ORCA-4 data analysis: systematic uncertainties

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Nikhef group meeting

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Parameters in models

- Parameters of interest: oscillation parameters
  - Physics parameters: Th23, Dm31sq, etc
- Nuisance parameters: to model uncertainties/biases
  - Flavor ratio of flux e/mu may be skewed
  - Cross section may be larger/smaller
  - ...

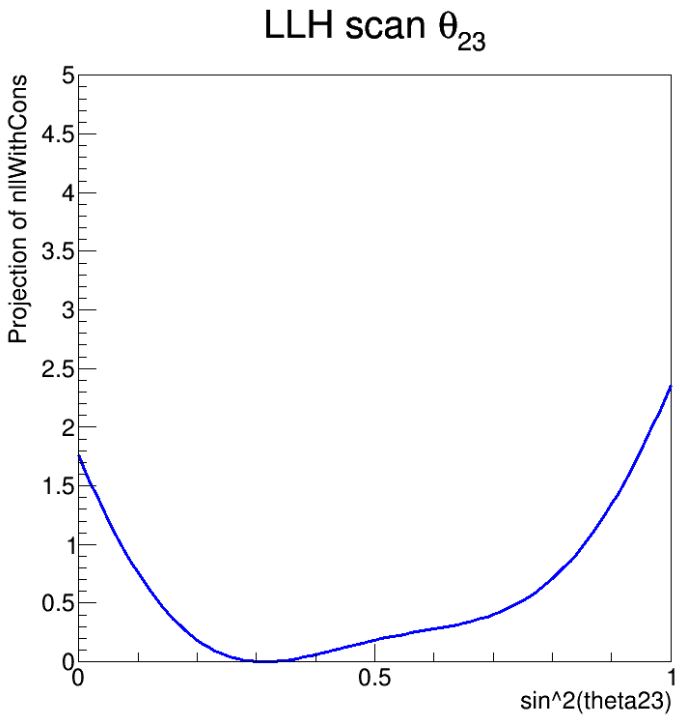
Procedure

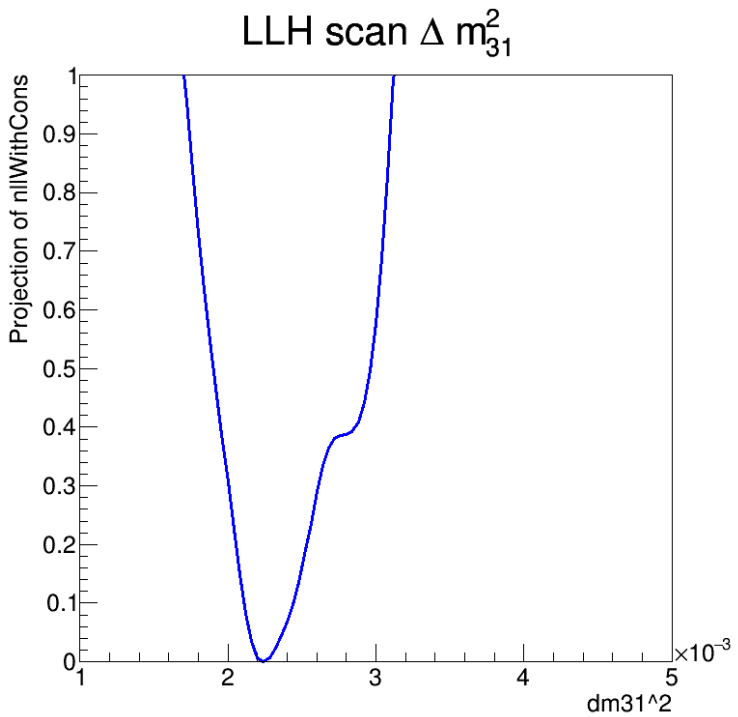
1. Fit model to only (SinsqTh23,Dm31sq)
   Provides the best fit values and statistical uncertainties for physics parameters
2. Fit model to (SinsqTh23,Dm31sq) and all nuisance parameters
   Provides the central values (cv) and uncertainties on the nuisance parameters.
   Provides the central values of (SinsqTh23,Dm31sq) used in step 3.
3. For every nuisance parameter:
   1. Fix value at c.v. +1 sigma and fit model --> Find change in physics parameters (SinsqTh23,Dm31sq)
   2. Fix value at c.v. -1 sigma and fit model --> Find change in physics parameters (SinsqTh23,Dm31sq)
4. Systematic uncertainty is squared sum of differences in physics parameters

1. Fit only (SinsqTh23, Dm31)

- Asymmetric uncertainty was added using MINOS in RooFit
- Size of uncertainty matches with LLH scan

$$\theta_{23} = 34.1^{+28.0}_{-11.7}\ (\text{stat.})$$
$$\Delta m^2_{31} = 2.21^{+0.80}_{-0.57}\ (\text{stat.})$$





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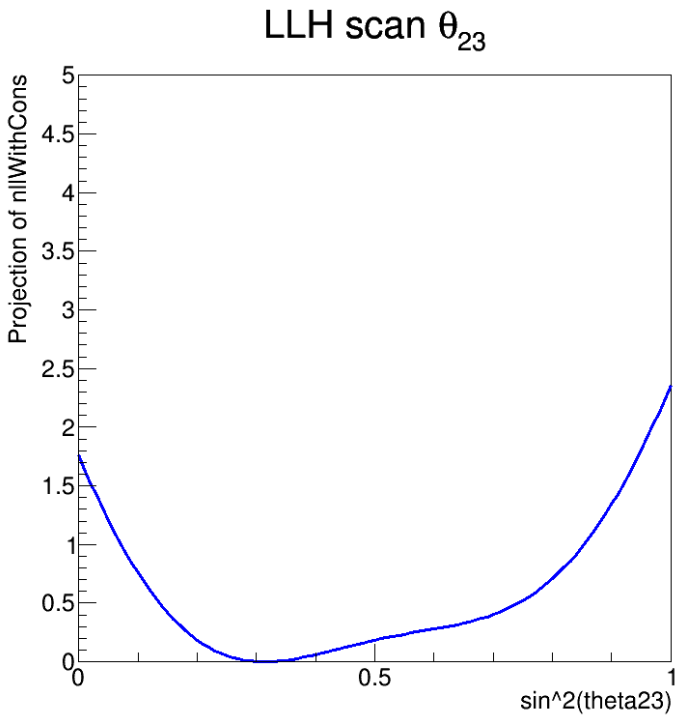
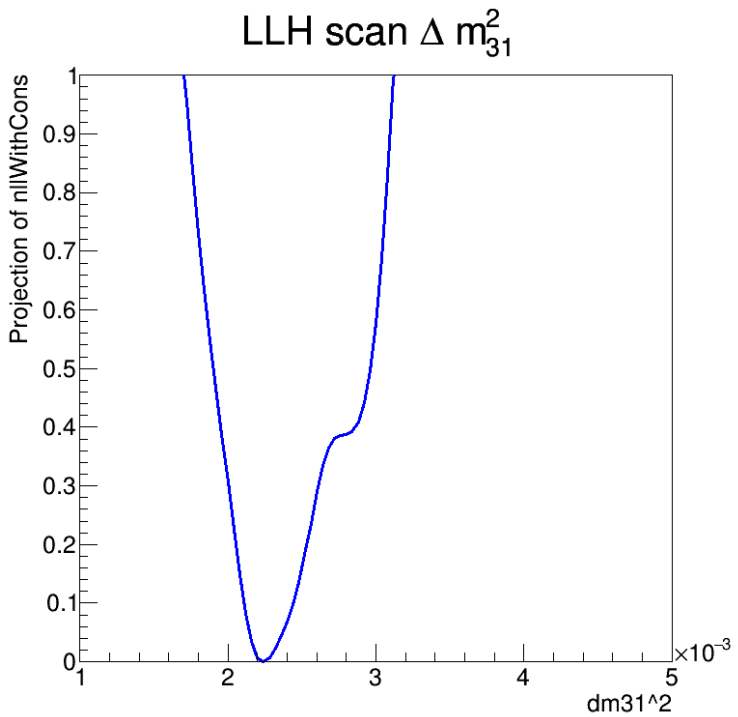
Nu-fit 2020:

$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.514^{+0.028}_{-0.027}$





2. Fit model to physics and all nuisance parameters

Parameter	Value	Error
Δm^2_{31}	2.37	0.65
θ_{23}	43.3	14.1
Flux: spectral index uncertainty	0.074	0.11
Flux: angle distribution bias	-0.28	0.32
Skew $\mu/\overline{\mu}$	-0.0019	0.10
Skew $e/\overline{e}$	-0.000049	0.10
Skew μ/e	0.00031	0.050
NC normalization	1.00	0.10
τ normalization	1.00	0.20
Energy scale	-0.029	0.026

Constrained by Barr:
10.1103/PhysRevD.74.094009

Constrained by SuperK:
10.1103/PhysRevD.98.052006

Not sure where prior on NC Xsection comes from (L. Quinn thesis)

Shown in the past as blue 'powerpoint' table

Issue: Shifting of nuisance parameters is mixed

- This procedure mixes *external constraints* and *fit output*
  - Example: *Skew e/mu* takes its range from the prior given by a publication
  - Range on *spectral index uncertainty* comes from output of minimizer
- Flux nuisance parameters: publication?
- Estimate the E-scale range in some other way?

3. Fix nuisance parameter at cv +/- 1sigma and perform model fit
4. Squared sum yields systematic uncertainty

When the spectral index unc. is set to: C.V. + 1sigma, it changes Dm31sq by –0.56

Statistical uncertainty				
Parameter	Δm^2_{31} difference		θ_{23} difference	
Variation in nuisance parameter	$+1\sigma$	-1σ	$+1\sigma$	-1σ
Flux: spectral index uncertainty	-0.56	0.17	1.4	-0.57
Flux: angle distribution bias	-0.015	-	8.9	-0.75
Skew $\mu\overline{\mu}$	-	-	-	-
Skew $e/\overline{e}$	-	-	-	-
Skew μe	-	-	-	-
NC normalization	-	-	-	-
τ normalization	-	-	-	-
Energy scale	-0.15	0.12	1.4	-0.88
Total uncertainty	-0.58	0.20	9.1	-1.28

Negligible effect (~0) due to constraints

Squared sum of all changes

Full table in backup without rounding small values

ORCA-4 result including systematic uncertainties

$$\theta_{23} = 34.1^{+28.0}_{-11.7}\ (\text{stat.})\ ^{+9.1}_{-1.3}\ (\text{syst.})\ [\text{deg}]$$
$$\Delta m^2_{31} = 2.21^{+0.80}_{-0.57}\ (\text{stat.})\ ^{+0.20}_{-0.58}\ (\text{syst.})\ [10^{-3}\text{GeV}^2]$$

- The measurement is dominated by statistics (expected)

Next steps

- Prior on the flux from a publication?
- Estimate an appropriate size for the E-scale range

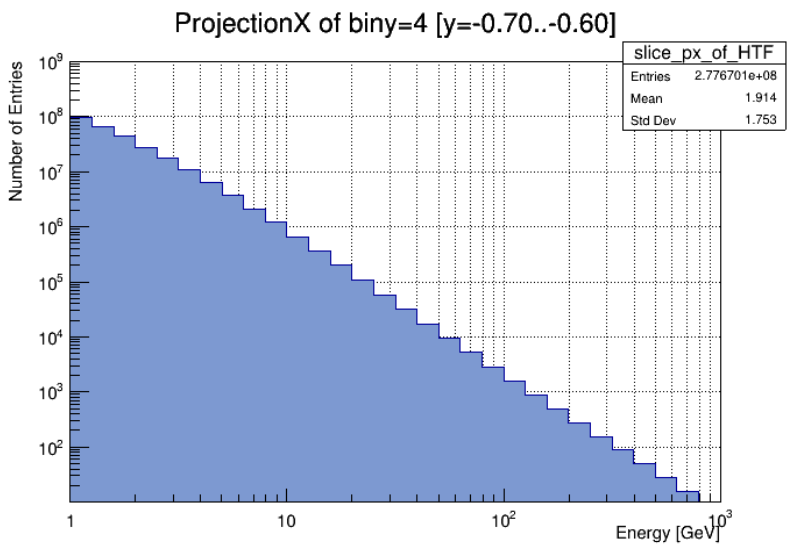
- Reconstruction resolutions are not yet accounted for
  - Energy and angle resolution are encoded into Response Matrix
  - Idea: add cut to create "good resolution" and "bad resolution" RM
  - Fit data with these RMs
  - Quantify effect on (SinsqTh23,Dm31sq) as systematic uncertainty
- Is E-scale correlated to energy resolution? Systematic over-/under-estimation of energy...

Flux: spectral index uncertainty

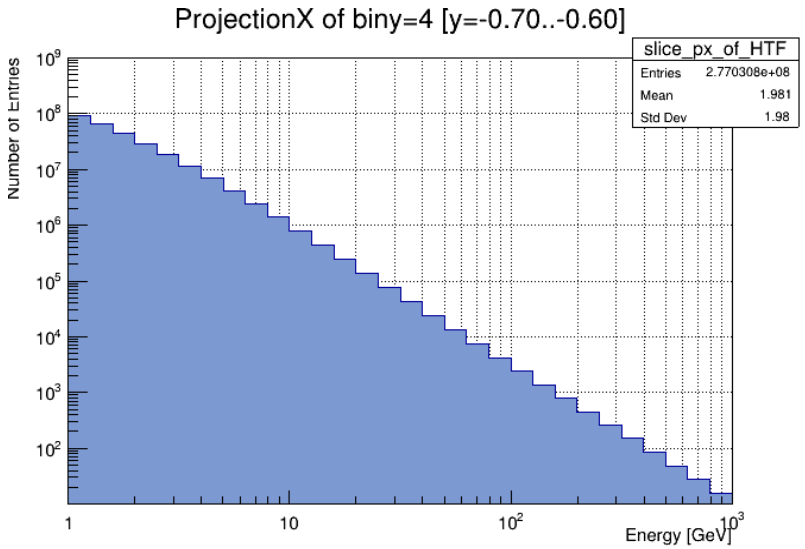
$$E^{-\gamma} \rightarrow E^{-(\gamma+\delta)}.$$

Total flux in *entire* phase space is conserved

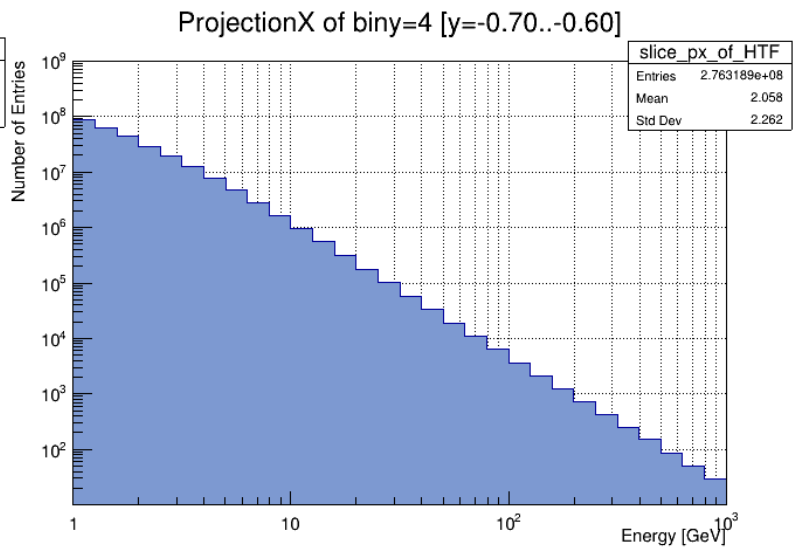
delta = -0.1



delta = 0



delta = 0.1

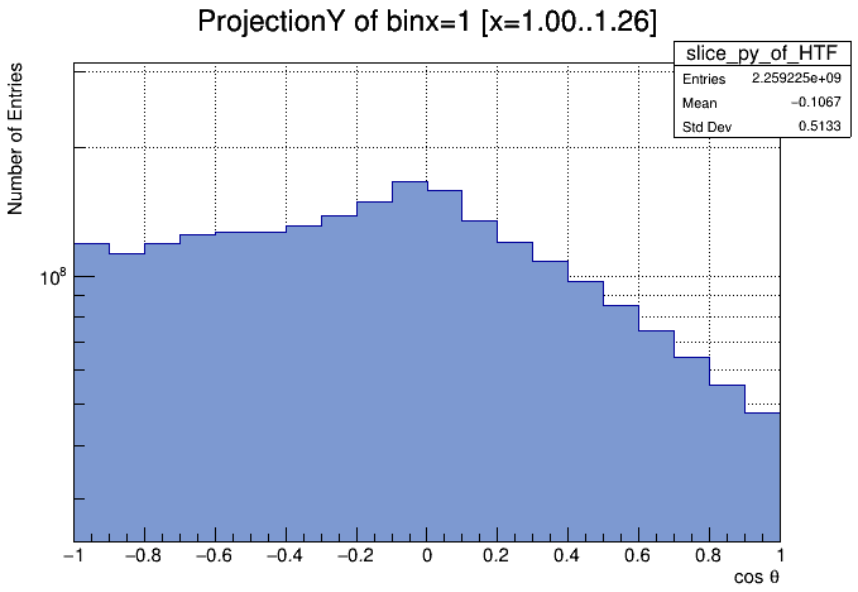


Flux: angular distribution

$\phi_\alpha(E,\theta) \rightarrow \phi_\alpha(E,\theta) \times (1 + t \times \cos\theta)$ → Give flux a linear bias in angular distribution

Total flux in *entire* phase space is conserved

t = -0.5



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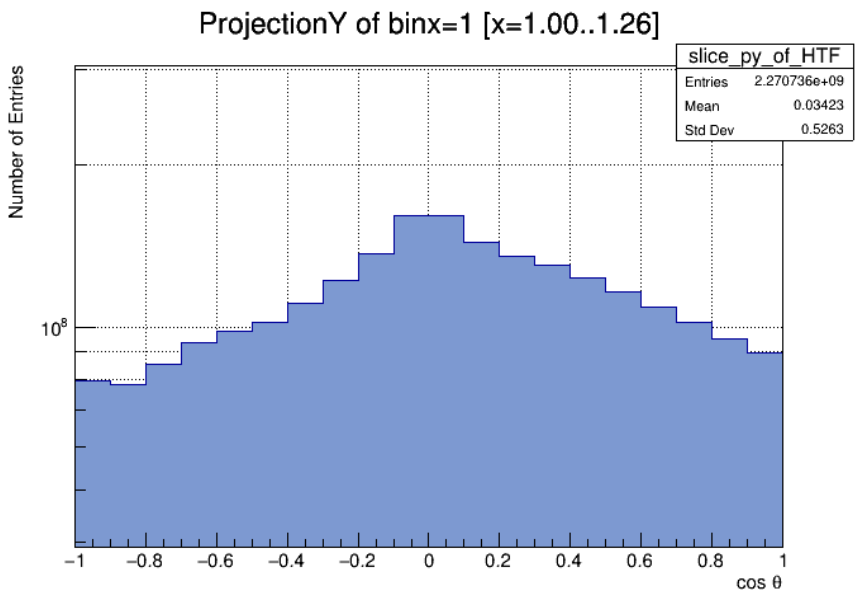
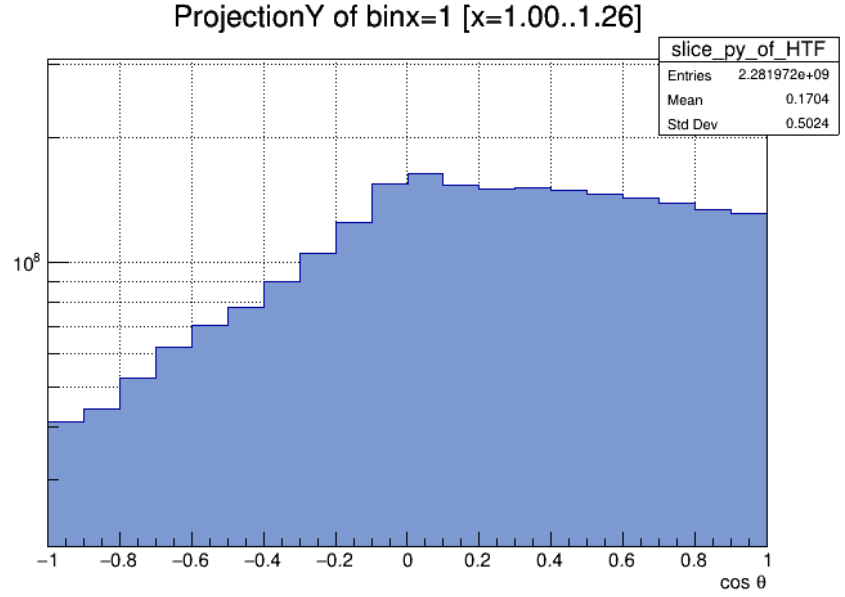


t = 0.5



Backup:
Systematic uncertainties on (SinsqTh23, Dm31)

Statistical uncertainty				
Parameter	Δm^2_{31} difference		θ_{23} difference	
Variation in nuisance parameter	$+1\sigma$	-1σ	$+1\sigma$	-1σ
Flux: spectral index uncertainty	-0.56	0.17	1.4	-0.57
Flux: angle distribution bias	-0.015	0.0046	8.9	-0.75
Skew $\mu/\overline{\mu}$	0.0026	-0.0076	0.042	-0.053
Skew $e/\overline{e}$	-0.0039	0.0027	-0.0044	0.0045
Skew μ/e	0.0039	-0.0062	0.016	0.021
NC normalization	-0.00049	-0.00098	-0.023	0.017
τ normalization	0.00032	0.0027	-0.064	0.017
Energy scale	-0.15	0.12	1.4	-0.88
Total uncertainty	0.58	0.20	9.1	1.28