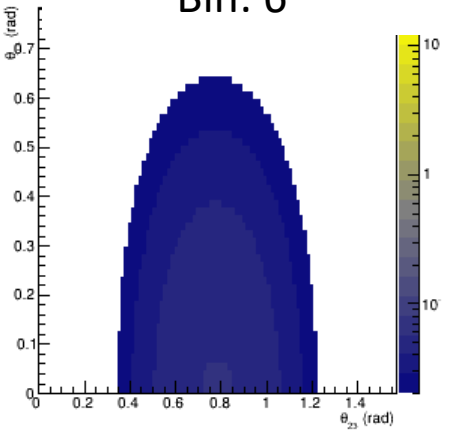
Bin: 4



Bin: 5



Bin: 6



3 + 1 model

Oscillation model & Mixing matrix representation

- 3+1 Model
  - $U = R(\theta_{34})\, R(\theta_{24})\, R(\theta_{23}, \delta_3)\, R(\theta_{14})\, R(\theta_{13}, \delta_2)\, R(\theta_{12}, \delta_1)$ [arXiv:0704.0388]
  - Last column is $\begin{pmatrix} s_{14} \\ s_{24}c_{14} \\ s_{34}c_{24}c_{14} \\ c_{14}c_{24}c_{14} \end{pmatrix}$ so $\begin{cases} \sin^2 2\theta_{\mu e} = 4\left|U_{\mu 4}\right|^2 |U_{e4}|^2 = s_{24}^2 \sin^2 2\theta_{14} \\ \sin^2 2\theta_{\mu\tau} = 4\left|U_{\mu 4}\right|^2 |U_{\tau 4}|^2 = c_{14}^2 s_{34}^2 \sin^2 2\theta_{24} \end{cases}$
- Matter effects (constant density)
- NH & $\Delta m^2_{41} > 0$

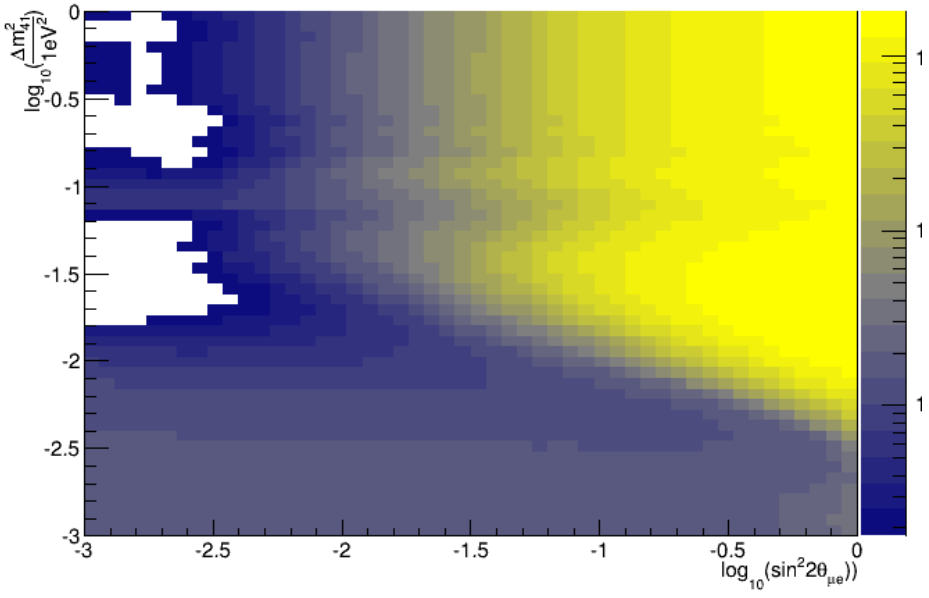
Δm^2_{41} VS $\sin^2 2\theta_{\mu e}$

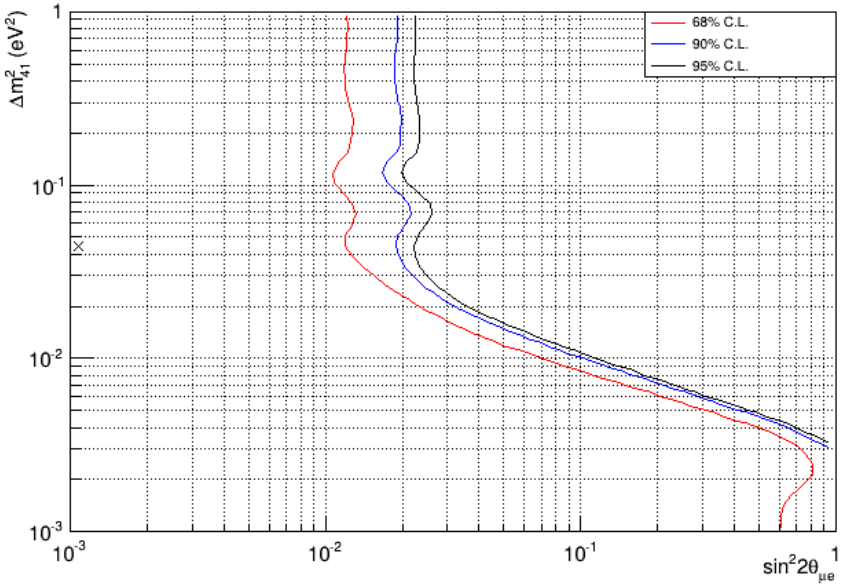
POI and nuisance params

- Parameters of interest:
  - $\sin^2 2\theta_{\mu e}$, Δm^2_{41}
- Nuisance parameters:
  - θ_{12}, θ_{13}, θ_{14}, θ_{23}, θ_{24}, δ_1, δ_2, δ_3, Δm^2_{31}
  - 10 sampling points in θ_{14} for likelihood profiling (to be increased [30])
- Constants
  - $\Delta m^2_{21} = 7.37 \times 10^{-5}$ eV^2

$\sin^2 2\theta_{\mu e}$ VS Δm^2_{41}

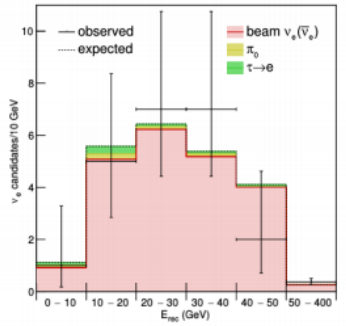
Now likelihood is ok





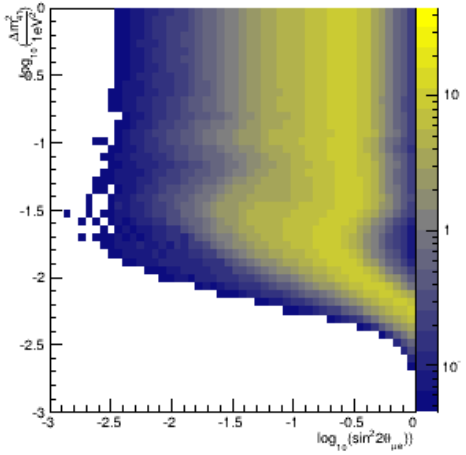
$\sin^2 2\theta_{\mu e} > 0.022$ [90% C.L.]
@ $\Delta m^2_{41} \sim 1$ eV^2

Bin contribution (ν_e channel)

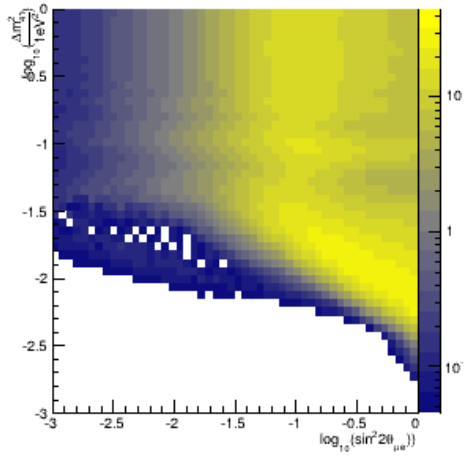


Z axis range: [0 - 45]

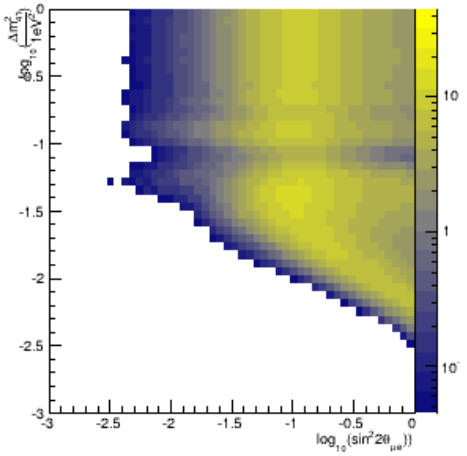
Bin: 1



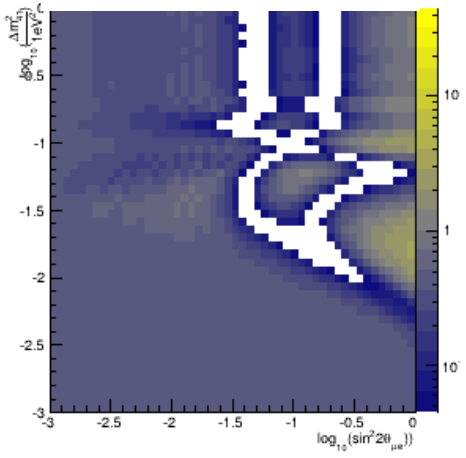
Bin: 2



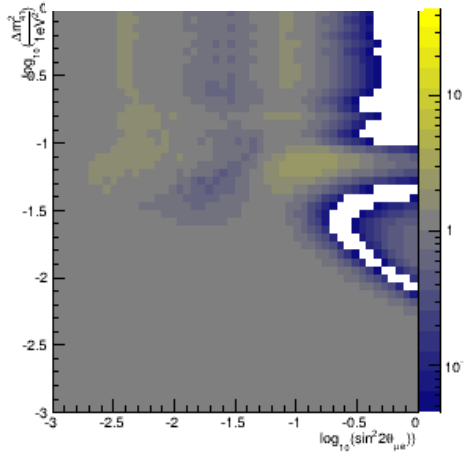
Bin: 3



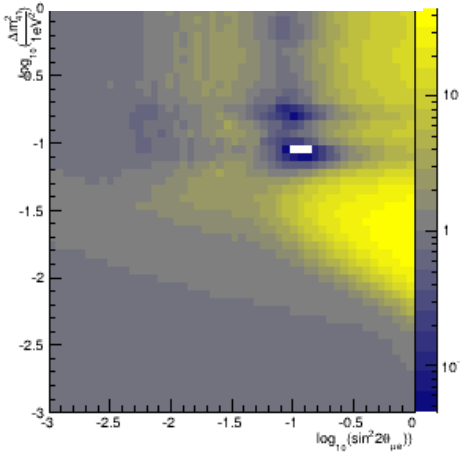
Bin: 4



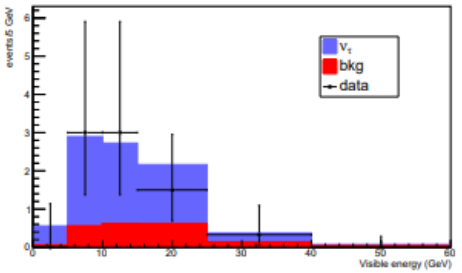
Bin: 5



Bin: 6

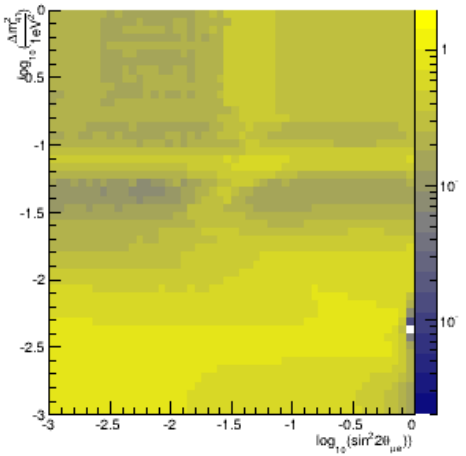


Bin contribution (ν_τ channel)

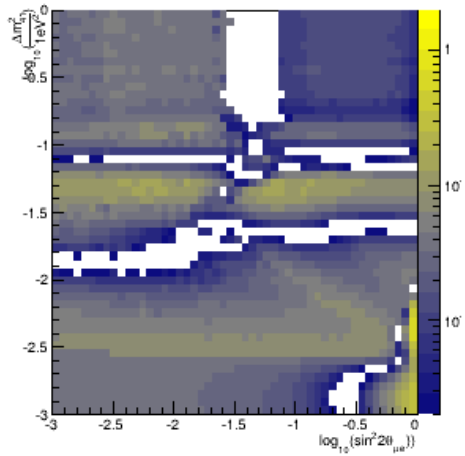


Z axis range: [0 - 2]

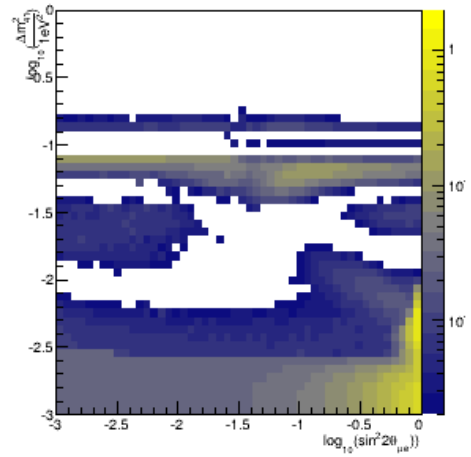
Bin: 1



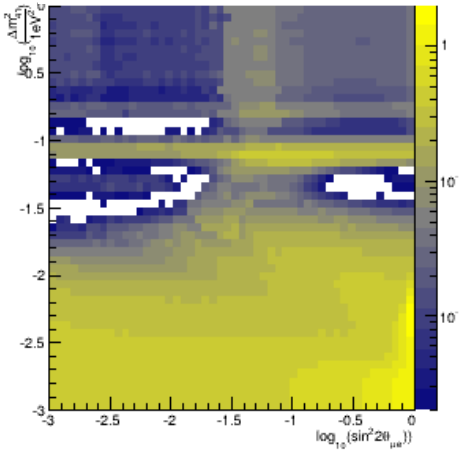
Bin: 2



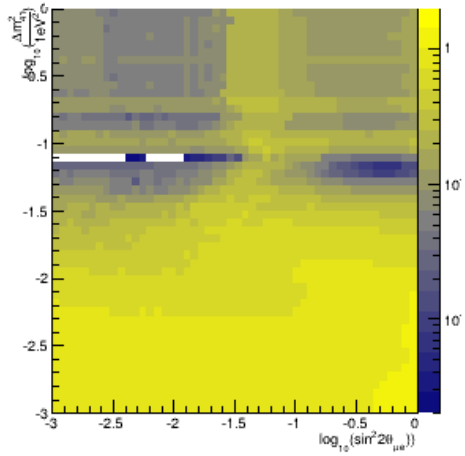
Bin: 3



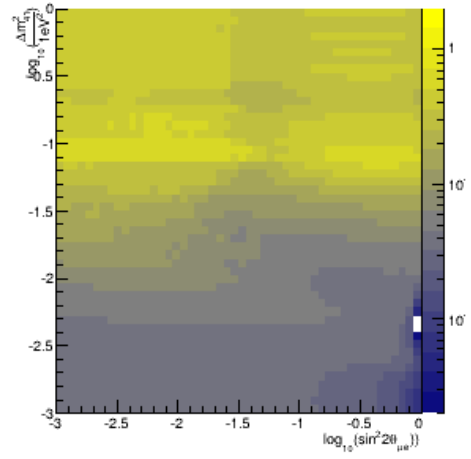
Bin: 4



Bin: 5



Bin: 6



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

POI and nuisance params

- Parameters of interest:
  - $\sin^2 2\theta_{\mu\tau}$, Δm^2_{41}
- Nuisance parameters:
  - θ_{12}, θ_{13}, θ_{14}, θ_{23}, θ_{24}, δ_1, δ_2, δ_3, Δm^2_{31}
  - 5 x 5 sampling points in θ_{14}, θ_{24} for likelihood profiling (to be increased [10 x 10])
- Constants
  - $\Delta m^2_{21} = 7.37 \times 10^{-5}$ eV^2

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

in progress

Conclusions and outlooks

- Code in
  - git@baltig.infn.it:opera-combined/opera-combined-globes.git
  - Readability to be improved
- Machinary seems to work as expected
  - Additional checks are on going
- $\sin^2 2\theta_{\mu\tau}$ VS Δm^2_{41} is in progress
- Once all is ok:
  - Profiling likelihood sampling will be increased, to improve profiling accuracy
  - IH can be investigated
  - the same for $\Delta m^2_{41} > 0$
- It will be cool to add also ν_μ disappearance channel