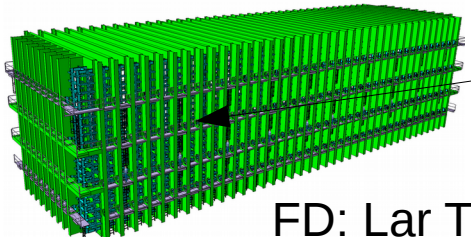
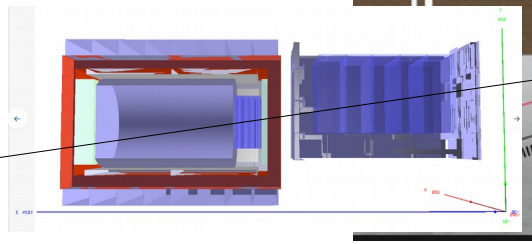
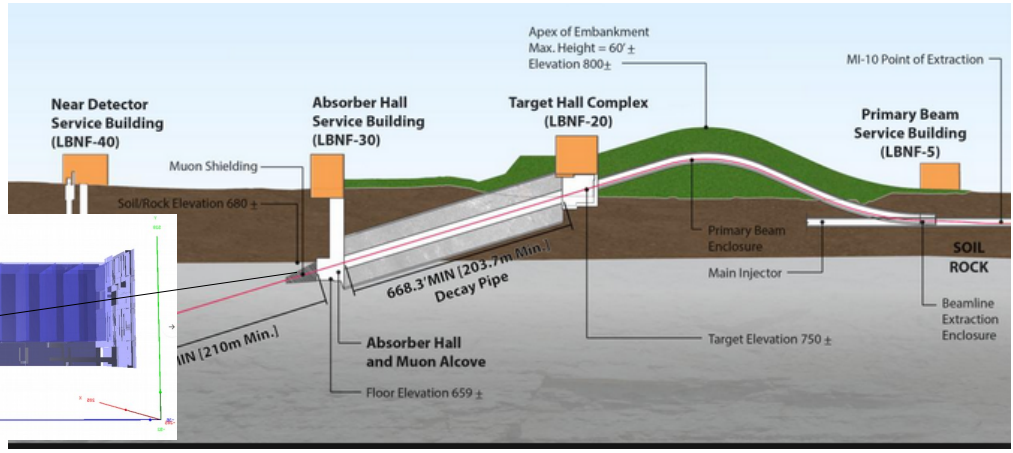
Sensitivity study of DUNE-PRISM

Guang Yang

Introduction (1)







FD: Lar TPC ND: Lar TPC+tracker Beam flux

We are trying to do a ND+FD fit.

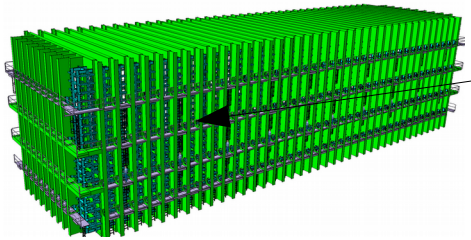
- ND and FD have same flux+xsec shifts (systematics “canceled”).
- ND and FD have same distortion in fake data.
- See if this make immune to having biased OA results.

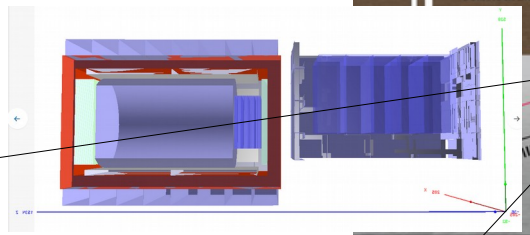
ND should be designed to identify model issues.

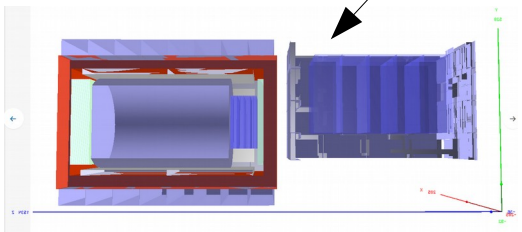
- If current model is not good enough to cover the data/MC discrepancy in ND, we will update the model.

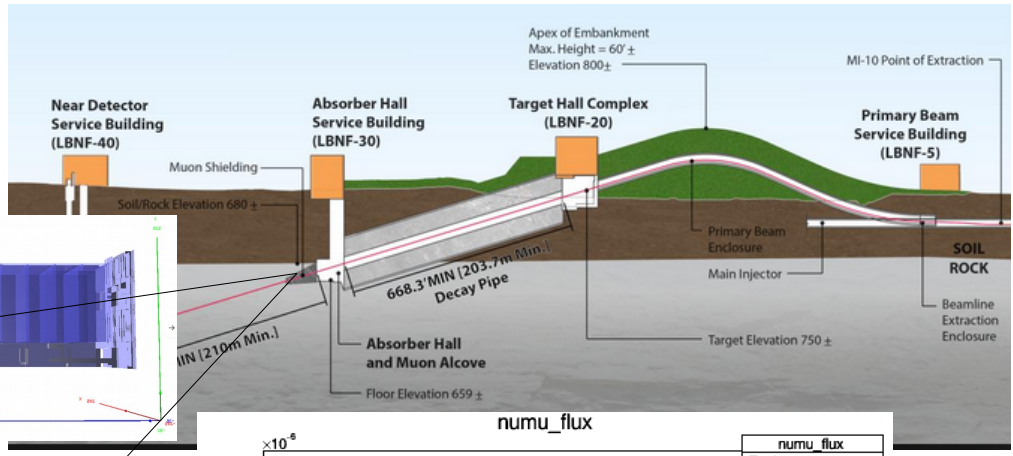
However, it is also possible that ND cannot identify model issues that ND data/MC agreement looks good..

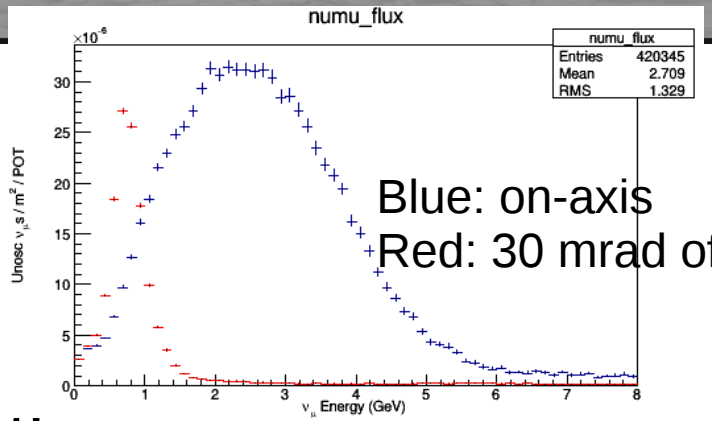
Introduction (2)











Blue: on-axis
Red: 30 mrad off

However, an off-axis detection can tell the issue.

For example, if we miss a fraction of neutrino energy:
For on-axis measurement, nu spectrum shift to the left and
by changing xsec parameters, We can find good agreement in on-axis measurement.

For off-axis measurement, nu spectrum shift to the left and
The on-axis best fit parameters higher up off-axis prediction, which gives big discrepancy between prediction/measurement.

Introduction (3)

Framework : “Official” CafAna fitter in DUNE

Statistics : based on 7 year operation of ND and FD,
with 40kton FD and 100 ton ND. (1.47 POT/year)

Systematics : Flux + Xsec + user defined

Lepton energy may be well understood , but hadronic energy may cause problems.
Tested Fake data samples (From GENIE) :

1. 10% and 20% missing proton energy
2. 10% and 20% missing charged pion energy

We are showing the missing charged pion energy case here.
Missing proton energy case tends to have a similar result.

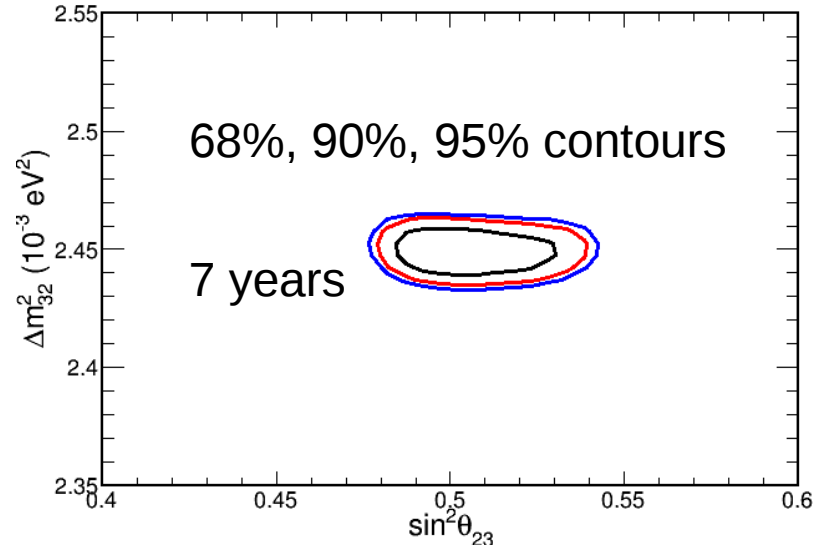
Fitting samples

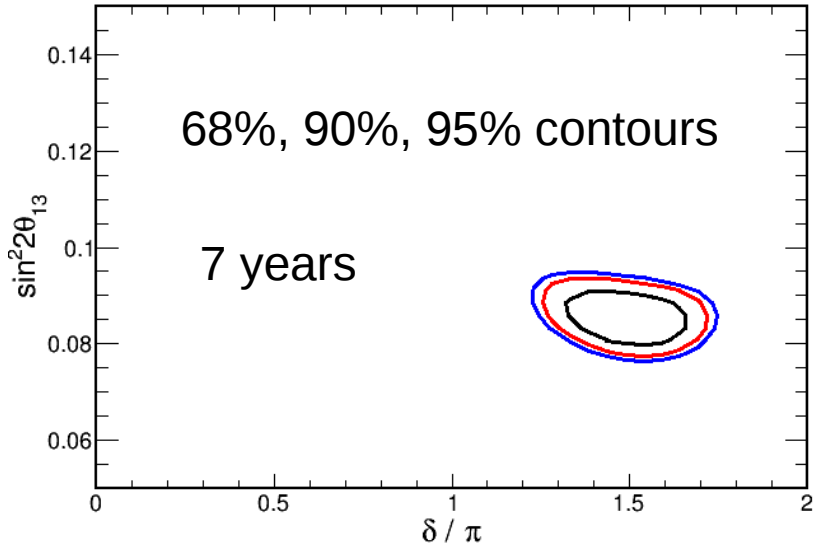
- Try to do Full ND+FD fit that DUNE may eventually do.

- ND : FHC and RHC
- FD: FHC numu, nue and RHC numu and nue
- Variables: oscillation parameters.
  Systematics variables:
  - 32 Xsec variables (in official Cafana)
  - First 5 Flux variables (in official Cafana)
  - 2% Energy scale and 6% energy resolution (in official Cafana)
  - many variables introduced by me (fake data variables..)
    “One sigma” means the standard variation in fake data.

FD+ND fit with Xsec+Flux systematics
20% Missing charged pion energy

True





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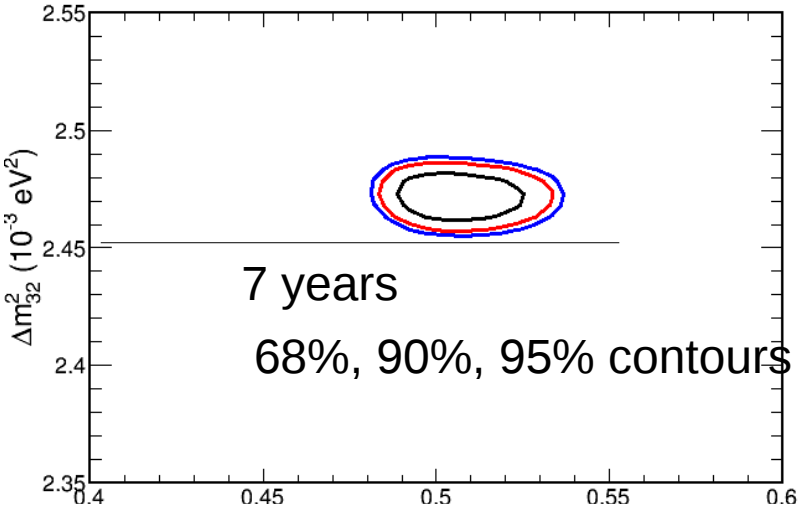
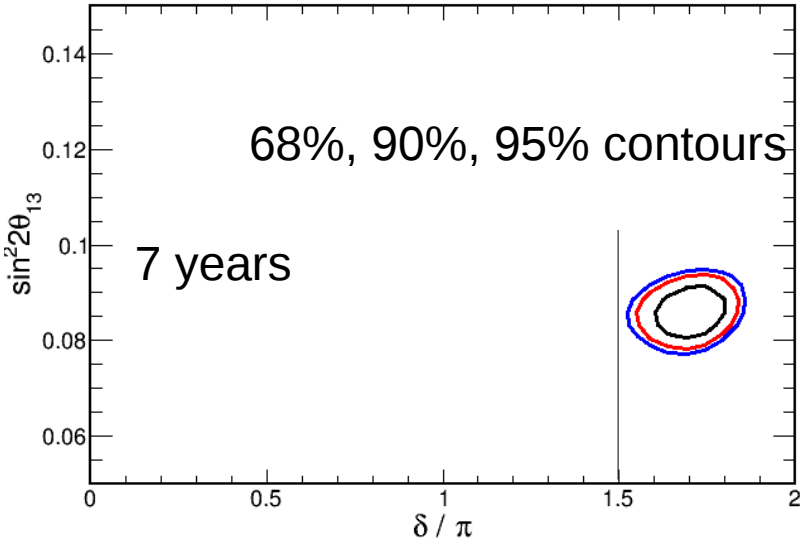
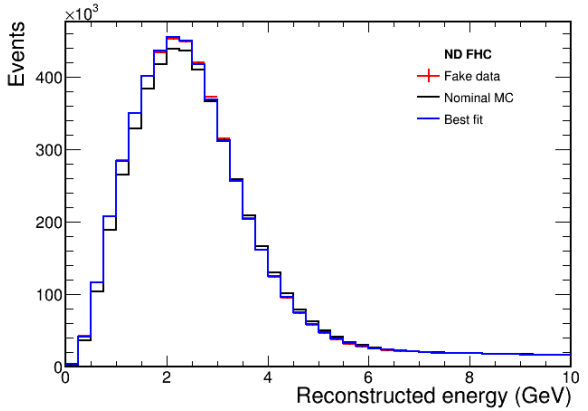
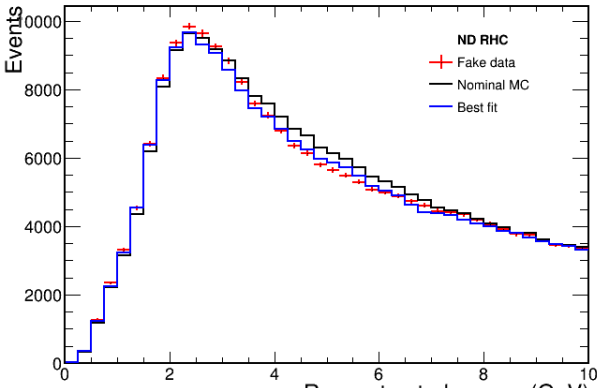
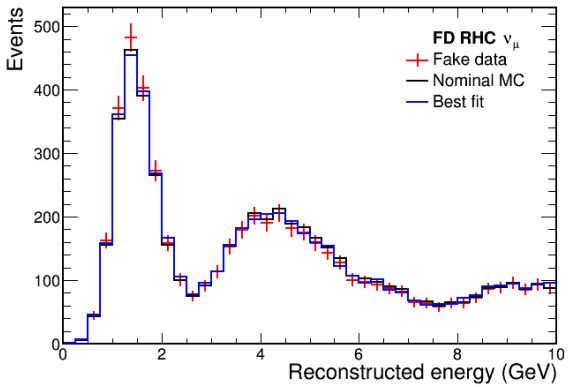


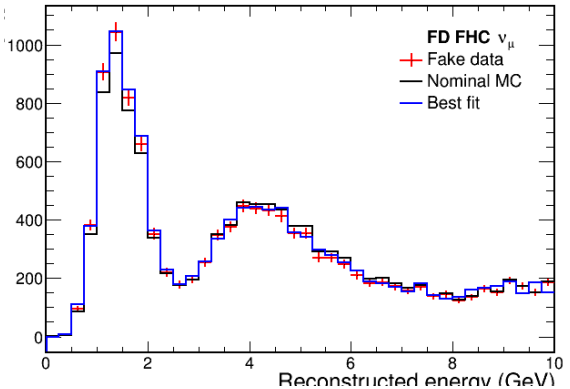


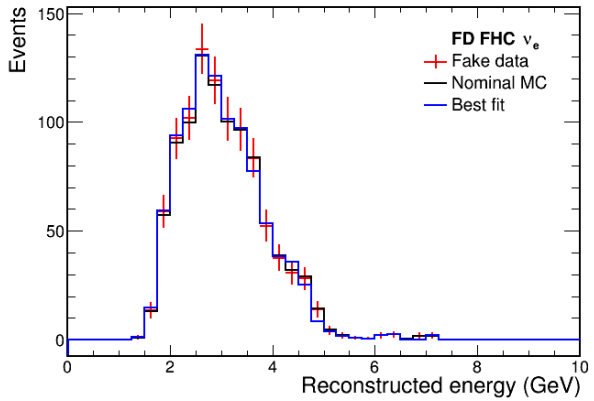
FD+ND fit with Xsec+Flux systematics
20% Missing charged pion energy

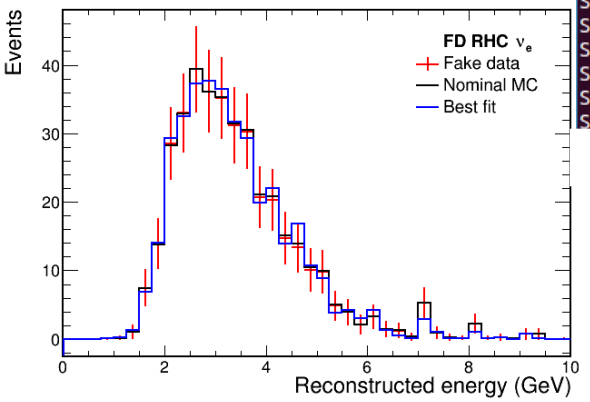










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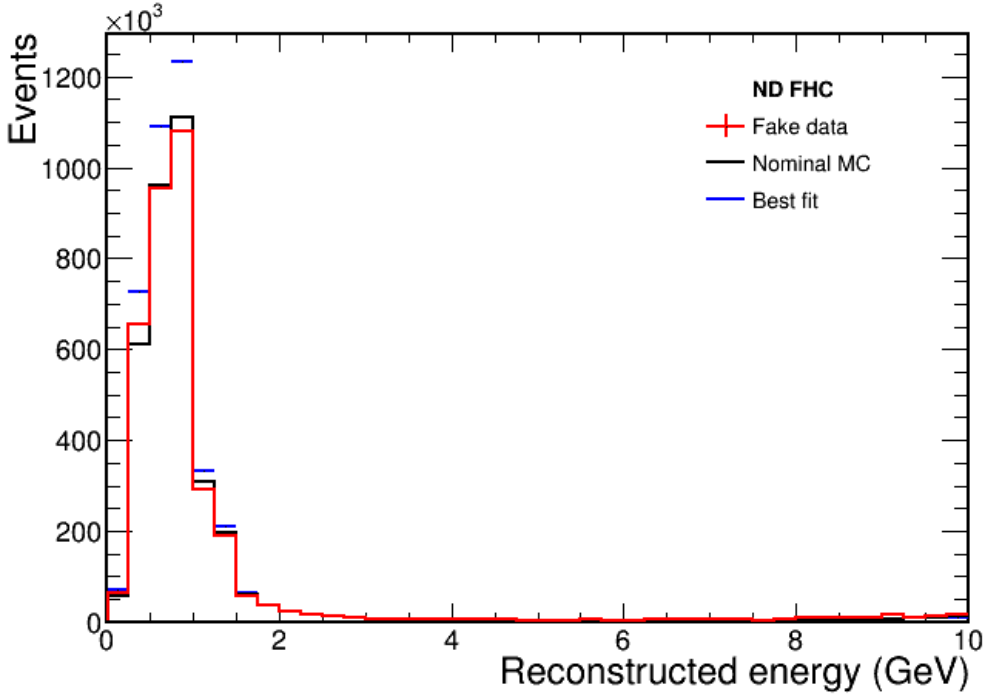
FD+ND fit with Xsec+Flux systematics
20% Missing charged pion energy
Off-axis FHC



Black : nominal 30mrad (1.7 degree) off-axis

Blue : with on-axis best fit

Red : real 20% MPE

Summary

- Even with identical ND and FD response, we may have oscillation parameter bias with a good ND prediction/data agreement.

- DUNE-prism may identify the problem of mis-modeling.

- With multiple off-axis, we may be able to “calibrate” the energy spectrum.

Next:

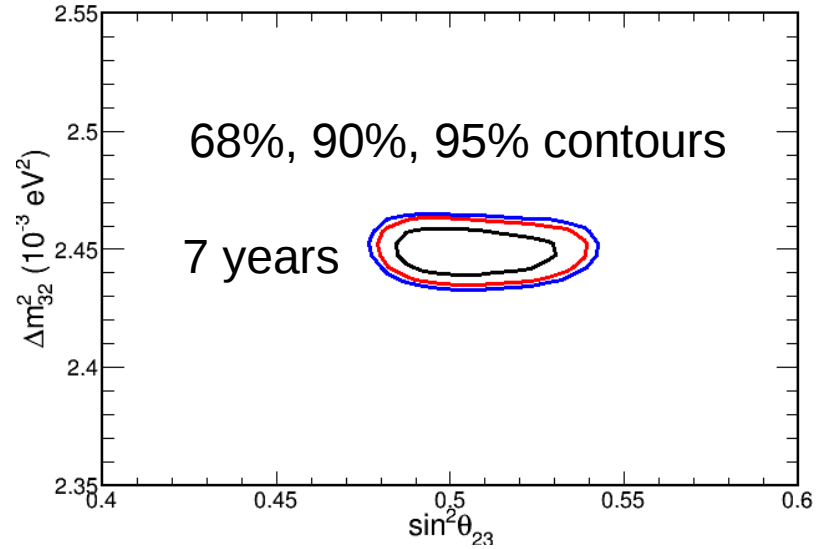
- Try to build FD prediction based on ND off-axis positions.
  We expect that this way can make immune to such a bias.

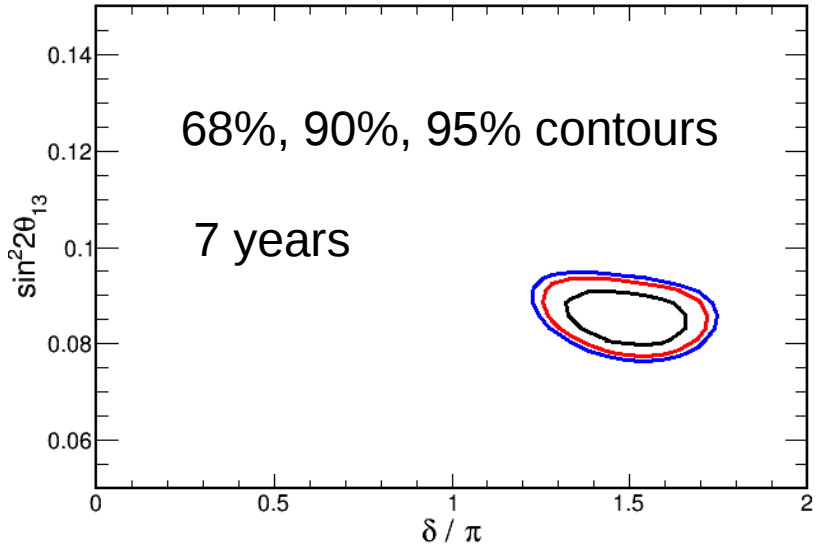
- May consider introduce some more energy-dependent systematics.

Backup..

FD+ND fit with Xsec+Flux systematics
10% Missing charged pion energy

True





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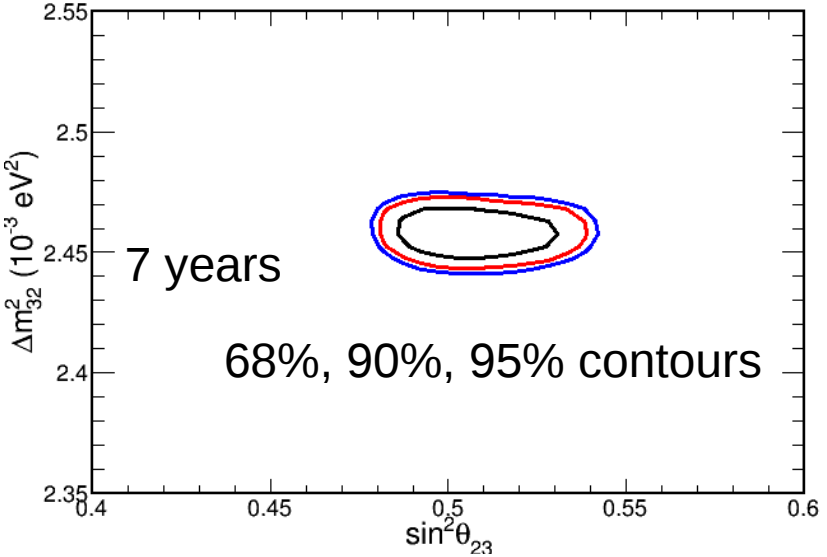
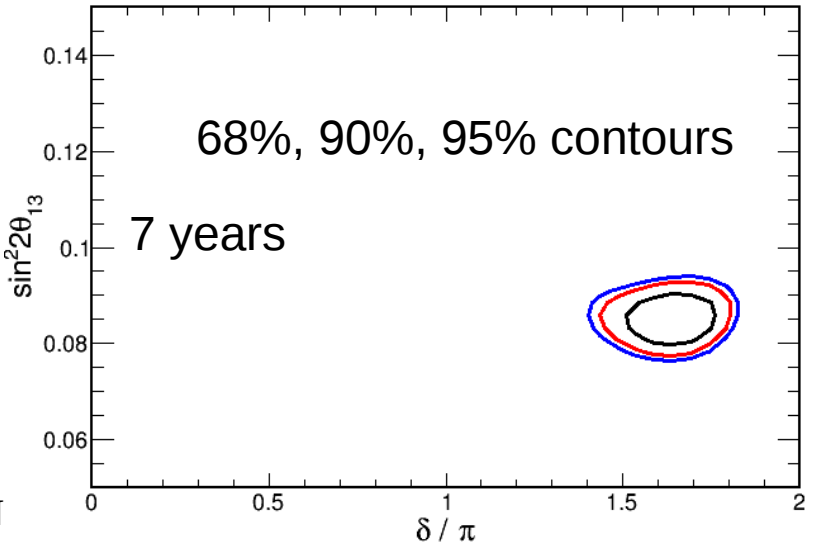
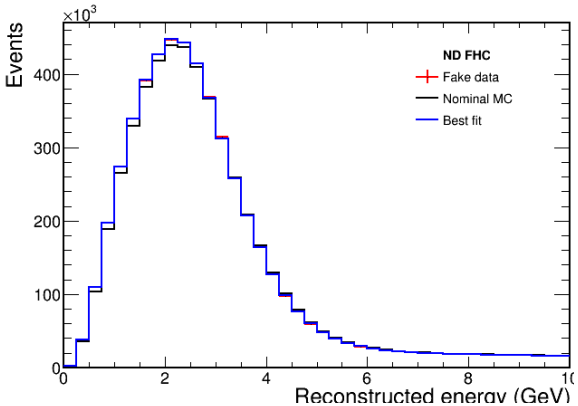
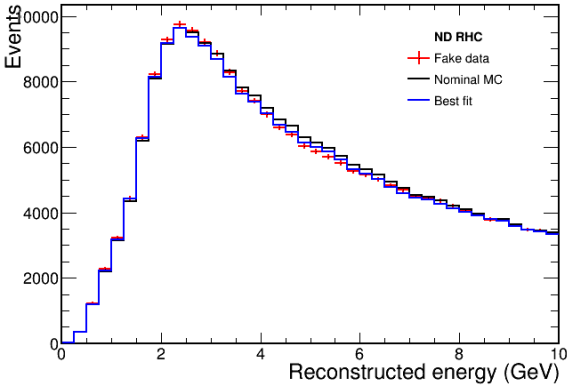


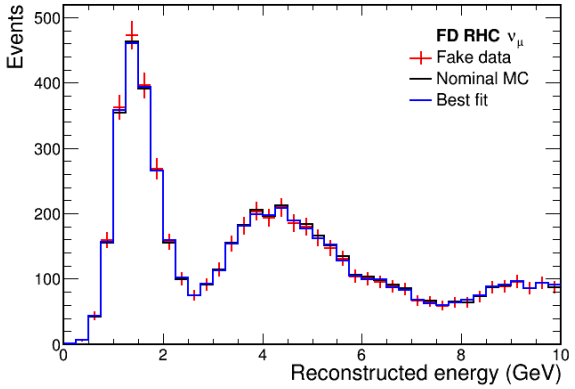


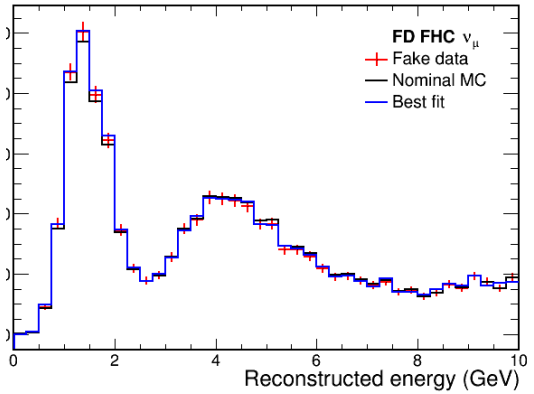
E N

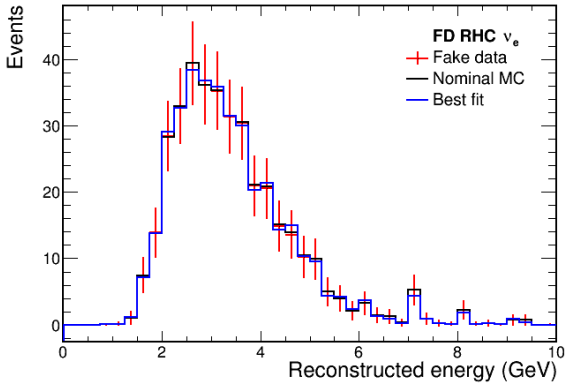
FD+ND fit with Xsec+Flux systematics
10% Missing charged pion energy

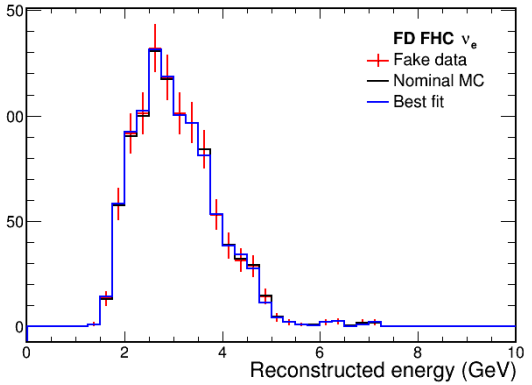










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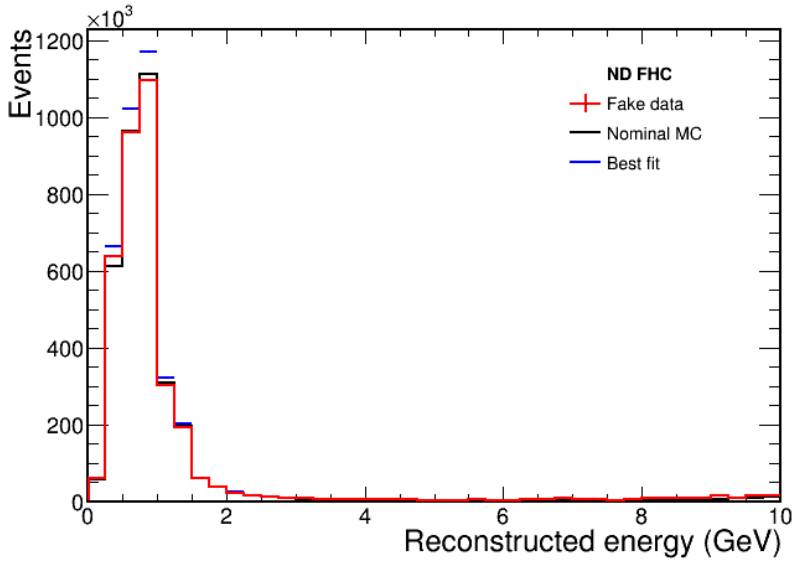
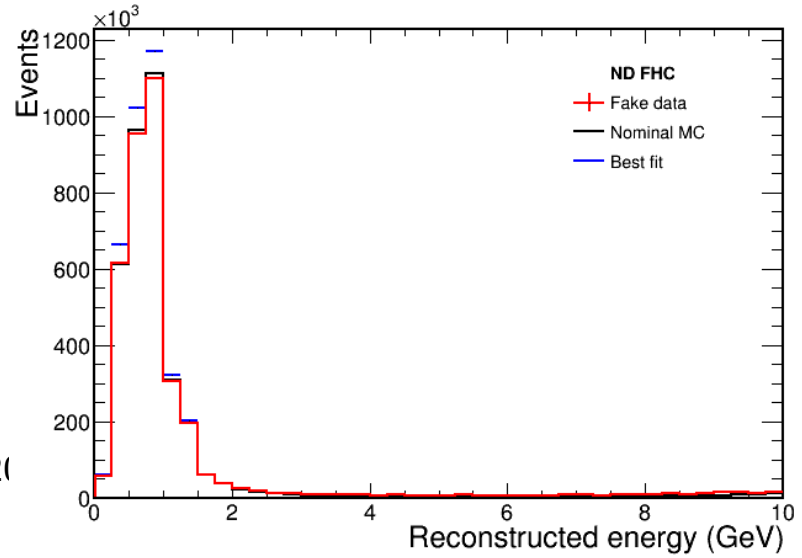
FD+ND fit with Xsec+Flux systematics
10% Missing charged pion energy
30 mrad off-axis FHC



Black : nominal 30mrad off-axis

Blue : with on-axis best fit

Red : real 10% MPE

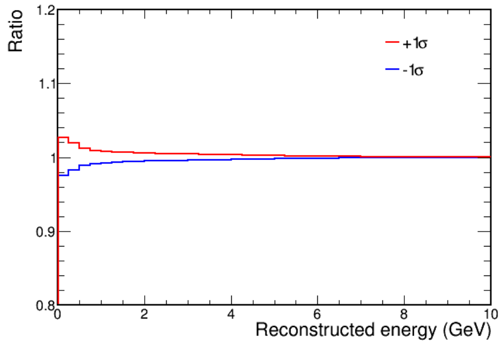


Black : nominal 45mrad off-axis

Blue : with on-axis best fit

Red : real 10% MPE

Xsec ND FHC


Ratio
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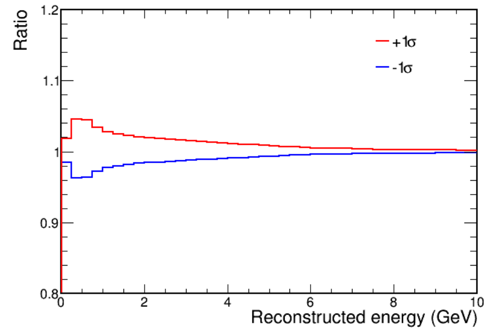
-1σ
Reconstructed energy (GeV)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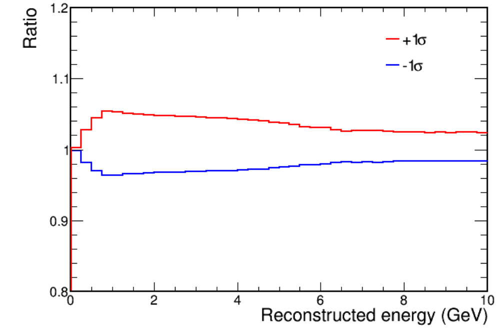
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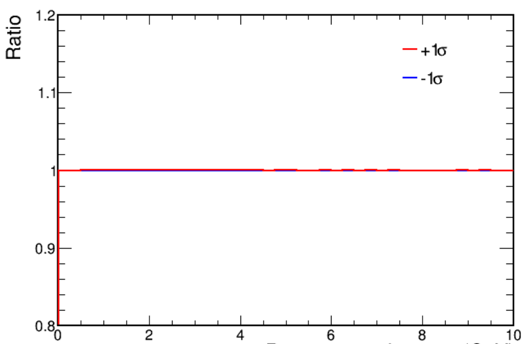
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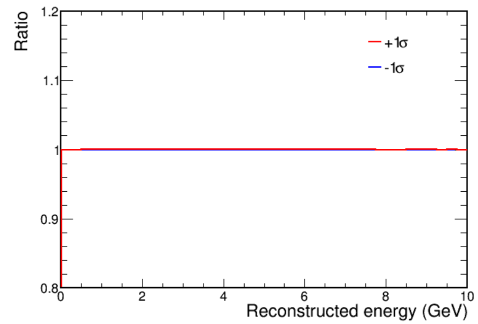
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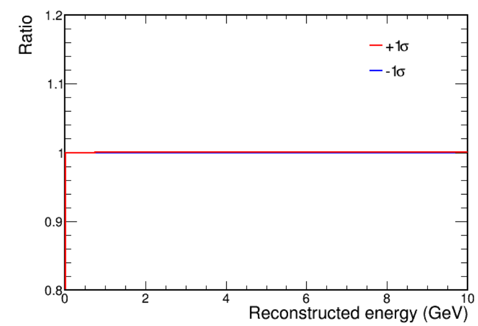
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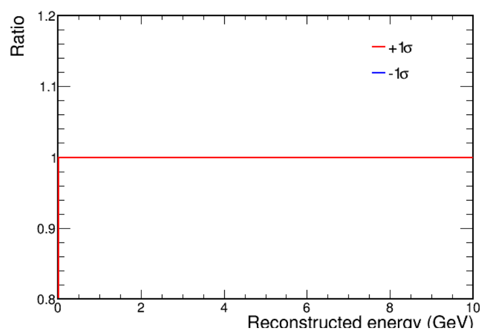
Reconstructed energy (GeV)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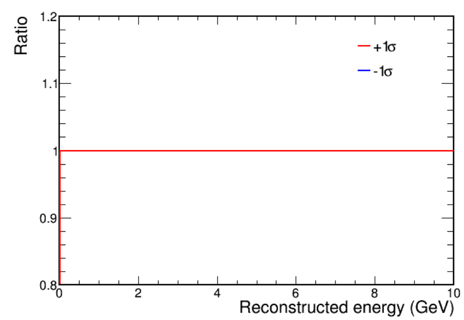
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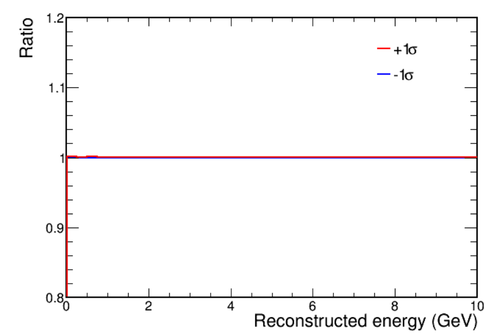
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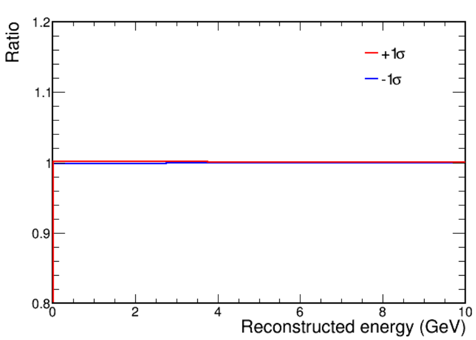
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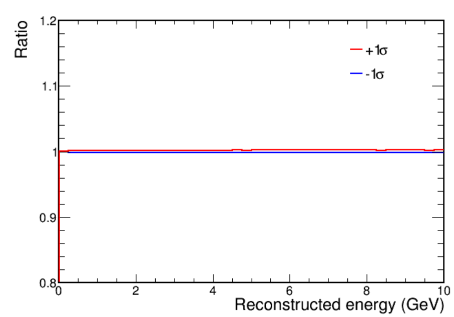
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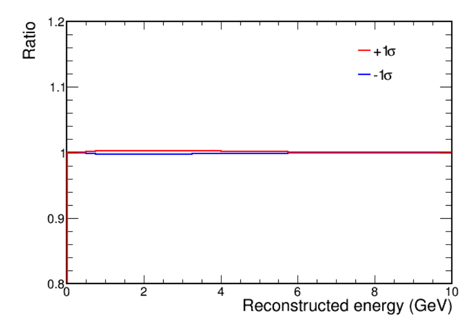
Reconstructed energy (GeV)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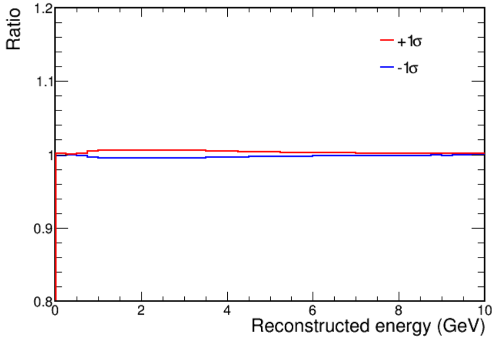
Reconstructed energy (GeV)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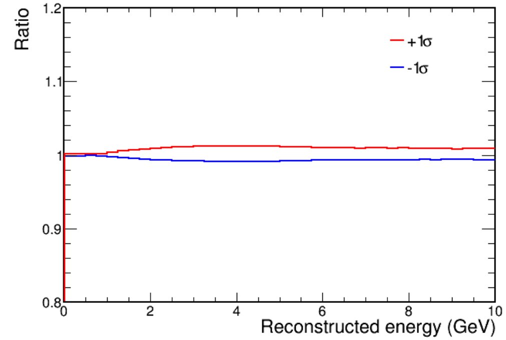
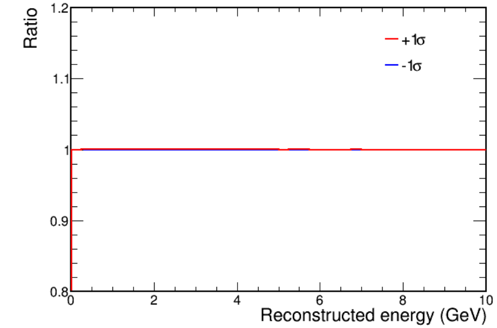
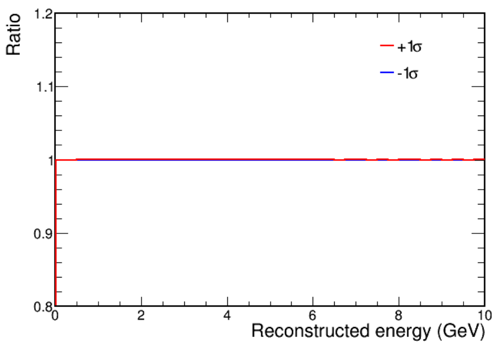
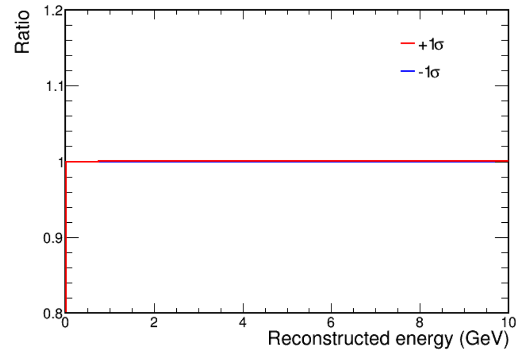
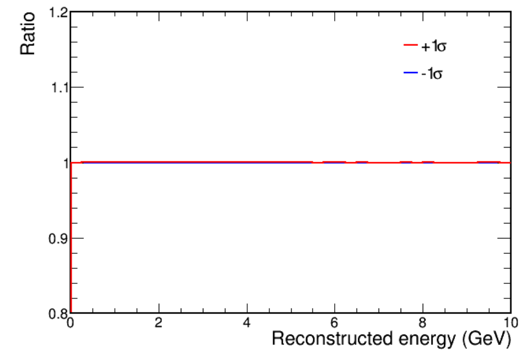
-1σ
Reconstructed energy (GeV)

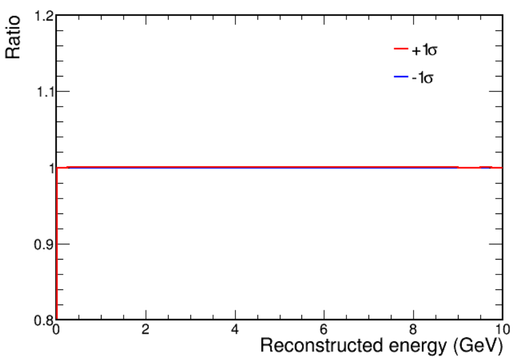

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

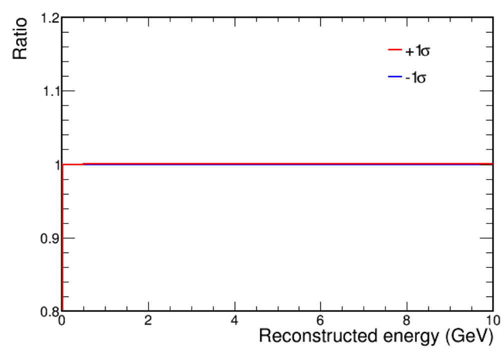

Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
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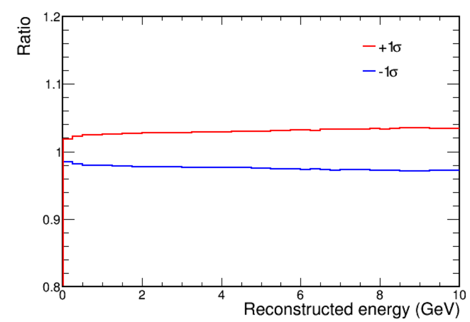
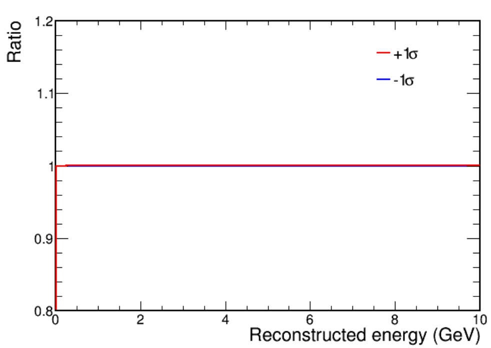
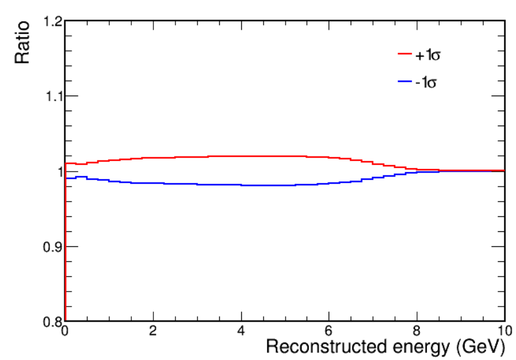
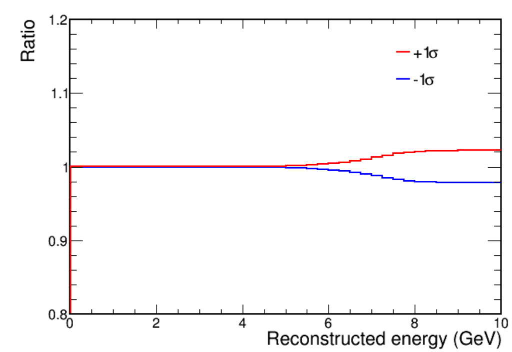
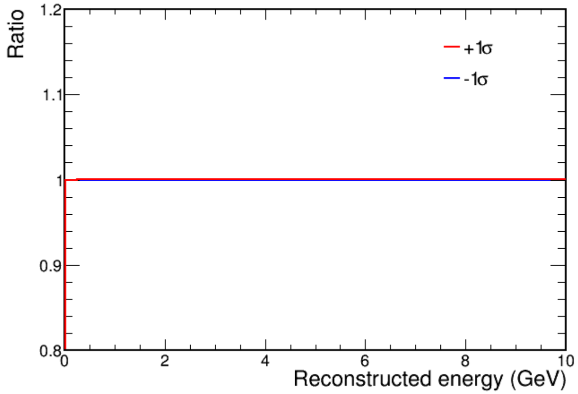
-1σ
Reconstructed energy (GeV)

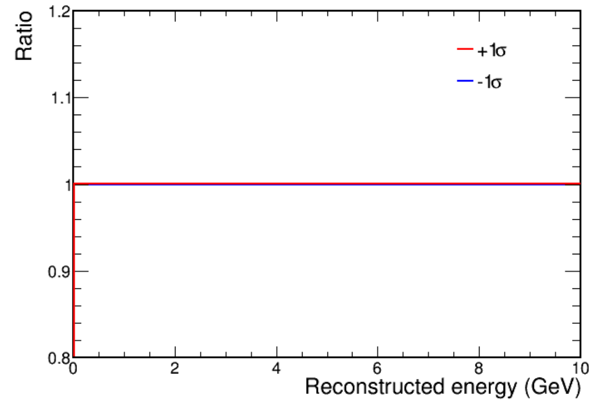

Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
1.2
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
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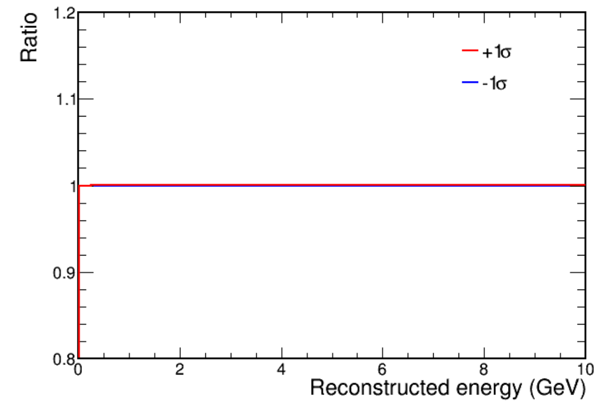
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
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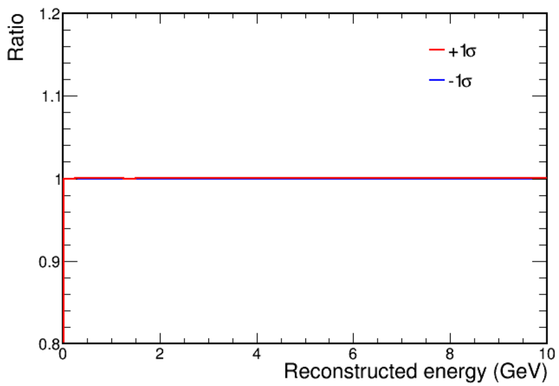
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
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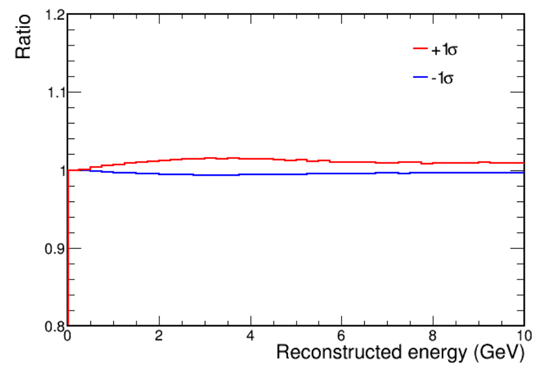
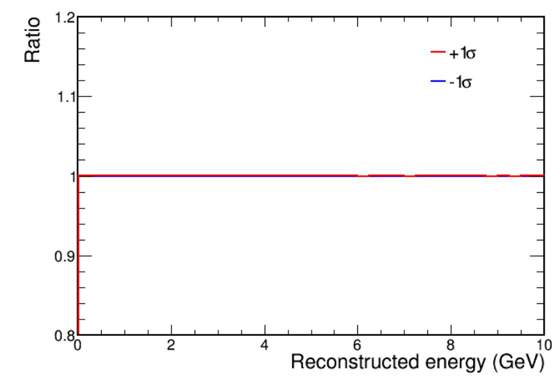
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
1.2
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
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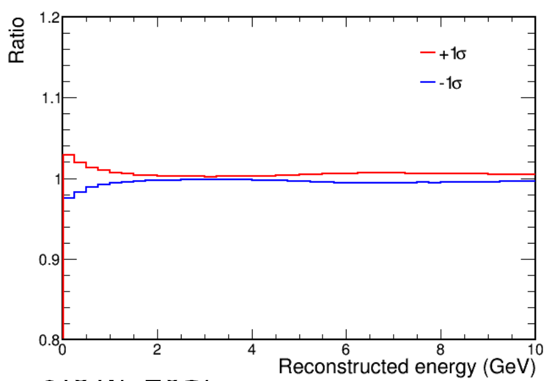
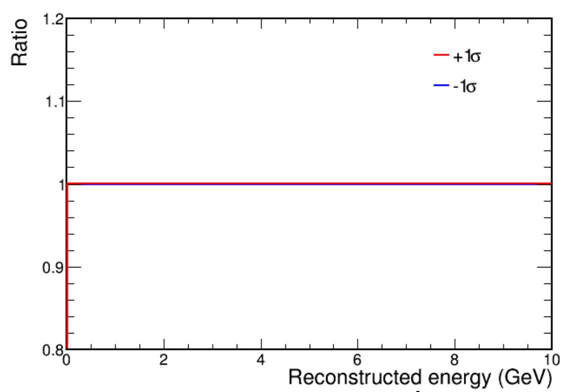
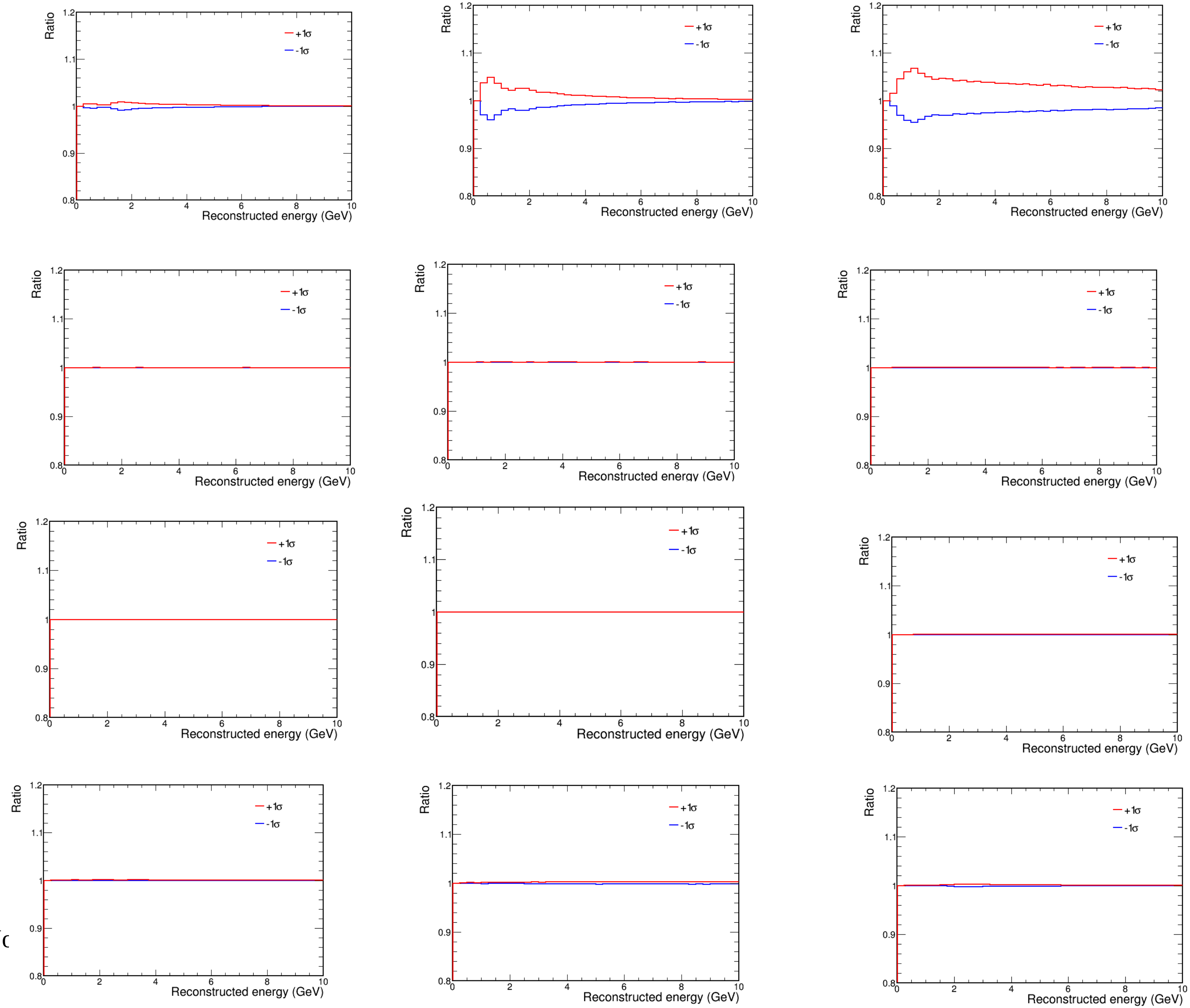
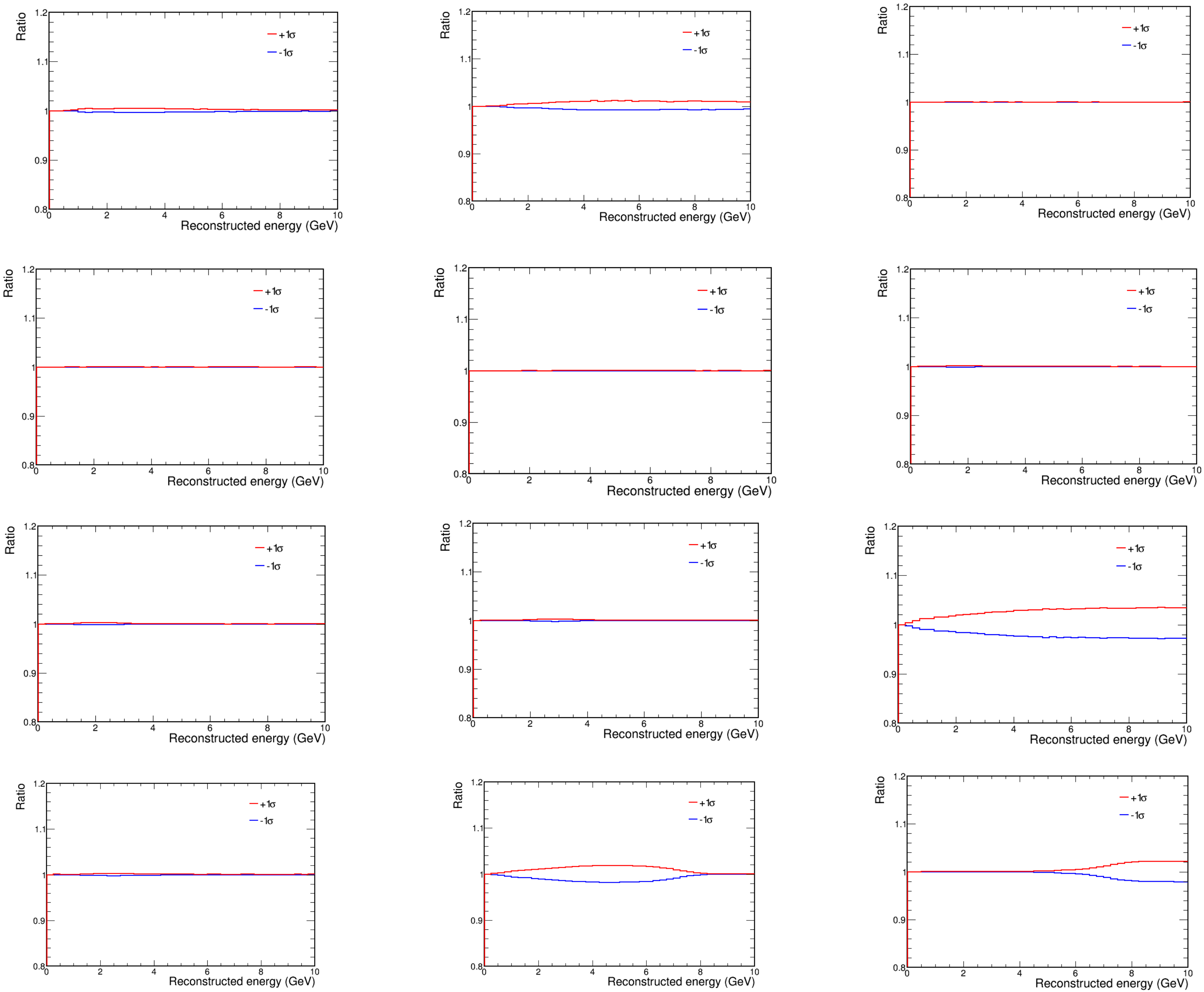
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)

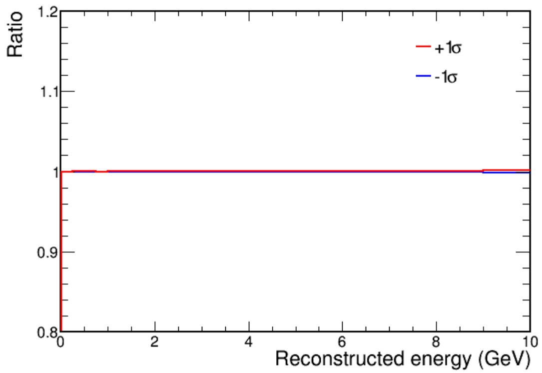

Ratio
1.2
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)

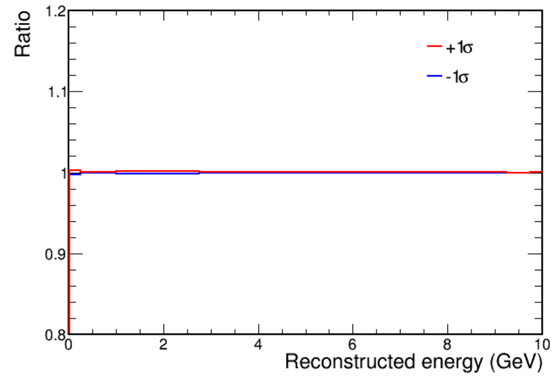

Ratio
1.2
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)

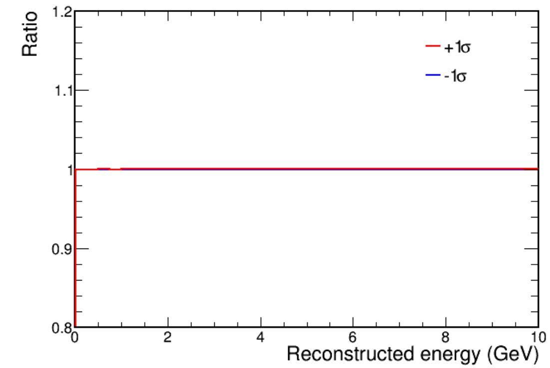
Xsec ND RHC

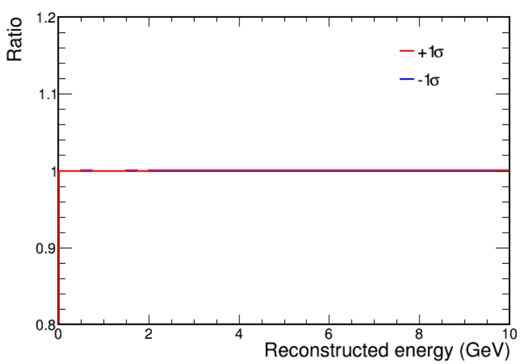


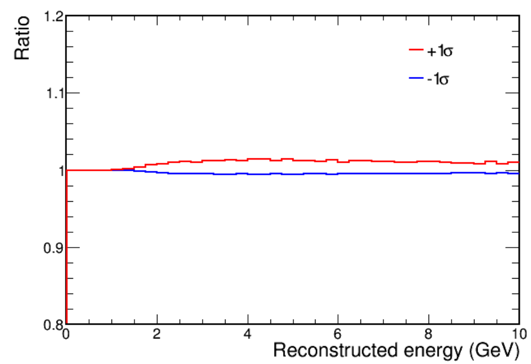

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

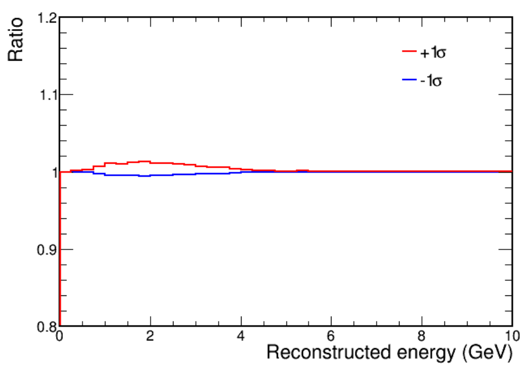

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

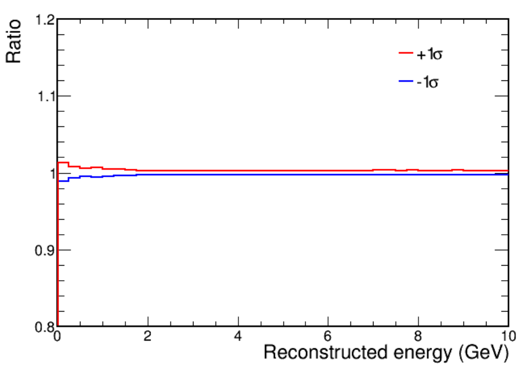

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

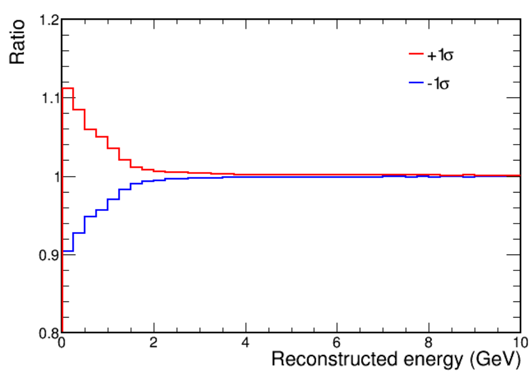

Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
+1σ
-1σ
Reconstructed energy (GeV)

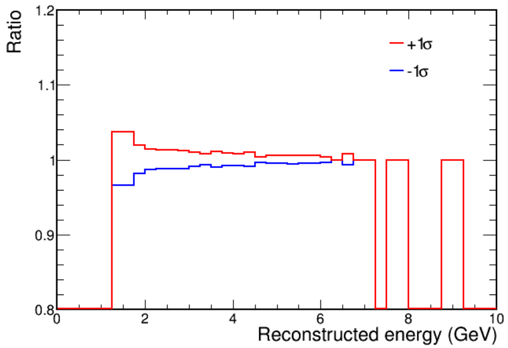

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

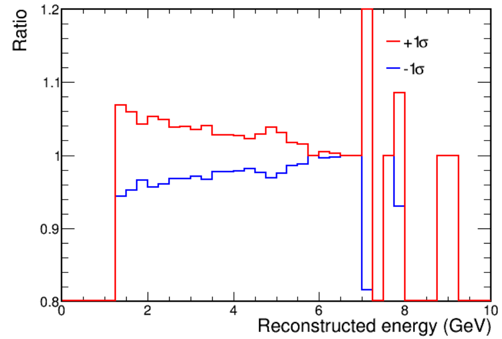

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

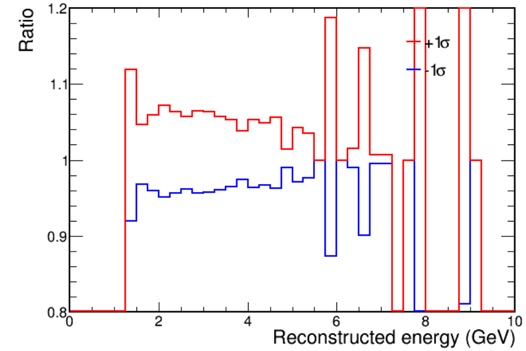

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

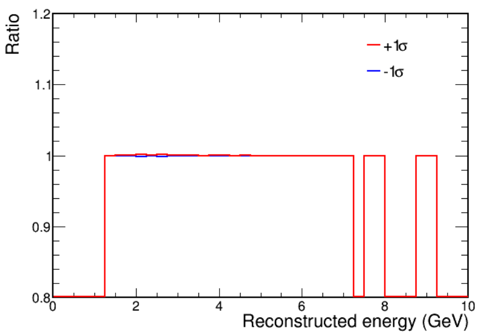

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

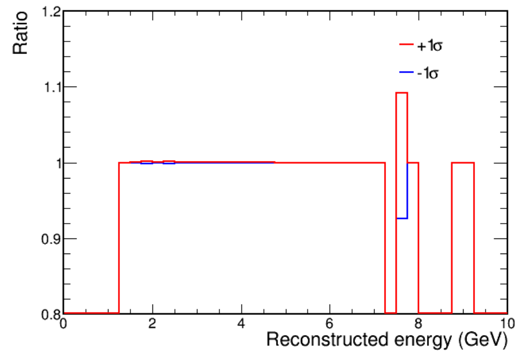
Xsec FD nue FHC

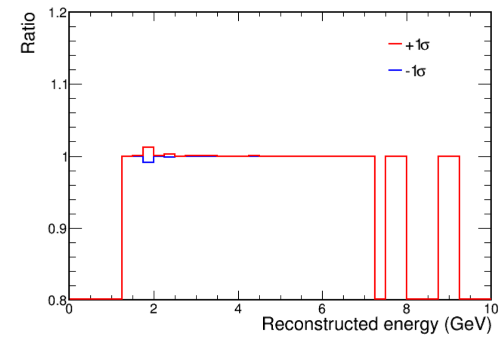


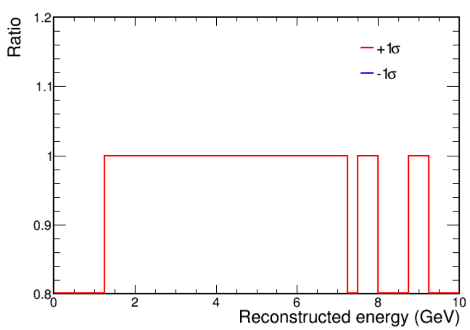


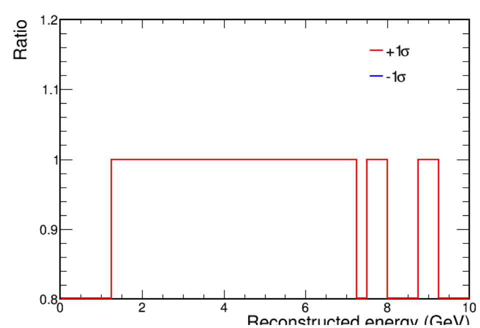


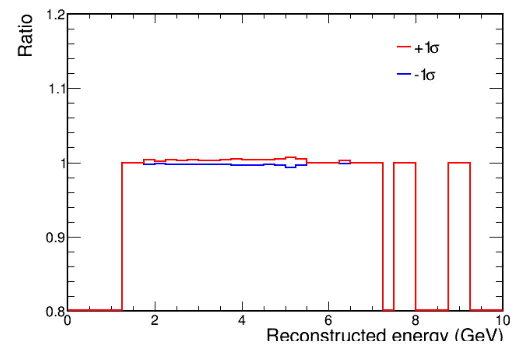


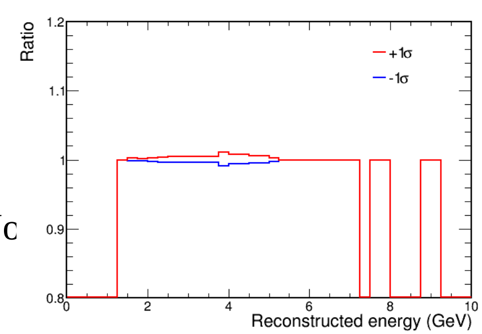


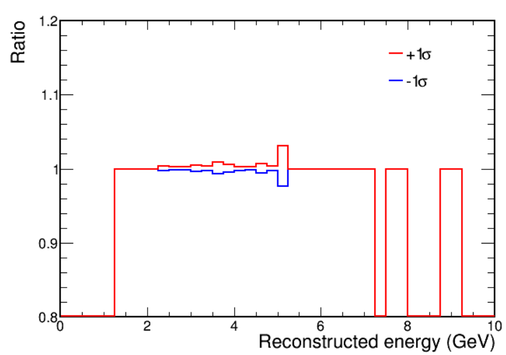


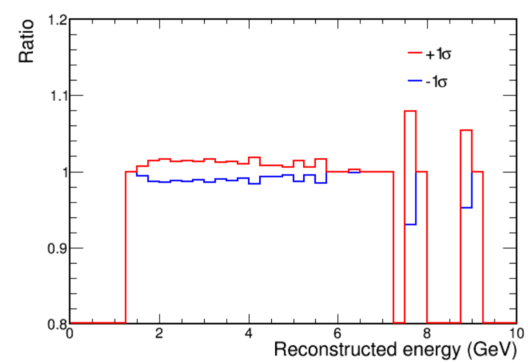


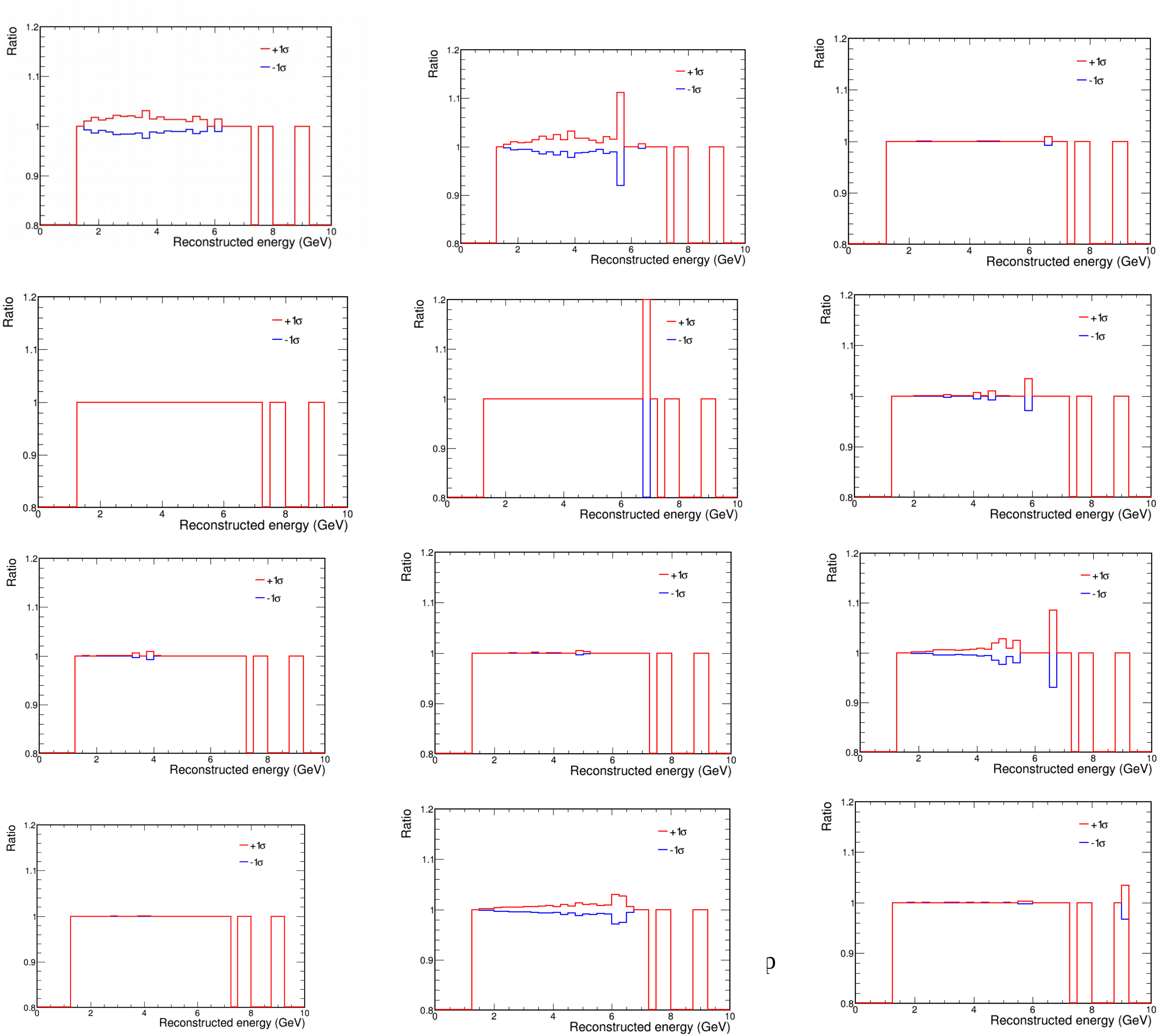


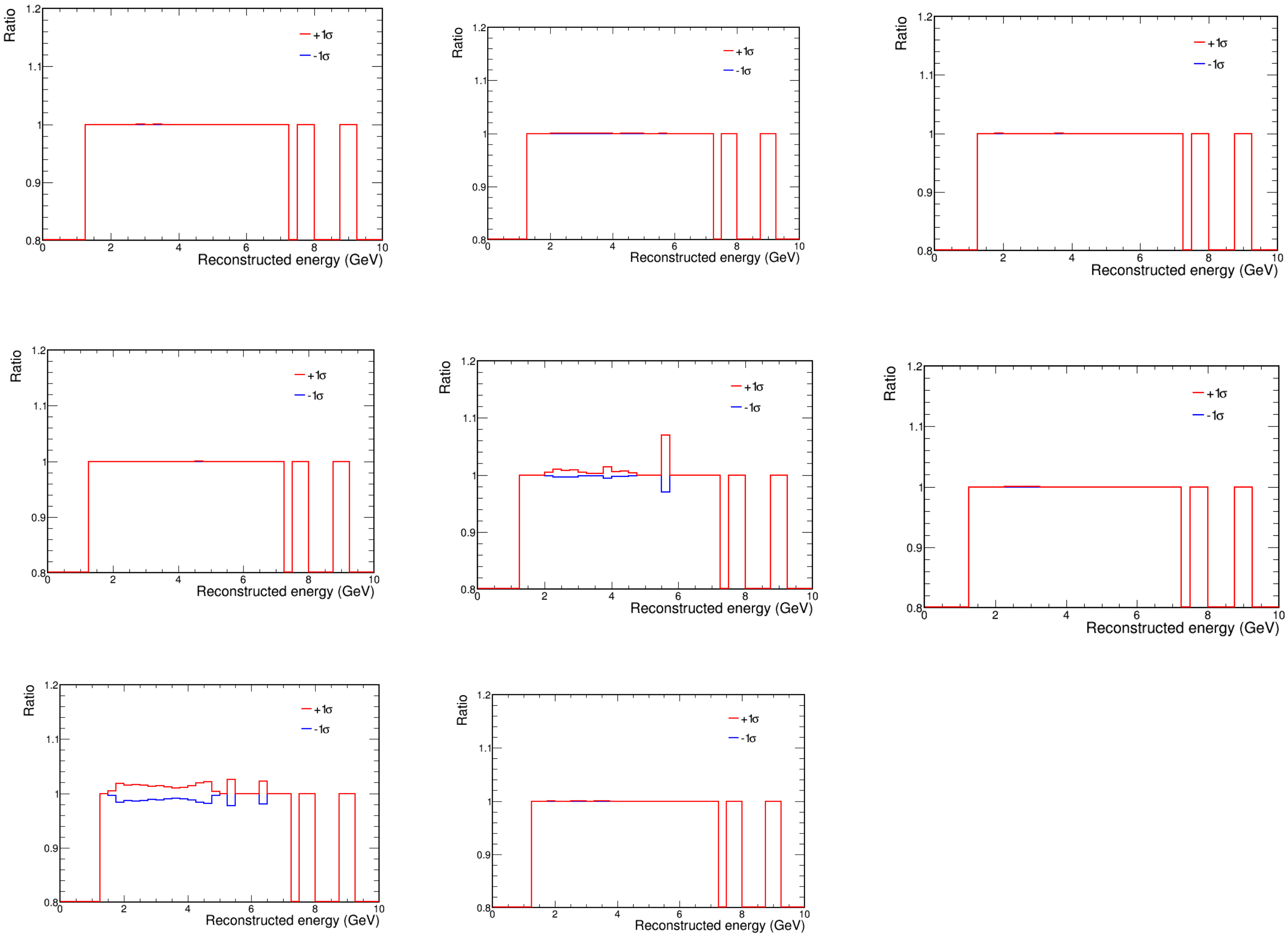




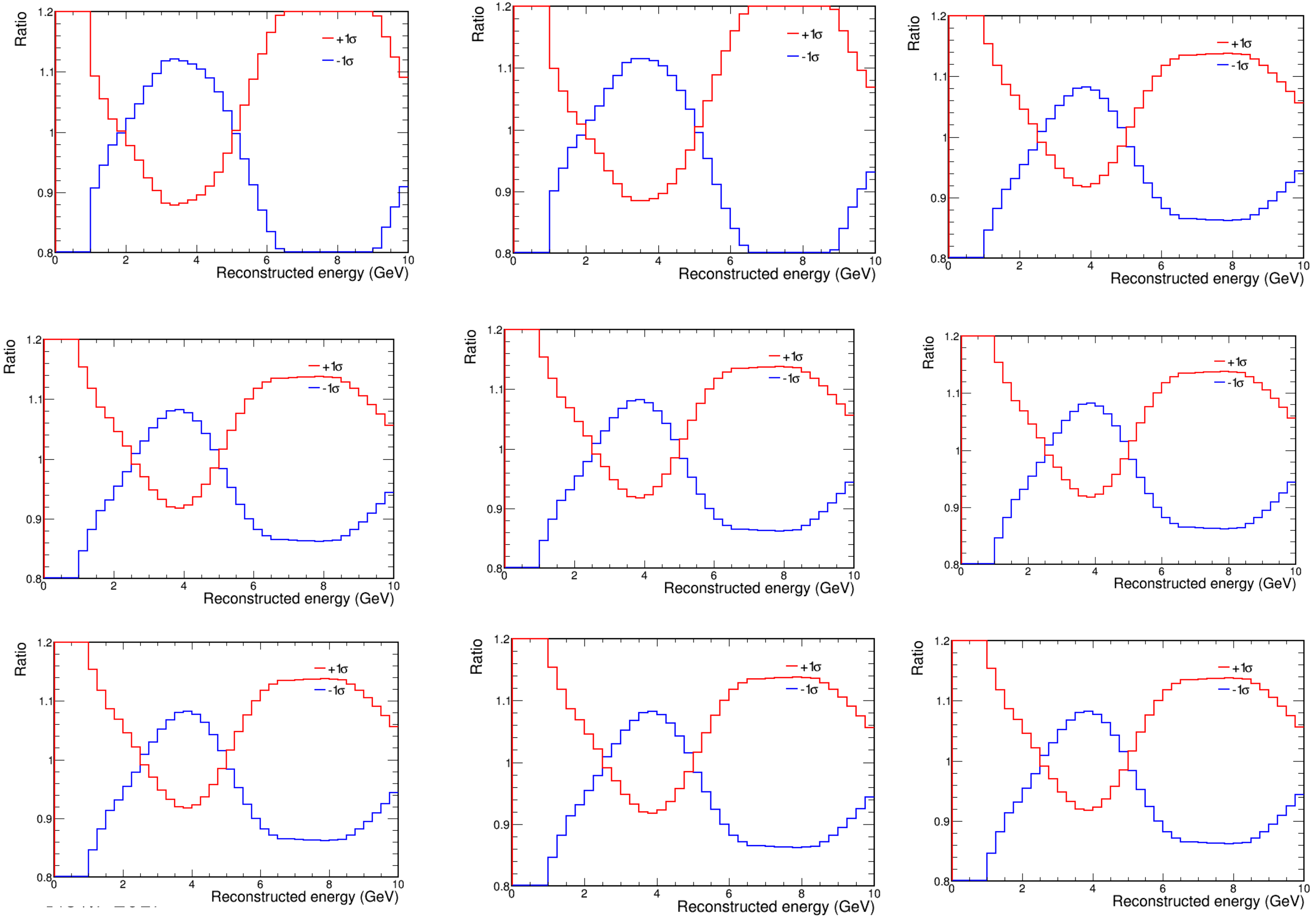




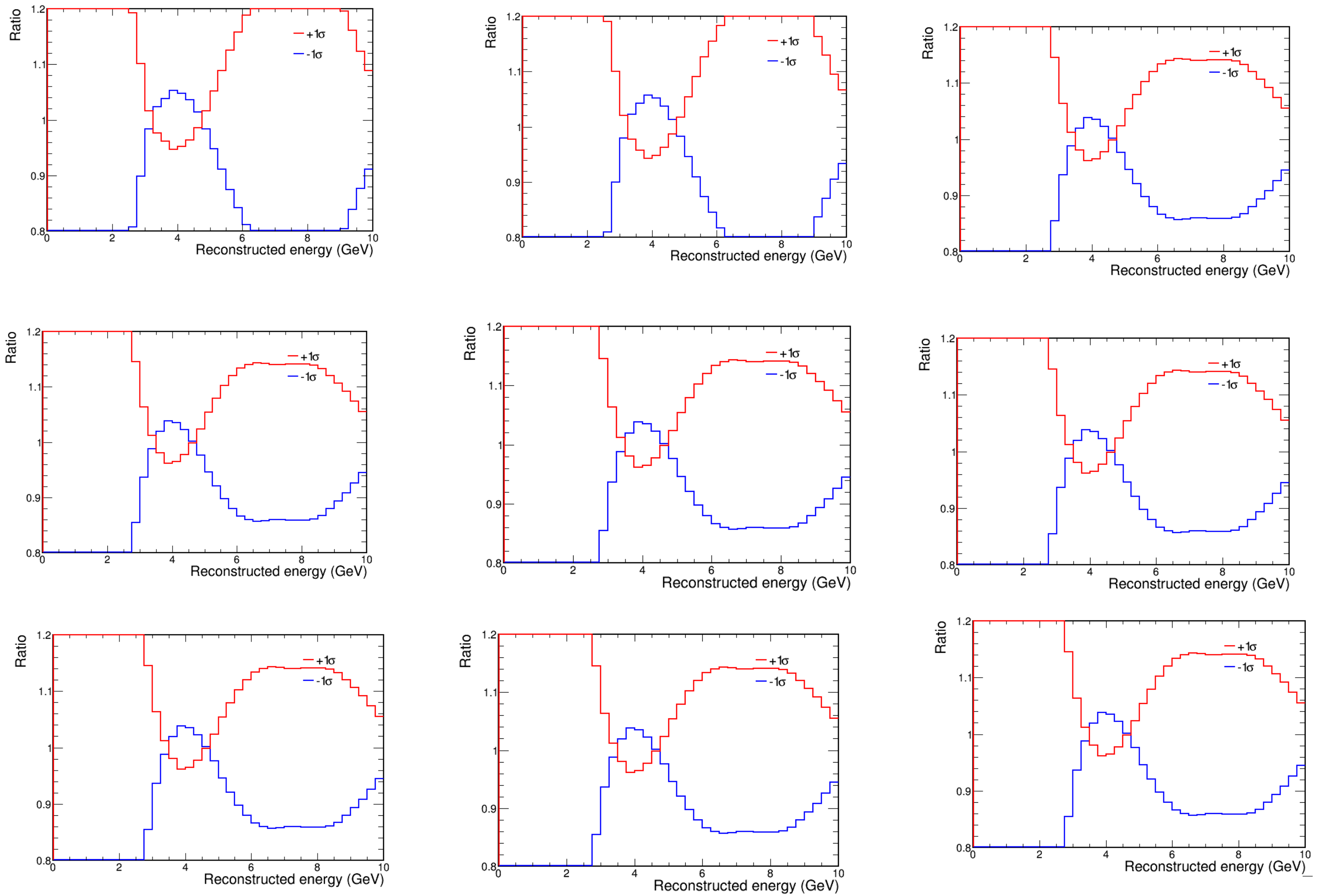

Ratio
+1σ
-1σ
Reconstructed energy (GeV)


Ratio
Reconstructed energy (GeV)
+1σ
-1σ

Flux systematics ND FHC



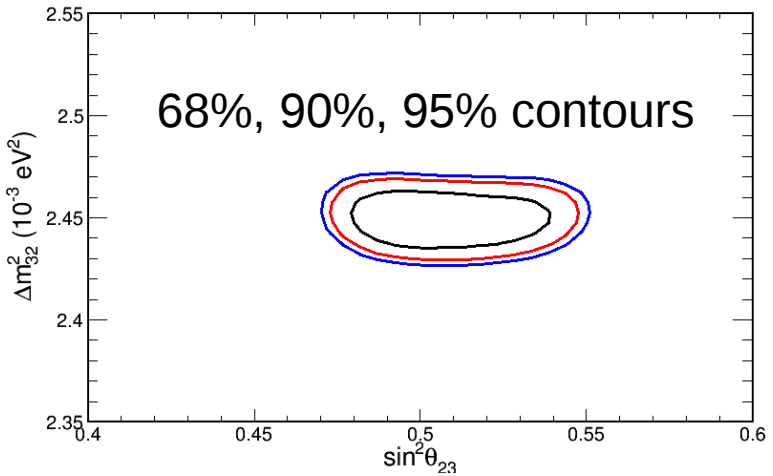
Flux systematics ND RHC

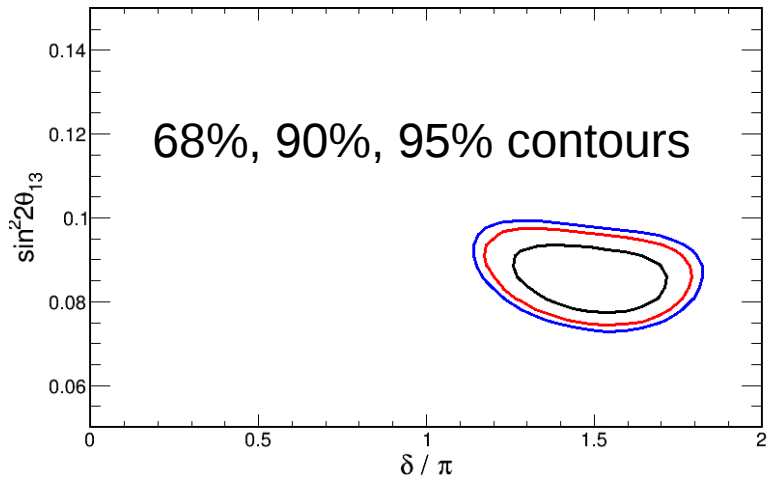


Systematics validation

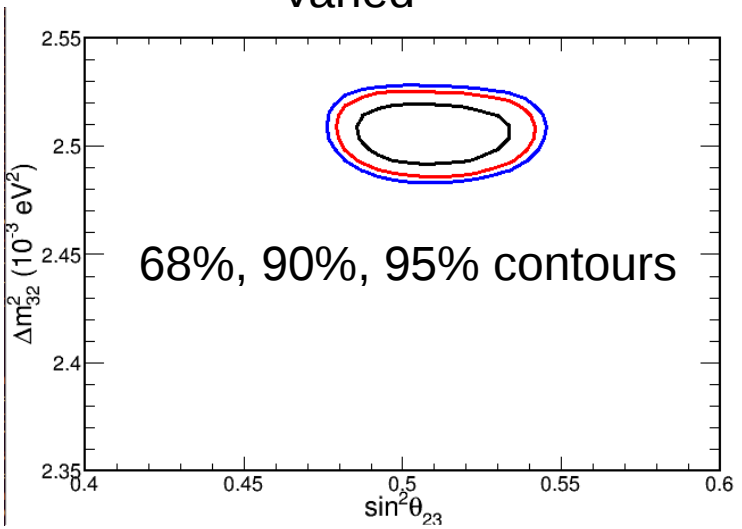
With Luke's variation and without systematics,
the true values cannot be recovered.

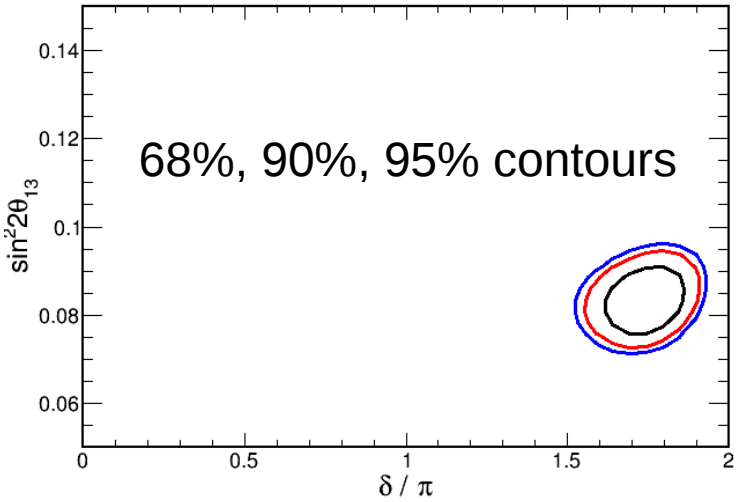
True





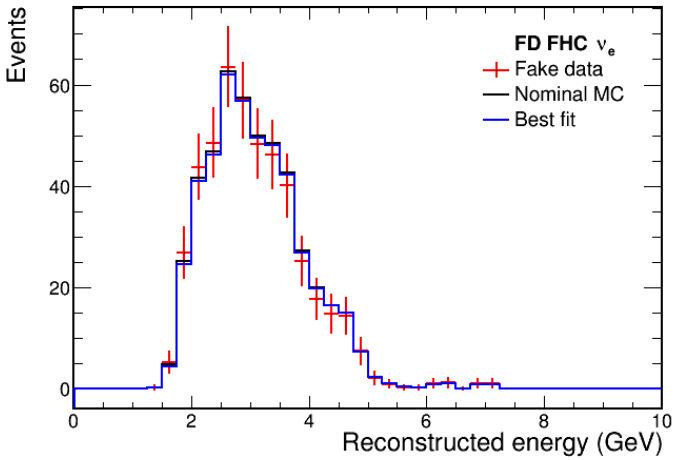
Varied

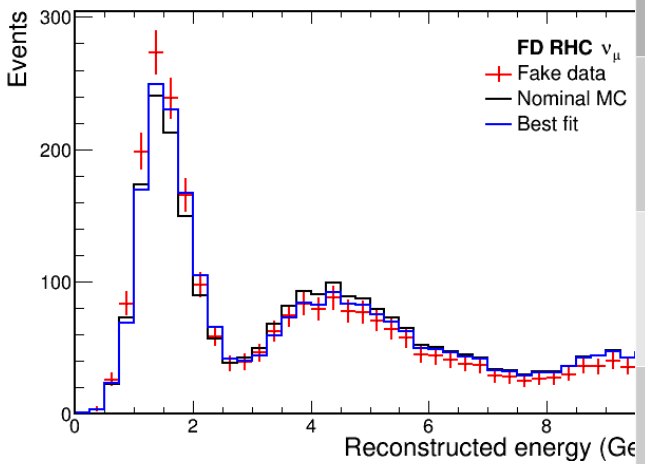


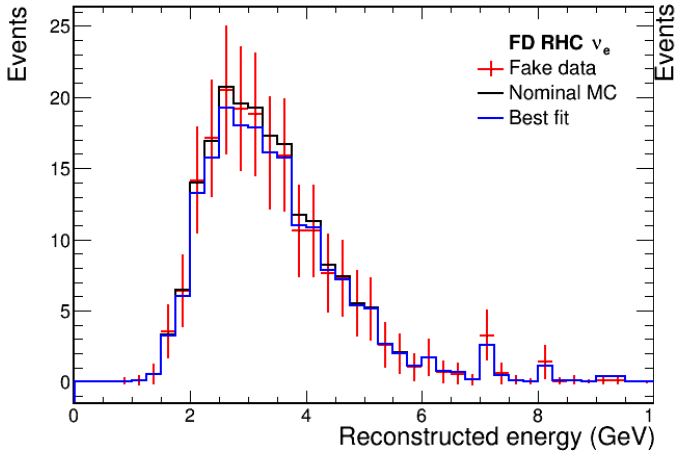


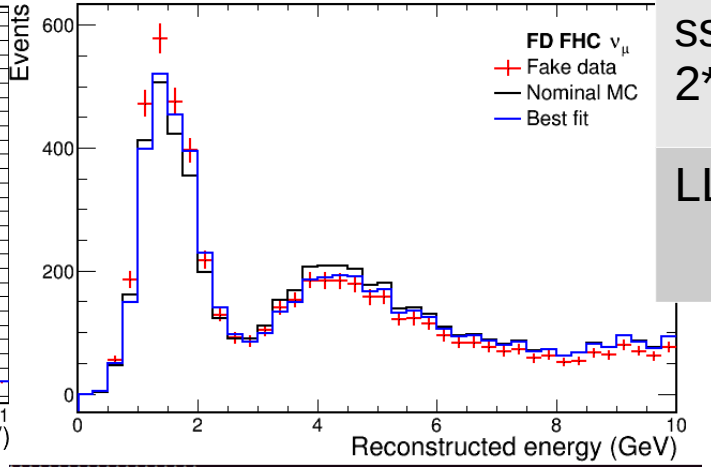
Systematics validation

With Luke's variation and without systematics, the true values cannot be recovered.







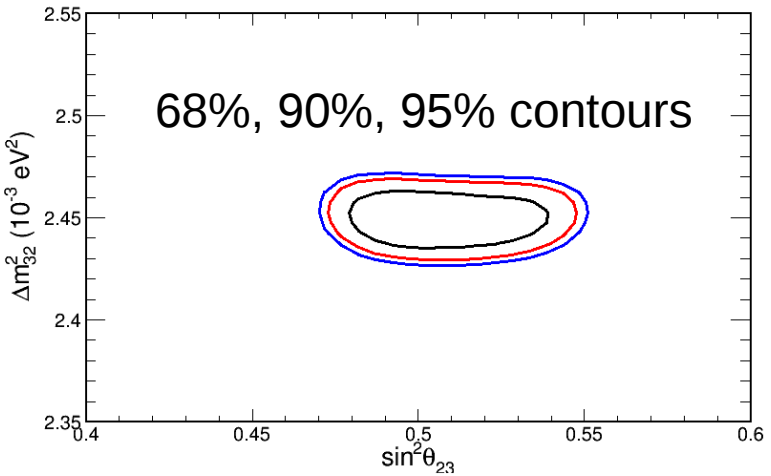


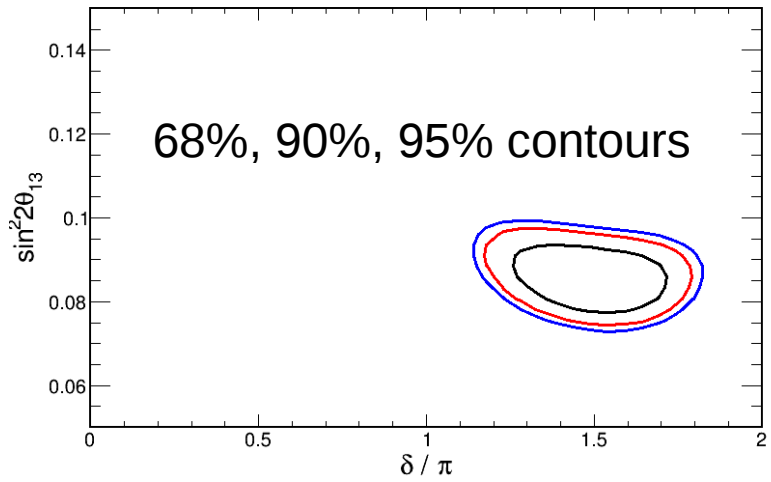
	true	FD+ND Best fit	FD only
CP (pi)	1.5	1.67	1.67
sst23	0.5	0.51	0.51
Dm32 (e-3)	2.45	2.57	2.57
ss(2*t13)	0.087	0.078	0.078
LL		126246	99.5

Systematics validation

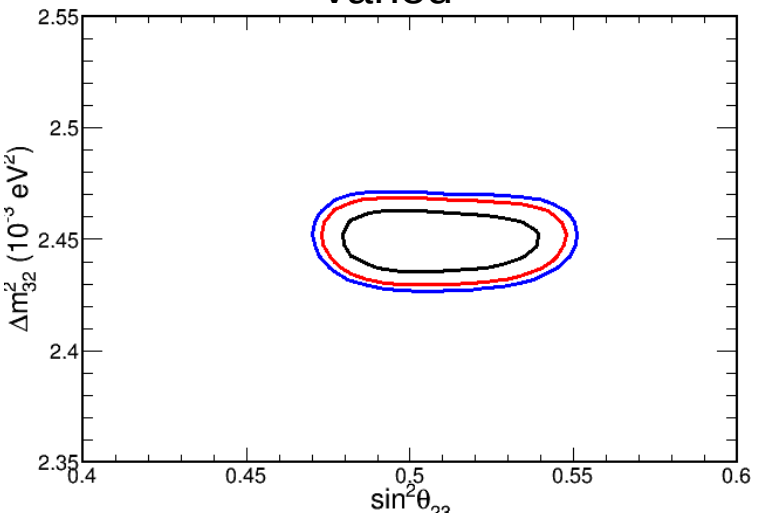
With Luke's variation and with the variation inserted as a systematic pull, the true values can be recovered.

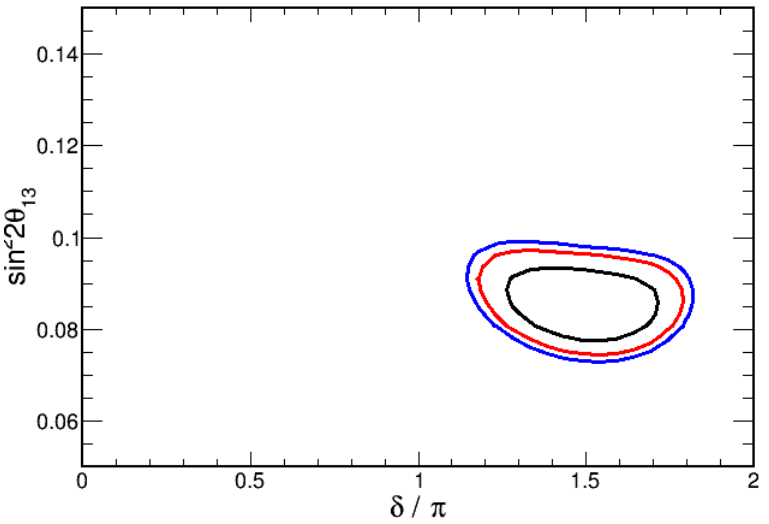
True





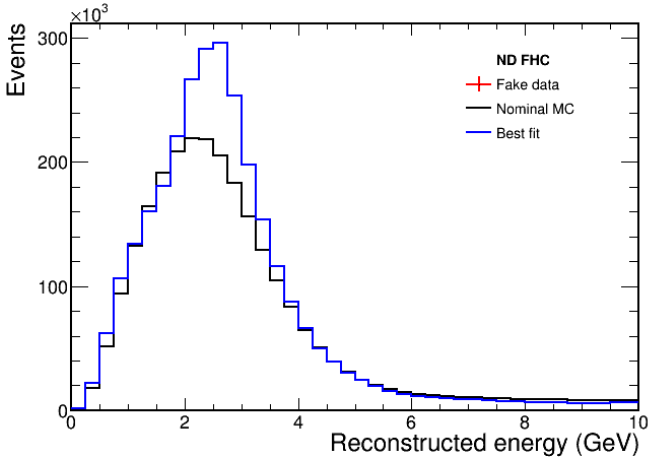
Varied

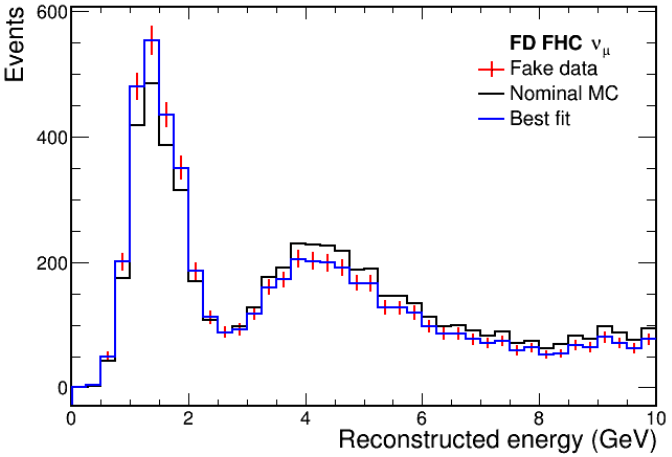


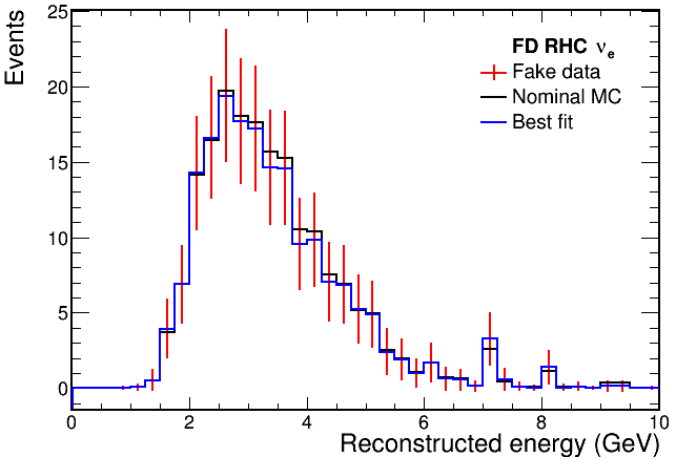


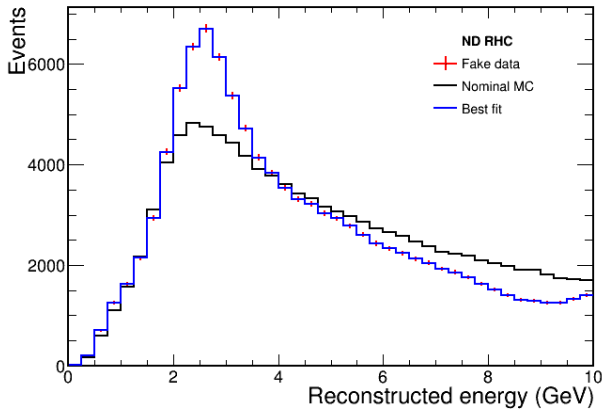
Systematics validation

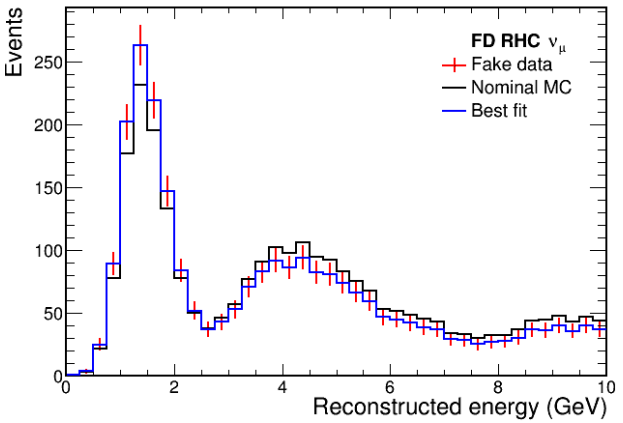
With Luke's variation and with the variation inserted as a systematic pull, the true values can be recovered.

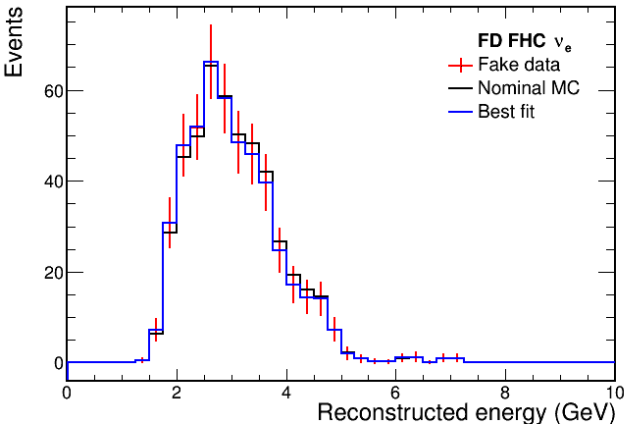












Xsec systematics (32)

Cross section systematics

- 32 "VALOR categories"
- With covariance matrix

  `/dune/data/users/marshalc/`

  `total_covariance_XS.root`

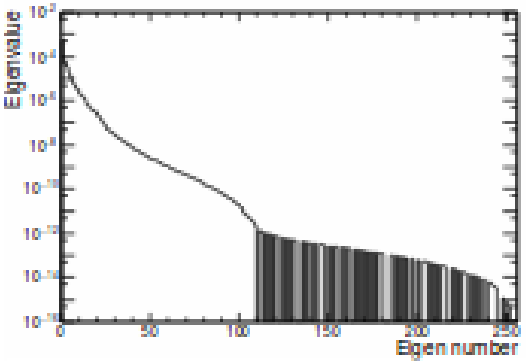
Correlations are included !

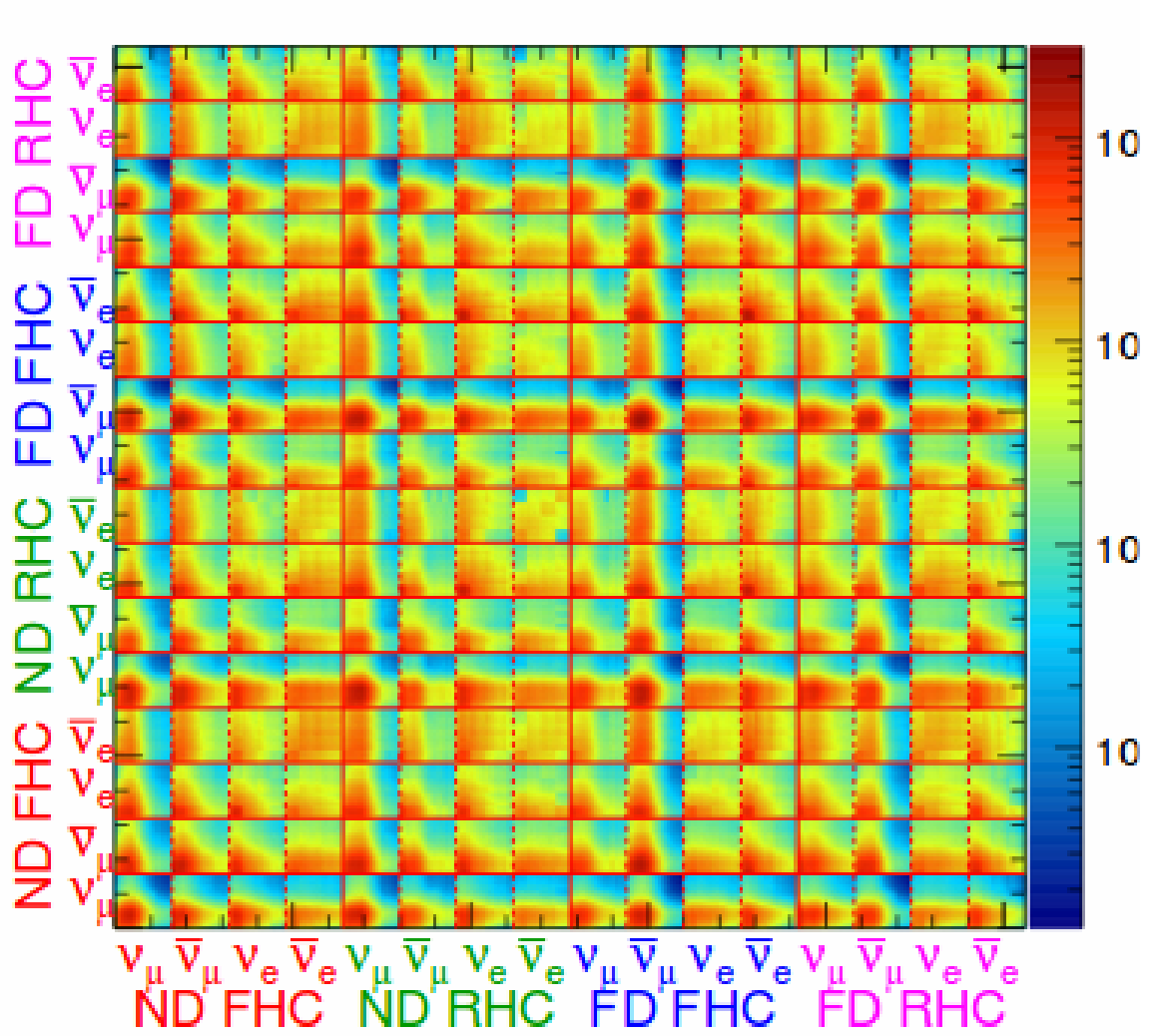
From Chris Backhouse

Component	Magnitude	Comment
ν CCQE 1	8.2%	$Q^2 < 0.2$
ν CCQE 2	23%	$0.2 < Q^2 < 0.55$
ν CCQE 3	48%	$Q^2 > 0.55$
$\bar{\nu}$ CCQE 1	8.7%	$Q^2 < 0.2$
$\bar{\nu}$ CCQE 2	24%	$0.2 < Q^2 < 0.55$
$\bar{\nu}$ CCQE 3	40%	$Q^2 > 0.55$
ν MEC dummy	100%	-
$\bar{\nu}$ MEC dummy	100%	-
ν CC1π^0 1	13%	$Q^2 < 0.35$
ν CC1π^0 2	23%	$0.35 < Q^2 < 0.90$
ν CC1π^0 3	35%	$Q^2 > 0.90$
ν CC1$\pi^\pm$ 1	13%	$Q^2 < 0.30$
ν CC1$\pi^\pm$ 2	24%	$0.30 < Q^2 < 0.80$
ν CC1$\pi^\pm$ 3	40%	$Q^2 > 0.80$
$\bar{\nu}$ CC1π^0 1	16%	$Q^2 < 0.35$
$\bar{\nu}$ CC1π^0 2	27%	$0.35 < Q^2 < 0.90$
$\bar{\nu}$ CC1π^0 3	35%	$Q^2 > 0.90$
$\bar{\nu}$ CC1$\pi^\pm$ 1	16%	$Q^2 < 0.30$
$\bar{\nu}$ CC1$\pi^\pm$ 2	30%	$0.30 < Q^2 < 0.80$
$\bar{\nu}$ CC1$\pi^\pm$ 3 3	40%	$Q^2 > 0.80$
ν 2π	22%	-
$\bar{\nu}$ 2π	22%	-
ν DIS 1	3.5%	$E_\nu < 7.5$
ν DIS 2	3.5%	$7.5 < E_\nu < 15$
ν DIS 3	2.7%	$E_\nu > 15$
$\bar{\nu}$ DIS 1	1%	$E_\nu < 7.5$
$\bar{\nu}$ DIS 2	1.7%	$7.5 < E_\nu < 15$
$\bar{\nu}$ DIS 3	1.7%	$E_\nu > 15$
ν COH	128%	-
$\bar{\nu}$ COH	134%	-
ν NC	16%	-
$\bar{\nu}$ NC	16%	-
ν_e / ν_μ dummy	3%	Not implemented yet

Flux Systematics (10)

Covariance matrix





- Eigenvalues 108+ should be zero. Floating precision → some negative
- Limit eigenvalues to 10^{-14}. $M = V^T \Lambda V$, $M \rightarrow V^T \Lambda' V$

Systematics

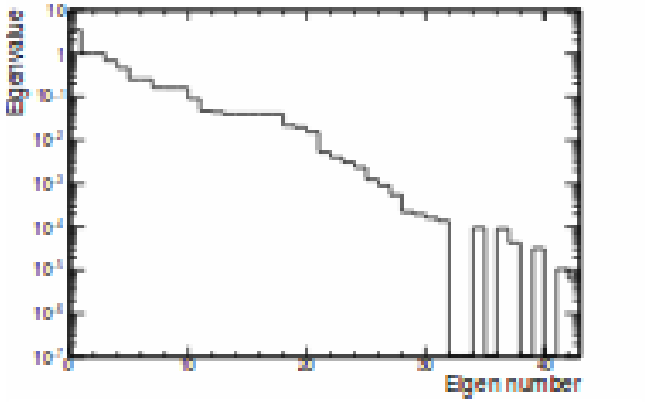
```
/// Absolute energy scale systematic
class EnergyScaleSyst: public ISyst
{
public:
  std::set<std::string> Requires() const override
  {
    return {"dune.Ev_reco"};
  }
  std::string ShortName() const override {return "eScale";}
  std::string LatexName() const override {return "Energy Scale";}

  void Shift(double sigma,
             Restorer& restore,
             caf::StandardRecord* sr, double& weight) const override
  {
    restore.Add(sr->dune.Ev_reco);

    const double scale = 1 + .02*sigma;
    sr->dune.Ev_reco *= scale;
  }
};

static const EnergyScaleSyst kEnergyScaleSyst;
```

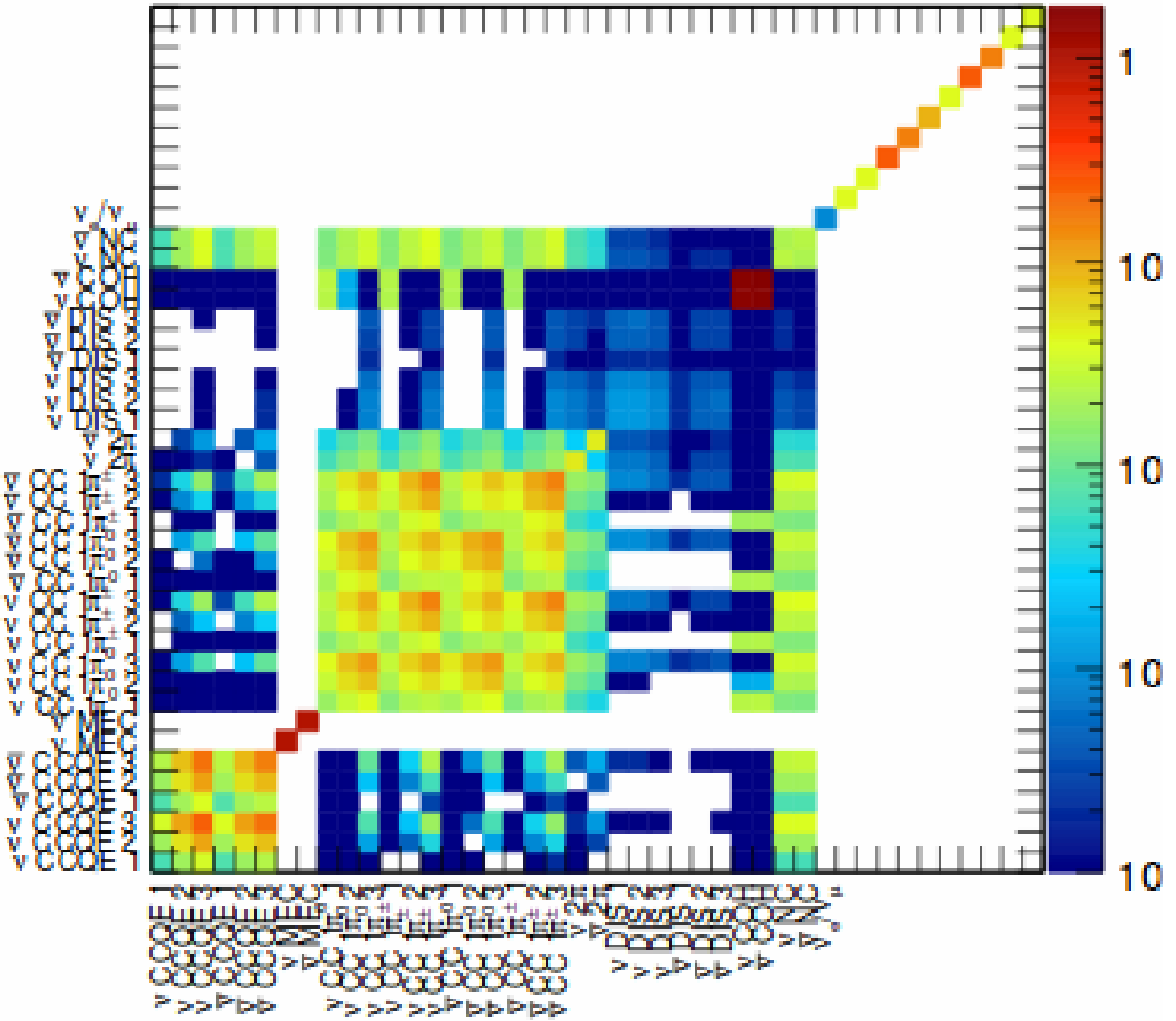
```
/// 5% normalization syst for NC on numu analysis
class NCSyst: public ISyst
{
public:
  std::set<std::string> Requires() const override
  {
    return {"dune.Ev","dune.Ev_reco", "dune.ccnc"};
  }
  std::string ShortName() const override {return "NC";}
  std::string LatexName() const override {return "NC Norm Syst";}

  void Shift(double sigma,
             Restorer& restore,
             caf::StandardRecord* sr, double& weight) const override
  {
    if(sr->dune.ccnc == 1) weight *= 1 + .05*sigma;
  }
};

static const NCSyst kNCSyst;
```

- An `ISyst` modifies or weights an event record as it's being loaded in
- Optional argument to `Spectrum` constructor taking a `SystShifts`

- `PredictionInterp` takes Predictions with various systematics applied and uses cubic interpolation between them
- If you only need scale systematics try `PredictionScaleComp`
- NOvA heritage means this machinery is a bit FD-centric (though ND sterile analyses have worked out), focus of upcoming development

Cross-sections





- Scale each vector by corresponding eigenvalue $\vec{v}_i \rightarrow \sqrt{\lambda_i}\vec{v}_i$
- Check normalization: $\vec{v}_i^T M^{-1} \vec{v}_i = 1$
- Check orthogonality: $(\vec{v}_i + \vec{v}_j)^T M^{-1} (\vec{v}_i + \vec{v}_j) = 2$
- Divide by flux to express as fractional error and save to root file