An approach to fast fits of the unintegrated gluon density

(\textit{PROFFIT} – a PROgram For FITting)

A. Bacchetta (Jef Lab), H. Jung, A. Knutsson, K. Kutak (DESY)

HERA-LHC workshop 2008, 26-30\textsuperscript{th} May, CERN

Outline

- The fitting method
- The unintegrated gluon density
- uPDF determination from HERA di-jet data
- Results
**Former fitting method:** Based on running the generator in an interactive procedure in parameter space. Time consuming.

**New Approach:** Describe parameter dependence before parameter fitting, by building up a grid in parameter space. On the following slides I present the details.
The new approach was developed for tuning Monte Carlo models

Suggested already 12 years ago...

“Tuning and test of fragmentation models based on identified particles and precision event shape data.”
Z.Phys.C73:11-60,1996

Also work on Tuning MC in Lund.

Parameter Optimisation in Monte Carlo Event Generators

Hendrik Hoeth
(University of Lund)
1st Mcnet School, IPPP Durham, 18-20th April 2007

We carry out the same method for fitting uPDFs.
1. Build up a grid in parameter – cross section space using Monte Carlo.
   If you have a CPU farm (or use the GRID) this ultimately takes the time of running the MC generator once.
New fitting approach

1. Build up a grid in parameter – cross section space using Monte Carlo.

   If you have a CPU farm (or use the GRID) this ultimately takes the time of running the MC generator once.

2. Fit polynomials to the Monte Carlo grid.

   \[ \sigma_{\text{poly}} = A + \sum_{i=1}^{N} B_i \cdot p_i + \sum_{i=1}^{N} C_i \cdot p_i^2 + \sum_{i=1}^{N} \sum_{j=i+1}^{N} D_{ij} \cdot p_i p_j + H.O. \]

   \( A, B, C \) and \( D \) are determined by fitting the polynomial to the parameter grid. (Singular Value Decomposition)
Singular Value Decomposition

Number of Monte Carlo grid points > Coefficients \[\text{Overdetermined system}\]

\[
\sigma_{\text{poly}}(p_1, p_2) = A + B_1 p_1 + B_2 p_2 + C_1 p_1^2 + C_2 p_2^2 + C_3 p_1 p_2 + H.O.
\]

i.e.

\[
P_{n,m} X_m = \sigma_{n,\text{poly}} \quad \text{where} \quad X_n = (A, B_1, B_2, C_1, C_2, C_3, \ldots) \\
P_n = (1, p_1, p_2, p_1^2, p_1 p_2, p_2^2, \ldots) \\
n = \text{Grid point}
\]

Approach based on SVD algorithm:

To obtain solution we minimize \[|PX - \sigma|^2\]

by \[\chi^2\]-minimization
New fitting approach

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Takes care of correlation between parameters
New fitting approach

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   \( A, B, C \) and \( D \) are determined by fitting the polynomial to the parameter grid.

Step 1. and 2. are done for each data point in the measurement. Takes only a few seconds.
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   If you have a CPU farm (or use the GRID) this ultimately takes the time of running the MC generator once.

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\]

\(A, B, C\) and \(D\) are determined by fitting the polynomial to the parameter grid.

**Step 1. and 2. are done for each data point in the measurement. Takes only a few seconds.**

3. Determine PDF parameters, \(p_i\), by fitting all the polynomials to data simultaneously. Also this takes only a few seconds.

**Step 3. are done by Chi2-minimization using MINUIT.**
1 dimensional example

Simplest possible example
1 parameter, 1 data cross-section

1. Build up the grid

Monte Carlos cross-sections
1 dimensional example

Simplest possible example
1 parameter, 1 data cross-section

2. Describe Monte Carlo by polynomial

![Graph showing Monte Carlo cross-sections and polynomial fit]
Simplest possible example
1 parameter, 1 data cross-section

3. Minimize Chi2 to data
• The method is implemented into a program – PROFFIT check for updates on www.hepforge.org/PROFFIT.

• A lot of data available for tuning in hztool

  (“HZTool is a library of routines which will allow you to reproduce an experimental result using the four-vector final state from Monte Carlo generators.”

  *In the future replaced by RIVET*)
The unintegrated gluon density

The uPDF starting distribution:

\[ x A_0(x, k_T, \bar{q}_0) = N \cdot x^{-B} \cdot (1 - x)^C \cdot \exp\left( -\frac{(k_T - \mu)^2}{2\sigma^2} \right) \]

- \( N \): Normalization (fitted)
- \( B \): Small x behaviour (fitted)
- \( C=4 \): Large x behaviour (kept fixed)
- \( \mu, \sigma \): Determines the shape of the intrinsic \( k_T \) of the gluon below \( k_T=1.2 \text{ GeV} \) (\( \mu \) fitted)

Calculated at some starting scale (\( \bar{q}_0 \)).
The uPDF is calculated for higher scales by emissions of gluons according to the CCFM evolution scheme.
(Monte carlo event generator \( \text{CASCADE(ep/pp)} \))

The parameters \( N, B, C, \mu, \sigma \), are not theoretically calculable.

We need to fit the uPDF to experimental data.
Example of application

Fit unintegrated gluon density to HERA di-jet data

H1 Collab., A. Aktas et al., Eur. Phys. J. C33 (2004) 477

Inclusive Dijet Production at Low $x_B$ in DIS

Target hard di-jets.
Dominated by BGF, sensitivity to gluon.

Require $E_T, \text{jet} \ 1 > (5 + \Delta) \text{ GeV}$
$E_T, \text{jet} \ 2 > 5 \text{ GeV}$

and measure jet cross-section as a function of $\Delta$

Sensitivity to gluon $k_t$
$E_T, \text{ jet } 1 > (5 + \Delta) \text{GeV}$

Total dijet cross-section as a function of $\Delta$

- NLO di-jet calculation fails in parts of phase space
- NLO di-jet calculation not possible for low $\Delta$ due to divergencies.

H1 Collab., A. Aktas et al., Eur. Phys. J. C33 (2004) 477
Di-jet data

\[ E_T, \text{jet } 1 > (5 + \Delta) \text{ GeV} \]

Total dijet cross-section as a function of \( \Delta \)

Existing **CASCADE** prediction has some problems describing data.

Best is “set A0” (determined by fit to proton structure functions), giving a \( \text{Chi2/ndf}=3.5 \)

Improve by fitting using PROFFIT...
Di-jet data - fit results

$E_T$, jet 1 > (5 + $\Delta$) GeV

Total dijet cross-section as a function of $\Delta$

Fitted uPDF improves data description!

| Chi2/ndf         | 2.01 |
|------------------|------|
| $N$              | 0.28 +/- 0.02 |
| $B$              | 0.25 +/- 0.03 |
| $\mu$            | 3.0 +/- 0.04 |
| $\sigma$         | 2, fixed |

$N \cdot x^{-B} \cdot (1 - x)^C \cdot \exp\left(-\frac{(k_T - \mu)^2}{2\sigma^2}\right)$
Comparison to existing uPDF

The new fit to the dijet data suggest **stronger rising x** and a **shifted gaussian for k_t**.

\[
N \cdot x^{-B} \cdot (1 - x)^C \cdot exp\left(-\frac{(k_T - \mu)^2}{2\sigma^2}\right)
\]
Inclusive Multijet Cross-section in DIS

Cross check with other data

ZEUS Collaboration, S. Chekanov et al, Nucl.Phys.B786:152-180,2007

Description of inclusive di-jet and 3-jet cross section improved by the new fit
D*-production in Photoproduction

H1 Collab., A. Aktas et al., Eur.Phys.J.C50:251-267, 2007

Inclusive D* production in PHP:

D* production and additional jet:

PDF fit to di-jet in DIS  Better description of D* and D*-jet correlation in PHP
The new PDF gives a pretty good over all description except at very low $x$ and “high” $x$.

What is required in order to describe the data in these bins?

Very fast (~5 sec) to remake fit with PROFFIT...
Di-jet data result

Fitting only the low x bin

\[ \langle Q^2 \rangle = 6.5 \text{ GeV}^2 \]
\[ \langle x \rangle = 0.00014 \]

Suggests a lower B value

|           | All bins | Low x fit |
|-----------|----------|-----------|
| B         | 0.25     | 0.13      |
| \(\mu\)  | 3        | 3         |

\[ x_{Bj} \]

\[ Q^2 \]

\[ \Delta [\text{GeV}] \]

\[ xA(x, k_t^2, \mu^2) \]

\[ k_t^2 = 1 \text{ GeV}^2 \]

\[ k_t^2 = 10 \text{ GeV}^2 \]
Di-jet data result

Fitting only the "high" x bin
\[ \langle Q^2 \rangle = 71 \text{ GeV}^2 \]
\[ \langle x \rangle = 0.0047 \]

Suggests a negative B value

|          | All bins | Low x fit | High x fit |
|----------|----------|-----------|------------|
| B        | 0.25     | 0.13      | -0.17      |
| \( \mu \) | 3        | 3         | 3          |

\[ \Delta \text{[GeV]} \]
Di-jet data result

Fitting only the “high” x bin
\[
\langle Q^2 \rangle = 71 \text{ GeV}^2 \\
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\]

Suggests a negative B value

|        | All bins | Low x fit | High x fit |
|--------|----------|-----------|------------|
| B      | 0.25     | 0.13      | -0.17      |
| \(\mu\) | 3        | 3         | 3          |

Suggests more flexible in parameterisation of starting distribution
A new approach for fitting (u)PDFs have successfully been tested.

It is based on determination of parameter dependence, by grid interpolation, before the fitting is performed.

The method will be available in the program PROFFIT (www.hepforge.com/PROFFIT).

Fitting uPDF to HERA dijet data suggests a strong dependence on x and a large shift of the intrinsic kt in the gluon starting distribution.
Backup slides
Azimuthal jet decorrelations (H1)
Former fitting approach

1. Calculate cross-section using Monte Carlo for a given set of parameter values
2. Compare to data, calculate Chi2 and feed it to MINUIT
3. MINUIT (e.g. the MIGRAD method) estimates new parameter values
4. Iterate 1. - 3. until Chi2 is minimized

This means that if MINUIT needs 100 iterations to minimize Chi2, the generator is run 100 times, not simultaneously:

If one MC generator run takes 1 hour, the minimization takes 100 hours.

One may need exclusive measurements

A lot of MC statistics. Minimization $>>$ 100h.
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**Also delicate:** Fitting several “event types” simultaneously, e.g. Charm production and inclusive jet production

**Above method makes separated event generation difficult.**
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   **Above method makes separated event generation difficult.**

**New Approach:** Describe parameter dependence before parameter fitting,
by using **grid in parameter space**.
Singular Value Decomposition

Number of Monte Carlo grid points > Coefficients → Overdetermined system

\[ \sigma_{\text{poly}}(p_1, p_2) = A + B_1p_1 + B_2p_2 + C_1p_1^2 + C_2p_2^2 + C_3p_1p_2 + H.O. \]

i.e.

\[ P_{n,m} X_m = \sigma_{n,\text{poly}} \quad \text{where} \quad X_n = (A, B_1, B_2, C_1, C_2, C_3, \ldots) \]
\[ P_n = (1, p_1, p_2, p_1^2, p_1p_2, p_2^2, \ldots) \]
\[ n = \text{Grid point} \]

Approach based on SVD algorithm:

To obtain solution we minimize \[ |PX - \sigma| \]
by \[ \chi^2 \]-minimization
Could also use MINUIT, but it is sensitive on starting values.

|                   | SVD | MINUIT | MINUIT bad starting values |
|-------------------|-----|--------|----------------------------|
| Chi2 [Polynomial-MC]/ndf: | 1.8 | 1.8    | 4.1                        |

Minimization of polynomial coefficients stuck in local minimum
Chi2 scans

N

B

\( \chi^2 \)

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## SVD vs MINUIT

Coefficients in 4\textsuperscript{th} order polynomial determined from:

|        | SVD       | MINUIT    | MINUIT bad starting values |
|--------|-----------|-----------|-----------------------------|
| -25404.9082 | -25315.4624 | 358.56777 |
| 765676.064  | 762720.857  | 694969.672 |
| 357293.297  | 358067.861  | -52198.7414|
| 3091.77111  | 2347.15353  | 3582.44715 |
| 114841.02   | 140499.037  | 52826.8157|
| 166905.85   | 157433.813  | 1929633.41|
| -31421.3098 | -32900.9618 | -61072.7505|
| -927589.152 | -927572.803 | 98180.9293 |
| -60480.3599 | -61180.0691 | -12538.2387|
| 2524.9688   | 4162.80871  | 1618.16049|
| -1064150.37 | -1135039.64 | -465510.961|
| 5799612.85  | 5804476.94  | 1334921.4  |
| 12981.5342  | 16228.0397  | 104971.842 |
| 2592311.1   | 2623536.1   | 1662889.02 |
| 313456.597  | 315635.922  | 284934.203 |
| -26463.828  | -26091.529  | -22961.2676|
| -429940.571 | -419854.565 | -72213.1127|
| -318899.245 | -320294.755 | 553178.07  |
| -23885.636  | -23727.0438 | 4989.53369 |
| 1446.24668  | 525.83837   | 308.86517  |
| 855372.625  | 918885.733  | -135820.813|
| -3554618.    | -3552083.15 | 354725.482 |
| 97974.8469  | 95580.1082  | 203313.617 |
| -5838295.7  | -5848044.35 | 536995.25  |
| -214807.392 | -216430.586 | -978685.349|
| -9020.6301  | -9326.67473 | -22832.1865|
| 10567702.9  | 10534823.1  | 2166665.32 |
| -437402.716 | -439016.175 | 427727.795 |

Chi2 [Polynomial-MC]/ndf: 1.8 1.8 4.1

For example here, large difference between Coefficients. Resulting in that MINUIT gets stuck in local minimum.
### Chi2/ndf for polynomial description of parameter space:

| Degree of polynomial: | 2nd  | 3rd  | 4th  | 5th  |
|-----------------------|------|------|------|------|
| chi2/ndf for histo 1, bin 1 = | 12.46 | 1.461 | 1.515 | 1.715 |
| chi2/ndf for histo 1, bin 2 = | 10.76 | 1.541 | 1.555 | 1.535 |
| chi2/ndf for histo 1, bin 3 = | 8.057 | 1.725 | 1.815 | 1.445 |
| chi2/ndf for histo 1, bin 4 = | 4.194 | 1.640 | 1.900 | 1.425 |
| chi2/ndf for histo 1, bin 5 = | 2.021 | 1.266 | 1.175 | 1.375 |
| chi2/ndf for histo 2, bin 1 = | 18.52 | 0.993 | 0.875 | 1.315 |
| chi2/ndf for histo 2, bin 2 = | 15.57 | 0.935 | 0.895 | 1.265 |
| chi2/ndf for histo 2, bin 3 = | 10.39 | 1.037 | 1.085 | 0.925 |
| chi2/ndf for histo 2, bin 4 = | 4.439 | 0.975 | 1.035 | 1.075 |
| chi2/ndf for histo 2, bin 5 = | 1.950 | 0.990 | 0.935 | 1.135 |
| chi2/ndf for histo 3, bin 1 = | 10.91 | 1.639 | 1.695 | 1.765 |
| chi2/ndf for histo 3, bin 2 = | 9.129 | 1.763 | 1.635 | 1.645 |
| chi2/ndf for histo 3, bin 3 = | 6.594 | 1.867 | 1.855 | 1.225 |
| chi2/ndf for histo 3, bin 4 = | 3.016 | 1.351 | 1.195 | 1.495 |
| chi2/ndf for histo 3, bin 5 = | 1.426 | 1.201 | 1.125 | 1.215 |
| chi2/ndf for histo 4, bin 1 = | 5.219 | 1.579 | 1.435 | 1.305 |
| chi2/ndf for histo 4, bin 2 = | 4.454 | 1.536 | 1.495 | 1.255 |
| chi2/ndf for histo 4, bin 3 = | 2.738 | 1.266 | 1.205 | 1.325 |
| chi2/ndf for histo 4, bin 4 = | 1.651 | 1.171 | 1.085 | 1.245 |
| chi2/ndf for histo 4, bin 5 = | 1.036 | 0.965 | 1.105 | 1.085 |
| chi2/ndf for histo 5, bin 1 = | 7.408 | 1.101 | 1.275 | 1.514 |
| chi2/ndf for histo 18, bin 1 = | 14.7 | 1.67 | 1.555 | 2.864 |
| chi2/ndf for histo 18, bin 2 = | 13.0 | 3.66 | 2.465 | 3.120 |
| chi2/ndf for histo 18, bin 3 = | 9.68 | 3.64 | 2.685 | 3.225 |
| chi2/ndf for histo 18, bin 4 = | 4.77 | 3.43 | 2.804 | 3.255 |
| chi2/ndf for histo 18, bin 5 = | 1.44 | 2.56 | 2.405 | 1.268 |

### Parameter values from fit to data:

| Parameter | Value | Error |
|-----------|-------|-------|
| p1        | 0.372 | ±0.047|
| p2        | 0.144 | ±0.041|
| p3        | 3.07  | ±0.08 |

- 2nd degree polynomial bad grid description.
- For higher orders the final fit is consistent within errors of fit.
Example of application

Fit unintegrated gluon density to HERA data

H1 Collab., A. Aktas et al., Eur. Phys. J. C33 (2004) 477
Inclusive Dijet Production at Low $x_{Bj}$ in DIS

Integrated PDF: DGLAP

**LO:** Gluon collinear with proton

\[ k_{t,\text{gluon}} = 0 \]
\[ \Delta E_{T,jets} = 0 \text{ in HCM} \]

**Higher orders:**

\[ k_{t,\text{gluon}} \neq 0 \]
\[ \Delta E_{T,jets} \neq 0 \]

Unintegrated PDF: CCFM or BFKL

\[ k_{t,\text{gluon}} \neq 0 \]
\[ \Delta E_{t,jets} \neq 0 \]
already at LO

Target hard di-jets.
Dominated by BGF, sensitivity to gluon.

Require

\[ E_{T,jet\ 2} > 5 \ \text{GeV} \]
\[ E_{T,jet\ 1} > (5 + \Delta) \ \text{GeV} \]

and measure jet cross-section as a function of $\Delta$

Sensitivity to $k_t$ of gluon
PROFFIT

Steering card

*  ***************  Name of grid file
GRFIL  steer_grid_dijets
*  ***************  Number of cross-sections for grid:
NXSEC  80
*  ***************  Grid fitting method (1=SVD, 2=minuit):
GRFIT  1
*  ***************  Functional form (1=poly, 2=user):
FUNCT  1
*  ***************  Degree of poly, (FUNCT=1)
***************  or Number of koefficients in function (FUNCT=2)
NPDGR  3
*  ***************  Number of parameters:
NPARA  3
*  ***************  Number of histos:
NHIST  18
*  ***************  Reference to histos and number of bins:
*  -dir-  -MC hist-  -Data hist-  -#bins-
HNAME
  03160  3011  -3111  5
  03160  3012  -3112  5
  03160  3013  -3113  5
  03160  3014  -3114  5
PROFFIT

**Steering card**

* ****************************************************** Name of grid file
  GRFIL steer_grid_dijets
* ****************************************************** Number of cross-sections for grid:
  NXSEC 80
* ****************************************************** Grid fitting method
  GRFIT 1
* ****************************************************** Functional form (FRTEX)
  FUNCT 1
* ****************************************************** Degree of poly. (FRTPOLY) or Number of koef.
  NPDGR 3
* ****************************************************** Number of parameters
  NPRA 3
* ****************************************************** Number of histos:
  NHIST 18
* ****************************************************** Reference to hists.
  * -dir- -MC hist- -Data hist
  HNAME
  03160  3011  -3111
  03160  3012  -3112
  03160  3013  -3113
  03160  3014  -3114
  ******************************************************
  * MC FILES *
  ******************************************************
  * parameter values
  ******************************************************
  p1  p2  p3  p4
  0.03  0.1  0.0  2
  0.03  0.1  1  2
  0.03  0.1  2  2
  0.03  0.1  3  2
  0.03  0.2  0.0  2
  0.03  0.2  1  2
  0.03  0.2  2  2
  0.03  0.2  3  2
  0.03  0.3  0.0  2
  0.03  0.3  1  2
  0.03  0.3  2  2
  0.03  0.3  3  2
**PROFFIT**

**Steering card**

---

```
********** Name of grid file
GRFIL steer_grid_dijets
```

```
********** Number of cross-sections for grid:
NXSEC 80
```

```
********** Grid fitting method
GRFIT 1
```

```
********** Functional form (F or NPDGR or Number of koeff)
FUNCT 1
```

```
********** Degree of poly (F or NPDGR or Number of koeff)
NPDGR 3
```

```
********** Number of parameters
NPARA 3
```

```
********** Number of histos:
NHIST 18
```

```
********** Reference to histo file:
* -dir- -MC hist- -Data histo
HNAME
```

```
 03160 3011 -3111
 03160 3012 -3112
 03160 3013 -3113
 03160 3014 -3114
```

```
********** MC FILES
```

```
|    | p1   | p2   | p3   | p4   |
|----|------|------|------|------|
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
| 0.03| 0.3  | 0.2  | 0.1  | 0.0  |
```
PROFFIT

Steering card

* 
*********** Name of grid file
GRFIL steer_grid_dijets 
*
*********** Number of cross-sections for grid:
NXSEC 80
*
*********** Grid fitting method (1=SVD, 2=minuit):
GRFIT 1
*
*********** Functional form (1=poly, 2=user):
FUNCT 1
*
*********** Degree of poly (FUNCT=1)
*********** or Number of coefficients in function (FUNCT=2)
NPDGR 3
*
*********** Number of parameters:
NPARA 3
*
*********** Number of histos:
NHIST 18
*
*********** Reference to histos and number of bins:
* -dir- -MC hist- -Data hist- -#bins-
HNAME

| 03160 | 3011 | 3111 | 5 |
|-------|------|------|---|
| 03160 | 3012 | 3112 | 5 |
| 03160 | 3013 | 3113 | 5 |
| 03160 | 3014 | 3114 | 5 |

Degree of polynomial for description of Monte Carlo grid
PROFFIT

**Steering card**

```plaintext
* **************** Name of grid file
GRFIL steer_grid_dijets
*
**************** Number of cross-sections for grid:
NXSEC 80
*
**************** Grid fitting method (1=SVD, 2=minuit):
GRFIT 1
*
**************** Functional form (1=poly, 2=user):
FUNCT 1
*
**************** Degree of poly (FUNCT=1)
**************** or Number of koefficients in function (FUNCT=2)
NPDGR 3
*
**************** Number of parameters:
NPARA 3
*
**************** Number of histos:
NHIST 18
*
**************** Reference to histos and number of bins:
* -dir-  -MC hist- -Data hist- -#bins-
HNAME  
  03160  3011  -3111  5
  03160  3012  -3112  5
  03160  3013  -3113  5
  03160  3014  -3114  5
```

Number of parameters to fit
**PROFFIT**

**Steering card**

```plaintext
*  ********** Name of grid file
GRFIL steer_grid_dijets  
*  ********** Number of cross-sections for grid:
NXSEC 80
*  ********** Grid fitting method (1=SVD, 2=minuit):
GRFIT 1
*  ********** Functional form (1=poly, 2=user):
FUNCT 1
*  ********** Degree of poly, (FUNCT=1)
********** or Number of coefficients in function (FUNCT=2)
NPDGR 3
*  ********** Number of parameters:
NPARA 3
*  ********** Number of histos:
NHIST 18
*  ********** Reference to histos and number of bins:
* -dir- -MC hist- -Data hist- -#bins-
HNAME
  03160  3011  -3111  5 
  03160  3012  -3112  5 
  03160  3013  -3113  5 
  03160  3014  -3114  5
```

- **Number of histograms**
- **Histogram info**