Oscillation systematics: Swim

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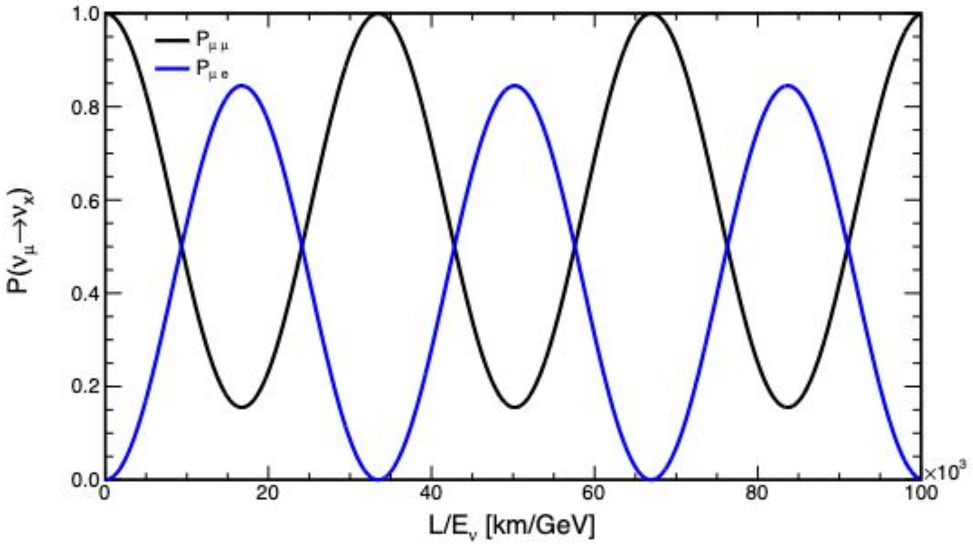
Oscillation probabilities

Assuming neutrinos propagate as plain waves and that they are ultrarrelativistics:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha \rangle|^2 = \sum_{ii} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}},$$



Assuming **two** flavour approximation:

- The mixing angle drives the **amplitude**.
- The mass splitting drives the **frequency**.

$$P(\nu_\mu \to \nu_e)(t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

$$P(\nu_\mu \to \nu_\mu)(t) = 1 - P(\nu_\mu \to \nu_e)(t) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

Matter effects

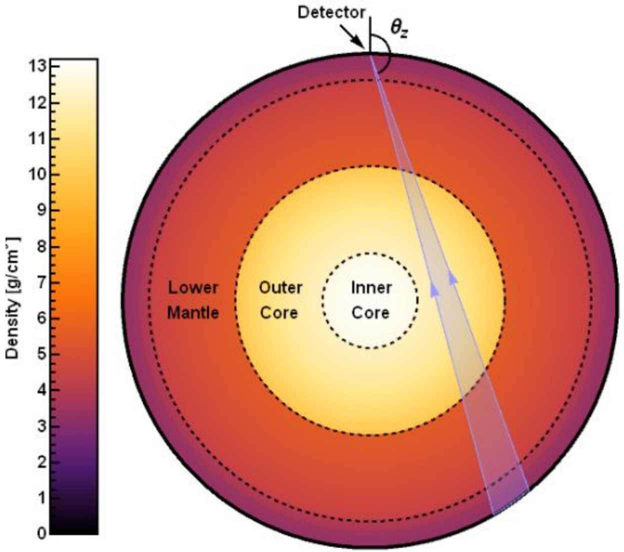
Neutrinos interact with matter via charged and neutral current interactions. Since ordinary matter contains **electrons** but not muons or taus, a difference is introduced in how electron neutrinos propagate that affect oscillations.

$$H(x) = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} V(x) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

$$V = \pm\sqrt{2} G_F n_e(x)$$

$$\sin^2 2\theta_{13}^M = \sin^2 2\theta_{13} \left(\frac{\Delta m_{31}^2}{\Delta^M} \right)^2,$$

$$\Delta^M = \sqrt{(\Delta m_{31}^2 \cos 2\theta_{13} - 2VE)^2 + (\Delta m_{31}^2 \sin 2\theta_{13})^2}.$$



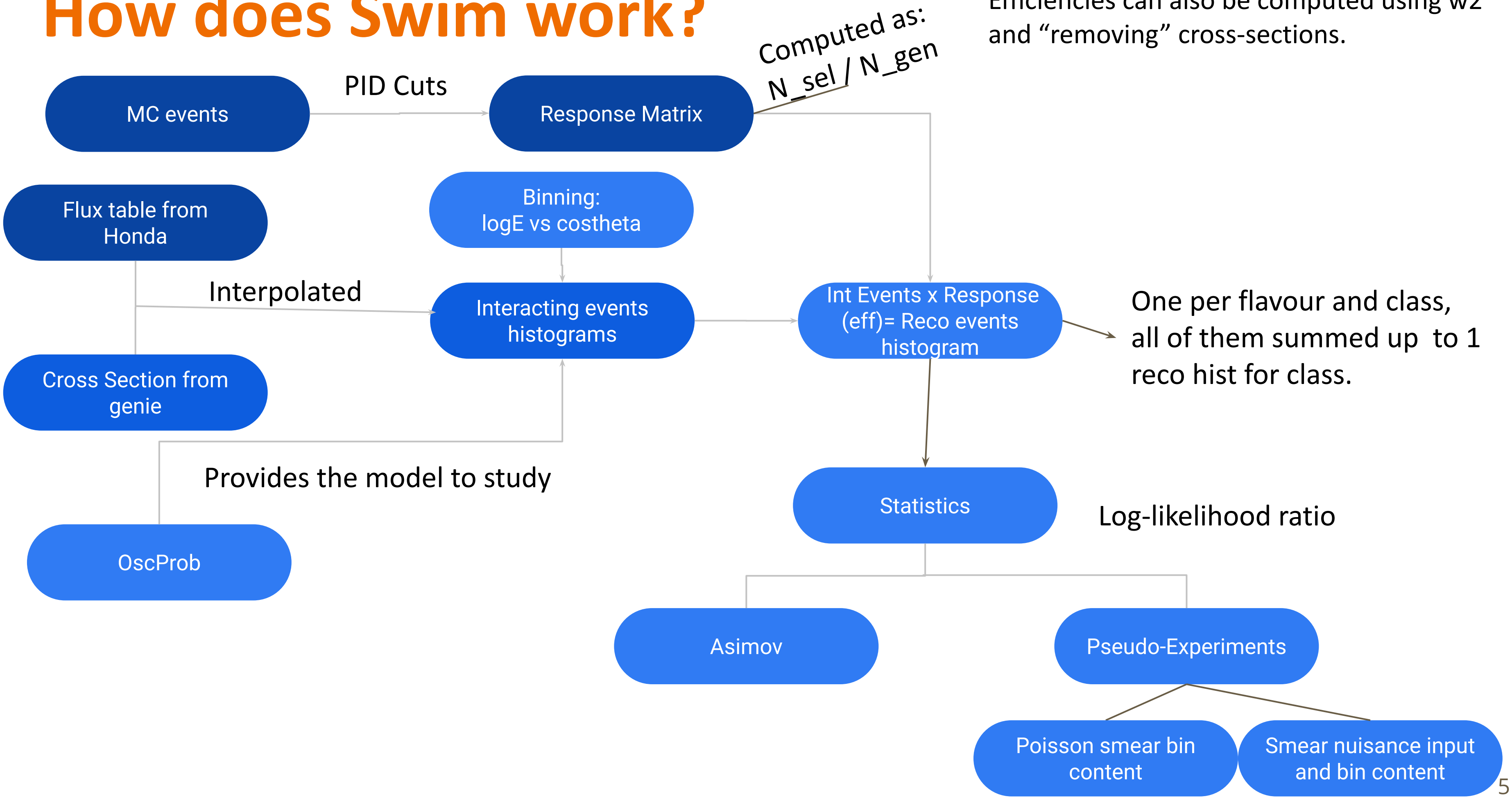
Statistical method

- **2D binned** analysis in reconstructed energy and cosine of the zenith angle.
- Log-likelihood ratio coming from Poisson statistics with respect to the saturated model.
- Model is fitted minimizing the negative log-likelihood ratio by varying all its parameters (**θ**).
- Systematics (oscillation + nuisance) parameters (**v**) could be accounted for by a prior, that comes from external experiments or previous knowledge. Gaussian distribution assumed, adding the prior as a penalty term.

$$-2\ln\lambda(\vec{\theta},\vec{v}) = 2\sum_{i=1}^{N}\left[\mu_i(\vec{\theta},\vec{v}) - n_i + n_i \ln\frac{n_i}{\mu_i(\theta)}\right] + \sum_{l}\left(\frac{v_l - \langle v_l\rangle}{\sigma_l}\right)^2$$

How does Swim work?

Efficiencies can also be computed using w2 and “removing” cross-sections.

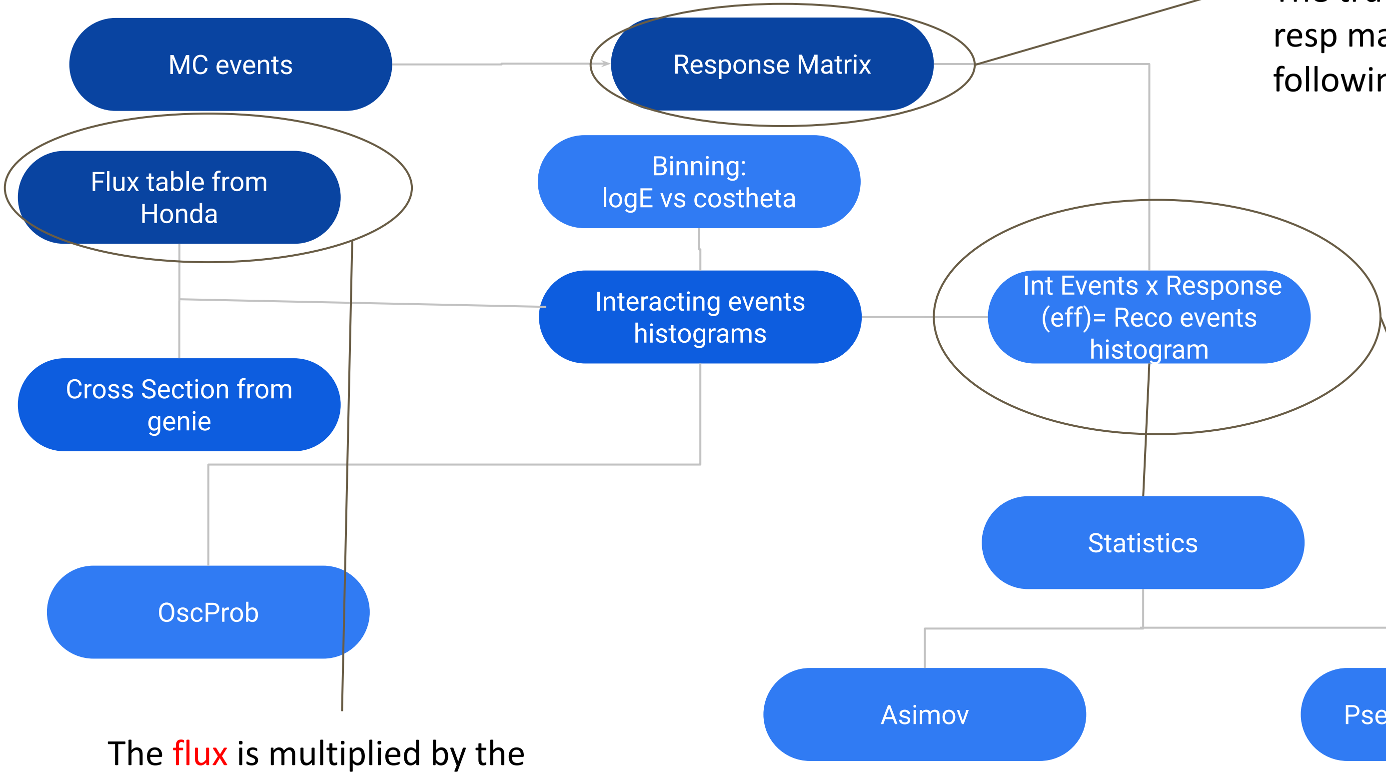


Nuisance parameters

Norm, Flux (Shape) and Detector systematics.

- Norm Systematics: Applied as a scaling of a histogram.
  - Class Norms
  - Tau Norm (CC only or CC+NC)
  - NC Scale
  - Muon Norm.
- Shape Systematics:
  - Flavour ratio: ν_μ/anti-ν_μ skew, ν_e/anti-ν_e skew, ν_μ/ν_e skew
  - Energy Slope.
  - Zenith Slope
- Detector effect systematics:
  - Energy Scale
  - High Energy Light Simulation

Systematics implementation



The true energy bins of the resp matrix are shifted following Escale value.

When combining each histogram (per class, e.g. numu_cc tracks, into the final) Norms **are applied as a factor.** (Class, NC, Tau CC, Atm. Muon)

The flux is multiplied by the three skews and energy slope / zenith slope syst

Shape systematics

- Zenith Slope and Energy Slope. They represent the uncertainties in energy and direction of our flux, applied as a power expansion:

$$\tilde{\phi}(E,\theta) = f_{\text{shape}}\phi(E,\theta) = E^{-s_{\text{energy}}}(1 + s_{\text{up/hor}}|\cos\theta|)\phi(E,\theta),$$

- The choice in the zenith slope is made to have an up/horizontal effect instead of an up/down effect.

Shape flux systematics

- Flux skews. They represent the skew in the ratio of numu/anumu, nue/anue and numu/nue.

$$f_e = (1 + s_{e\mu}) \cdot (1 + s_{e\bar{e}})$$

$$f_{\bar{e}} = (1 + s_{e\mu}) \cdot (1 - \frac{I_e}{I_{\bar{e}}} s_{e\bar{e}})$$

$$f_\mu = (1 - \frac{I_e + I_{\bar{e}}}{I_\mu + I_{\bar{\mu}}} s_{e\mu}) \cdot (1 + s_{\mu\bar{\mu}})$$

$$f_{\bar{\mu}} = (1 - \frac{I_e + I_{\bar{e}}}{I_\mu + I_{\bar{\mu}}} s_{e\mu}) \cdot (1 - \frac{I_\mu}{I_{\bar{\mu}}} s_{\mu\bar{\mu}})$$

Systematic implementation (Shape)

- They are all applied assuming a **conservation of the total incident flux.** (Renormalisation)

$$I_x = \int \int \phi_x(E,\theta) dE d\theta.$$

$$I_e + I_{\overline{e}} + I_\mu + I_{\overline{\mu}} = \tilde{I}_e + \tilde{I}_{\overline{e}} + \tilde{I}_\mu + \tilde{I}_{\overline{\mu}}$$

$$\int \int \overline{\phi}(E,\theta) \equiv \int \int \phi(E,\theta) E^{-s_{\text{energy}}} (1 + s_{\text{up/hor}} |\cos\theta|) = \int \int \phi(E,\theta)$$

Response Matrix

- Response matrix first computed as a generation weights matrix. Then the "efficiency" is computed by "removing" cross-sections.

$$R^c_{\nu_x} = \frac{m_p}{2\pi \Delta E \Delta \cos\theta \Delta y M} \frac{\sum_i w^c_{\text{gen},i,\nu_x} \frac{t_i}{\sum_j t_j}}{\frac{d\sigma_{\nu x}}{dy}}.$$

- Energy scale can be applied directly to this matrix.

Energy Scale

- In reality, there are two response matrices:
  - P_TV gives the probability of having some visible energy E_V, given some true neutrino energy E_T
  - P_VR gives the probability of having some reco energy E_R, given some visible energy E_V
- But we only have access in principle to a combination of the two:
  - P_TR gives the probability of having some reco energy E_R, given some true neutrino energy E_T
- We shift the bins of true energy in the Response Matrix to emulate the effect of the uncertainty in water properties and quantum efficiencies.

$$N(E_R) = \int \int P_{VR}(E_R, E_V) \times P_{TV}(E_V + \delta E, E_T) \times \sigma(E_T) \times \phi(E_T) \times P_{osc}(E_T)\, dE_V dE_T$$

$$P_{TR}(E_R, E_T, \delta E) = \int P_{VR}(E_R, E_V) P_{TV}(E_V + \delta E, E_T) dE_V$$

$$\text{assuming: } P_{TV}(E_V + \delta E, E_T) = P_{TV}(E_V, E_T - \delta E)$$

$$N(E_R) = \int P_{TR}(E_R, E_T - \delta E) \times \sigma(E_T) \times \phi(E_T) \times P_{osc}(E_T)\, dE_T$$

Compare with IceCube

- E scale: **9%**
- E slope: **0.3**
- ν_e/ν_μ: **2%**
- up/horiz: **2%**
- ν_e / anti-ν_e **7%**
- ν_μ / anti-ν_μ : **5%**
- NC norm: **20%**
- Tau norm: **20%**
- Atm muons free
- PID class norms: **free**
- Jsirene-norm : 50%

Parameter	Prior	Fit value	Pull (σ)
Detector	Baseline from calibration data		
DOM efficiency	10%	+6%	0.63
Rel. eff. p_0	Unconstrained	-0.27	-
Rel. eff. p_1	Unconstrained	-0.04	-
Ice absorption	Unconstrained	-3%	-
Ice scattering	Unconstrained	-1%	-
Flux	Baseline from Honda et al.		
$\Delta\gamma_\nu$	0.1	+0.07	0.7
$\Delta\pi^\pm$ yields [A-F]	30%	+10%	0.35
$\Delta\pi^\pm$ yields G	30%	-6%	-0.18
$\Delta\pi^\pm$ yields H	15%	-2%	-0.12
ΔK^+ yields W	40%	+8%	0.21
ΔK^- yields W	40%	-1%	-0.02
ΔK^+ yields Y	30%	+11%	0.35
Cross-section	Baseline from GENIE		
M_A^{CCQE}	0.99 GeV $^{+25\%}_{-15\%}$	+1%	0.03
M_A^{CCRES}	1.12 GeV$\pm$20%	+11%	0.57
σ_{NC}/σ_{CC}	20%	+13%	0.63
DIS CSMS	1.0	0.04	0.04
Atm. muons	Baseline from Gaisser et al.+Sibyll2.1		
Atm. μ scale	Unconstrained	+39%	-
Normalisation	Baseline from calibration+flux models		
A_{eff} scale	Unconstrained	-18%	-

Decoupled effects

Change in particles from CR

Appart from NC scale they apply GENIE changes.

Single Norm

Conclusions

- Our weakest point is the energy response of the detector.
- Implement a template approach as IceCube is a priority.
- Simulate absorption and QE of PMTs and redo MC, then extract the template and use it for the fits.
- Different approach for flux than them, no necessarily wrong.
- We use too many free normalisations.