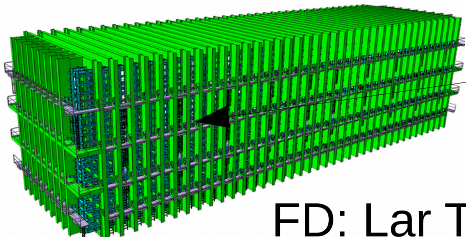
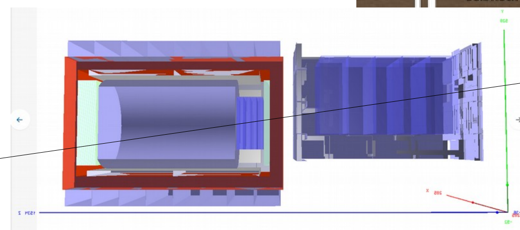
Sensitivity study of DUNE-Prism

Guang Yang

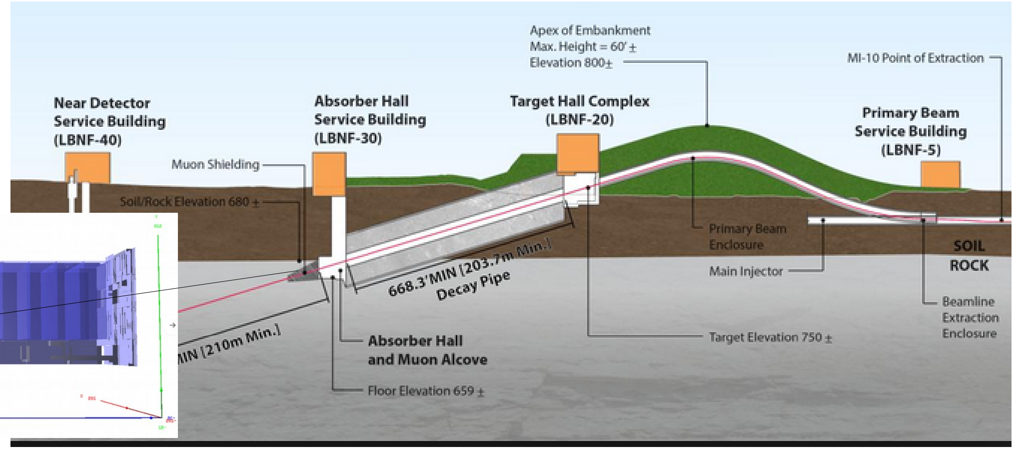
Introduction (1)



FD: Lar TPC



ND: Lar TPC+tracker



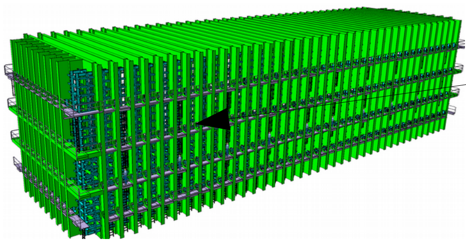
Beam flux

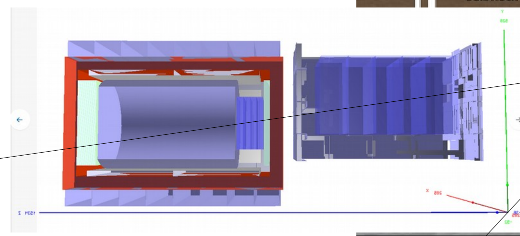
Best scenario 1: ND can see all the same effects (flux, xsec, detection) that being seen in the FD.

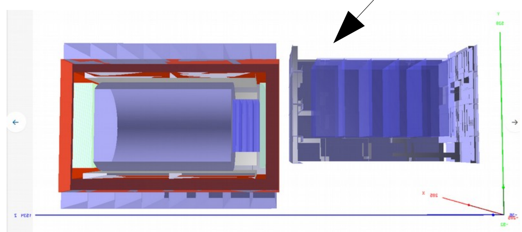
ND should be designed to identify model issues.
- If current model is not good enough to cover the data/MC discrepancy in ND, we will update the model.

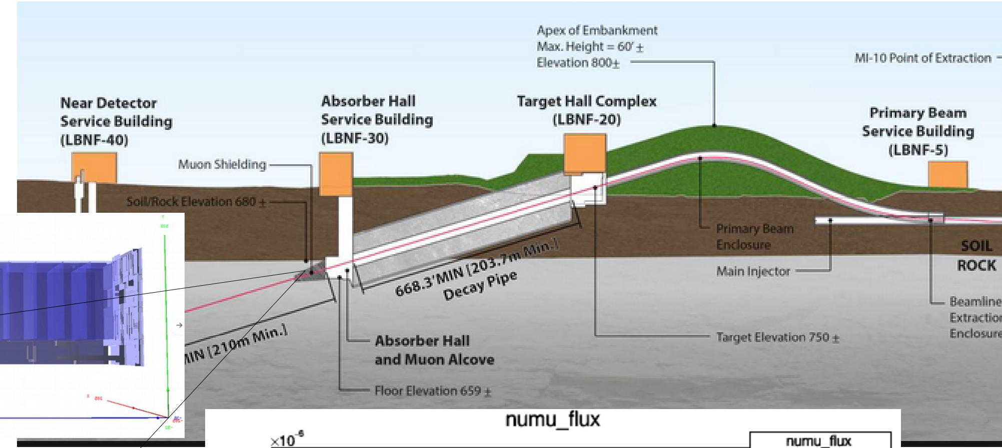
However, it is also possible that ND cannot identify model issues that ND data/MC agreement looks good..

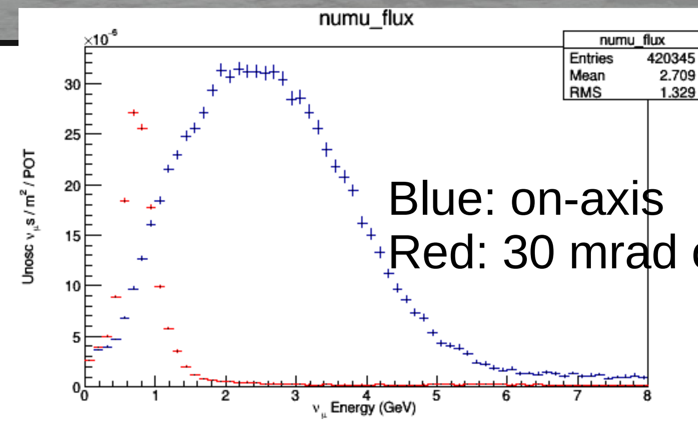
Introduction (2)











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 : 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

Tested Fake data samples (From GENIE) :

1. 10% and 20% missing proton mom.
2. 10% and 20% missing charged pion mom.
3. 10% and 20% missing muon mom.

We are showing the missing charged pion mom. case here.

Fitting samples

```
PredictionInterp& predNDFHC = *ana::LoadFrom<PredictionInterp>(fin.GetDirectory("nd_fhc")).release();
PredictionInterp& predNDRHC = *ana::LoadFrom<PredictionInterp>(fin.GetDirectory("nd_rhc")).release();

PredictionInterp& predFDNumuFHC = *ana::LoadFrom<PredictionInterp>(fin.GetDirectory("fd_numu_fhc")).release();
PredictionInterp& predFDNueFHC = *ana::LoadFrom<PredictionInterp>(fin.GetDirectory("fd_nue_fhc")).release();
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PredictionInterp& predFDNueRHC = *ana::LoadFrom<PredictionInterp>(fin.GetDirectory("fd_nue_rhc")).release();
```
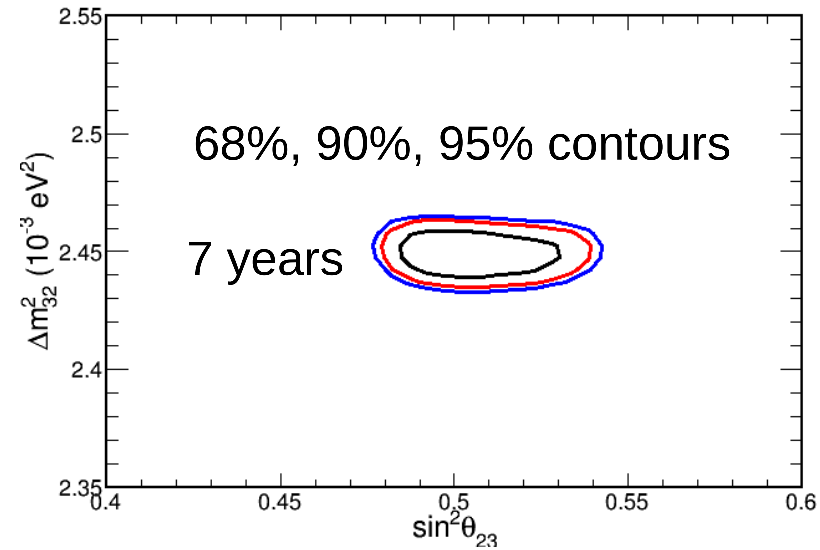
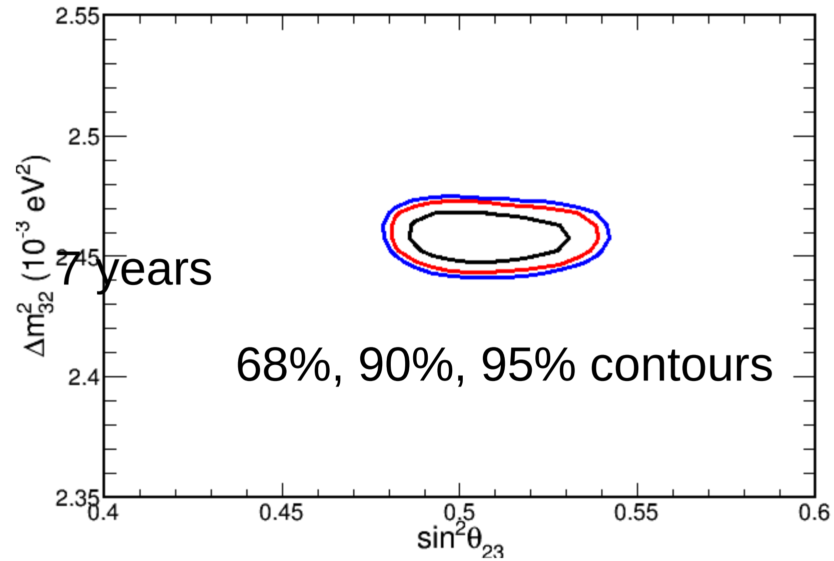

- ND : FHC and RHC numu
- FD: FHC numu, nue and RHC numu and nue
- Variables: oscillation parameters.
  Systematics variables:
    - 32 Xsec variables (channel specific, introduced later)
    - 10 Flux variables (Channel specific)
    - 2% Energy scale and 6% energy resolution
    - many variables introduced by me (fake data variables..)
      "One sigma" means the standard variation in fake data.

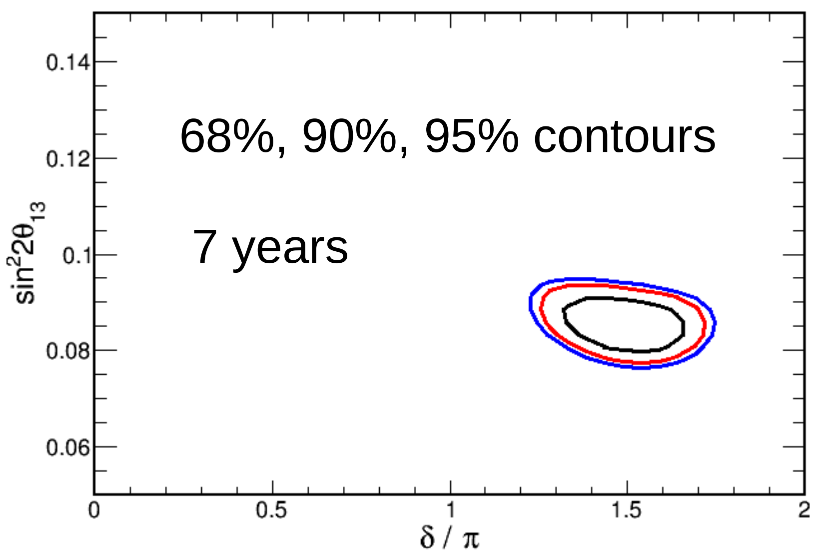
FD+ND fit with Xsec+Flux systematics
10% Missing charged pion energy

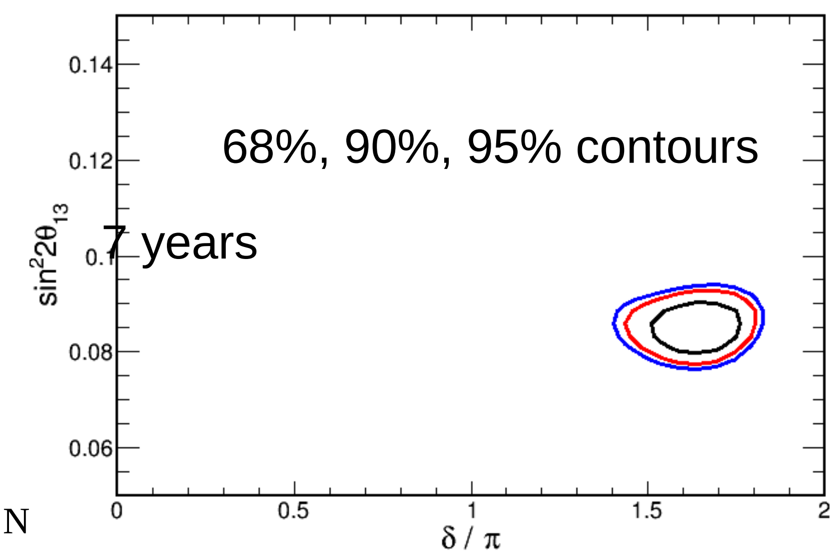
True



Varied







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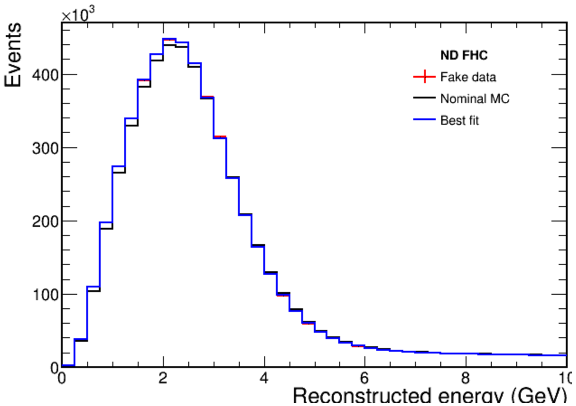
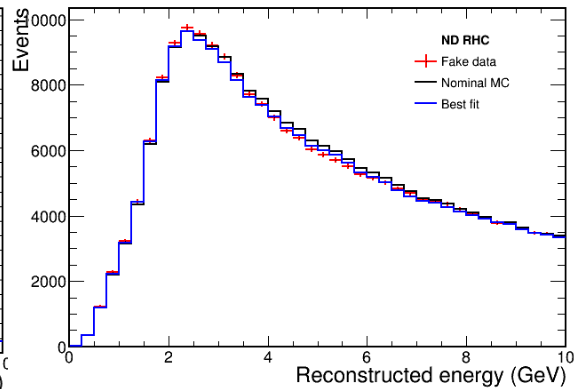
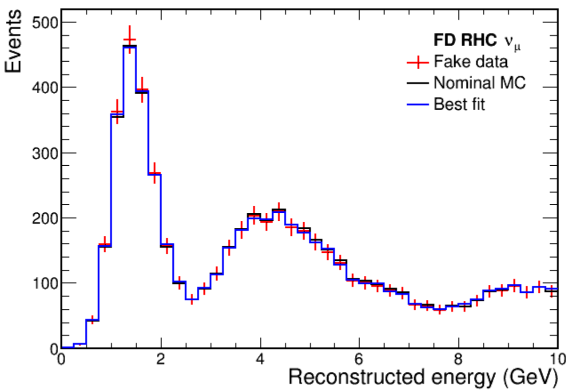
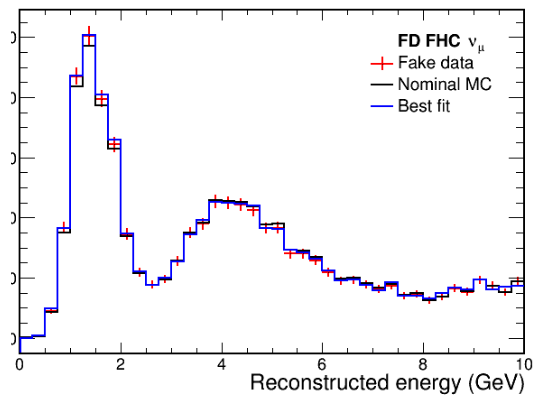
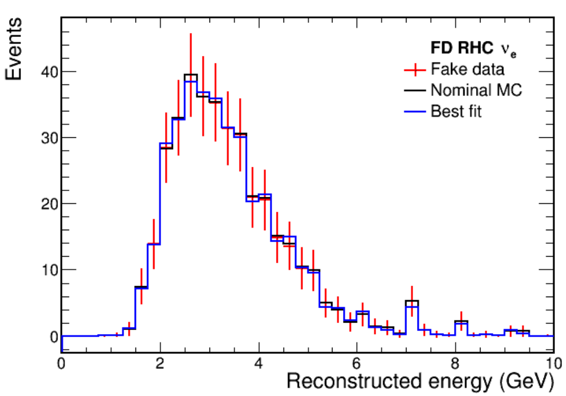
FD+ND fit with Xsec+Flux systematics
10% Missing charged pion energy

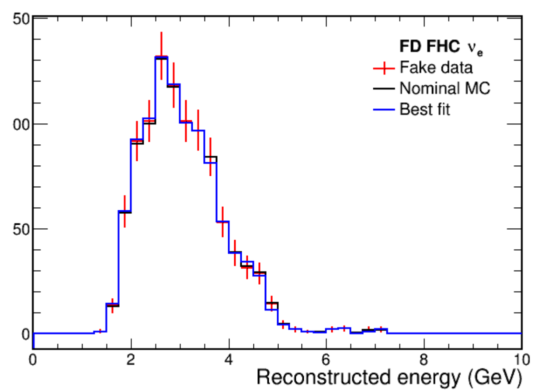










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Syst. shift  nu_ccqe_3_scale -0.000226543
Syst. shift  nubar_ccqe_1_scale 0.00184792
Syst. shift  nubar_ccqe_2_scale 0.00035097
Syst. shift  nubar_ccqe_3_scale 0.000492375
Syst. shift  nu_MEC_dummy_scale 6.70996e-07
Syst. shift  nubar_MEC_dummy_scale -5.30937e-07
Syst. shift  nu_cc1piz_1_scale 0.000210088
Syst. shift  nu_cc1piz_2_scale 0.000806721
Syst. shift  nu_cc1piz_3_scale -0.000600518
Syst. shift  nu_cc1pic_1_scale 0.000811001
Syst. shift  nu_cc1pic_2_scale -0.000855719
Syst. shift  nu_cc1pic_3_scale 0.00168443
Syst. shift  nubar_cc1piz_1_scale -0.00188379
Syst. shift  nubar_cc1piz_2_scale -0.000654449
Syst. shift  nubar_cc1piz_3_scale 0.000486619
Syst. shift  nubar_cc1pic_1_scale -0.000358289
Syst. shift  nubar_cc1pic_2_scale 0.00034559
Syst. shift  nubar_cc1pic_3_scale -0.000518118
Syst. shift  nu_2pi_scale -0.450305
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Syst. shift  nu_dis_1_scale 0.00208606
Syst. shift  nu_dis_2_scale -0.00763268
Syst. shift  nu_dis_3_scale 0.00178071
Syst. shift  nubar_dis_1_scale 0.0152618
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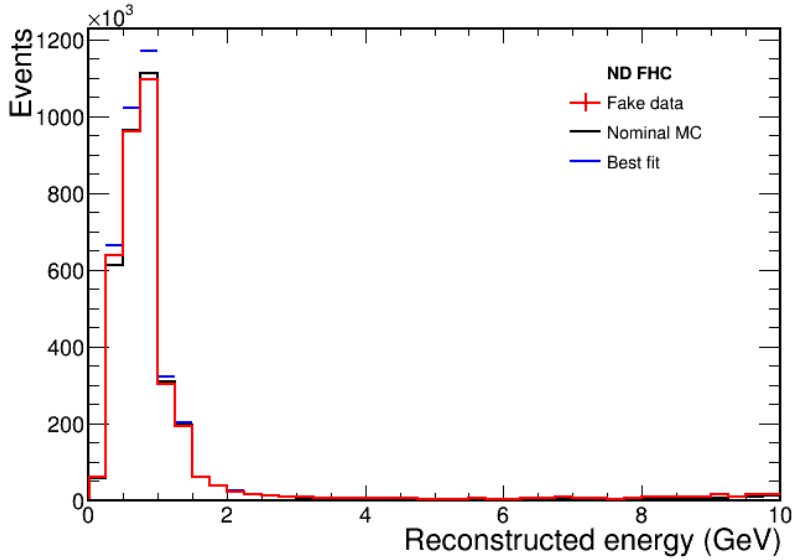
Syst. shift  nubar_nc_scale 0.0698415
Syst. shift  flux26 0.320399
Syst. shift  flux27 -1.23085
Syst. shift  flux28 1.58179
Syst. shift  flux29 -1.44371
Syst. shift  flux30 0.800996
Syst. shift  eScale -0.459696
Syst. shift  eRes -0.0432047
True dCP 0pi, best fit -0.452273pi, chi2 189.852 delta=0 chi2 189.852
```

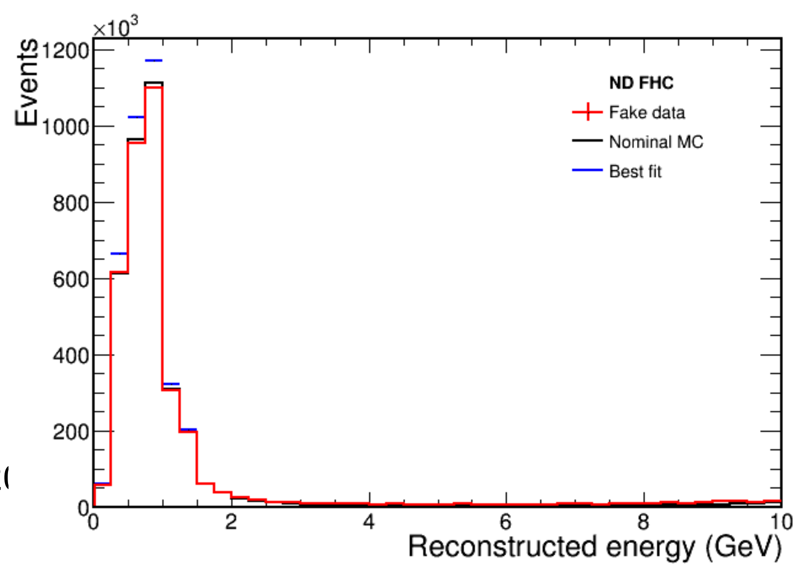
FD+ND fit with Xsec+Flux systematics
20% Missing charged pion energy
30 mrad off-axis FHC



Black : nominal 30mrad off-axis

Blue : with on-axis best fit

Red : real 10% MPE



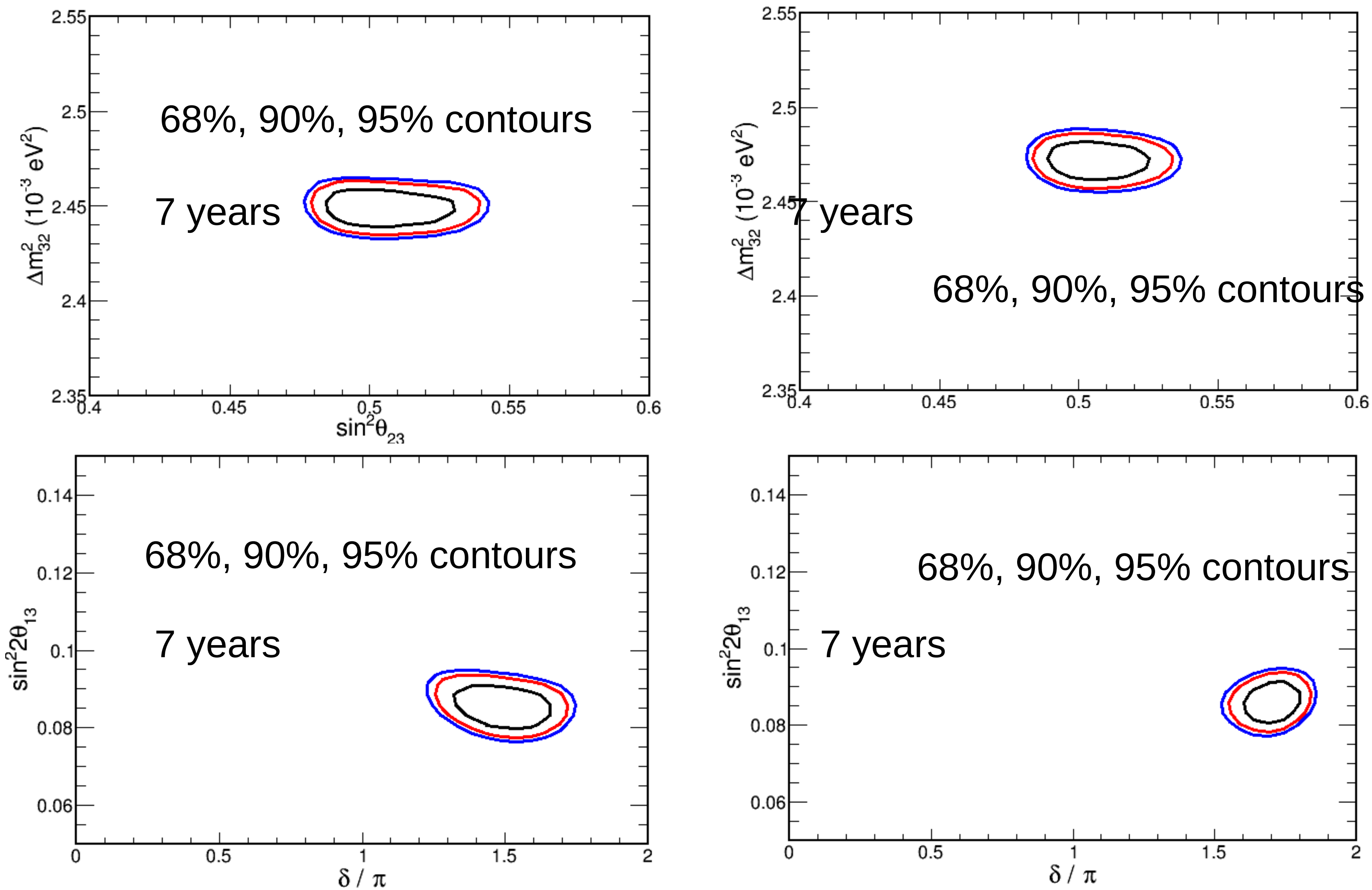
Black : nominal 45mrad off-axis

Blue : with on-axis best fit

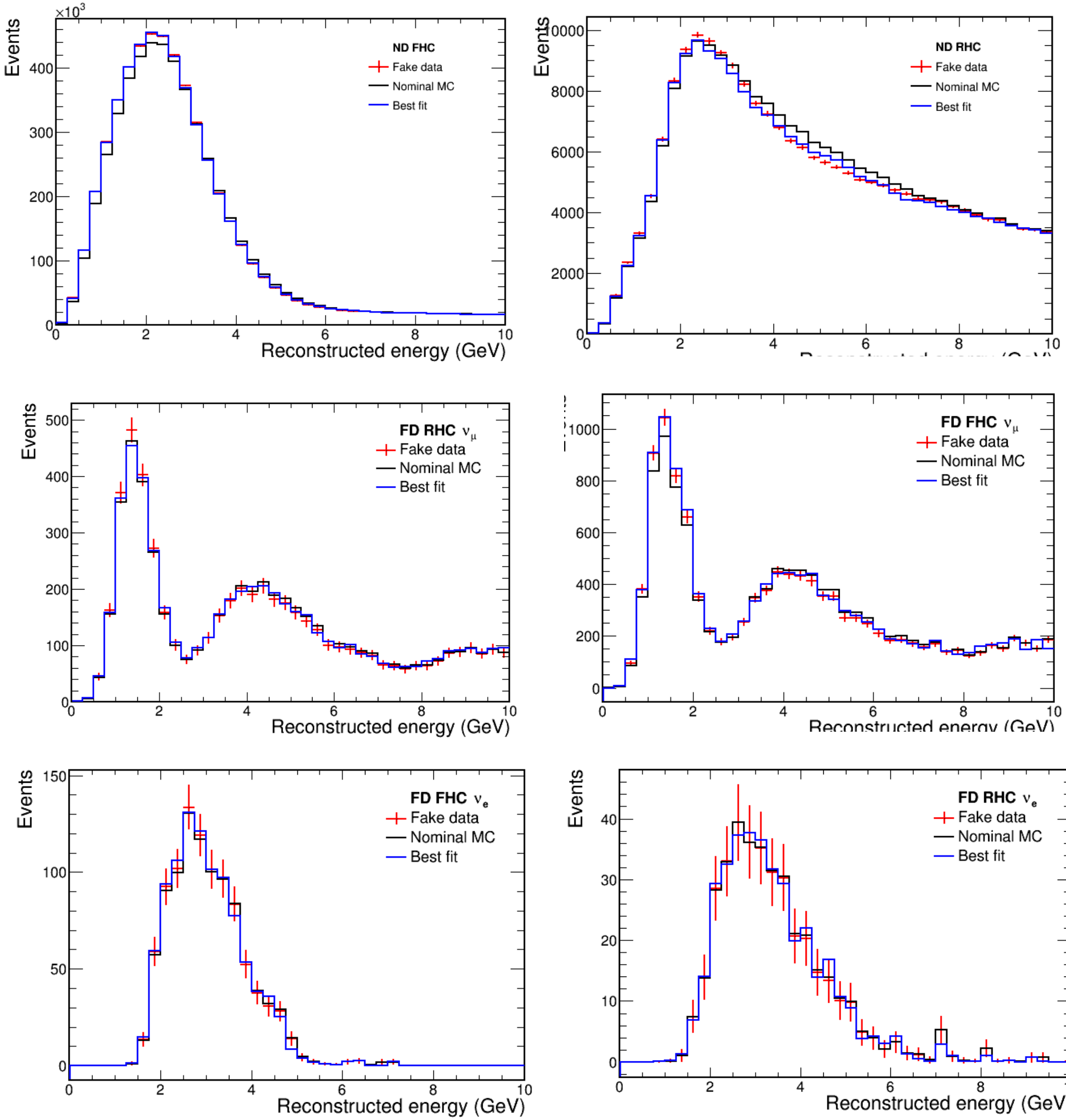
Red : real 10% MPE

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

True | Varied



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

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Syst. shift  nubar_ccqe_1_scale 0.00331504
Syst. shift  nubar_ccqe_2_scale 0.000759089
Syst. shift  nubar_ccqe_3_scale 0.000992179
Syst. shift  nu_MEC_dummy_scale -4.4206e-07
Syst. shift  nubar_MEC_dummy_scale -8.11205e-07
Syst. shift  nu_cc1piz_1_scale 0.000780108
Syst. shift  nu_cc1piz_2_scale 0.00158366
Syst. shift  nu_cc1piz_3_scale -0.00128412
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Syst. shift  nu_dis_2_scale -0.0154014
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Syst. shift  nubar_dis_1_scale 0.0361961
Syst. shift  nubar_dis_2_scale -0.0526717
Syst. shift  nubar_dis_3_scale 0.0490354
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Syst. shift  nubar_coh_scale -0.00060759
Syst. shift  nu_nc_scale -0.35255
Syst. shift  nubar_nc_scale 0.124744
Syst. shift  flux26 0.794495
Syst. shift  flux27 -2.68711
Syst. shift  flux28 3.56615
Syst. shift  flux29 -3.04143
Syst. shift  flux30 1.70414
Syst. shift  eScale -0.891228
Syst. shift  eRes -0.0484774
True dCP 0pi, best fit -0.42125pi, chi2 682.52 delta=0 chi2 682.52
```
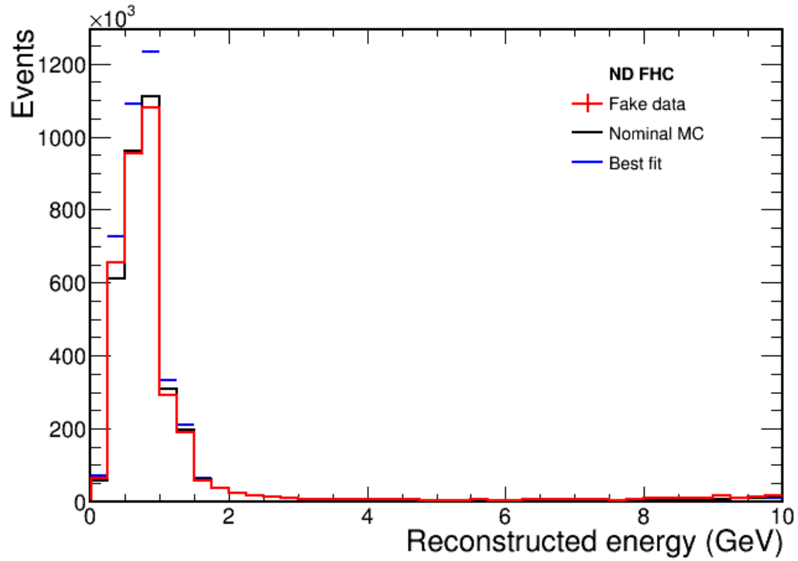
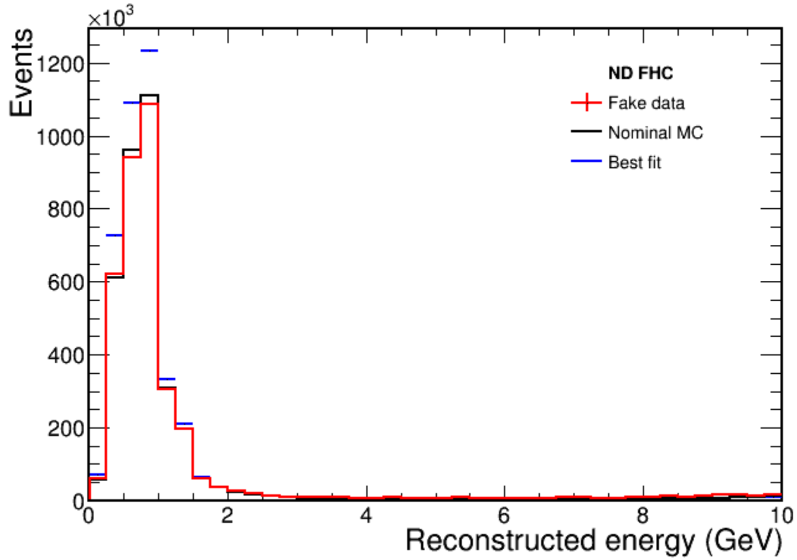

FD+ND fit with Xsec+Flux systematics
20% Missing charged pion energy
30 mrad off-axis FHC



Black : nominal 30mrad off-axis

Blue : with on-axis best fit

Red : real 20% MPE



Black : nominal 45mrad off-axis

Blue : with on-axis best fit

Red : real 20% MPE

Conclusion

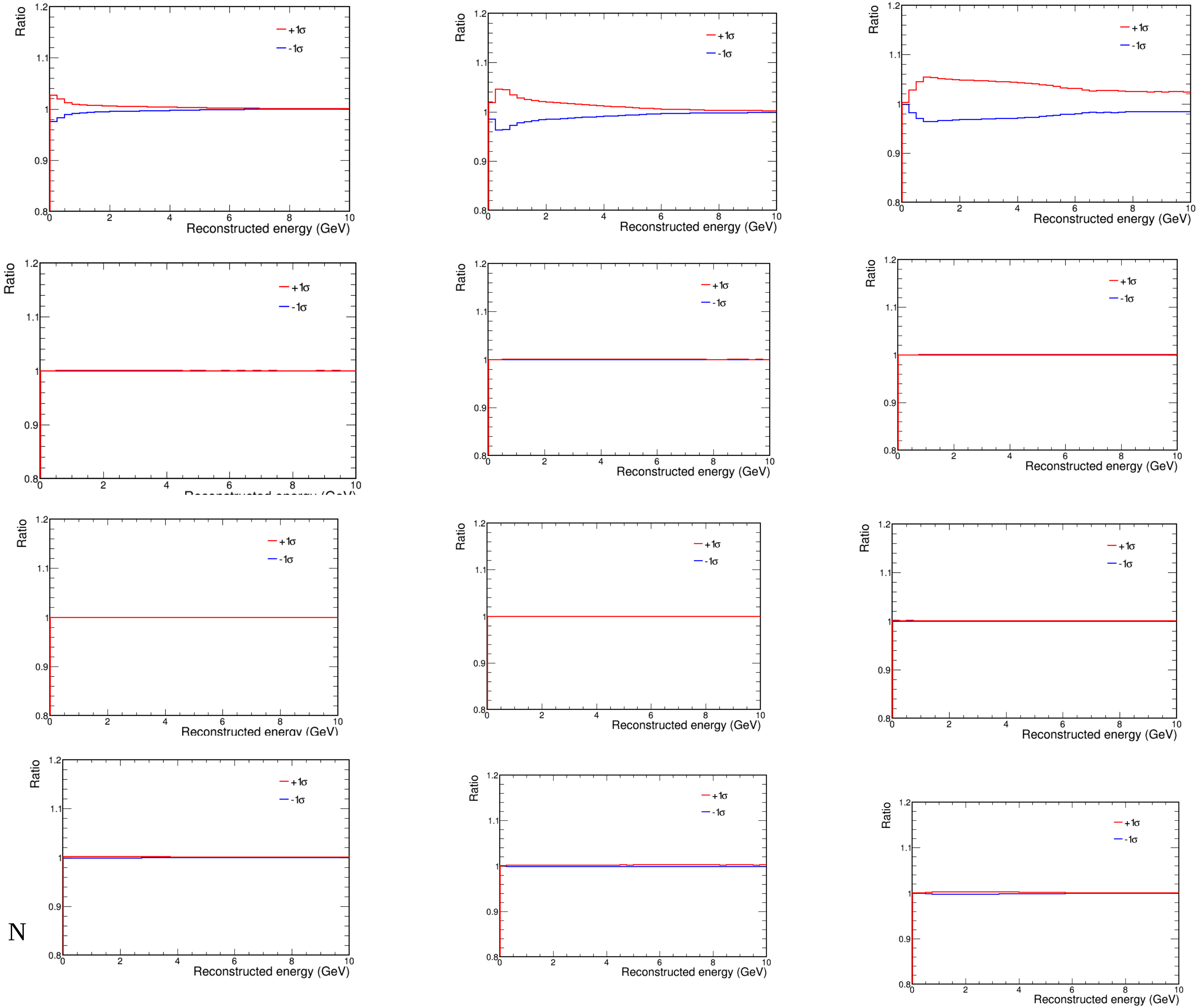
- Even with identical ND and FD response, we may have oscillation parameter bias with a good ND prediction/data agreement.

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

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

Backup..

Xsec ND FHC



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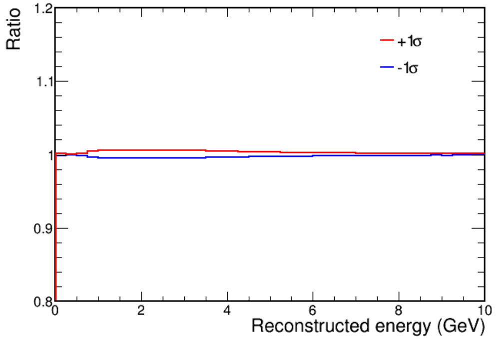
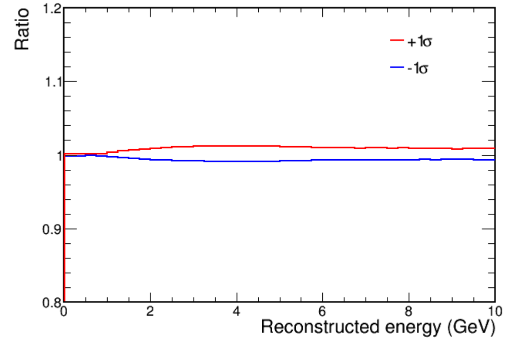

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

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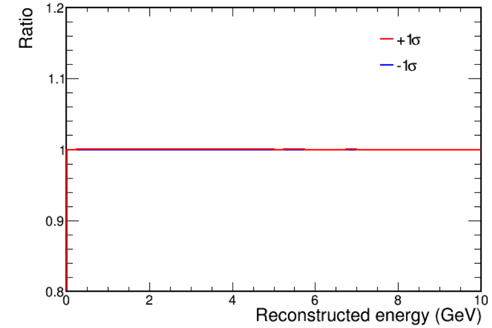
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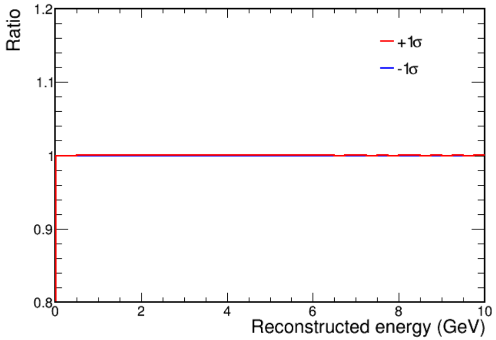
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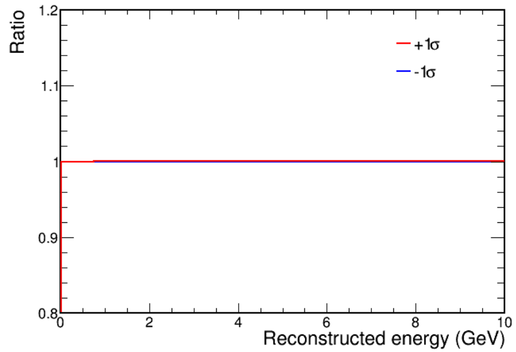
Reconstructed energy (GeV)

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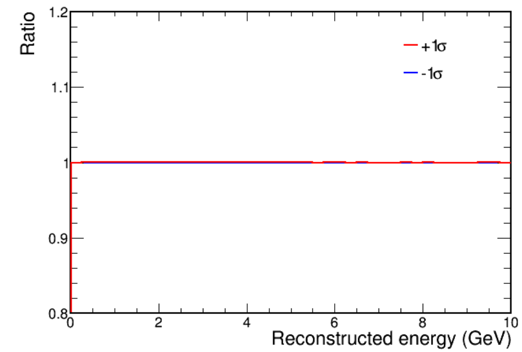
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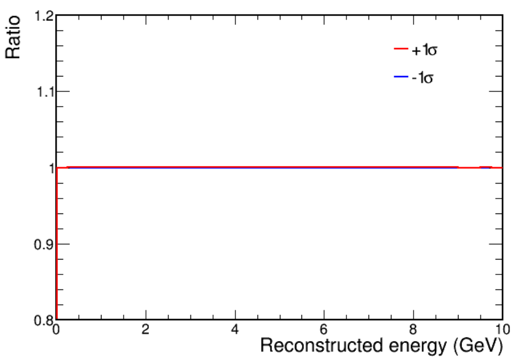
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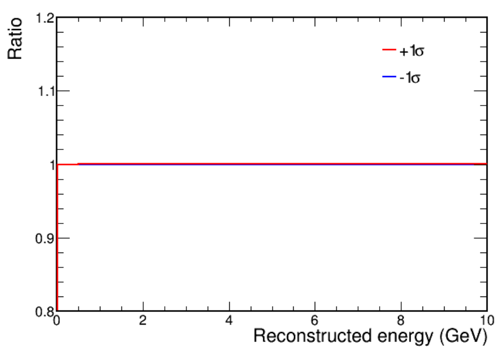
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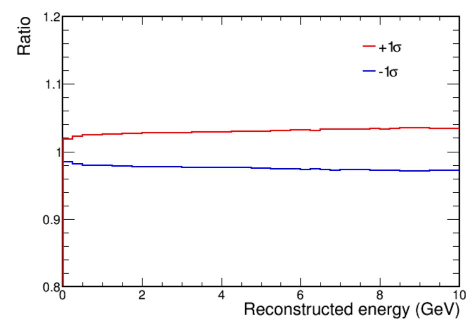
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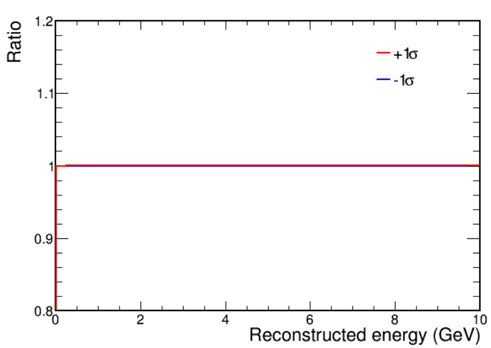
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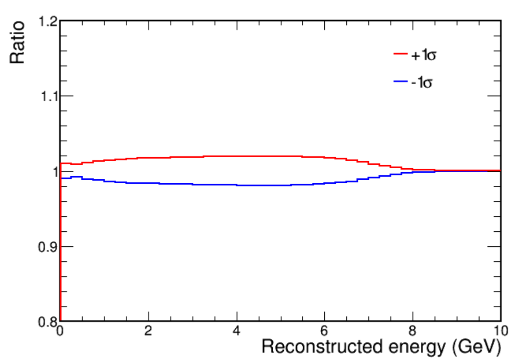
Ratio
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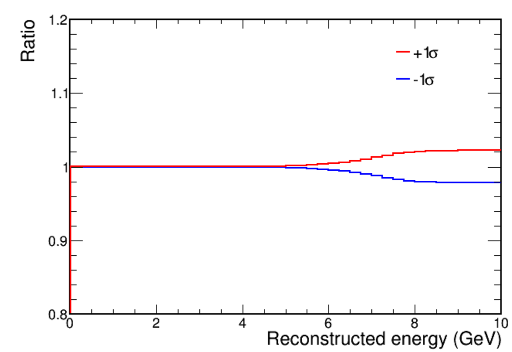
Ratio
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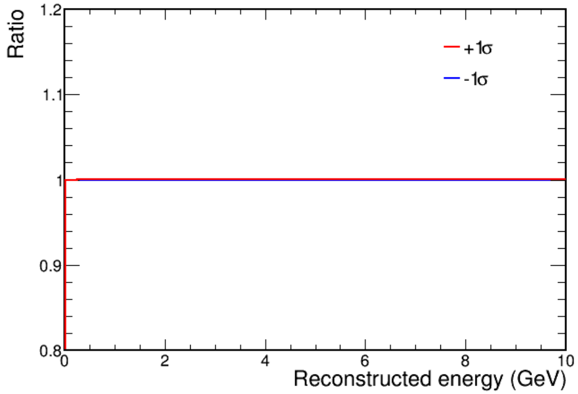
-1σ
Reconstructed energy (GeV)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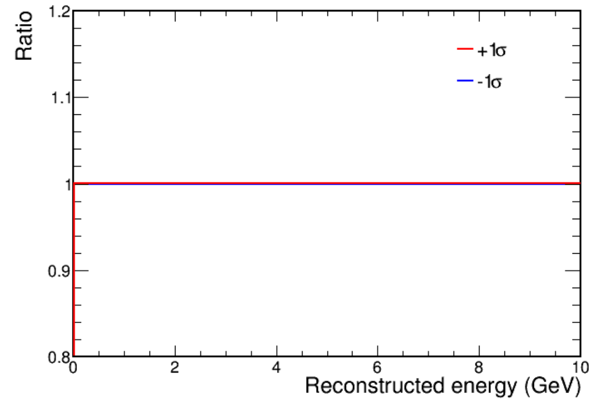
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)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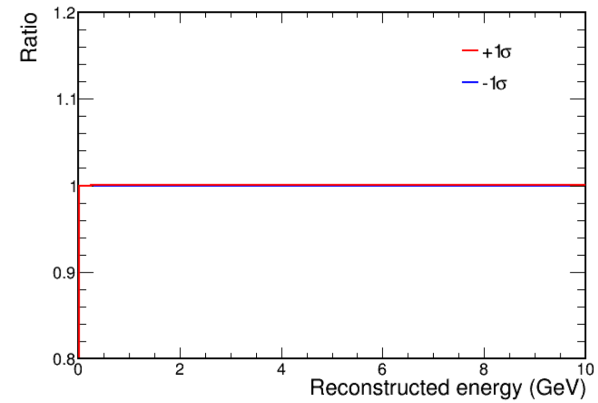
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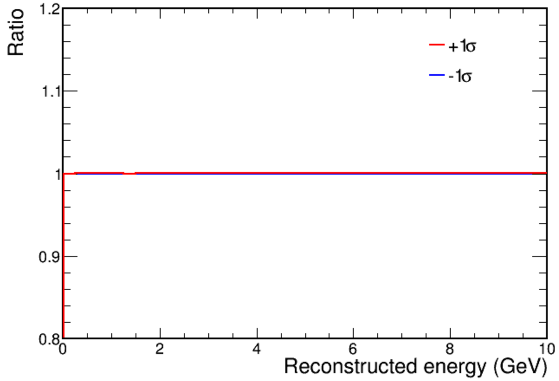
Reconstructed energy (GeV)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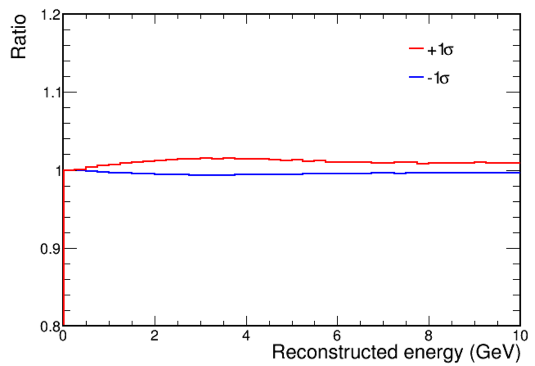
Reconstructed energy (GeV)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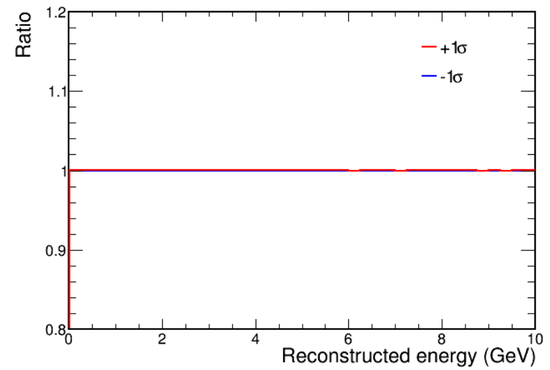
Reconstructed energy (GeV)


Ratio
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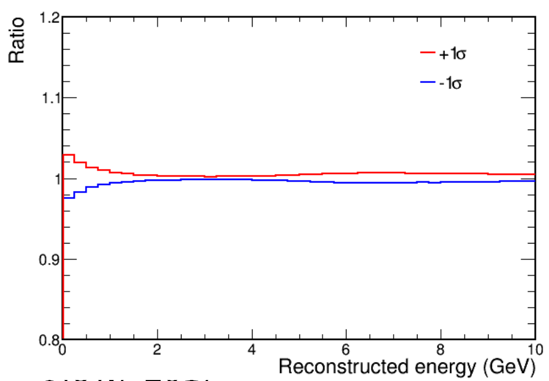
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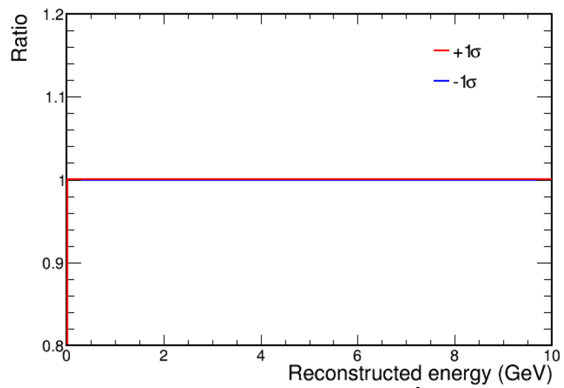
-1σ
Reconstructed energy (GeV)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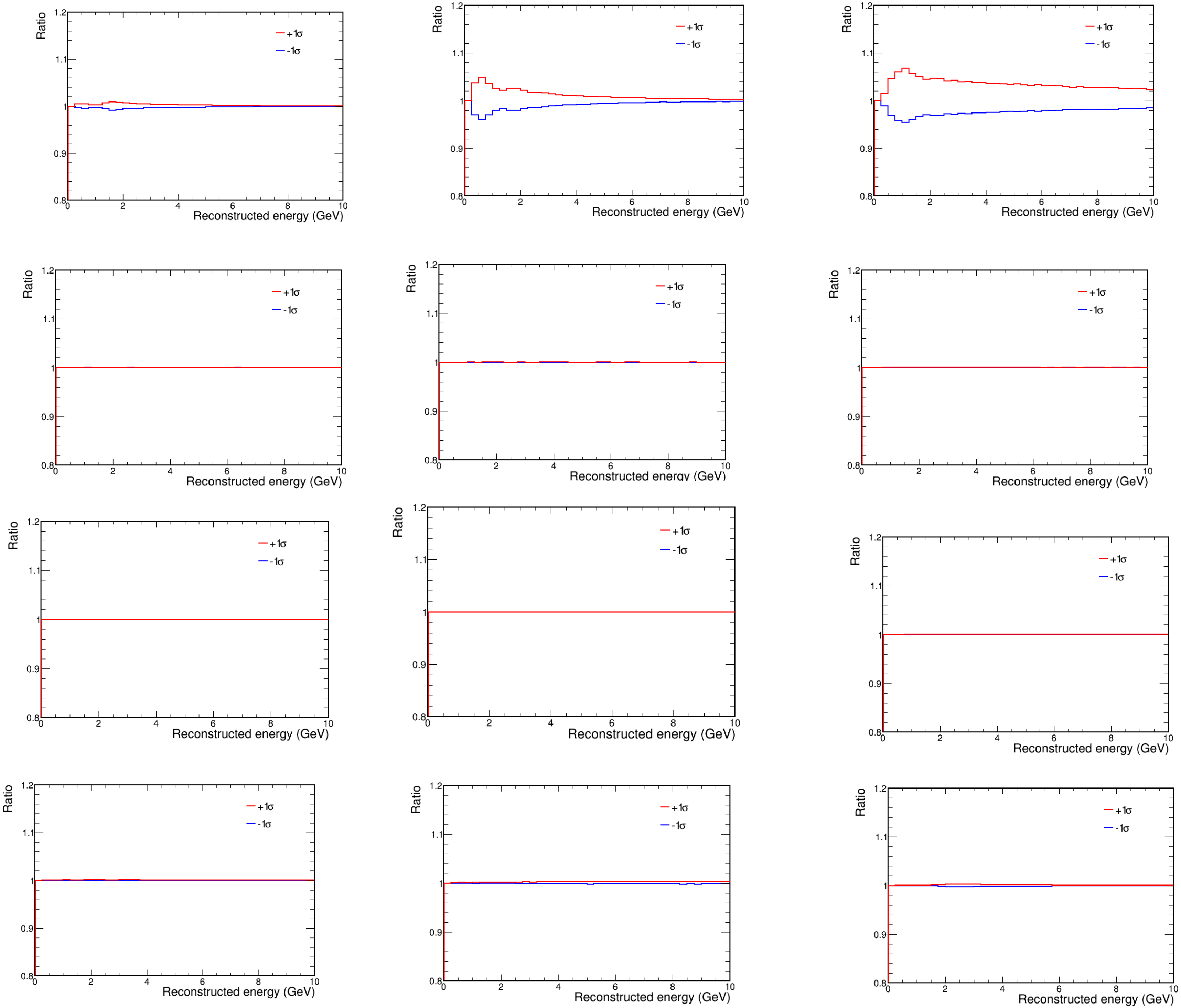
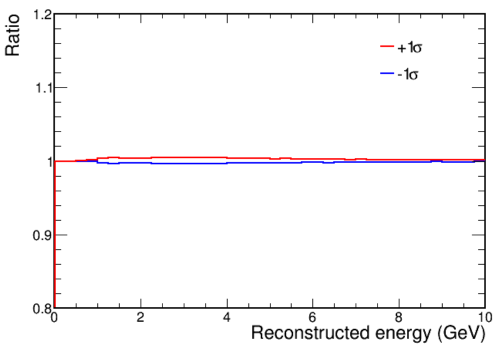
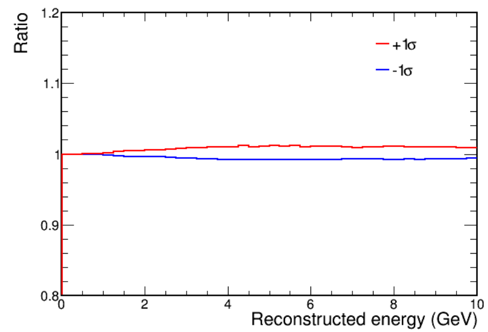
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)

Xsec ND RHC




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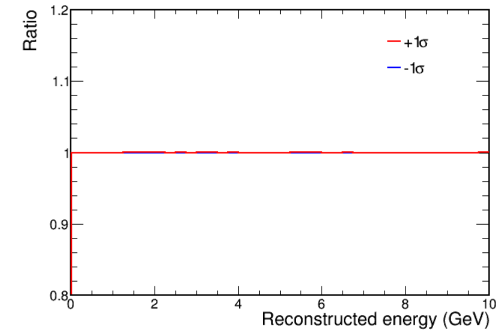
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)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1
0.9
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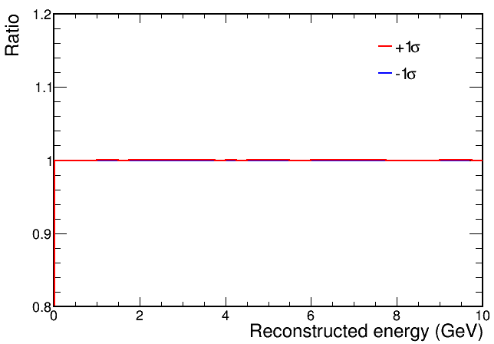
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)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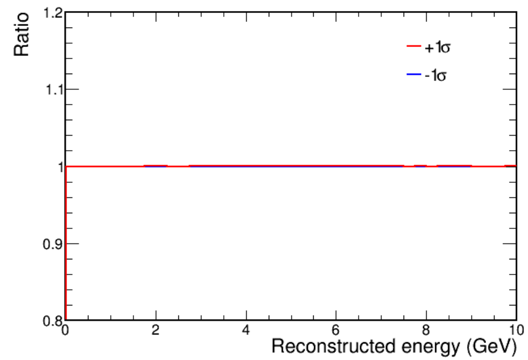
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)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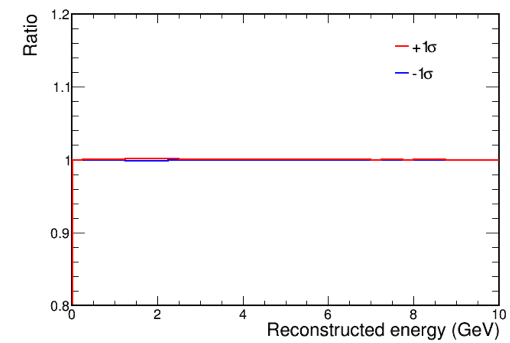
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


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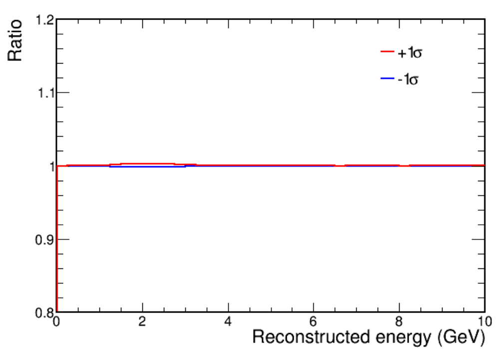
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


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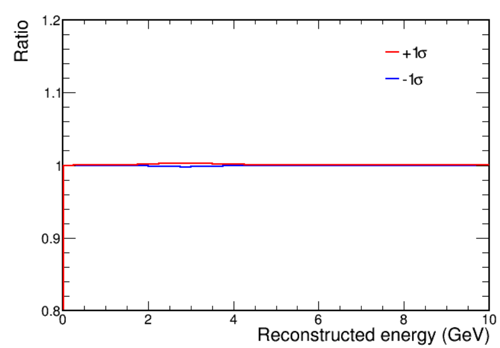
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


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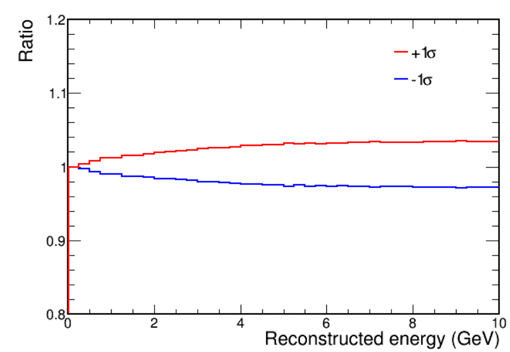
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


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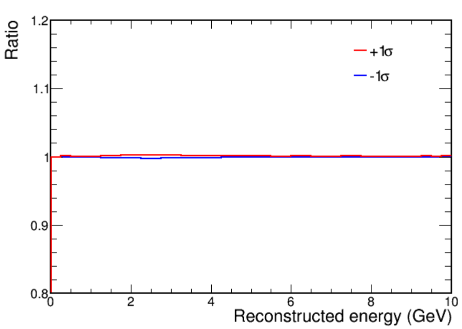
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


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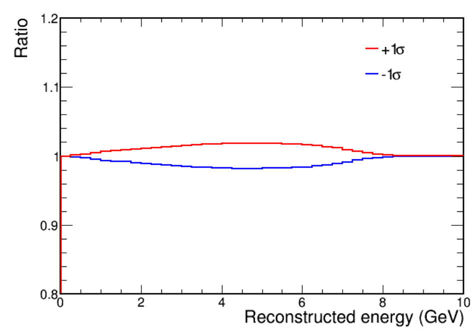
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)


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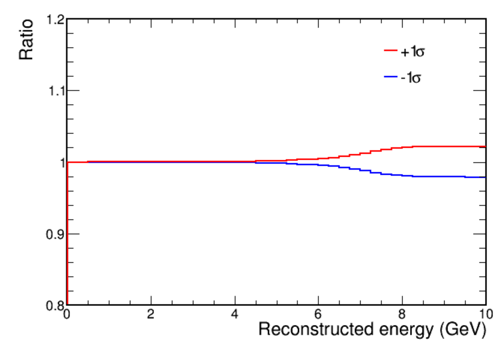
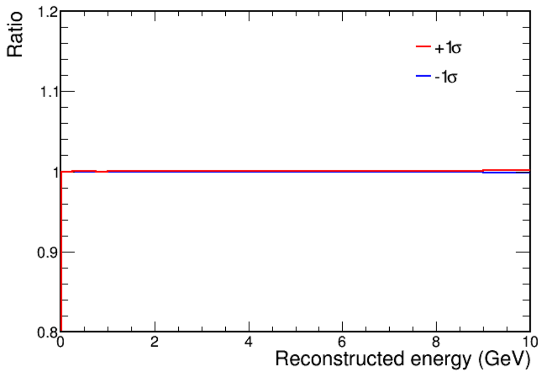
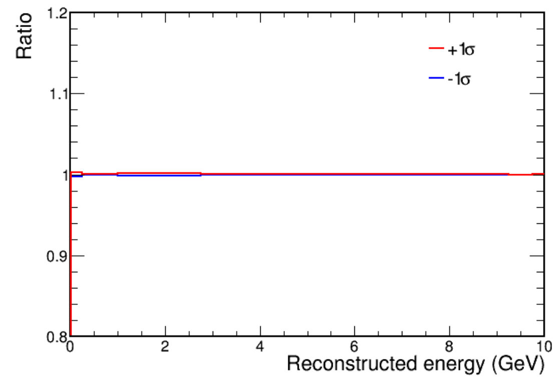
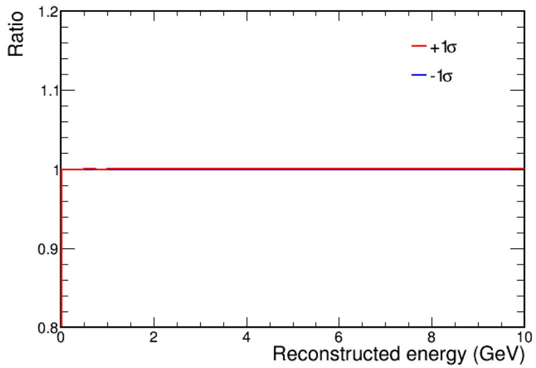
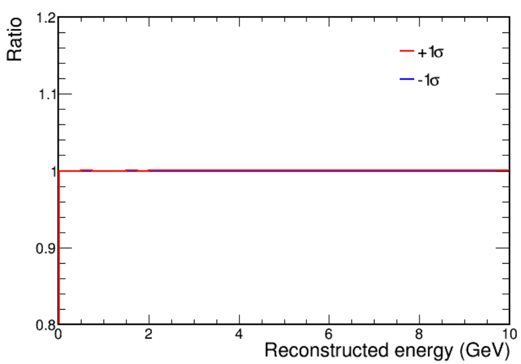
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)

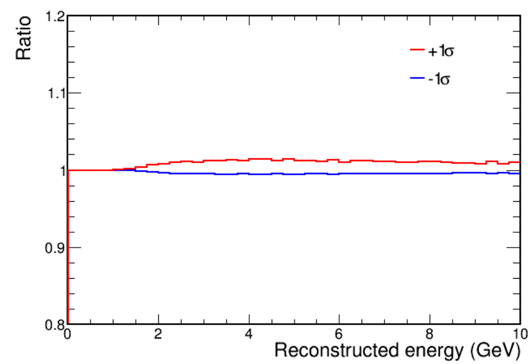

Ratio
1.2
1.1
1
0.9
0.8
0
2
4
6
8
10
+1σ
-1σ
Reconstructed energy (GeV)

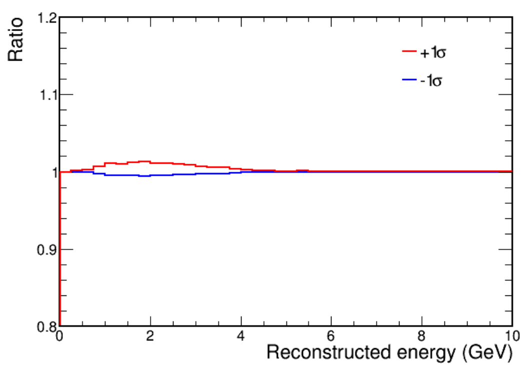

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

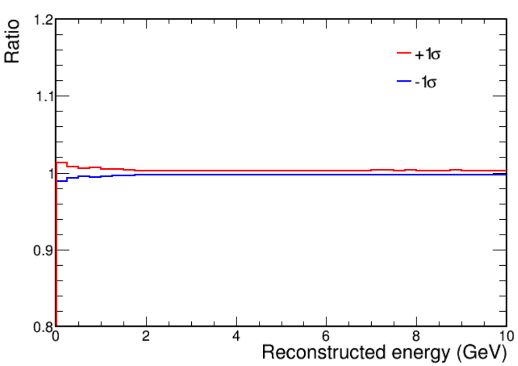

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

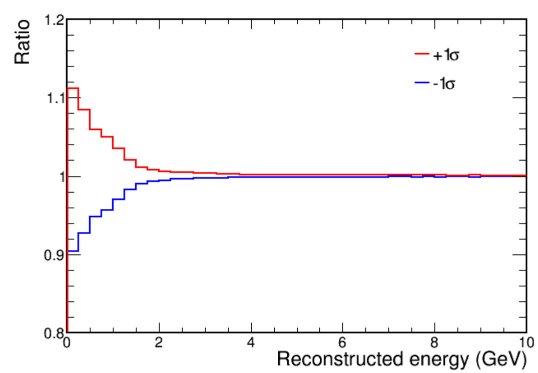

Ratio
+1σ
-1σ
Reconstructed energy (GeV)


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

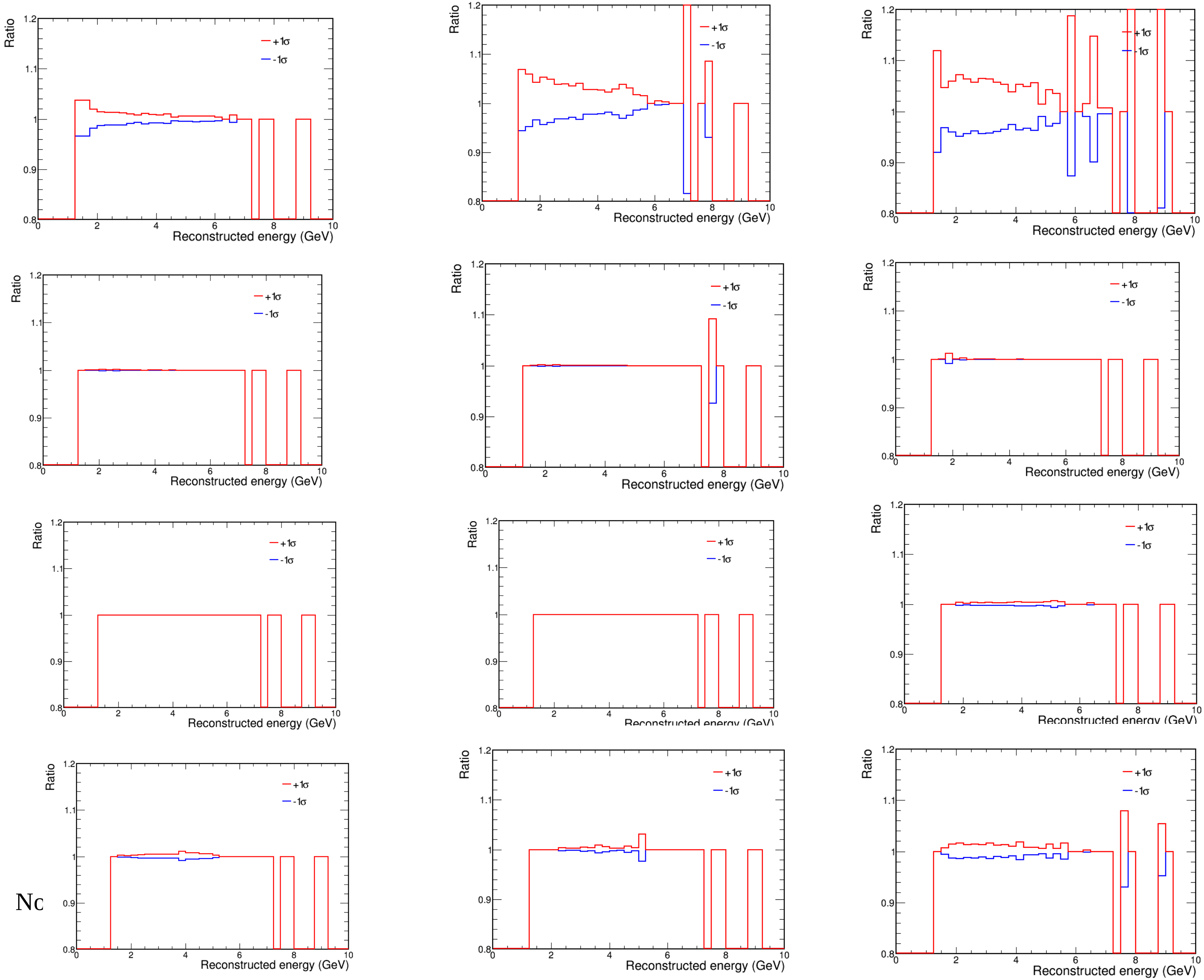

Ratio
+1σ
-1σ
Reconstructed energy (GeV)


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

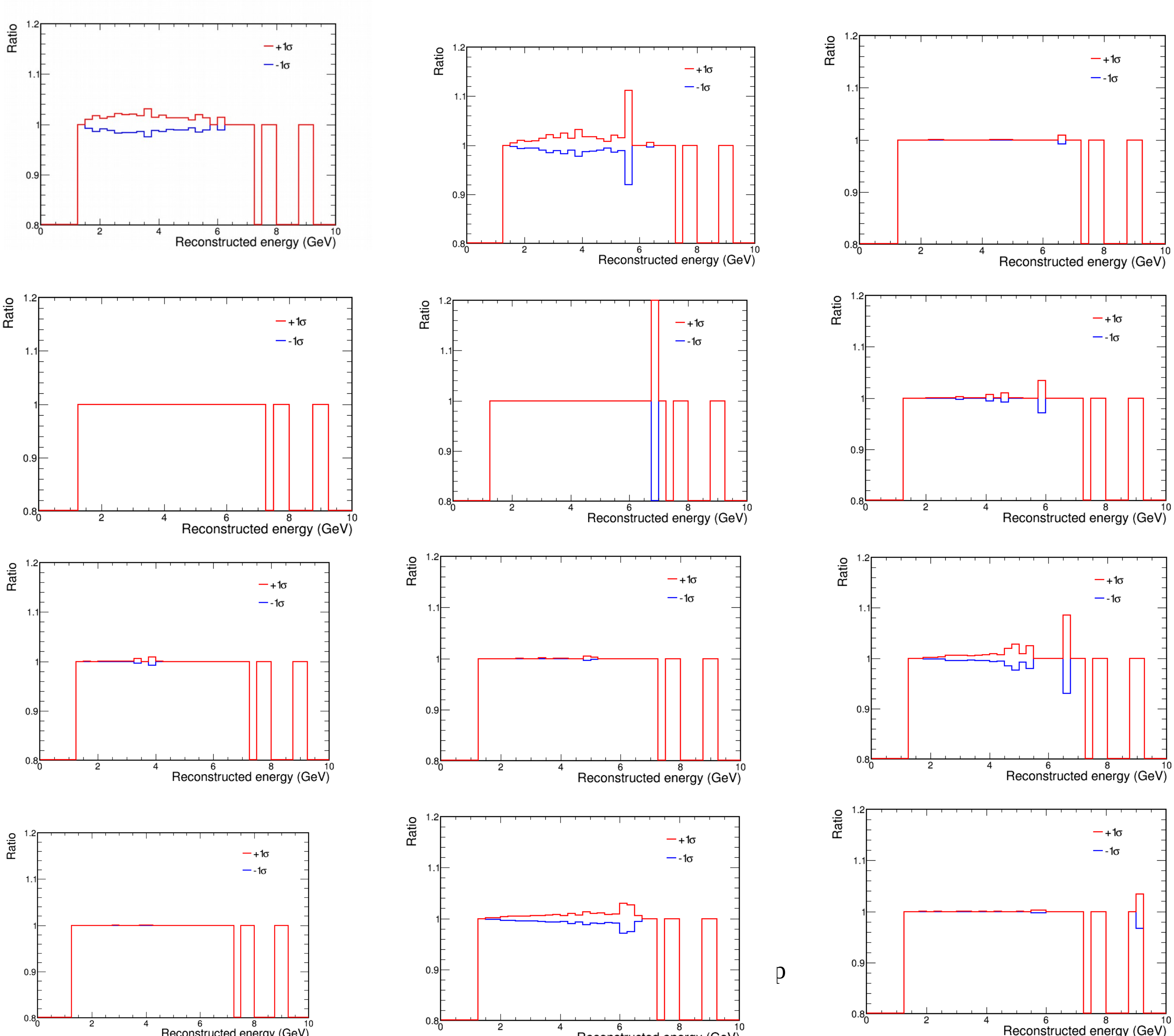

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

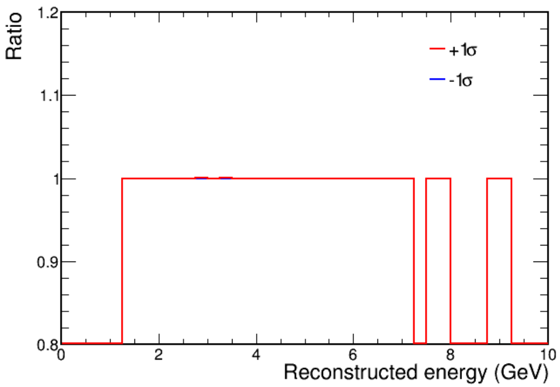

Ratio
+1σ
-1σ
Reconstructed energy (GeV)

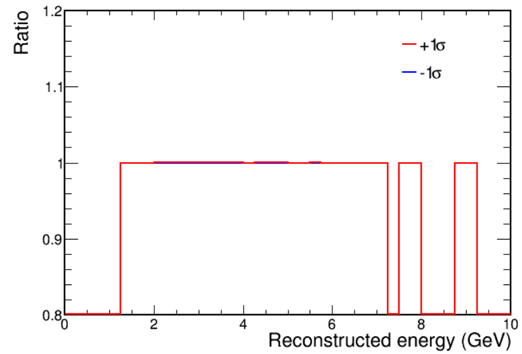
Xsec FD nue FHC

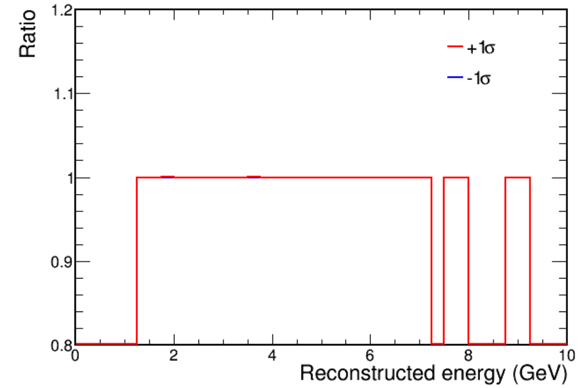


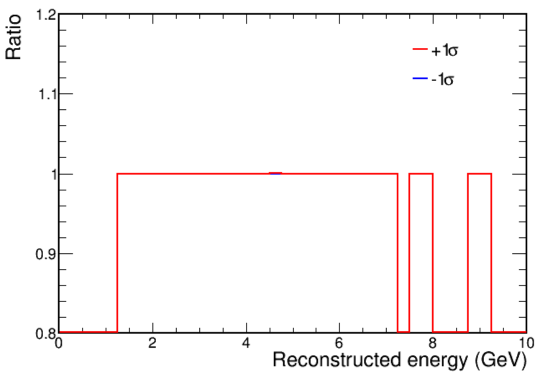
Nc

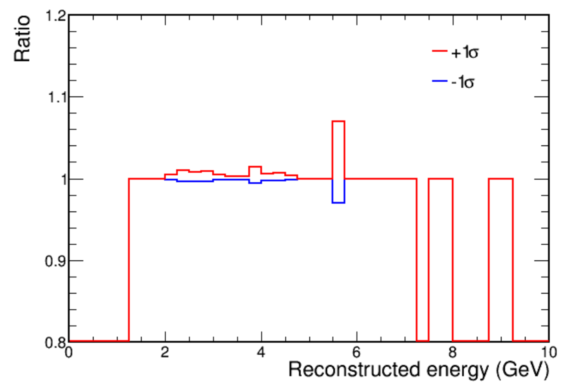

Ratio
Reconstructed energy (GeV)
+1σ
-1σ

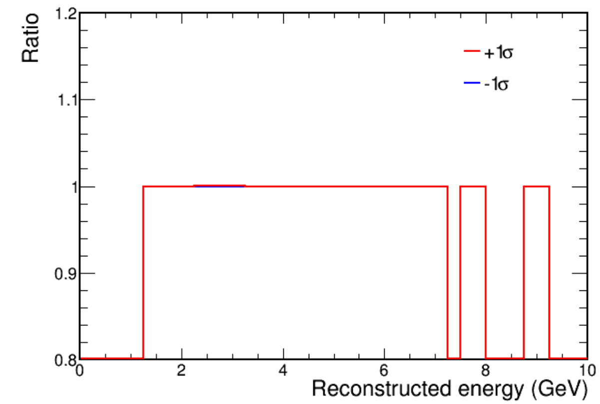

Ratio
1.2
1.1
1
0.9
0.8
+1σ
-1σ
0 2 4 6 8 10
Reconstructed energy (GeV)

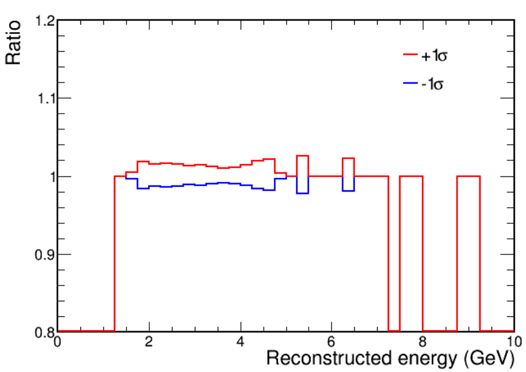

Ratio
1.2
1.1
1
0.9
0.8
+1σ
-1σ
0 2 4 6 8 10
Reconstructed energy (GeV)

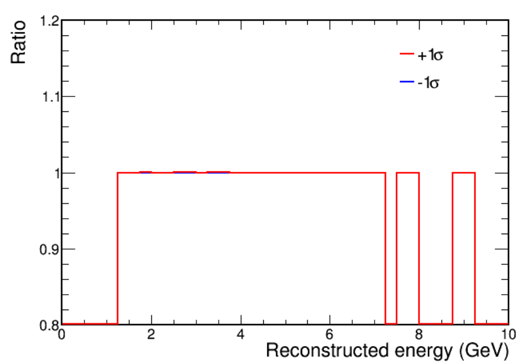

Ratio
1.2
1.1
1
0.9
0.8
+1σ
-1σ
0 2 4 6 8 10
Reconstructed energy (GeV)


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

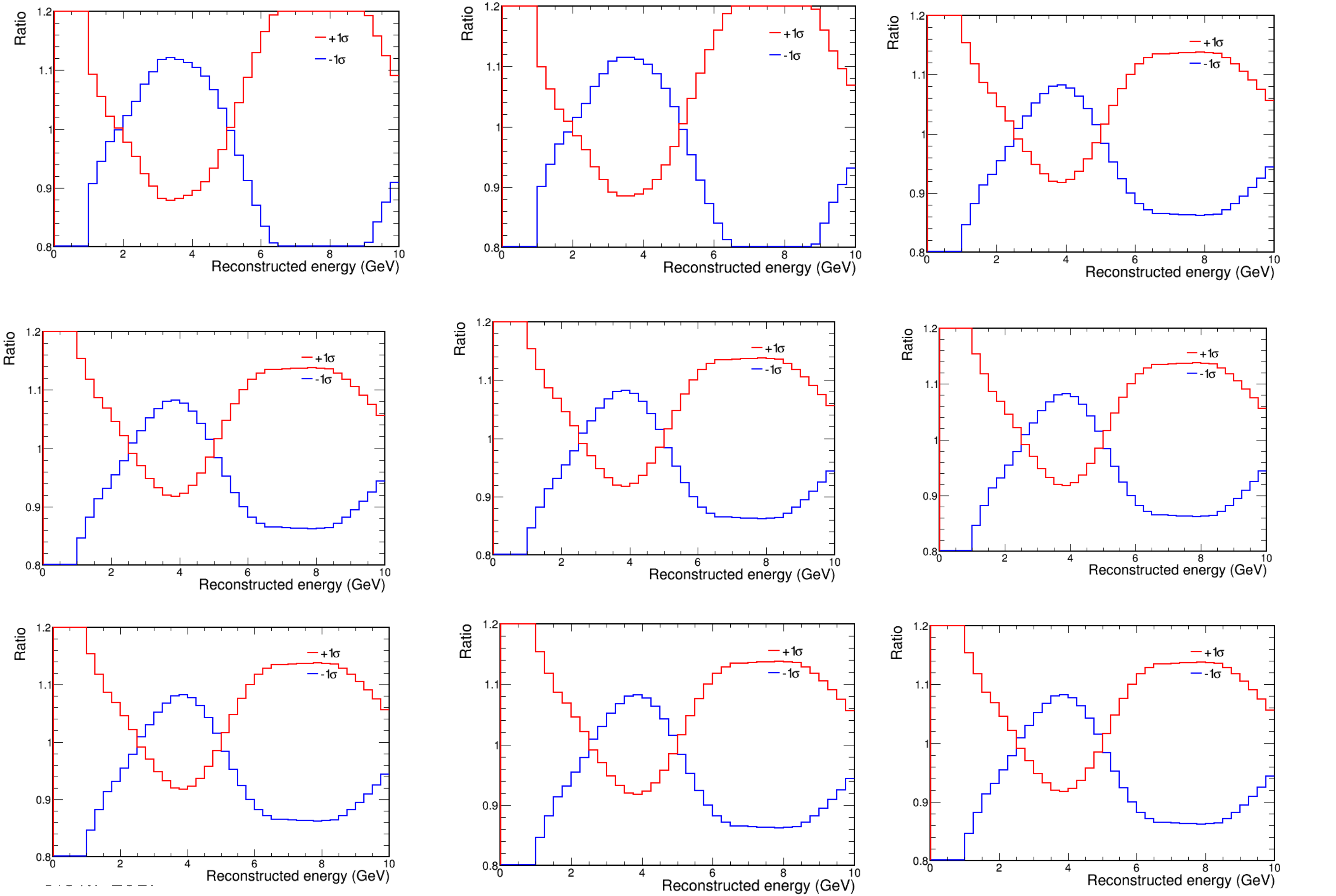

Ratio
1.2
1.1
1
0.9
0.8
+1σ
-1σ
0 2 4 6 8 10
Reconstructed energy (GeV)


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

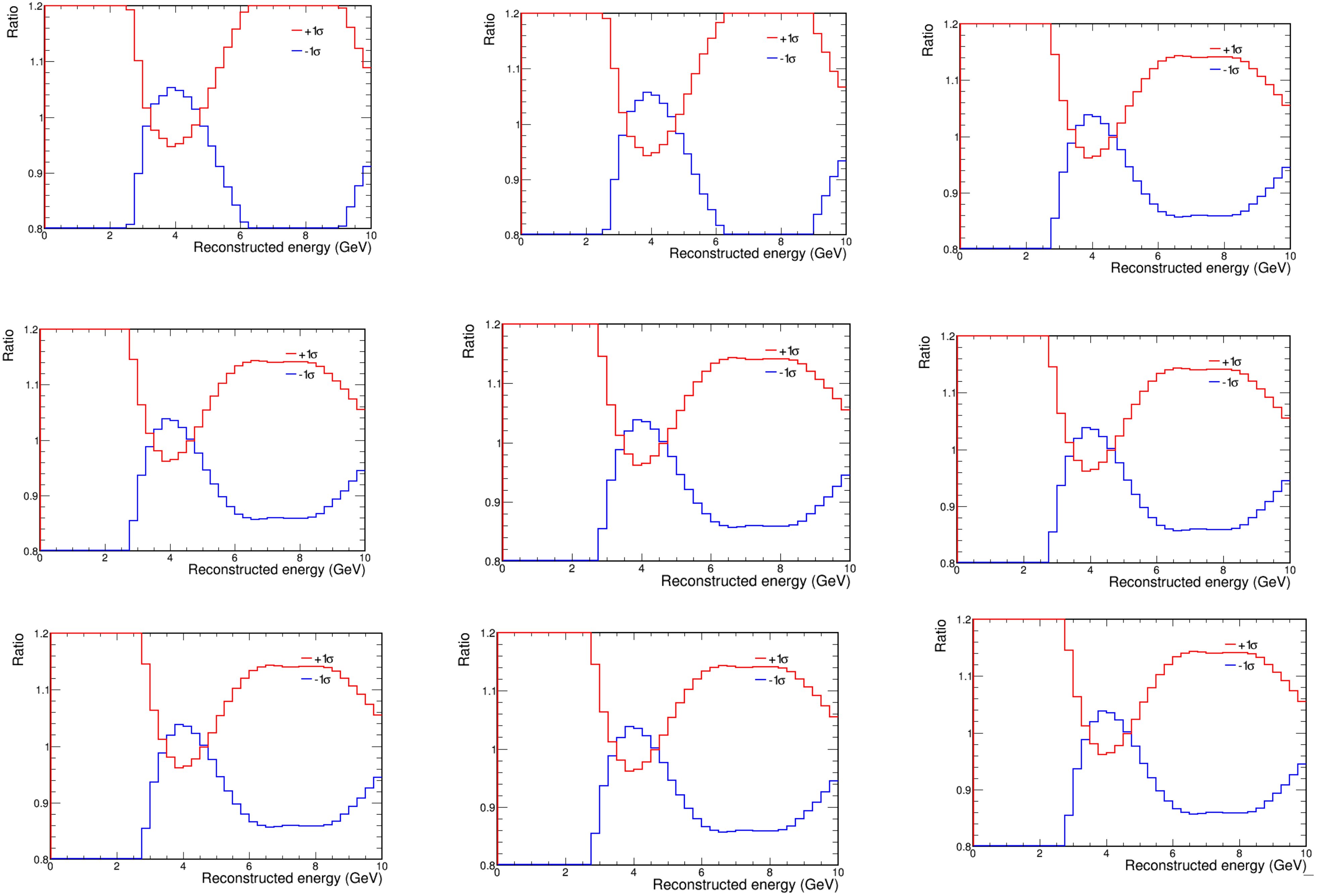

Ratio
1.2
1.1
1
0.9
0.8
+1σ
-1σ
0 2 4 6 8 10
Reconstructed energy (GeV)


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

Flux systematics ND FHC



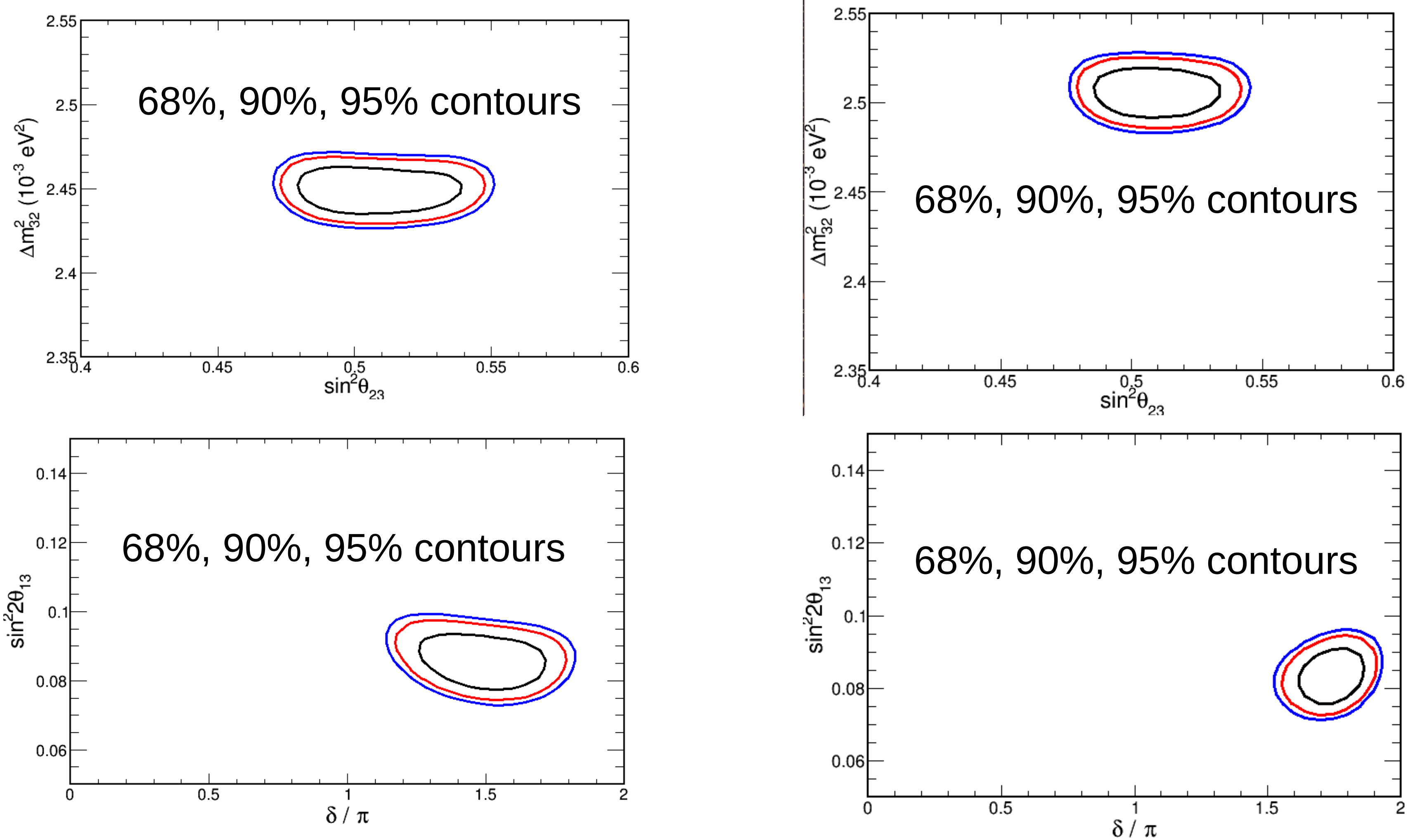
Flux systematics ND RHC



Systematics validation

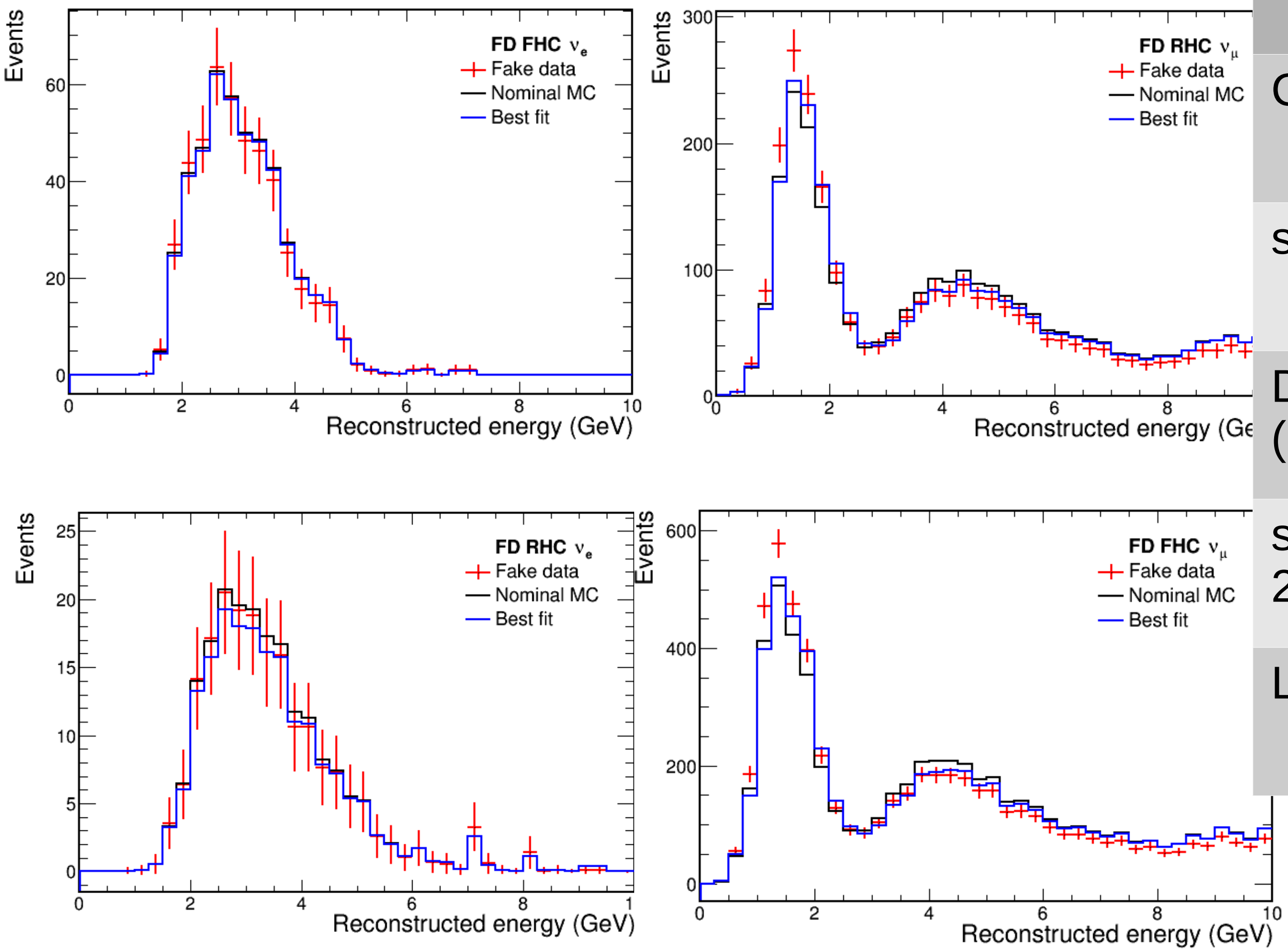
With Luke's variation and without systematics, the true values cannot be recovered.

True | Varied



Systematics validation

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

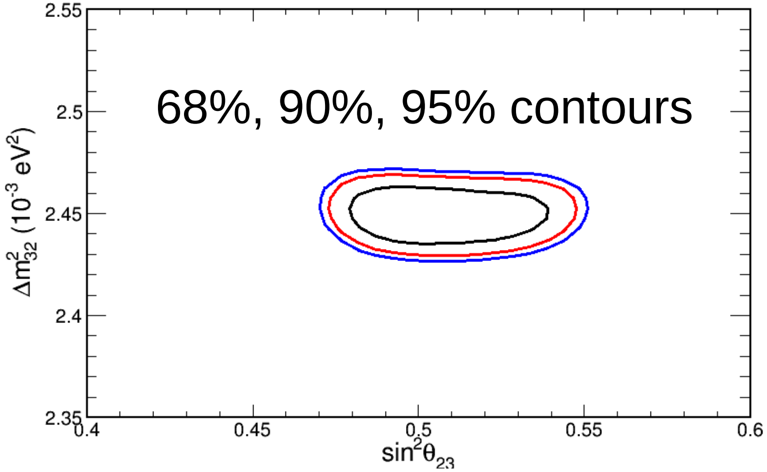


	true	FD+ND Best fit	FD only
CP (pi)	1.5	1.67	1.67
sst23	0.5	0.51	0.51
Dm32 (e-3)	2.45	2.57	2.57
ss(2*t13)	0.087	0.078	0.078
LL		126246	99.5

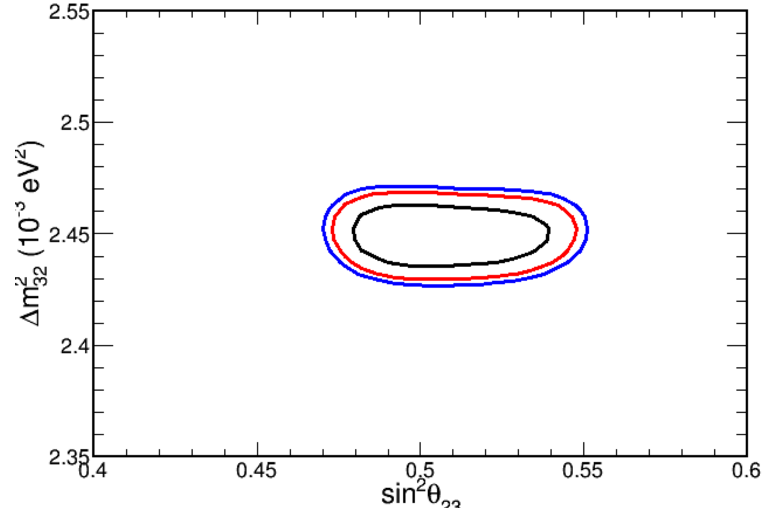
Systematics validation

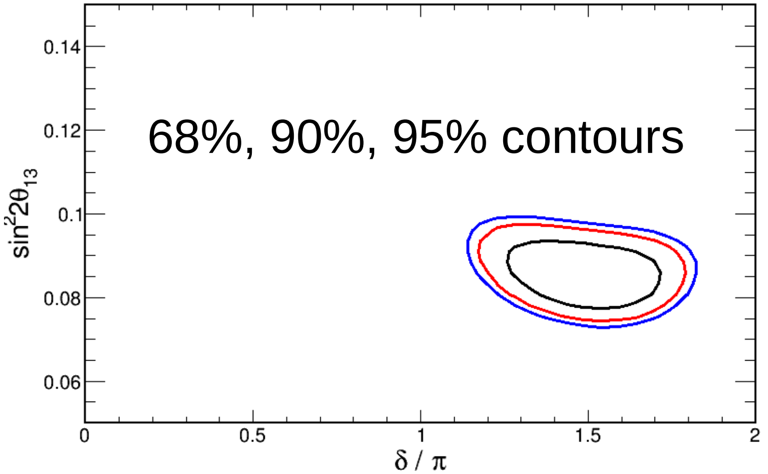
With Luke's variation and with the variation inserted as a systematic pull, the true values can be recovered.

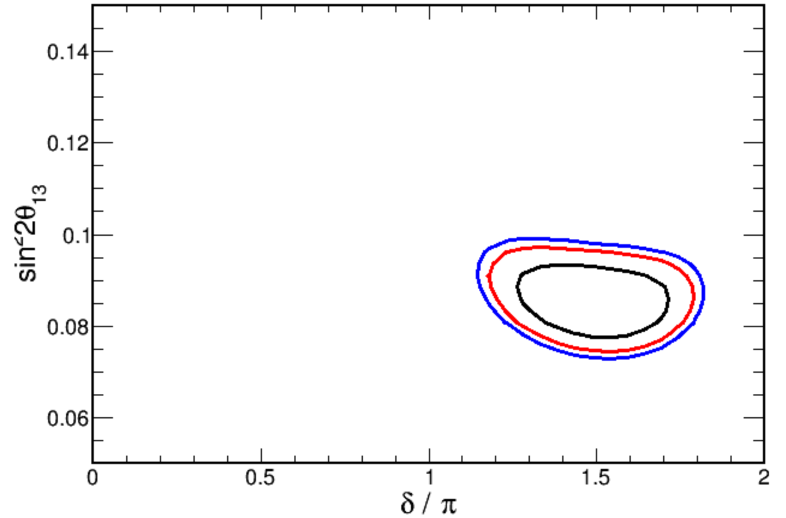
True



Varied

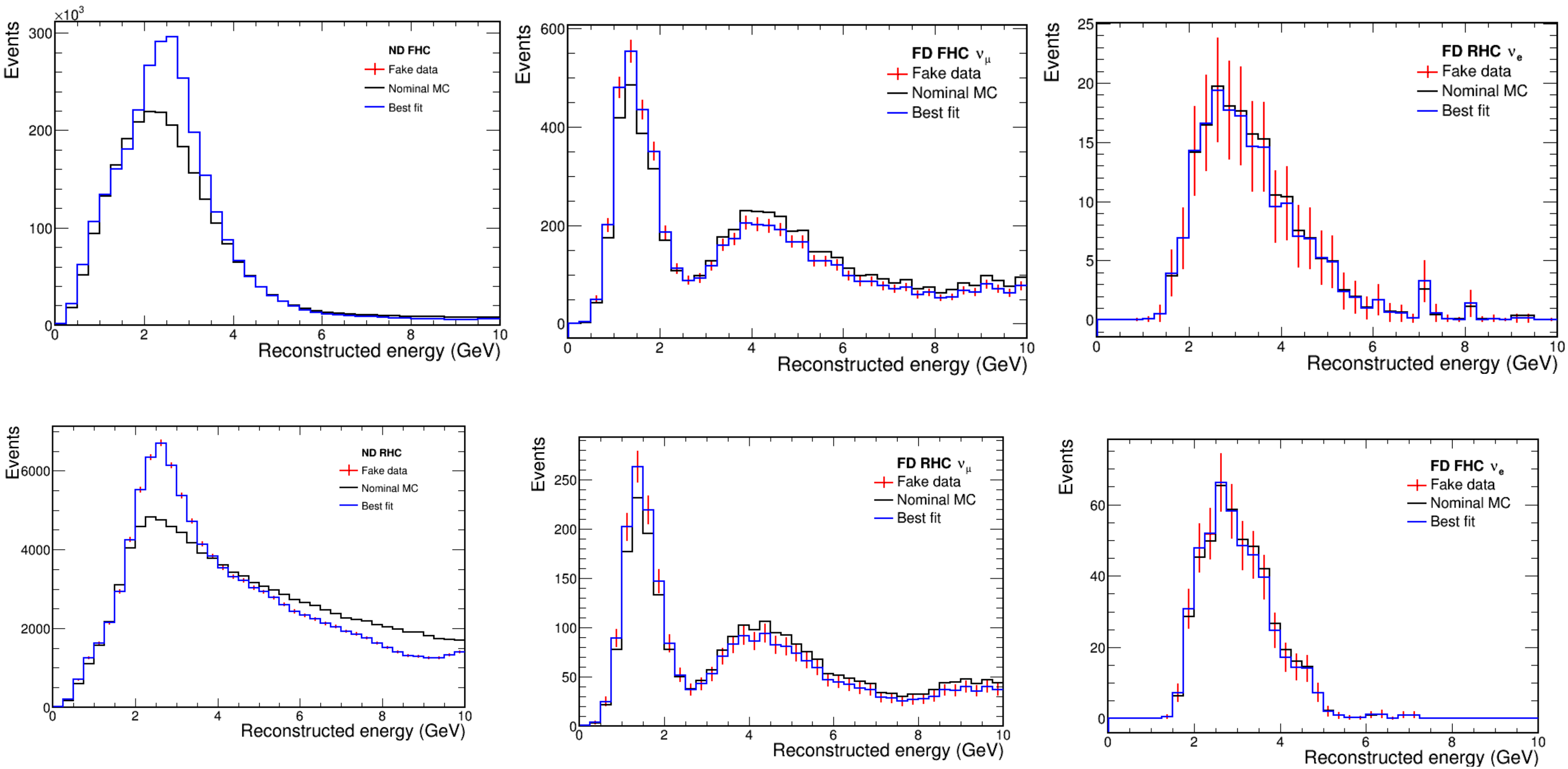






Systematics validation

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`

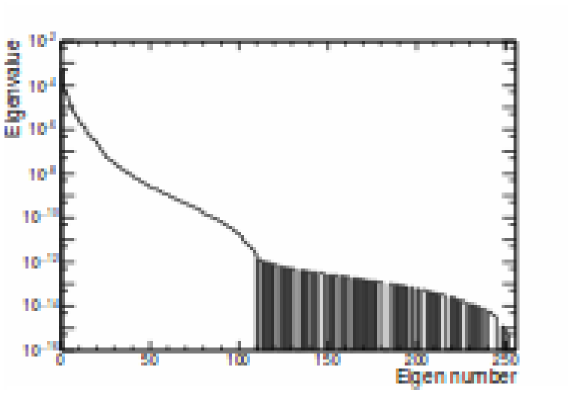
Correlations are included !

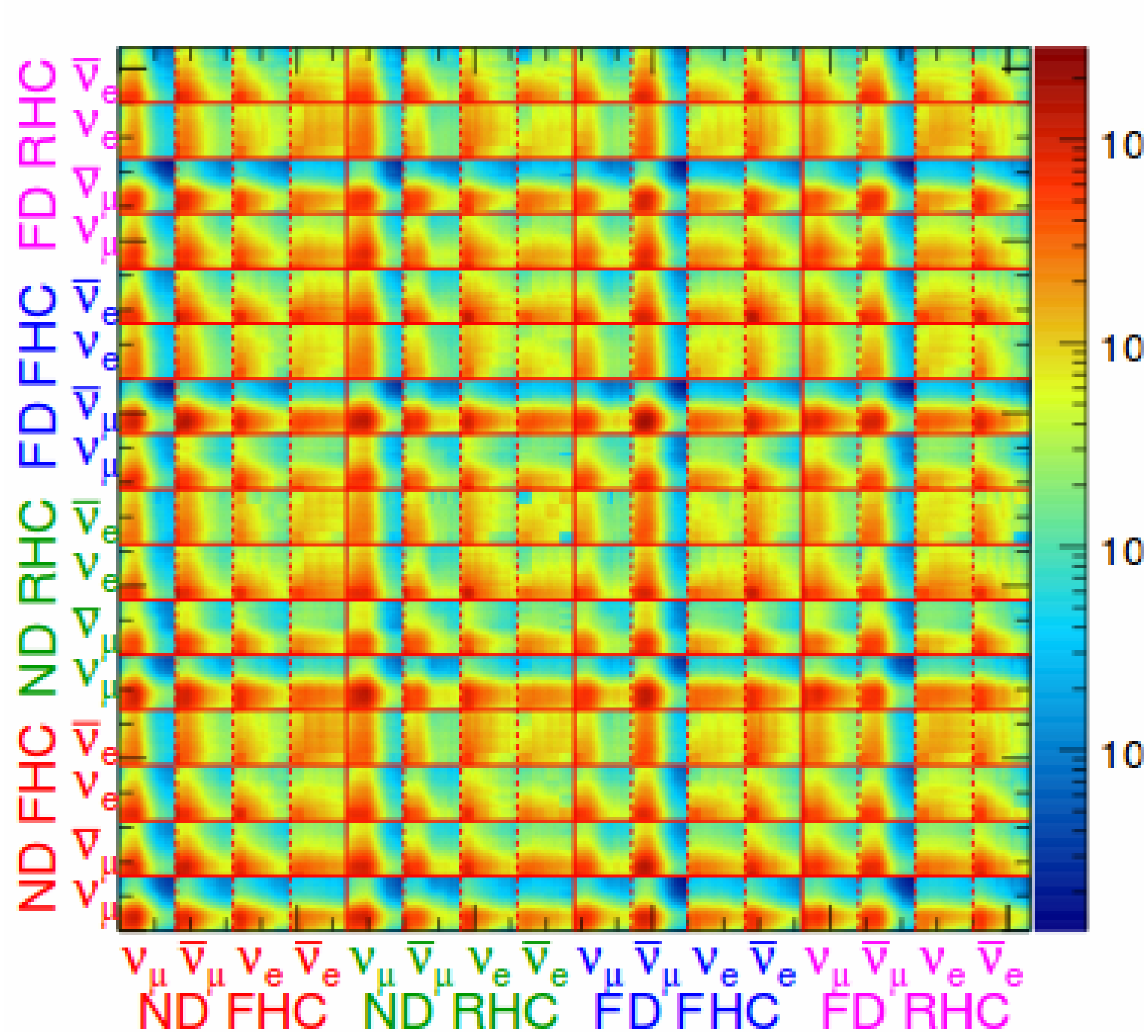
From Chris Backhouse

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}. $M = V^T \Lambda V$, $M \to V^T \Lambda' V$

Systematics

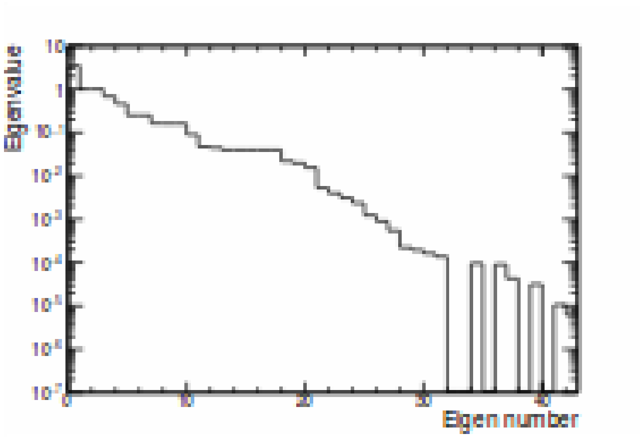
```cpp
/// Absolute energy scale systematic
class EnergyScaleSyst: public ISyst
{
public:
  std::set<std::string> Requires() const override
  {
    return {"dune.Ev_reco"};
  }
  std::string ShortName() const override {return "eScale";}
  std::string LatexName() const override {return "Energy Scale";}

  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;
```

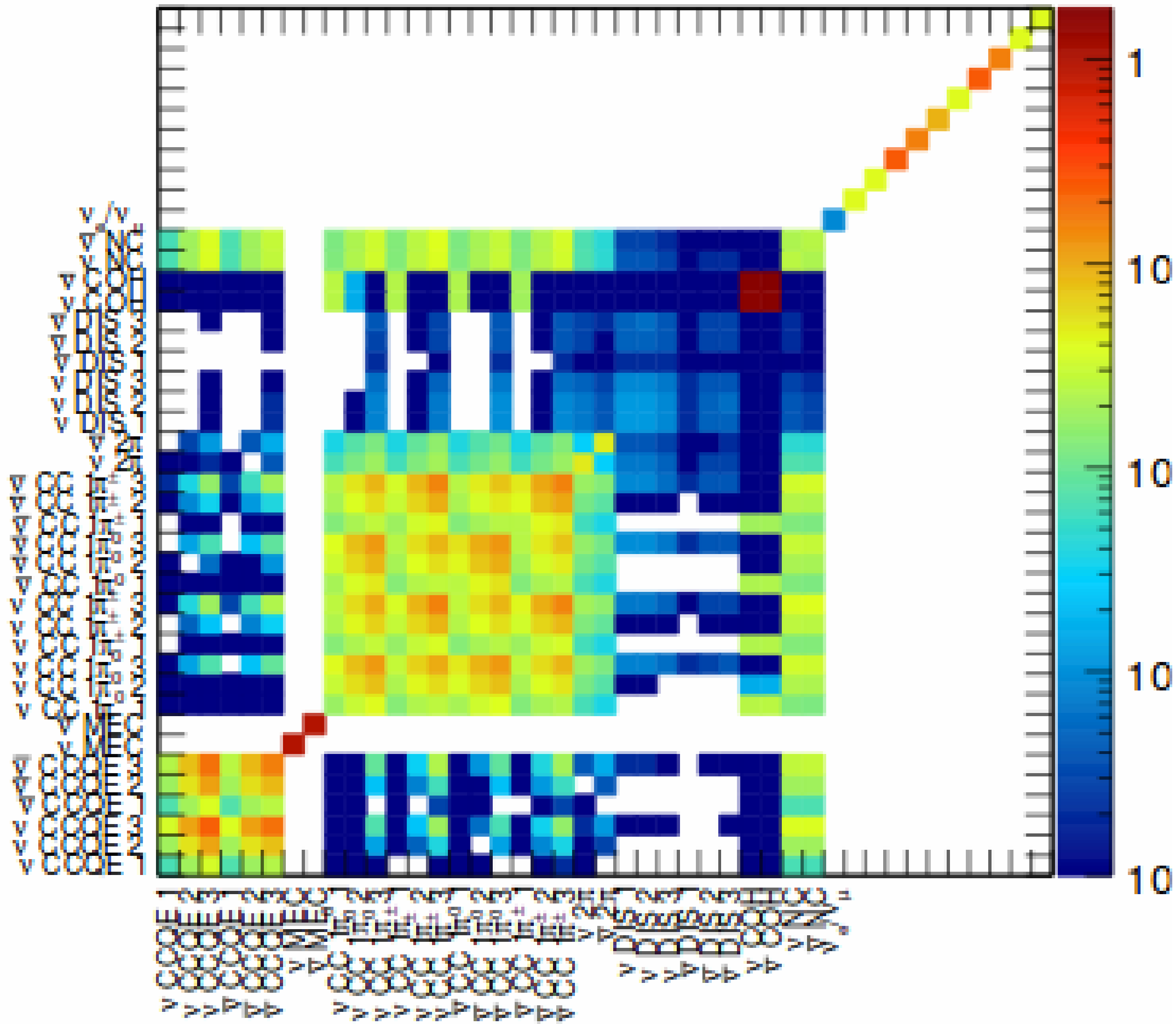
```cpp
/// 5% normalization syst for NC on numu analysis
class NCSyst: public ISyst
{
public:
  std::set<std::string> Requires() const override
  {
    return {"dune.Ev","dune.Ev_reco", "dune.ccnc"};
  }
  std::string ShortName() const override {return "NC";}
  std::string LatexName() const override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