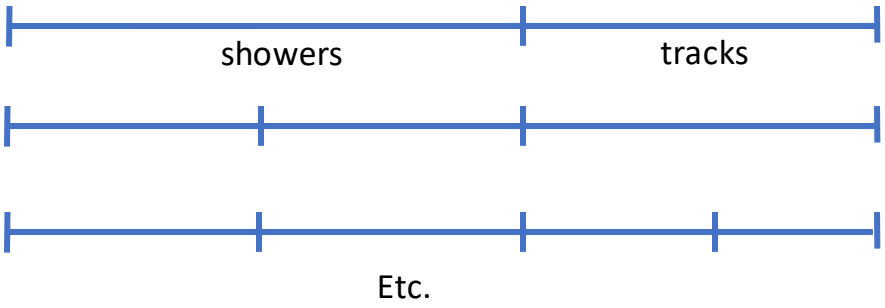
To Infinity and Beyond!

Lodewijk Nauta

Goal

- Goal:
  Show whether the Neutrino Mass Ordering sensitivity increases when using multiple categories in the PID variable q

- Method: introduce some binning scheme in PID variable q and calculate the sensitivity



Tool

- MONA: Mass Ordering Nikhef Analysis (previous name: nikhefNMO)
  - Input: PID mass production files → summary format
  - Calculate Detector Response Matrix (R.M.)
  - Apply RM to True flux calculated w/ oscillation parameters **P**
  - Calculate #Evts after 3 years
  - Fit oscillation parameters **P** to generated data (Asimov method) w/ **RooFit**
    - Simultaneous pdf fit:
      - χ^2 fit
      - Maximum likelihood
    - Pseudo-experiments
    - Contouring

https://git.km3net.de/bstrandberg/MONA

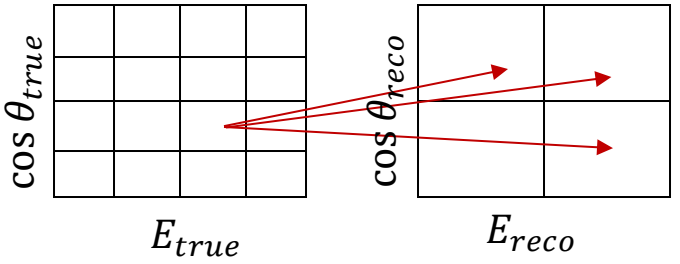
- Advantage of MONA:
  - Very flexible in RM construction: changing #PID categories is trivial
  - Uses well established RooFit package for fitting
  - Standard summary data format for users

- URL: git.km3net.de/bstrand/MONA

Issue

- We see: Sensitivity increases with more `PID categories`
- Due to signal in PID variable q
- Due to statistics of response matrix
  - More categories → less events per Response Matrix (track, shower, etc.)
  - Response matrix mapping gets worse with less events
  - Event distributions deviate more from a true detector response
  - Easier to distinguish two hypotheses H0, H1
  - Sensitivity to hypothesis H1 goes up
- Decouple these 2 effects

Detector Response Matrix



Map true events to reco events

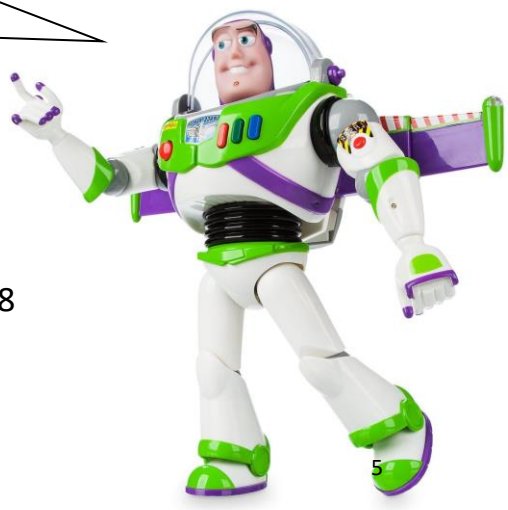
Response matrix property

- When calculating the average chi2 for a RM [1]:

$$\langle \Delta\chi^2 \rangle(N) = \langle \Delta\chi^2_\infty \rangle + \sum_i^{true} \sum_j^{reco} \frac{K_{ij}}{N_i} + O(N^{-\frac{3}{2}})$$

$$K_{ij} \approx N_j^A \left(\frac{n_i^A}{N_j^A} - \frac{n_i^B}{N_j^B} \right) \Phi_i(X_j) V_j e_i$$

$$\langle \Delta\chi^2 \rangle(N) \approx \langle \Delta\chi^2_\infty \rangle + \frac{K}{N_{MC}}$$



- See backup for details on K_{ij}

[1] Neutrino oscillations and Earth tomography with KM3NeT-ORCA, S. Bourret, 2018

Fit to chi2 of sampled response matrix

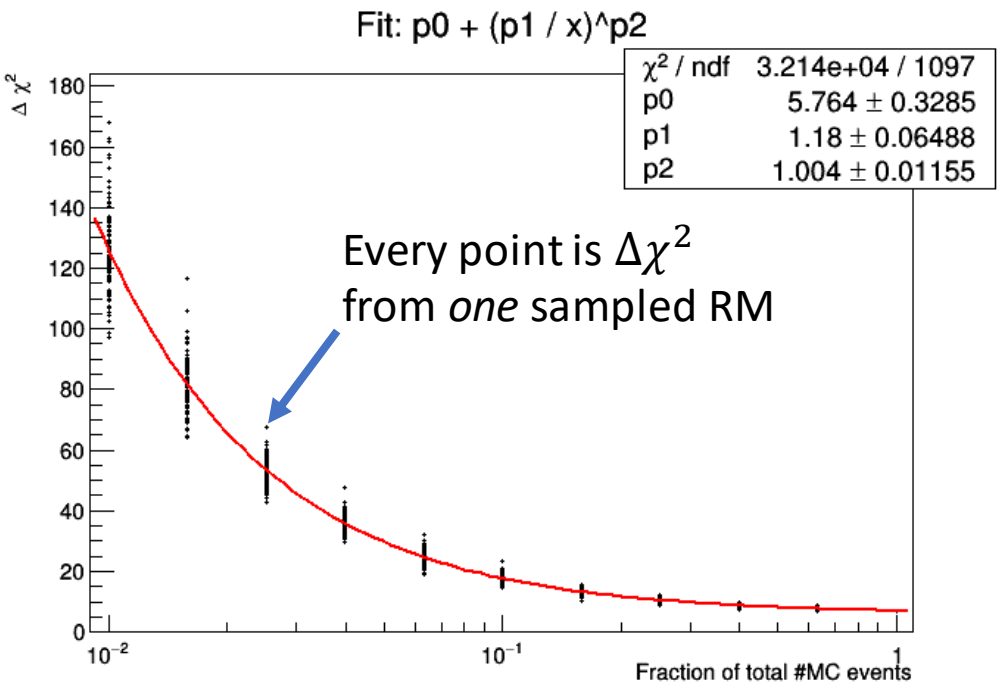
1. Create response matrix with ***fraction*** of total MC events
2. Calculate sensitivity with ***sampled*** RM
3. Do 1. and 2. many times
4. Sensitivity should follow

$$\langle \Delta\chi^2 \rangle \approx \langle \Delta\chi^2_\infty \rangle + \frac{K}{N_{MC}}$$

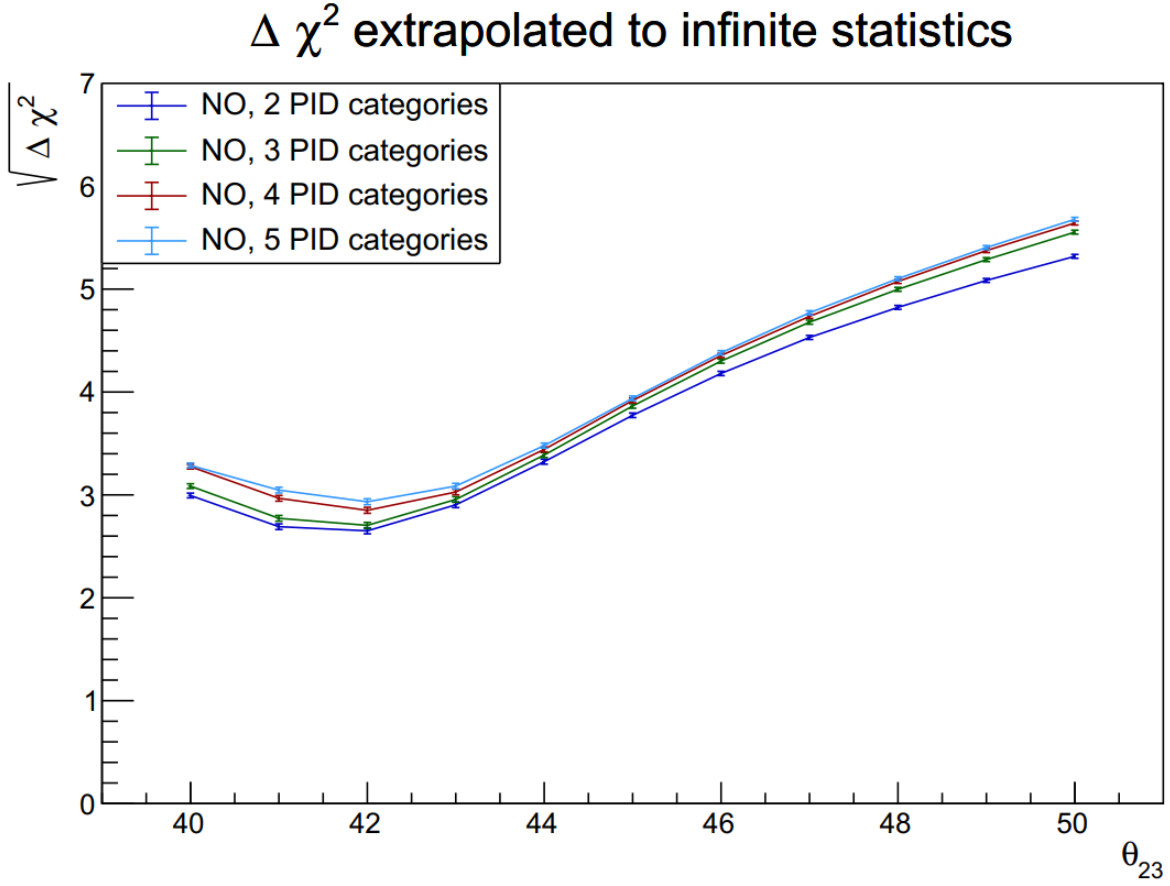
5. Fit to function **p0 + (p1 / N)^p2** as a check on the behavior: p2 = 1

6. Fit to function **p0 + (p1 / N)**

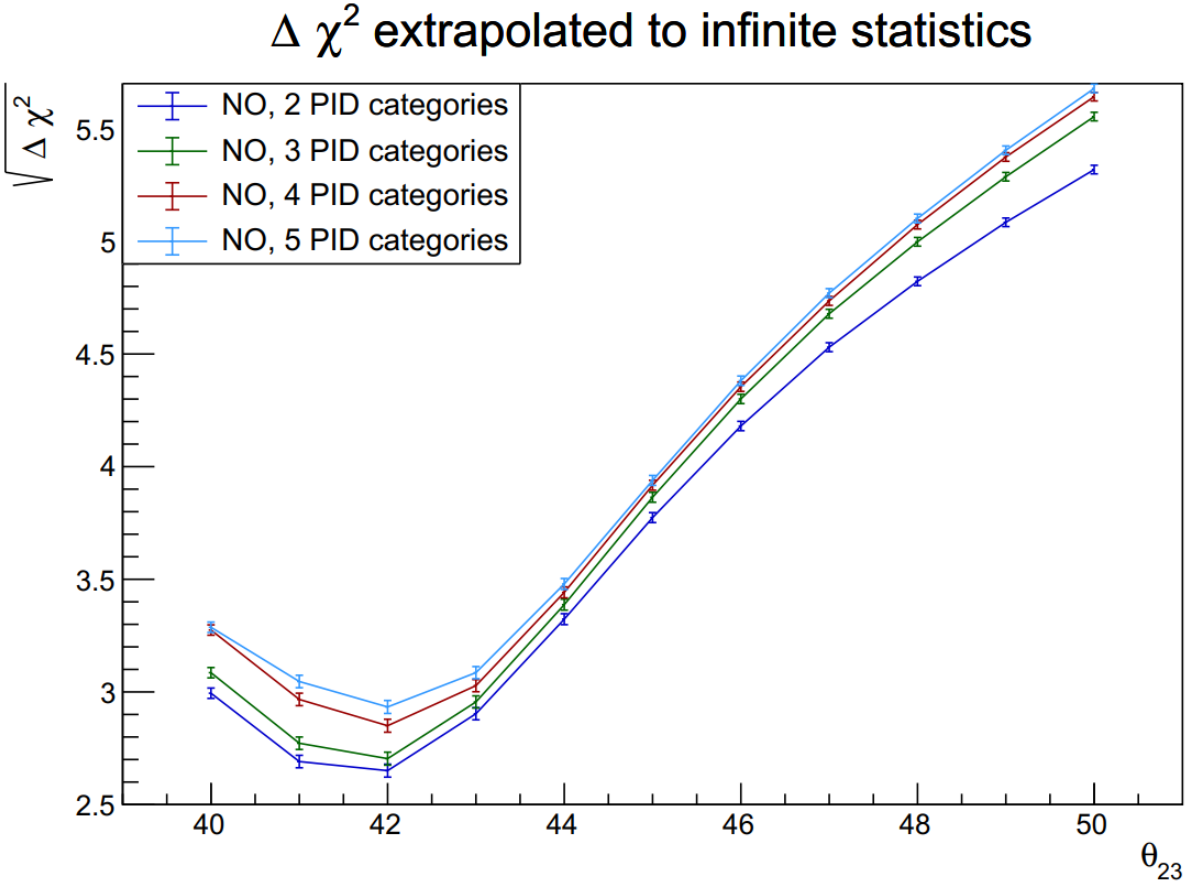
$$\Delta\chi^2(1) = 7.65$$
$$\langle \Delta\chi^2_\infty \rangle = 5.66$$



Extrapolated Sensitivities

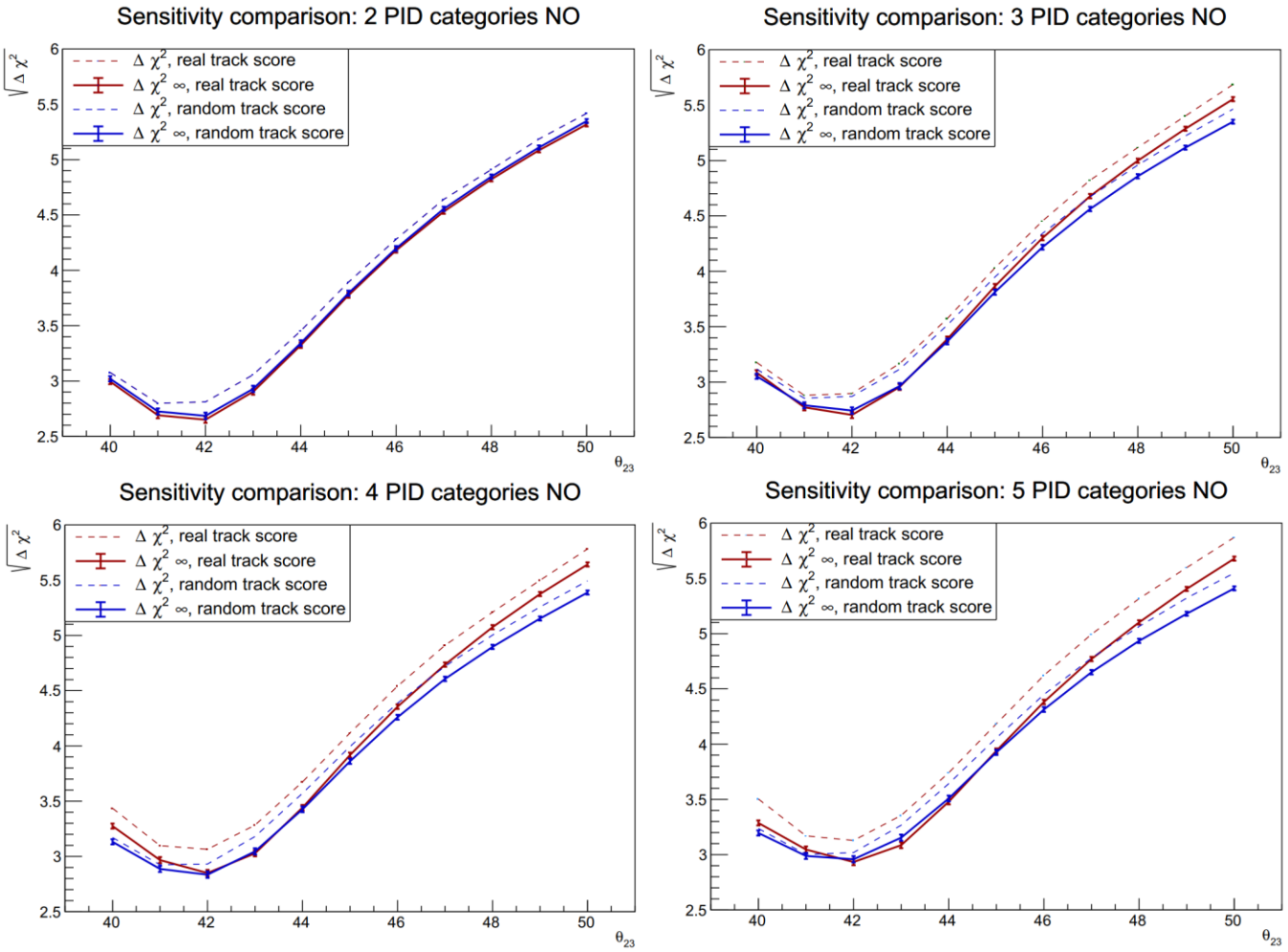


Extrapolated Sensitivities – enhance!



Cross-check: random track score

- Random* track score for the events removes any possible signal in our data, showing the baseline sensitivity



*Random means: randomize the track score of a MC event within its own class of event (track/shower) while keeping the track score distribution identical.

How many events does it take?

- Current production: 10M events

$$\langle \Delta\chi^2 \rangle \approx \langle \Delta\chi^2_\infty \rangle + \frac{K}{N_{MC}}$$

- Calculate N! (to reach 1% accuracy)

PID Categories	Number of MC events needed
2	29.3M
3	40.2M
4	52.1M
5	62.0M

Conclusion

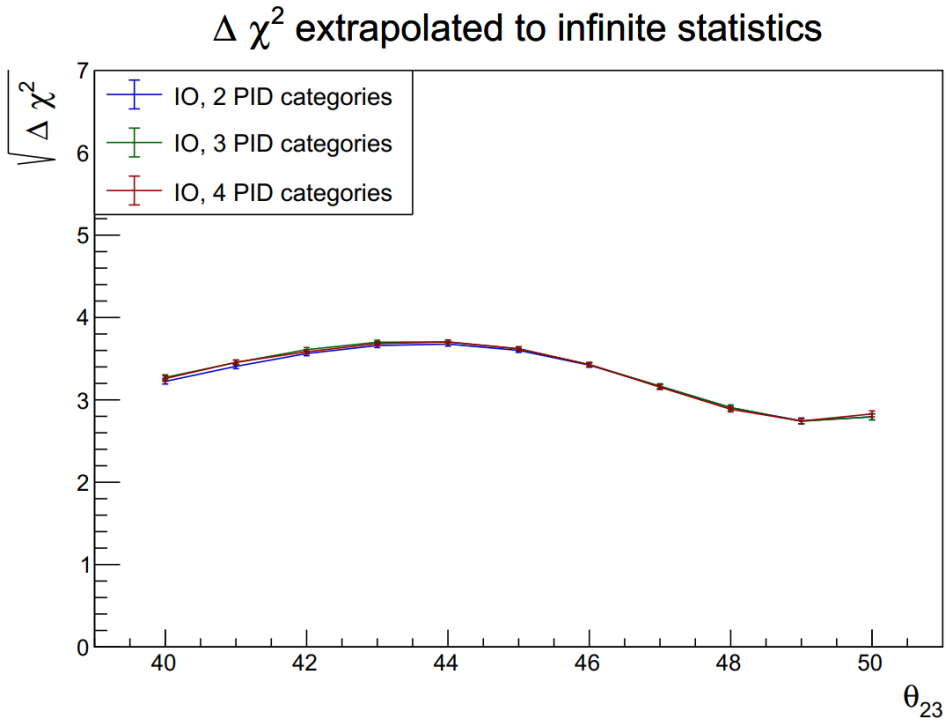
Make conclusion FINAL

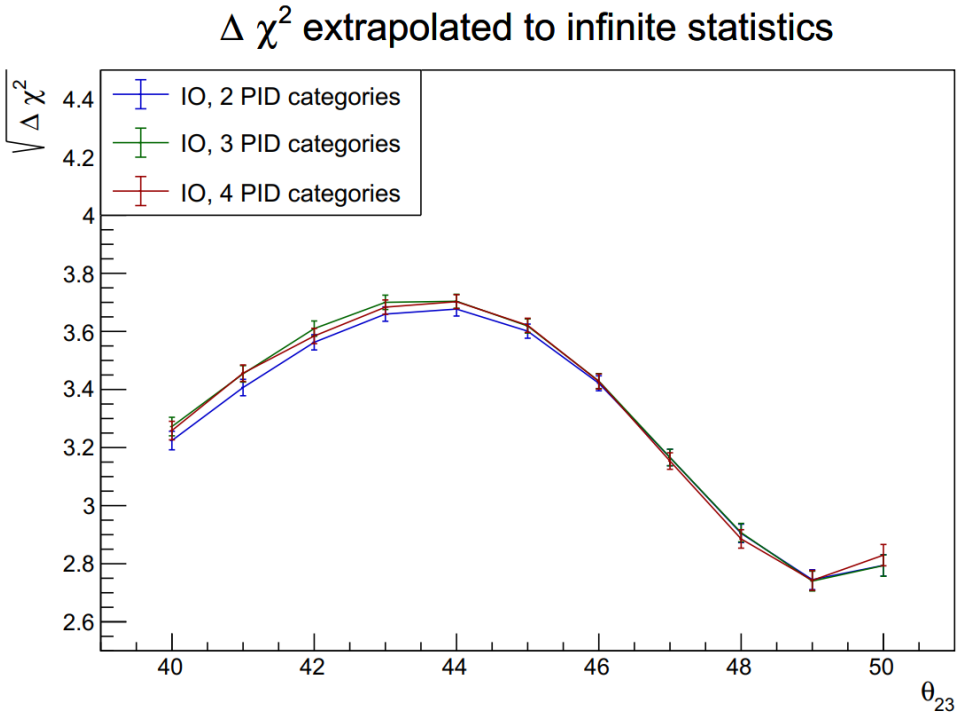
- We can extrapolate to infinite statistics and sensitivity of the *true* detector
- Using more than 2 PID categories increases our sensitivity to the NMO signal: by 0.2-0.4σ
- The ideal number of PID categories used with this scheme is: **3 OR 4**
- To negate DR effects in the calculation we would need >20 times more MC events

- Model breaks down for 5+ PID categories
- Different cuts for the PID categories might be better

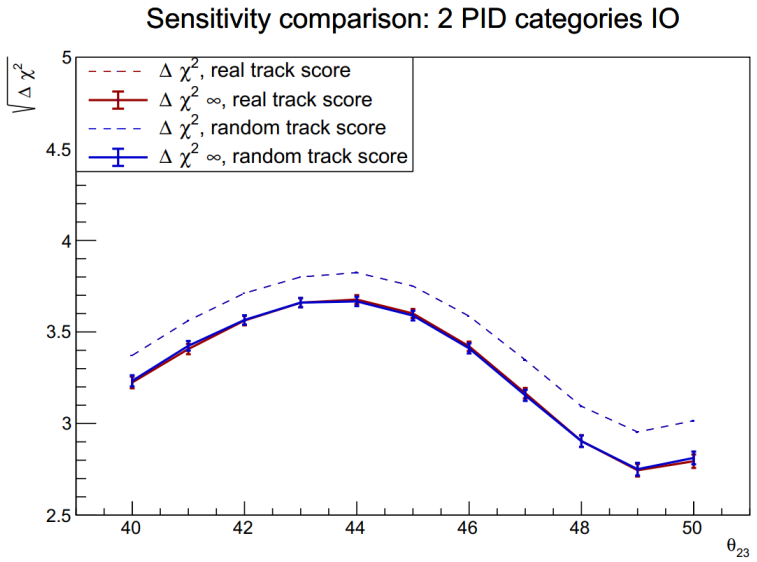
Backup

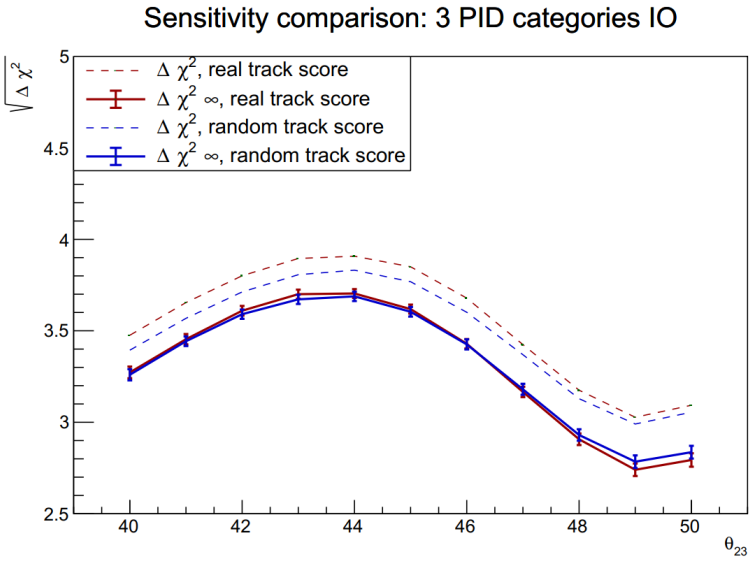
Extrapolated Sensitivities - IO

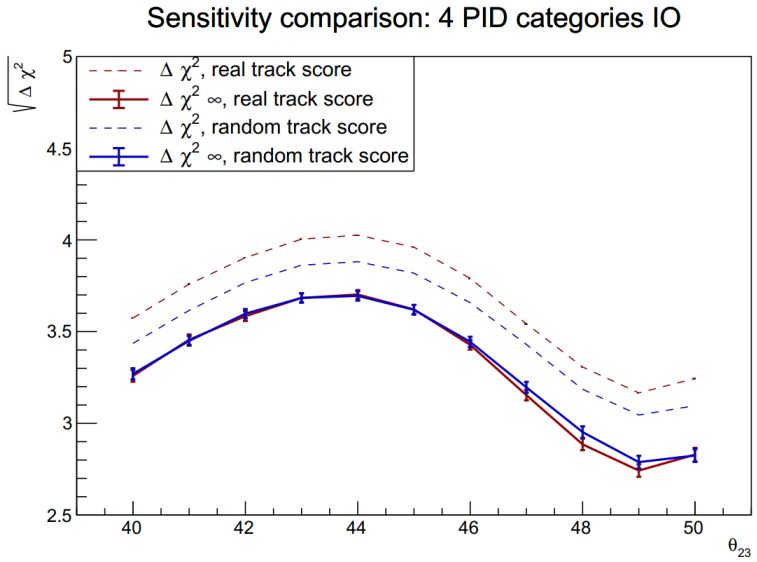




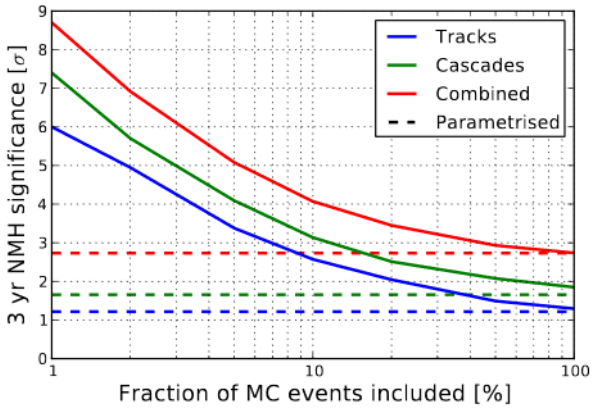
Cross-check: random track score



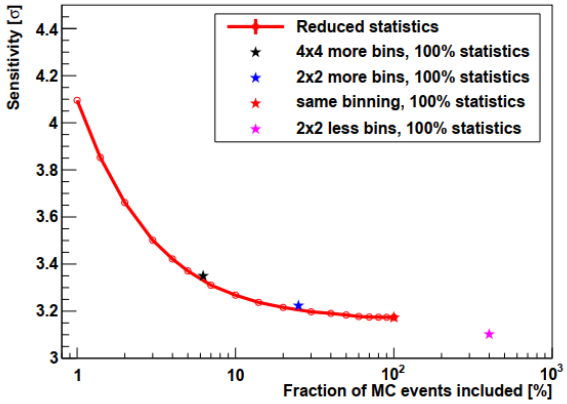




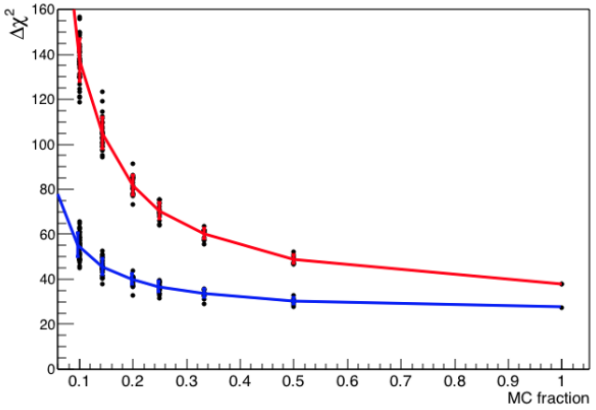
Literature



Determining the Neutrino Mass Hierarchy with the Precision IceCube Next Generation Upgrade, *L. Schulte*, 2015



Measuring the neutrino mass hierarchy with the future KM3NeT/ORCA detector, *J. Hofestädt*, 2017



Neutrino oscillations and Earth tomography with KM3NeT-ORCA, *S. Bourret*, 2018

Backup: K parameter

$$\langle \Delta\chi^2 \rangle(N) = \langle \Delta\chi^2_\infty \rangle + \sum_i^{true} \sum_j^{reco} \frac{K_{ij}}{N_i} + O(N^{-\frac{3}{2}})$$

$$K_{ij} \approx N_j^A \left(\frac{n_i^A}{N_j^A} - \frac{n_i^B}{N_j^B} \right) \Phi_i(X_j) V_j e_i$$

N_j^A: average number of events in reco bin j under hypothesis A

n_i^B: average number of events in true bin i under hypothesis B

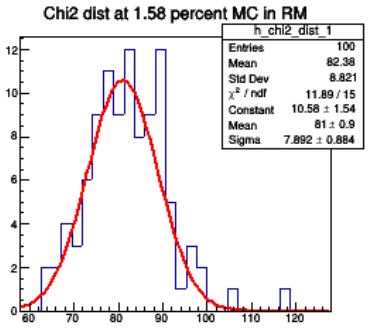
Φ_i: the pdf that maps true events from bin i to bin j

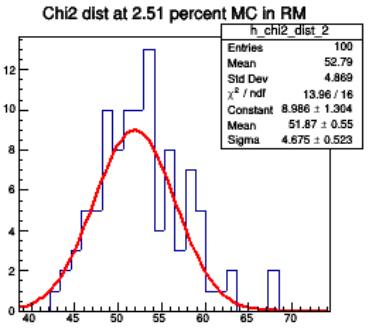
X_j: bin center of reco bin j

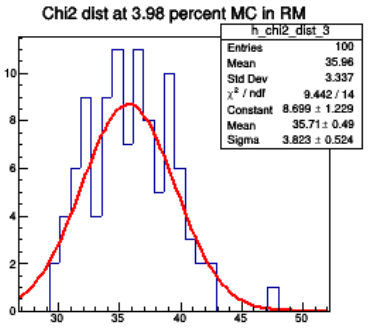
V_j: bin volume of reco bin j

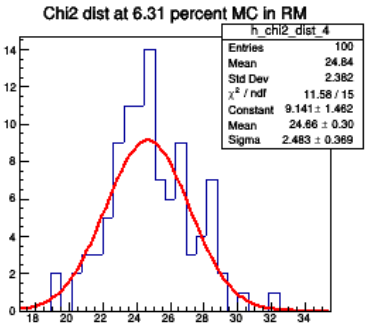
e_i: detector efficiency at true bin i

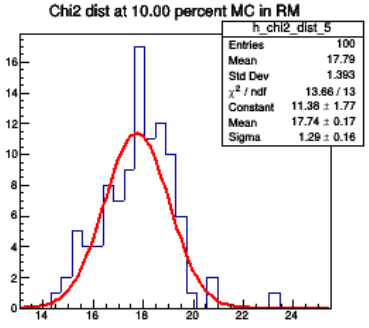
NB: When randomizing the track score, this K is ***NOT*** the same as not randomizing.
K depends the pdf Φ. Randomizing will change the value of this pdf, since events can now be mapped to another bin (in 2+ categories).

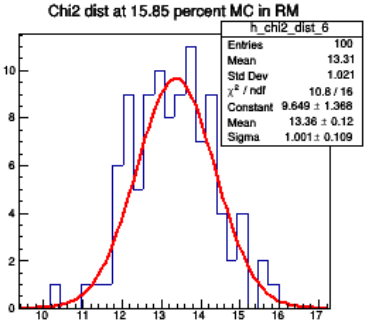

Chi2 dist at 1.58 percent MC in RM
h_chi2_dist_1
Entries 100
Mean 82.38
Std Dev 8.821
χ² / ndf 11.89 / 15
Constant 10.58 ± 1.54
Mean 81 ± 0.9
Sigma 7.892 ± 0.884

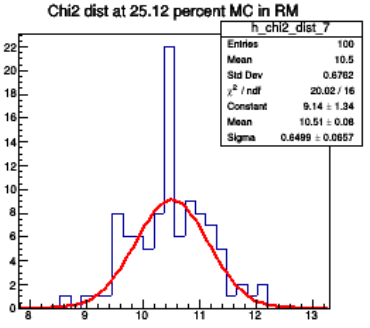

Chi2 dist at 2.51 percent MC in RM
h_chi2_dist_2
Entries 100
Mean 52.79
Std Dev 4.869
χ² / ndf 13.96 / 16
Constant 8.986 ± 1.304
Mean 51.87 ± 0.55
Sigma 4.675 ± 0.523

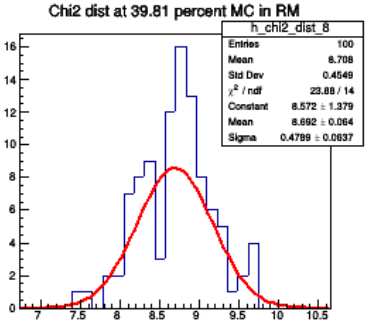

Chi2 dist at 3.98 percent MC in RM
h_chi2_dist_3
Entries 100
Mean 35.96
Std Dev 3.337
χ² / ndf 9.442 / 14
Constant 8.699 ± 1.229
Mean 35.71 ± 0.49
Sigma 3.823 ± 0.524

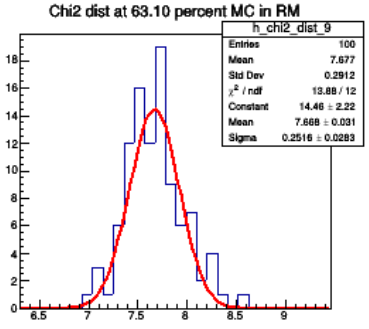

Chi2 dist at 6.31 percent MC in RM
h_chi2_dist_4
Entries 100
Mean 24.84
Std Dev 2.382
χ² / ndf 11.58 / 15
Constant 9.141 ± 1.462
Mean 24.66 ± 0.30
Sigma 2.483 ± 0.369

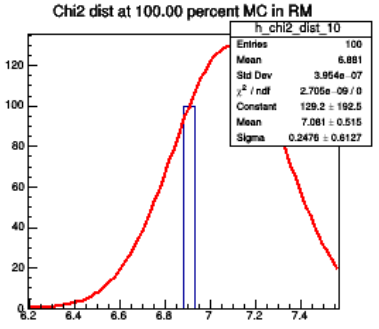

Chi2 dist at 10.00 percent MC in RM
h_chi2_dist_5
Entries 100
Mean 17.79
Std Dev 1.393
χ² / ndf 13.66 / 13
Constant 11.38 ± 1.77
Mean 17.74 ± 0.17
Sigma 1.29 ± 0.16


Chi2 dist at 15.85 percent MC in RM
h_chi2_dist_6
Entries 100
Mean 13.31
Std Dev 1.021
χ² / ndf 10.8 / 16
Constant 9.649 ± 1.368
Mean 13.36 ± 0.12
Sigma 1.001 ± 0.109


Chi2 dist at 25.12 percent MC in RM
h_chi2_dist_7
Entries 100
Mean 10.5
Std Dev 0.6762
χ² / ndf 20.02 / 16
Constant 9.14 ± 1.34
Mean 10.51 ± 0.08
Sigma 0.6499 ± 0.0657


Chi2 dist at 39.81 percent MC in RM
h_chi2_dist_8
Entries 100
Mean 8.708
Std Dev 0.4549
χ² / ndf 23.88 / 14
Constant 8.572 ± 1.379
Mean 8.692 ± 0.064
Sigma 0.4789 ± 0.0637


Chi2 dist at 63.10 percent MC in RM
h_chi2_dist_9
Entries 100
Mean 7.677
Std Dev 0.2912
χ² / ndf 13.88 / 12
Constant 14.46 ± 2.22
Mean 7.668 ± 0.031
Sigma 0.2516 ± 0.0283

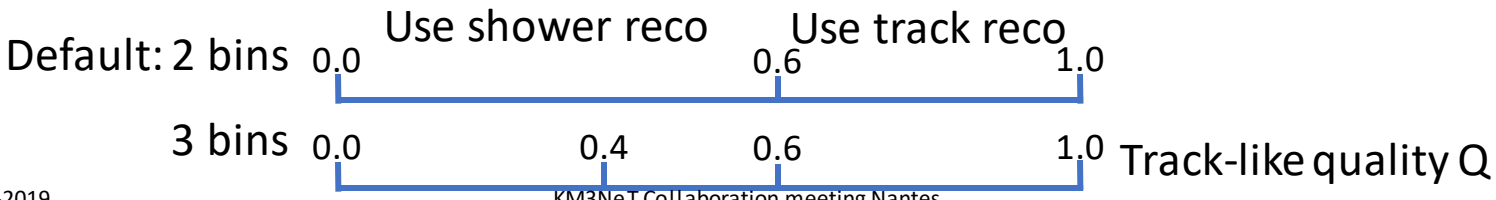

Chi2 dist at 100.00 percent MC in RM
h_chi2_dist_10
Entries 100
Mean 6.881
Std Dev 3.954e-07
χ² / ndf 2.705e-09 / 0
Constant 129.2 ± 192.5
Mean 7.081 ± 0.515
Sigma 0.2476 ± 0.6127

Parameters, track quality, fit procedure

- For *Nature*: evaluate the model for N at PDG central values.
- RooFit: χ^2-minimization, fitted in both θ_{23} quadrants
- Simultaneous pdf fit for track and shower channels (2/3/4/5 PID bins)
- Sensitivity: $S = \sqrt{\Delta\chi^2}$

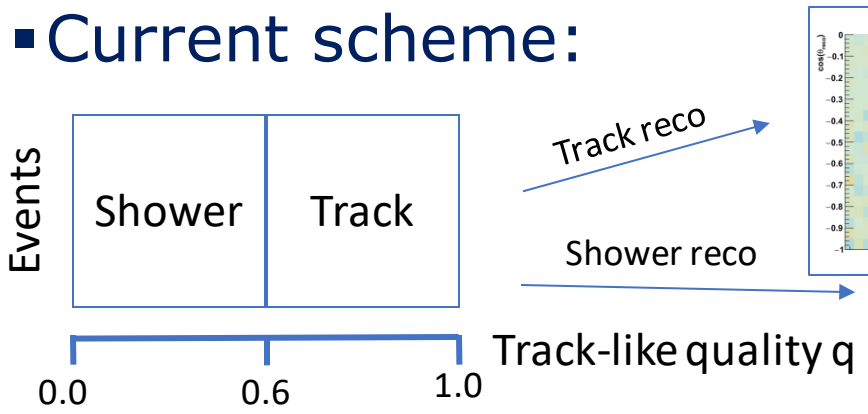
Do we still u
PDG value i
MONA or do
use nufit,
something els

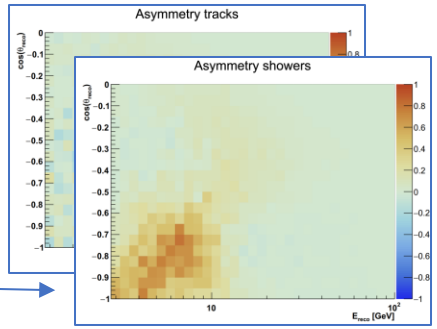
Parameter	Central value NO	Central value IO	Treatment
θ_{12} (°)	0.297	0.297	Fixed
θ_{13}(°)	0.215	0.216	Fixed
θ_{23}(°)	0.425	0.589	**Fitted**
$\Delta m^2_{21}(\mathrm{eV}^2)$	7.37e-5	7.37e-5	Fixed
$\Delta m^2_{31}(\mathrm{eV}^2)$	**2.56e-3**	**-2.54e-3**	**Fitted**
δ_{CP}	1.38π	1.31π	Fixed



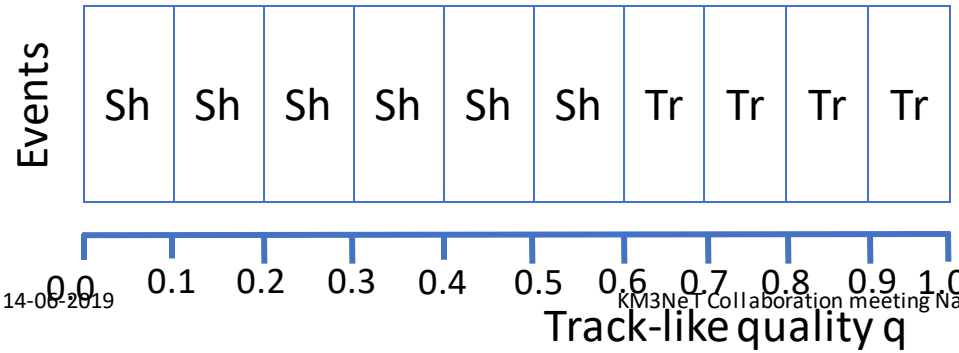
Multi-binned event classification

- Reconstruct all events as shower and track
- Use PID algorithm to give all events a track-like quality factor q
- Current scheme:



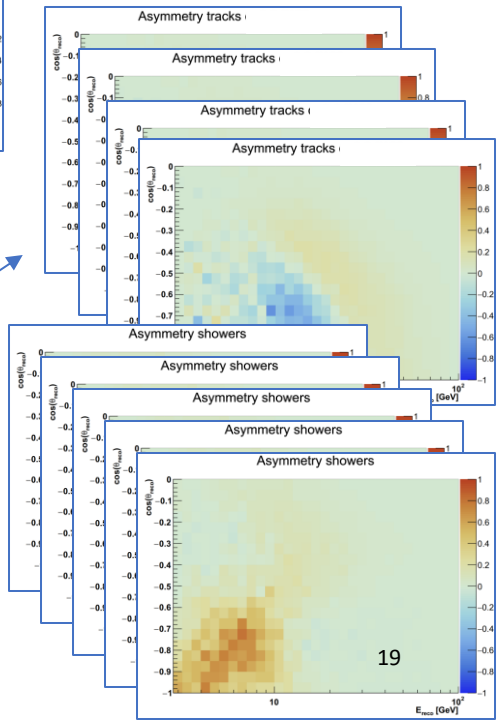


- Multi-bin scheme:



Track reco

Shower reco



Asimov Sensitivity

"How well can we reject the other hypothesis?"

Model: N(θ_{ij}, Δm^2_{ij}, δ_{CP}) in (E,cos θ) after 3 years

1. Assuming NO: N($\Delta m^2_{31} > 0$) = *Nature*
2. Fit N in IO-parameter space on *Nature* data: N($\Delta m^2_{31} < 0$)
   Fitted parameters: $\boldsymbol{\theta_{23}}$, $\boldsymbol{\Delta m^2_{31}}$, **no systematics** in this work
3. N(Fitted parameters) = *Fitted*
4. Calculate $S = \sqrt{\chi^2}$ between *Nature* and *Fitted*