DISCUSSION STARTER FOR PRISM MEASUREMENT SCHEME

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THE NEED FOR (VIRTUALLY) IDENTICAL DETECTOR RESPONSES

- PRISM **only** works when we make all off-axis positions behave equally

$$\vec{n}_a \sim \vec{v}_a = R_a S \vec{\phi}_a$$

$$\vec{n}_\theta = \sum_a c_a(\vec{\theta}) \vec{n}_a \sim \vec{v}_\theta = \sum_a c_a(\vec{\theta}) \vec{v}_a = \sum_a c_a(\vec{\theta}) R_a S \vec{\phi}_a$$

$$\stackrel{!}{=} R_{ND} S \sum_a c_a(\vec{\theta}) \vec{\phi}_a = R_{ND} S \vec{\phi}_\theta$$

SYMBOLS

$\vec{n}_a, \vec{n}_\theta$	• Actually measured spectra of N bins, binned in reconstructed variables
$\vec{v}_a, \vec{v}_\theta$	• Expectation values for measured spectra of N bins, binned in reconstructed variables
R_a, R_{ND}	• (N x M) Response matrices, translating finely binned true event rates to expected reconstructed event rates, includes efficiency and smearing
S	• (M x K) Cross section matrix, translating neutrino fluxes into true event rates, each column corresponds to cross sections of a neutrino type & energy
$\vec{\phi}_a, \vec{\phi}_\theta$	• Neutrino flux spectrum of length K, binned in neutrino energy
$c_a(\vec{\theta})$	• PRISM coefficients, calculated to reproduce the assumed FD (oscillated) flux with the linear combination of ND fluxes

ND EFFICIENCY CORRECTIONS DEPEND ON MODEL AND FLUX

- Previous idea:
  - Calculate geometric efficiency for all events
  - Add event weight of 1/efficiency
- Problem:
  - Some ND events with lots of invisible hadronic energy outside the detector are accepted by selection
    - no energy in veto region
  - Estimated geometric efficiency much higher than actual efficiency
  - Severity of effect depends on rate of such events
    - High E_ν flux, cross section
    - Different for all angles!
    - Where model-dependence creeps in

PHYSICAL AVERAGING

- New idea:
  - Detector response depends almost exclusively on detector slice, and **not** on angle position
  - Measure every detector slice at every angle position
  - Construct average detector directly from data
- Advantages:
  - No efficiency correction necessary!
  - Uses only actual data

THE MATHS

- Constructs the same response at all angles

$$\vec{n}_{as} \sim \vec{v}_{as} = R_s S \vec{\phi}_{as} = R_s S \vec{\phi}_a t_{as}$$

$$\vec{n}_a = \sum_s \frac{1}{t_{as}} \vec{n}_{as} \sim \vec{v}_a = \sum_s \frac{1}{t_{as}} \vec{v}_{as} = \sum_s R_s S \vec{\phi}_a = R_{ND} S \vec{\phi}_a$$

$$\vec{n}_\theta = \sum_a c_a(\vec{\theta}) \vec{n}_a \sim \vec{v}_\theta = \sum_a c_a(\vec{\theta}) \vec{v}_a = \sum_a c_a(\vec{\theta}) R_{ND} S \vec{\phi}_a$$

$$= R_{ND} S \sum_a c_a(\vec{\theta}) \vec{\phi}_a = R_{ND} S \vec{\phi}_\theta$$

Please ignore wonky units re. time, events vs. rate, etc...

SYMBOLS

$\vec{n}_{as}, \vec{v}_{as}$	• Measured spectrum, and expectation value for combination of off-axis angle and detector slice
$\vec{\phi}_{as}, t_{as}$	• Total neutrino flux, and exposure time for a combination of off-axis angle and detector slice
R_s	• Detector response matrix for a given detector slice
$\vec{n}_a, \vec{v}_a, \vec{\phi}_a$	• Measured spectrum, expectation value and flux for a given off-axis position
$\vec{n}_\theta, \vec{v}_\theta, \vec{\phi}_\theta$	• Measured spectrum, expectation value and flux for the virtual flux
R_{ND}	• Detector response matrix for the “average” near detector

PIECEWISE EXPOSURE

- Can also think about it as shooting the same flux at the detector slices in turn
- Combine into single “picture” of whole detector in flux

$$t_{a1}\vec{\phi}_a \quad t_{a2}\vec{\phi}_a \quad t_{a3}\vec{\phi}_a \quad t_{a4}\vec{\phi}_a \quad t_{a5}\vec{\phi}_a \quad t_{a6}\vec{\phi}_a \quad t_{a7}\vec{\phi}_a$$

FAR DETECTOR EVENTS

- FD also needs to be “corrected” to look like ND for 1-to-1 comparisons
- Requires efficiency and smearing corrections
  - Geometry shifts
  - ML event translations
  - MC assumptions

$$\vec{n}_{FD} \sim \vec{v}_{FD} = R_{FD} S \vec{\phi}_{FD}$$

$$\vec{n}_{ND'} = \sum_{i \in FD\,evts.} \frac{\vec{p}_{ND,i}}{\epsilon_{FD,i}} \sim \vec{v}_{ND'} = R_{ND'} S \vec{\phi}_{FD} \approx R_{ND} S \vec{\phi}_{FD}$$

SYMBOLS

- $\vec{n}_{FD}, \vec{v}_{FD}$ — Measured spectrum, and expectation value at the far detector
- $\vec{n}_{ND'}, \vec{v}_{ND'}$ — Measured spectrum, and expectation value for the far-to-near translated, virtual near detector
- $\epsilon_{FD,i}$ — Efficiency of FD event i, to be reconstructed in the FD, used for FD efficiency correction
- $\vec{p}_{ND,i}$ — Vector of probabilities to reconstruct FD event i, in each bin of the ND reconstructed spectrum, length N, sums up to estimated ND efficiency
- $R_{ND'}$ — Detector response matrix of the virtual near detector from far-to-near translation

BEGINNING OF A STATISTICAL TREATMENT

- Aim: Figure out flux at FD $\vec{\phi}_{FD}$
  - Or rather, which oscillation parameters produce it
- Naive method: Minimise distance

$$\left|\vec{n}_{ND'} - \vec{n}_{\theta}(\vec{\theta})\right| = \left|\vec{\Delta}(\vec{\theta})\right|$$

- What is the distribution of distance?
- Treat as sum of random vectors / weighted events
  - Weights can be negative

$$\vec{\Delta}(\vec{\theta}) = \sum_i w_i \vec{e}_i$$

$$V = cov(\vec{\Delta}(\vec{\theta})) = \sum_i w_i^2 cov(\vec{e}_i)$$

$$D_M^2 = \vec{\Delta}^T V^{-1} \vec{\Delta}$$

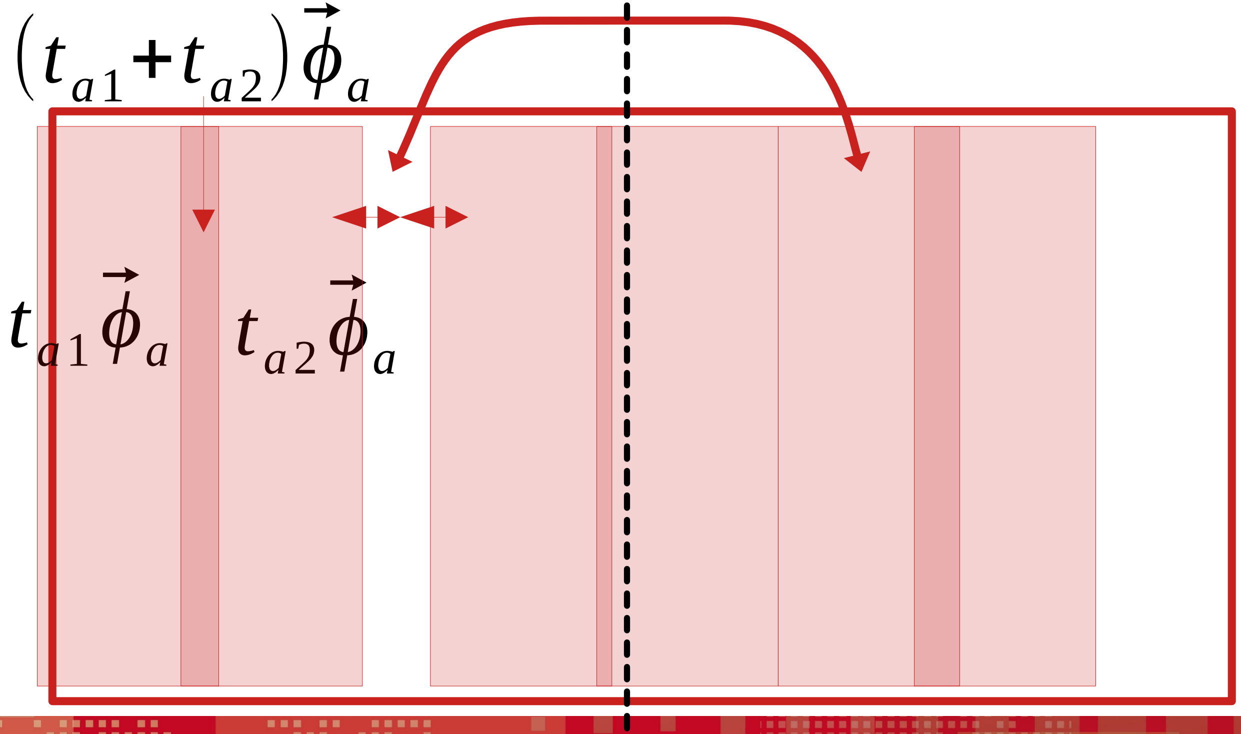
- Can construct M-distance
  - Minimise this?
  - χ^2 distributed?
  - V depends on θ
- Should be able to construct Likelihood

SYMBOLS

$\vec{n}_{ND'}$	• Measured spectrum from far-to-near translation at the FD
$\vec{n}_{\theta}(\vec{\theta})$	• Measured spectrum for the “average” ND in the flux constructed with the PRISM coefficients as function of oscillation parameters
$\vec{\Delta}(\vec{\theta})$	• Difference between the measured FD to ND translated spectrum and the PRISM “ND in oscillated flux” spectrum, as a function of osc. parameters
w_i	• Weight with which event i contributes to Δ, events from both ND and FD, weight includes PRISM coefficients and any detector corrections
$\vec{e}_i$	• Reconstructed spectrum of the single event i; for ND events, all elements will be 0 except 1 (the bin where the event actually resides in); for FD events this corresponds to the probability vector of reconstructing the event in the different ND reco bin

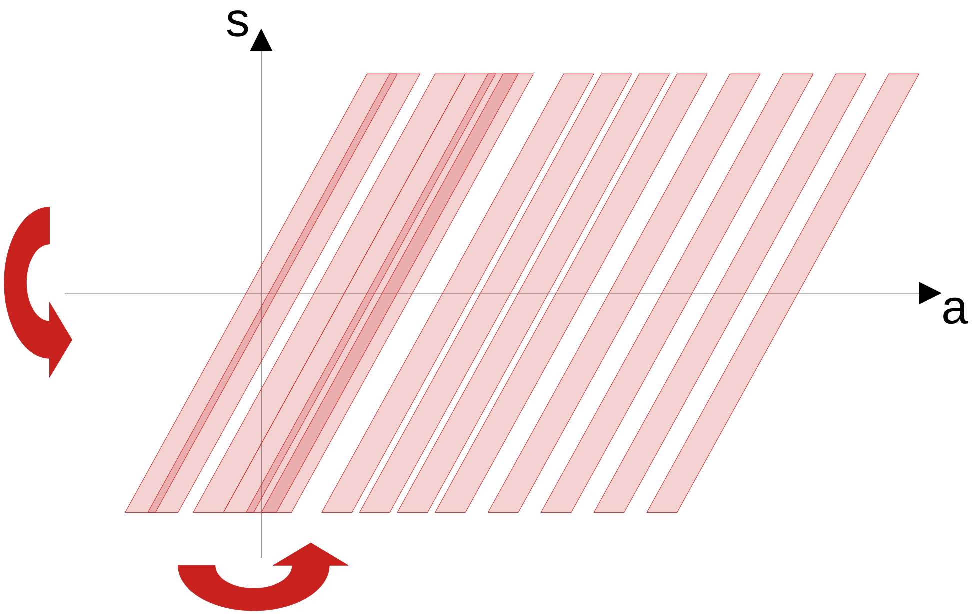
IMPERFECT ALIGNMENT

- Should be able to handle imperfect alignment
- Dynamic slice edges? Something unbinned?
- Use detector symmetry → only need to expose half of it
- Fill gaps with ND corrections? Interpolate?



2D PICTURE

- Try to expose all combinations of detector position s and off axis position a
- Fill gaps
  - Use symmetries
  - Interpolate
  - Apply corrections



BEAM CHANGES

- ν flux might change over time
  - run to run, not day to day
- Need to expose enough of the detector (at least one half) within a stable beam period
- Fill gaps with ND corrections?
- Does not affect FD data
  - FD correction towards average ND in **total FD flux**
  - Of course need to calculate correct oscillated flux

FINAL THOUGHTS ON METHOD

- No ND corrections (ideally)
  - No geometry shifts
  - No ML translation
  - Saves lots of compute and model assumptions
  - Assumes response does **not** depend on angle, only on position in detector
    - Probably able to correct small effects of angle
- FD corrections still necessary
  - Much fewer events than ND
  - Much more information reconstructed
    - We see the hadr. energy that would be missed in ND
  - Biggest correction geometric
  - Correction corrections with ML and MC models
- Requires specific run plan (with some slack)
  - Every detector slice at every angle within stable beam period
  - Feasible to move the detector that often, by ~0.5 m?
- Issues at edges of movable range?
  - Cannot measure highest angle with lowest detector slice
    - Fill gaps with ND corrections?
  - Can use detector symmetry and flux symmetry around a = 0° at least