Exploring Z couplings constraints using AFB and xFitter. Update and General overview

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Project motivation

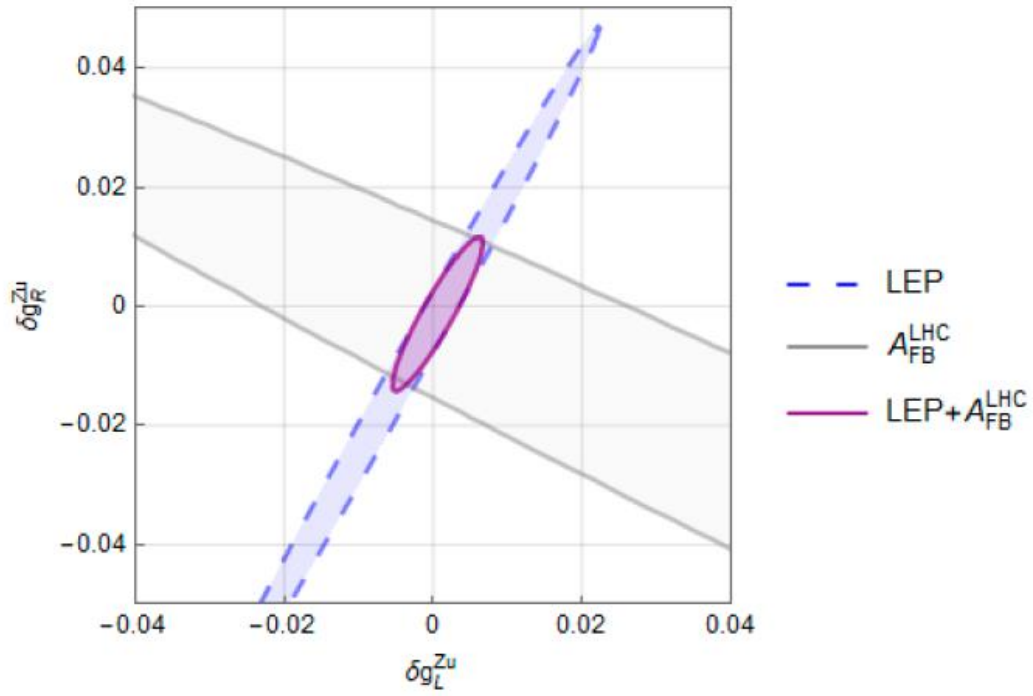
- Improve current constraints on coupling constant of u and d quarks from arXiv:2103.12074 using AFB as a observable variable in DY NC production

Coupling constant for u and d

$$g_R^{Zu}, g_L^{Zu}, g_R^{Zd}, g_L^{Zd}$$

Why AFB?

Answer: Due to cancellations of various QCD and PDF uncertainties



General plan of our work

1. Setup and upgrade xFitter
2. Study non-SM constraints using ATLAS data following arXiv:2103.12074v1 (internal cross-check, not for the paper?)
3. Create different pseudodata sets including statistical and theoretical error
4. Exploring different number of bins for rapidity and invariant mass
5. Various cross-checks connected with PDFs
6. Study of derivatives of AFB

} New results

Setup and upgrade xFitter

- Setup xFitter
- Added rapidity (y_min, y_max) as changing parameters
- Added variational values (deltas) with naming as it was in arXiv:2103.1207 (left, right u, and d quarks)
- Some additional code so that it works appropriately
- Variate them as parameters in parameters.yaml

```
1653  // Z-boson couplings
1654  Z_Vu = (1.0/2.0)*gsm_param*(1.0/6.0)*(3*cos(smangle_param)+8*sin(smangle_param));
1655  Z_Au = (1.0/2.0)*gsm_param*(cos(smangle_param)/2.0);
1656  Z_Vd = (1.0/2.0)*gsm_param*(1.0/6.0)*(-3*cos(smangle_param)-4*sin(smangle_param));
1657  Z_Ad = (1.0/2.0)*gsm_param*(-cos(smangle_param)/2.0);
1658  Z_Vl = (1.0/2.0)*gsm_param*((-cos(smangle_param)/2.0)+(-2*sin(smangle_param)));
1659  Z_Al = (1.0/2.0)*gsm_param*(-cos(smangle_param)/2.0);
1660
1661  // non-SM variation constants
1662  double delta_Z_Ru = 0, delta_Z_Lu = 0, delta_Z_Rd = 0, delta_Z_Ld = 0;
1663
1664  if (td->hasParam("delta_Z_Ru")) {
1665    delta_Z_Ru  = *td->getParamD("delta_Z_Ru");
1666  }
1667
1668  if (td->hasParam("delta_Z_Lu")) {
1669    delta_Z_Lu  = *td->getParamD("delta_Z_Lu");
1670  }
1671
1672  if (td->hasParam("delta_Z_Rd")) {
1673    delta_Z_Rd  = *td->getParamD("delta_Z_Rd");
1674  }
1675
1676  if (td->hasParam("delta_Z_Ld")) {
1677    delta_Z_Ld  = *td->getParamD("delta_Z_Ld");
1678  }
1679
1680  double Z_Ru = 1.0/2.0*(Z_Vu + Z_Au) + delta_Z_Ru;
1681  double Z_Lu = 1.0/2.0*(Z_Vu - Z_Au) + delta_Z_Lu;
1682  double Z_Rd = 1.0/2.0*(Z_Vd + Z_Ad) + delta_Z_Rd;
1683  double Z_Ld = 1.0/2.0*(Z_Vd - Z_Ad) + delta_Z_Ld;
1684
1685  Z_Vu = Z_Ru + Z_Lu;
1686  Z_Au = Z_Ru - Z_Lu;
1687  Z_Vd = Z_Rd + Z_Ld;
1688  Z_Ad = Z_Rd - Z_Ld;
1689
```

ReactionAFB.cc

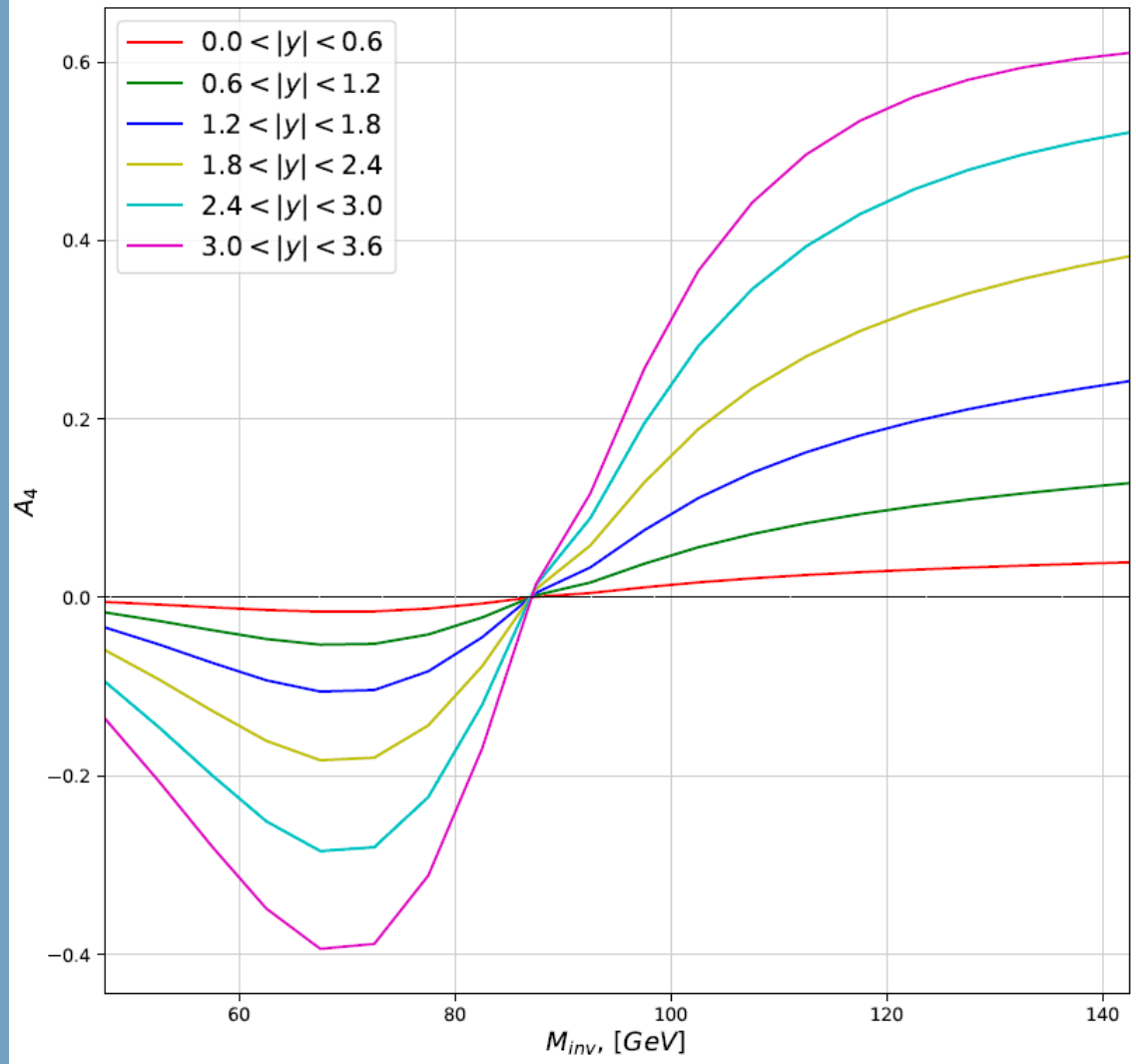
More details of changes https://gitlab.com/fitters/xfitter/-/merge_requests/7
https://gitlab.cern.ch/fitters/xfitter/-/merge_requests/317

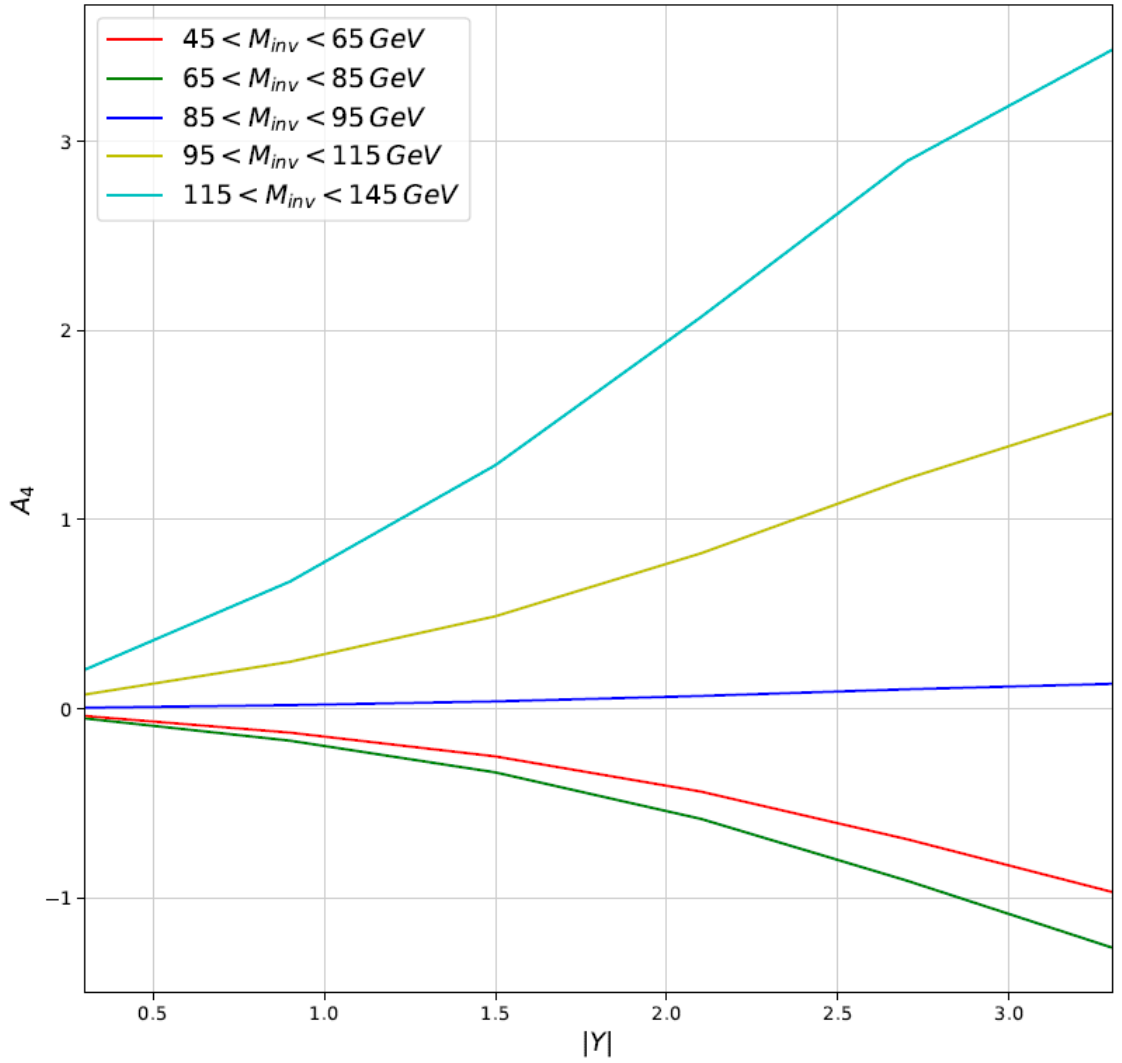
AFB as function of M_{inv} and $|Y|$

20 M_{inv} bins

6 rapidity bins

M_{inv} range: 45-145 GeV
Rapidity: 0-3.6

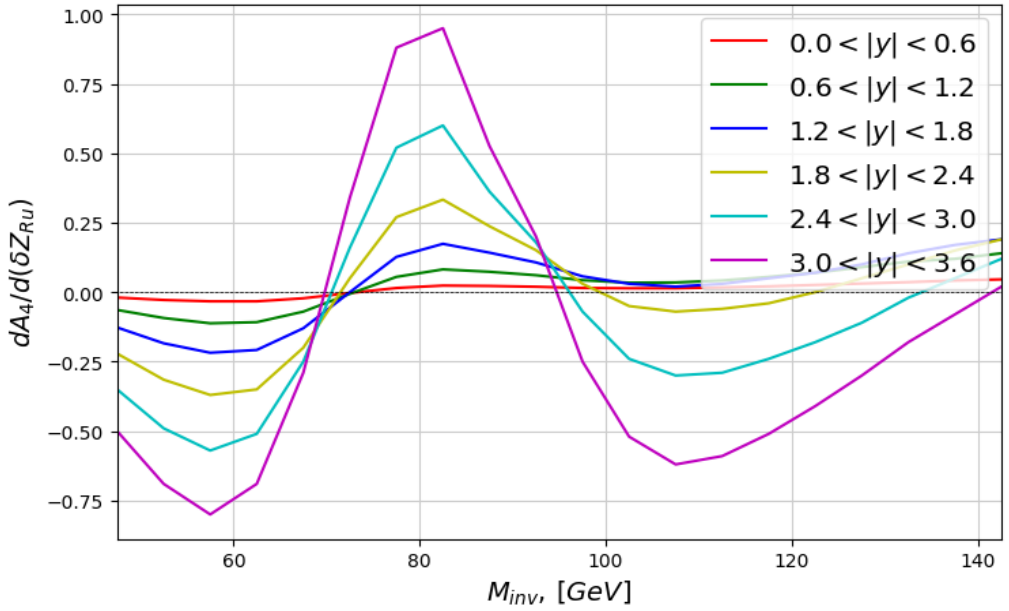


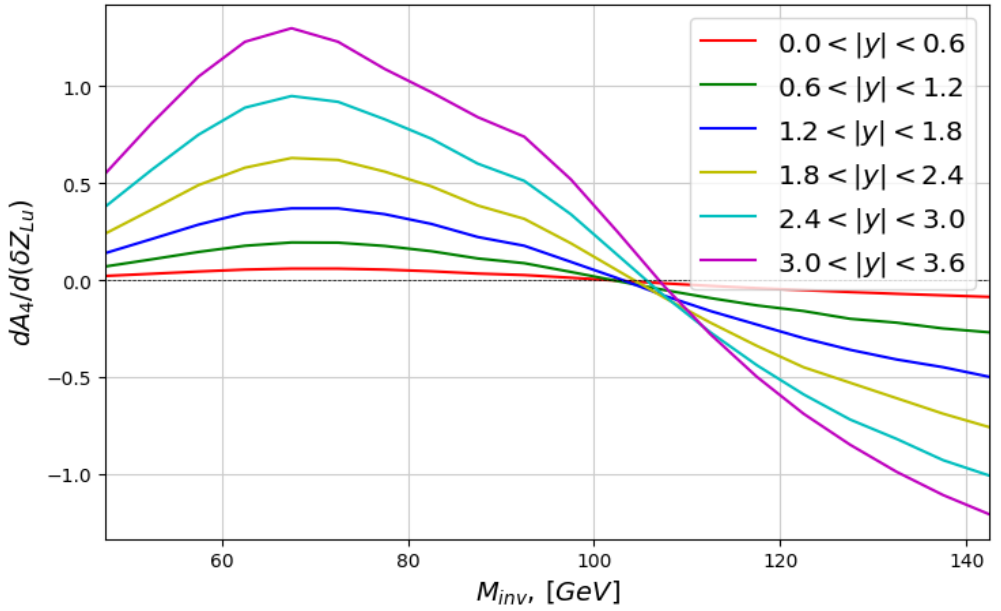


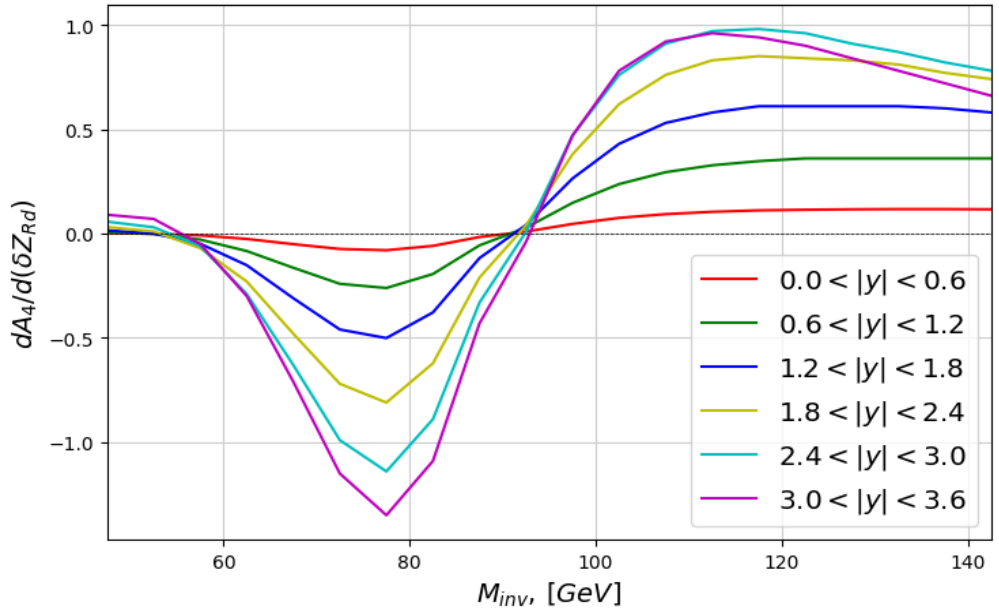
Derivatives from AFB as function of M_{inv}

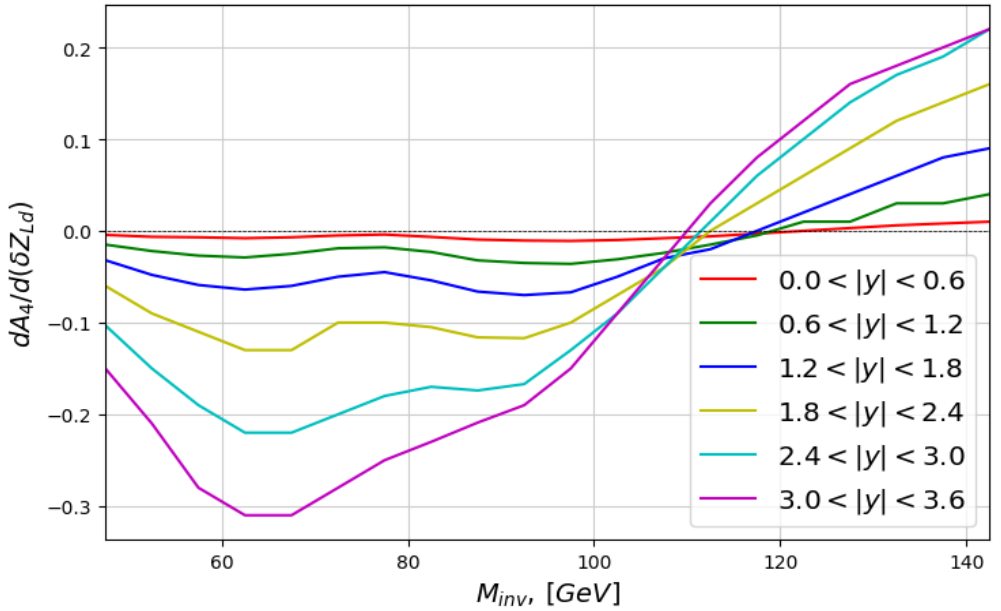
M_{inv} range: 45-145 GeV
Rapidity: 0-3.6

20 M_{inv} bins





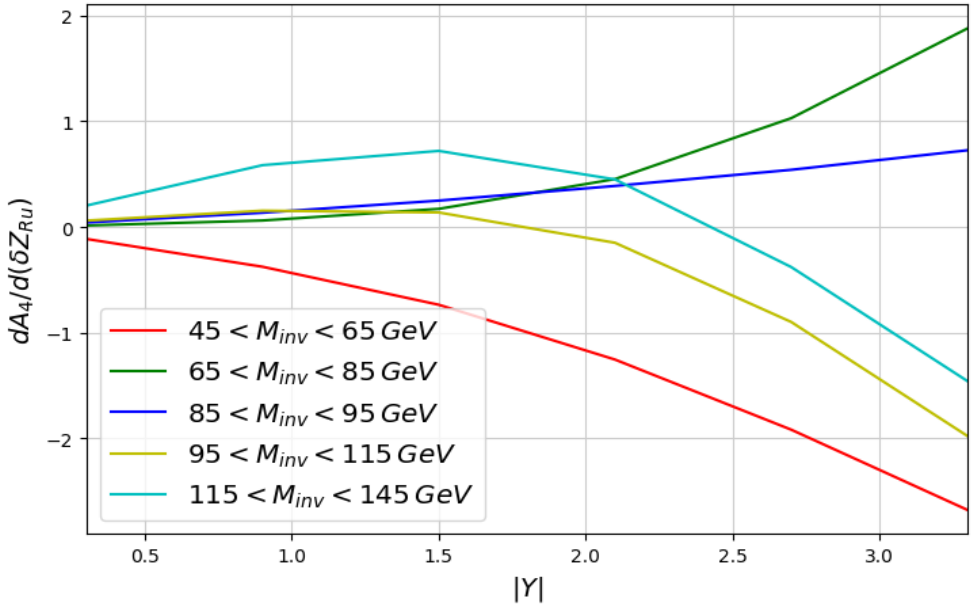


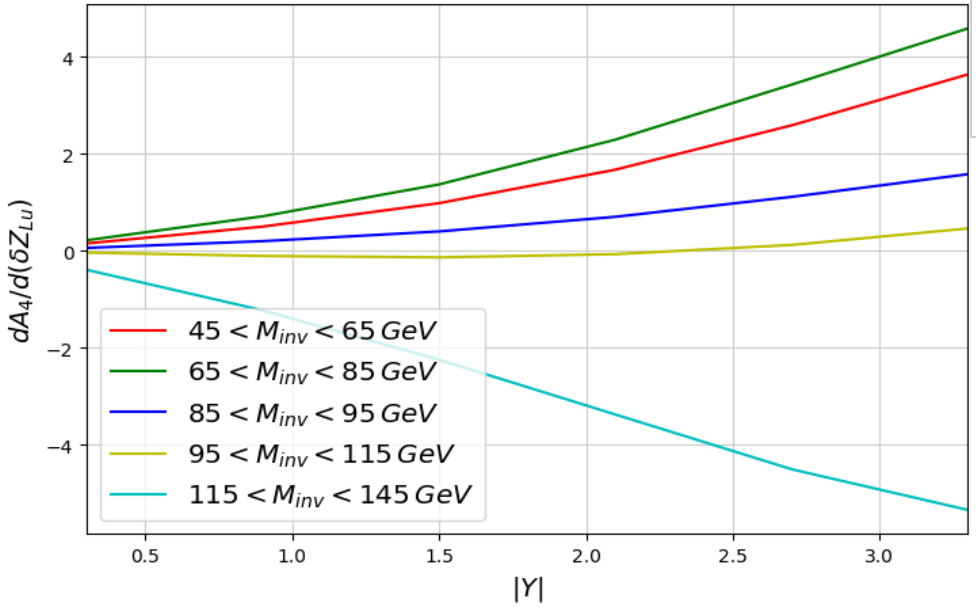


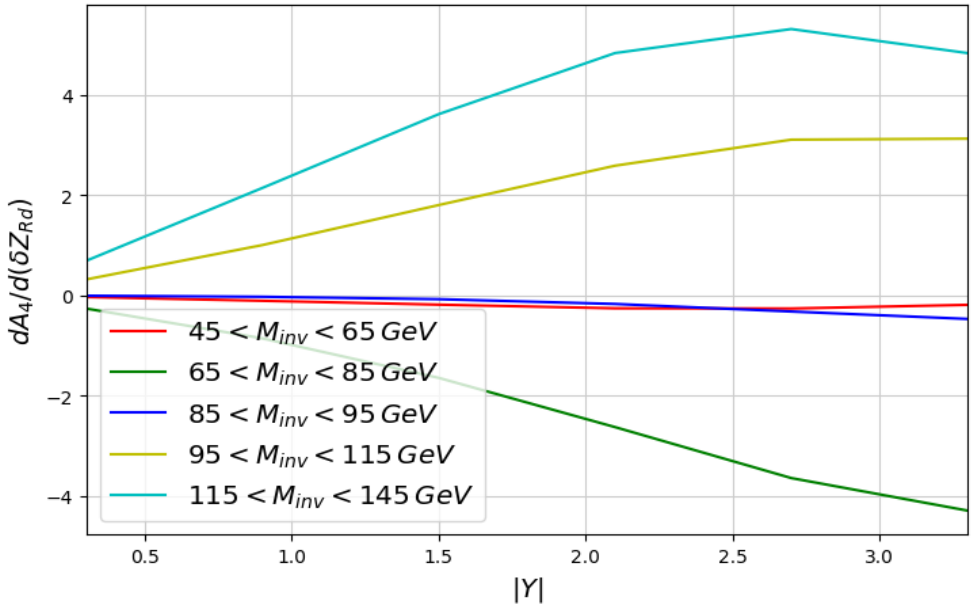
Derivatives from AFB as function of $|Y|$

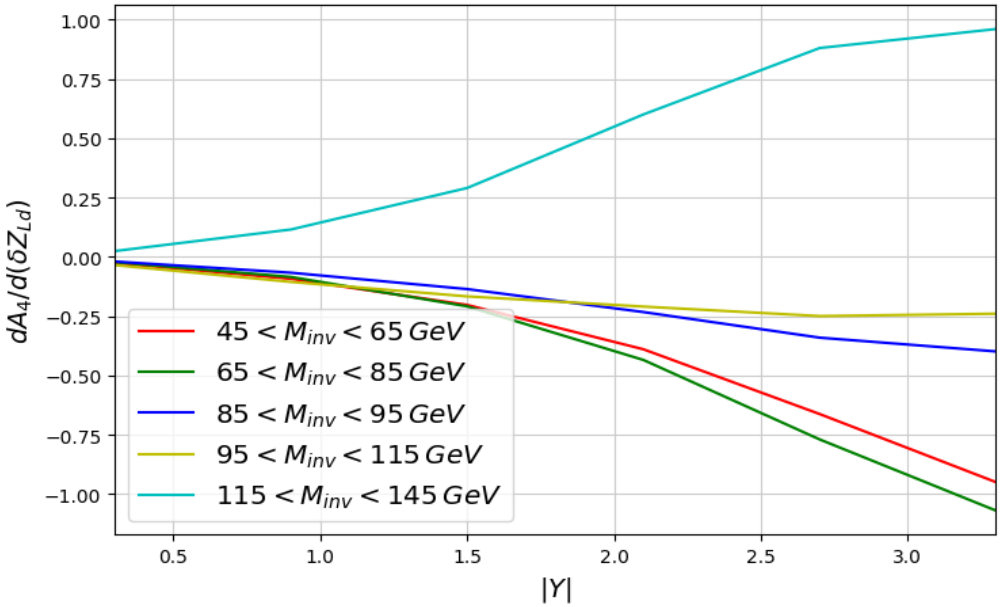
M_{inv} range: 45-145 GeV
Rapidity: 0-3.6

6 rapidity bins









Results for 4 bins from arXiv:2103.12074

- Big correlation
- Very big values

```
energy: 8000.0
eta_cut: 999.0
pT_cut: 0.0
y_min: 0.0
y_max: 0.0
```

Without restrictions

```
FCN=   17.59691     FROM HESSE     STATUS=OK            23 CALLS      429 TOTAL
                    EDM=  0.21E-04    STRATEGY= 2      ERROR MATRIX ACCURATE

 EXT PARAMETER                                          INTERNAL      INTERNAL
 NO.   NAME         VALUE           ERROR              STEP SIZE       VALUE
  1  delta_Z_Ld  -0.30795E-01    7.6980               0.32713E-02  -0.30795E-01
  2  delta_Z_Lu   -10.429        24.640               0.80158E-04   -10.429
  3  delta_Z_Rd   -17.216        40.912               0.94750E-03   -17.216
  4  delta_Z_Ru    17.399        41.141               0.15163E-03    17.399
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL     1     2     3     4
       1  0.00197  1.000-0.000-0.000 0.000
       2  0.99997 -0.000 1.000 0.995-1.000
       3  0.99849 -0.000 0.995 1.000-0.994
       4  0.99996  0.000-1.000-0.994 1.000
```

With restrictions for deltas between -1 to 1

```
78 FCN=   17.64500     FROM HESSE     STATUS=OK            23 CALLS      711 TOTAL
79                     EDM=  0.15E-02    STRATEGY= 2      ERROR MATRIX ACCURATE
80
81  EXT PARAMETER                                          INTERNAL      INTERNAL
82  NO.   NAME         VALUE           ERROR              STEP SIZE       VALUE
83   1  delta_Z_Ld  -0.28990E-01    0.34483              0.78124E-03  -0.28994E-01
84   2  delta_Z_Lu  -0.48142        0.31306              0.24371E-04  -0.50227
85   3  delta_Z_Rd  -0.78536        0.48827              0.38807E-03  -0.90328
86   4  delta_Z_Ru   0.78902        0.46971              0.65107E-04   0.90921
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL     1     2     3     4
       1  0.05230  1.000-0.002-0.006 0.004
       2  0.99949 -0.002 1.000 0.936-0.998
       3  0.97827 -0.006 0.936 1.000-0.916
       4  0.99934  0.004-0.998-0.916 1.000
```

Extend for 10 bins from ATLAS-CONF-2018-037

	$70 < m^{\ell\ell} < 80$ GeV			$80 < m^{\ell\ell} < 100$ GeV				$100 < m^{\ell\ell} < 125$ GeV		
$\lvert y^{\ell\ell}\rvert$	0 – 0.8	0.8 – 1.6	1.6 – 2.5	0 – 0.8	0.8 – 1.6	1.6 – 2.5	2.5 – 3.6	0 – 0.8	0.8 – 1.6	1.6 – 2.5
Central value	−0.0681	−0.2684	−0.5087	0.0195	0.0448	0.0923	0.1445	0.0975	0.3311	0.6722
	Uncertainties			Uncertainties				Uncertainties		
Total	0.0176	0.0199	0.0391	0.0015	0.0016	0.0026	0.0046	0.0086	0.0099	0.0234

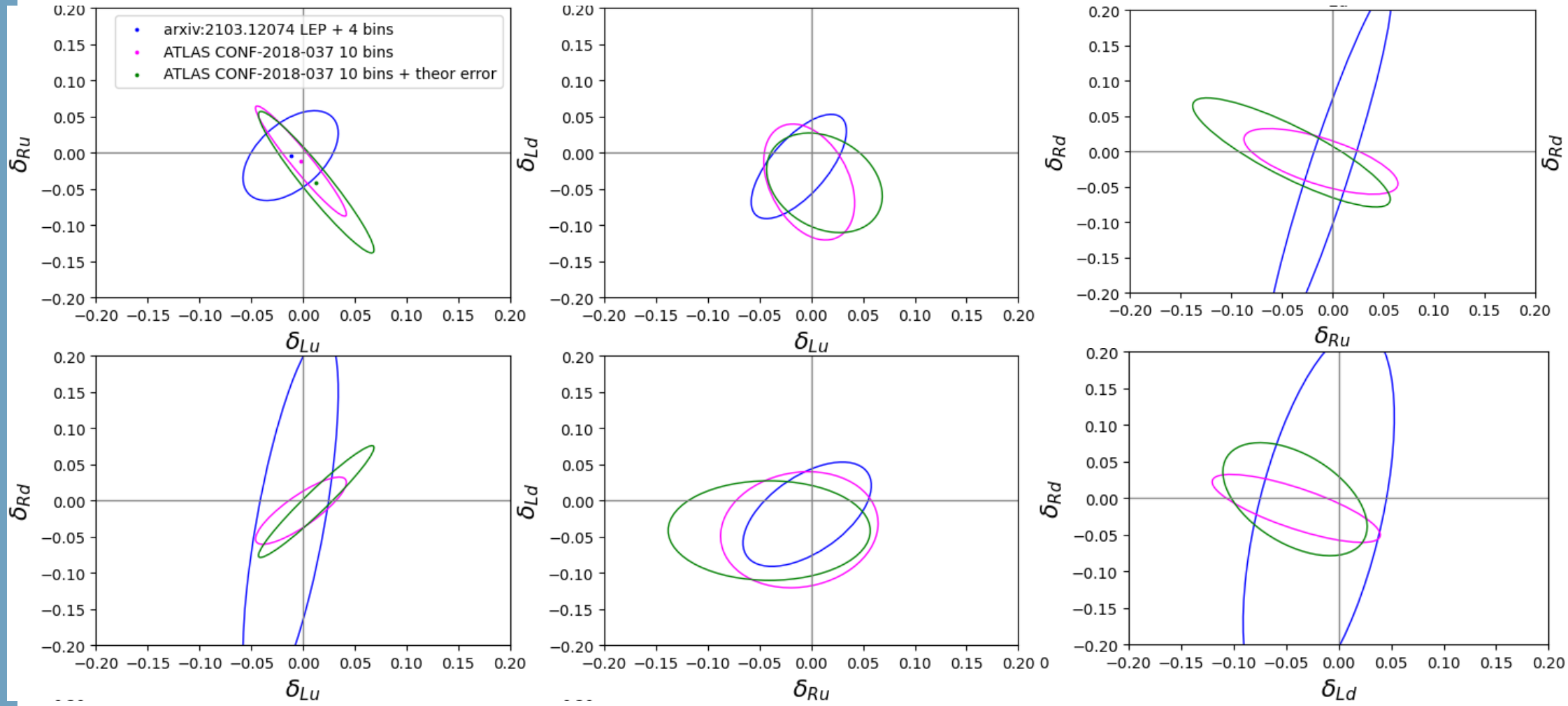
- Big, but lower correlation than for 4 bins
- Reasonable χ^2

```
energy: 8000.0
eta_cut: 999.0
pT_cut: 0.0
y_min: 0.0
y_max: 0.0
```

```
FCN=   22.53033      FROM HESSE     STATUS=OK             23 CALLS      278 TOTAL
                     EDM=  0.14E-04    STRATEGY= 2      ERROR MATRIX ACCURATE

 EXT PARAMETER                                          INTERNAL      INTERNAL
 NO.   NAME         VALUE            ERROR             STEP SIZE       VALUE
  1  delta_Z_Ld  -0.40386E-01   0.40033E-01   0.48077E-05  -0.40386E-01
  2  delta_Z_Lu  -0.20242E-02   0.21948E-01   0.89360E-06  -0.20242E-02
  3  delta_Z_Rd  -0.14089E-01   0.23198E-01   0.20266E-05  -0.14089E-01
  4  delta_Z_Ru  -0.11526E-01   0.38038E-01   0.17800E-05  -0.11526E-01

EXTERNAL ERROR MATRIX.    NDIM=  50    NPAR=  4    ERR DEF=  1.00
 0.160E-02-0.318E-03-0.723E-03 0.169E-03
-0.318E-03 0.482E-03 0.428E-03-0.803E-03
-0.723E-03 0.428E-03 0.538E-03-0.598E-03
 0.169E-03-0.803E-03-0.598E-03 0.145E-02

PARAMETER  CORRELATION COEFFICIENTS
       NO.  GLOBAL     1     2     3     4
        1  0.96845  1.000-0.361-0.779 0.111
        2  0.99630 -0.361 1.000 0.840-0.962
        3  0.98286 -0.779 0.840 1.000-0.678
        4  0.99511  0.111-0.962-0.678 1.000
```

Confidence ellipses for obtained data

Correction ellipses



Allowed regions (at 95% CL) for four corrections of the Z couplings.

How we generate pseudodata

Range for rapidity: 0 – 3.6
9 bins with step 0.4

Range for invariant mass: 70 – 125 GeV
11 bins with step 5 GeV

Luminosity (L) – 3000 fb^{-1}

Detector acceptance (ε) – 0.2

```
EXT PARAMETER
NO.   NAME        VALUE           ERROR
 1  delta_Z_Ld   0.51111E-05   0.31596E-02
 2  delta_Z_Lu   0.12485E-05   0.80108E-03
 3  delta_Z_Rd   0.60258E-06   0.39503E-03
 4  delta_Z_Ru   0.82996E-06   0.63236E-03

PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL     1     2     3     4
        1  0.99491  1.000 0.972 0.848 0.691
        2  0.99362  0.972 1.000 0.777 0.528
        3  0.92731  0.848 0.777 1.000 0.830
        4  0.95717  0.691 0.528 0.830 1.000
 .....
```

Smaller correlation than in previous pseudodata

Used formula from arXiv:1907.07727 to find stat error

$$\Delta A^*_{\mathrm{FB}} = \sqrt{\frac{1 - {A^*_{\mathrm{FB}}}^2}{N}},$$

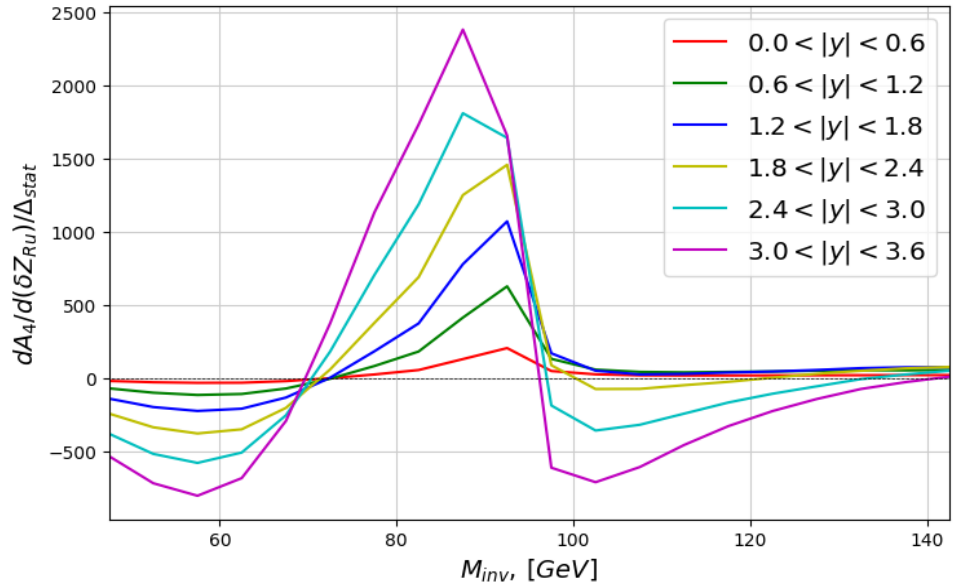
In our case $N_{min} \approx 12000$

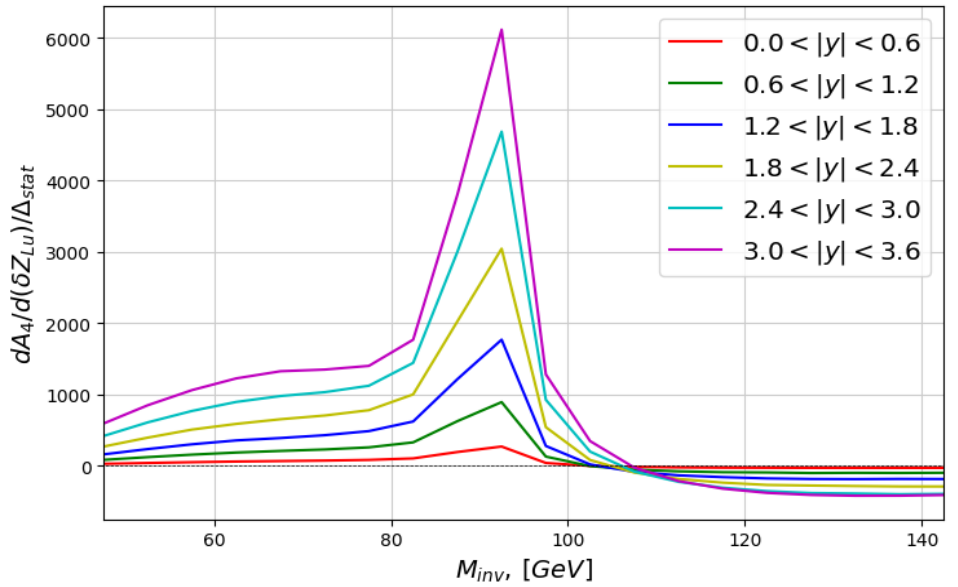
$$N = L\varepsilon(F + B)$$

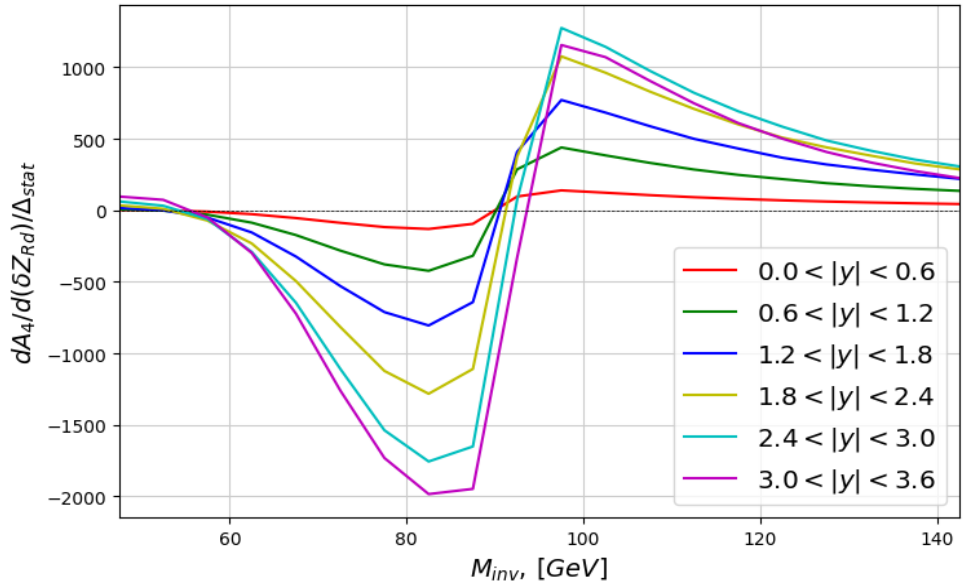
A^*_{FB} - value of forward-backward asymmetry, N – number of events, F and B –forward and backward cross-sections, respectively

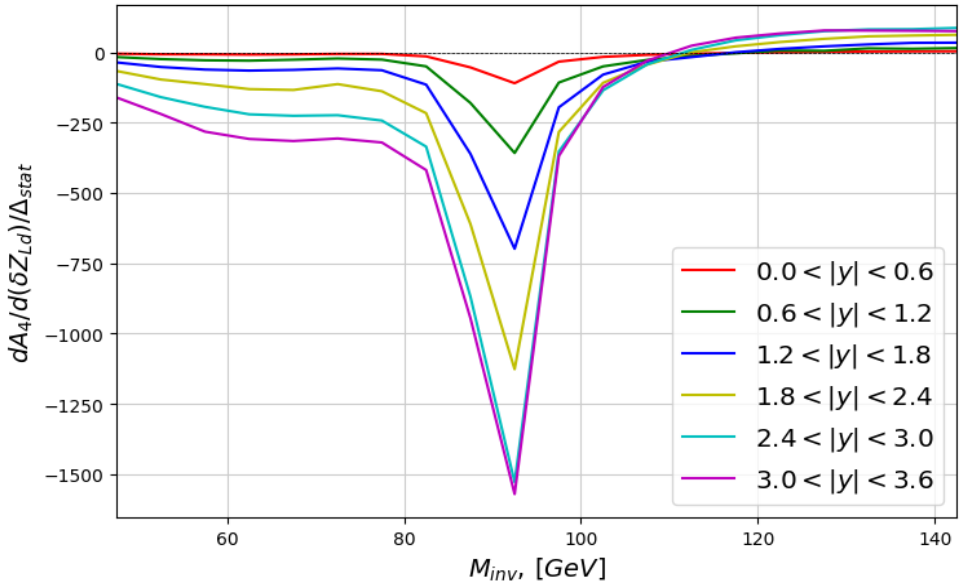
```
energy : 13000.0
eta_cut: 5.0
pT_cut : 20.0
y_min : 0.0
y_max : 0.0
```

Derivatives from AFB divided by Δ_{stat} as function of M_{inv}







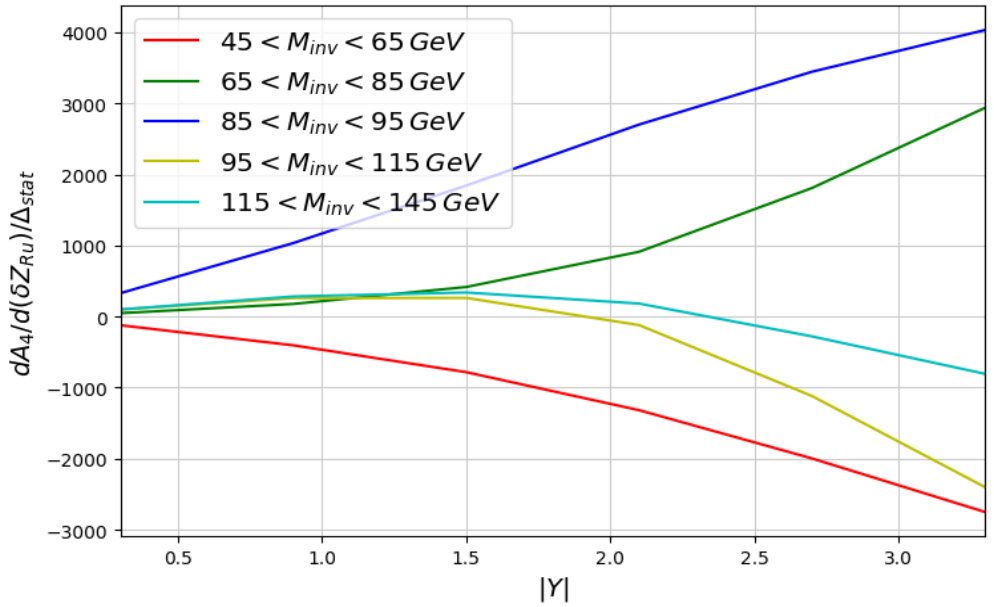


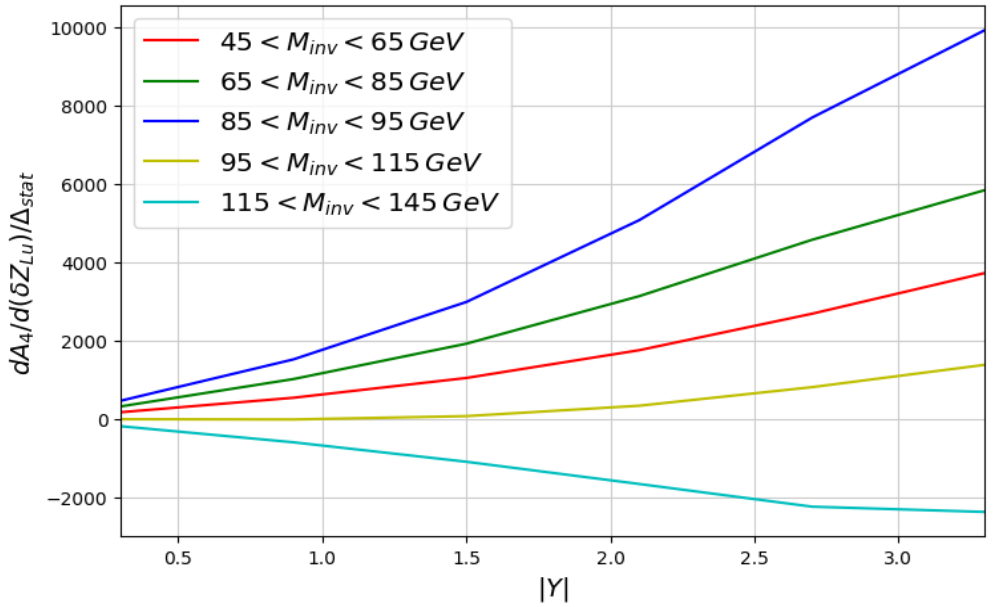
M_{inv} range: 45-145 GeV
Rapidity: 0-3.6

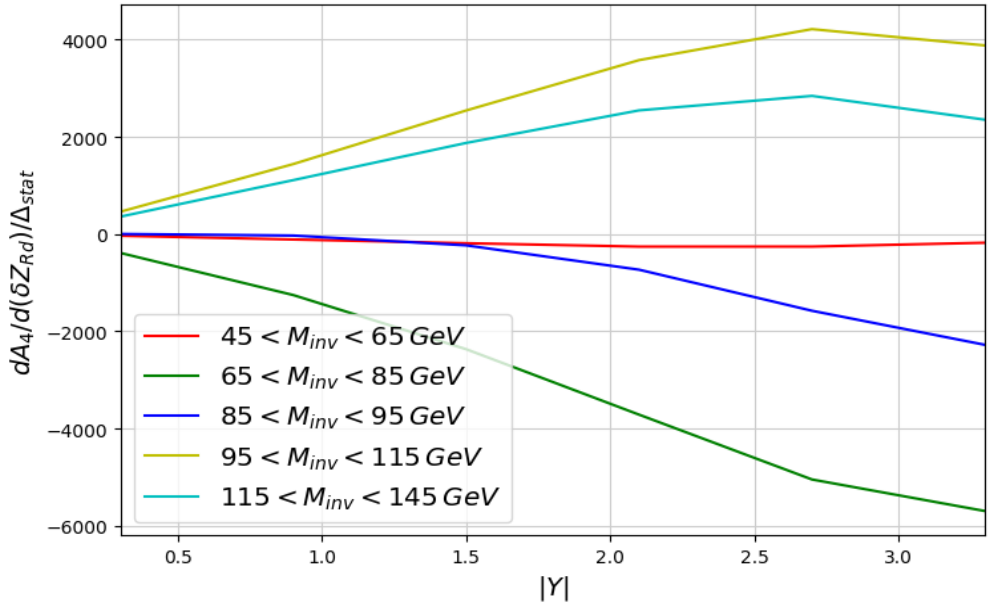
20 M_{inv} bins

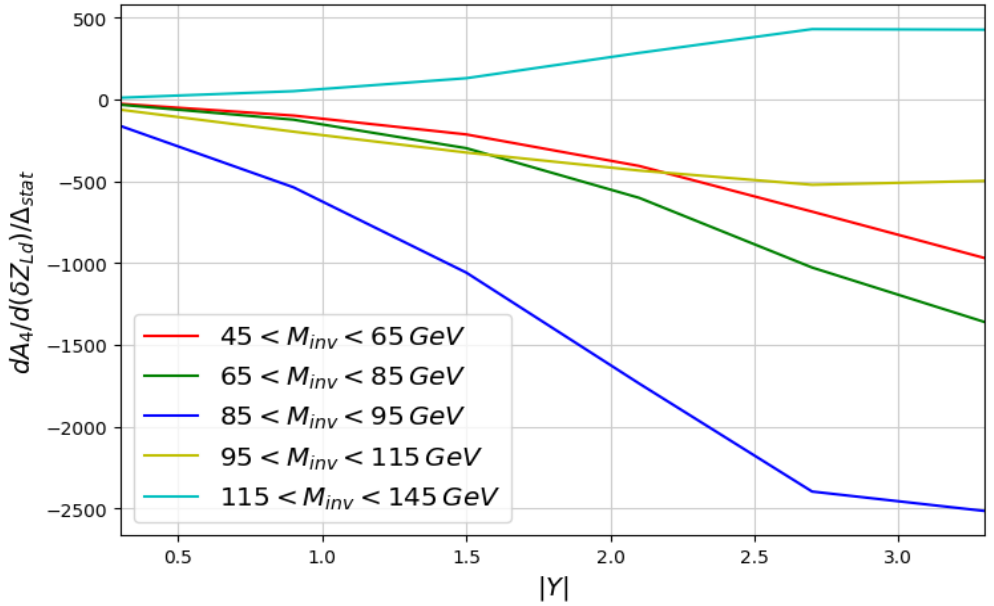
Stat error from HERAPDF20

Derivatives from AFB divided by Δ_{stat} as function of $|Y|$









M_{inv} range: 45-145 GeV
Rapidity: 0-3.6

6 rapidity bins

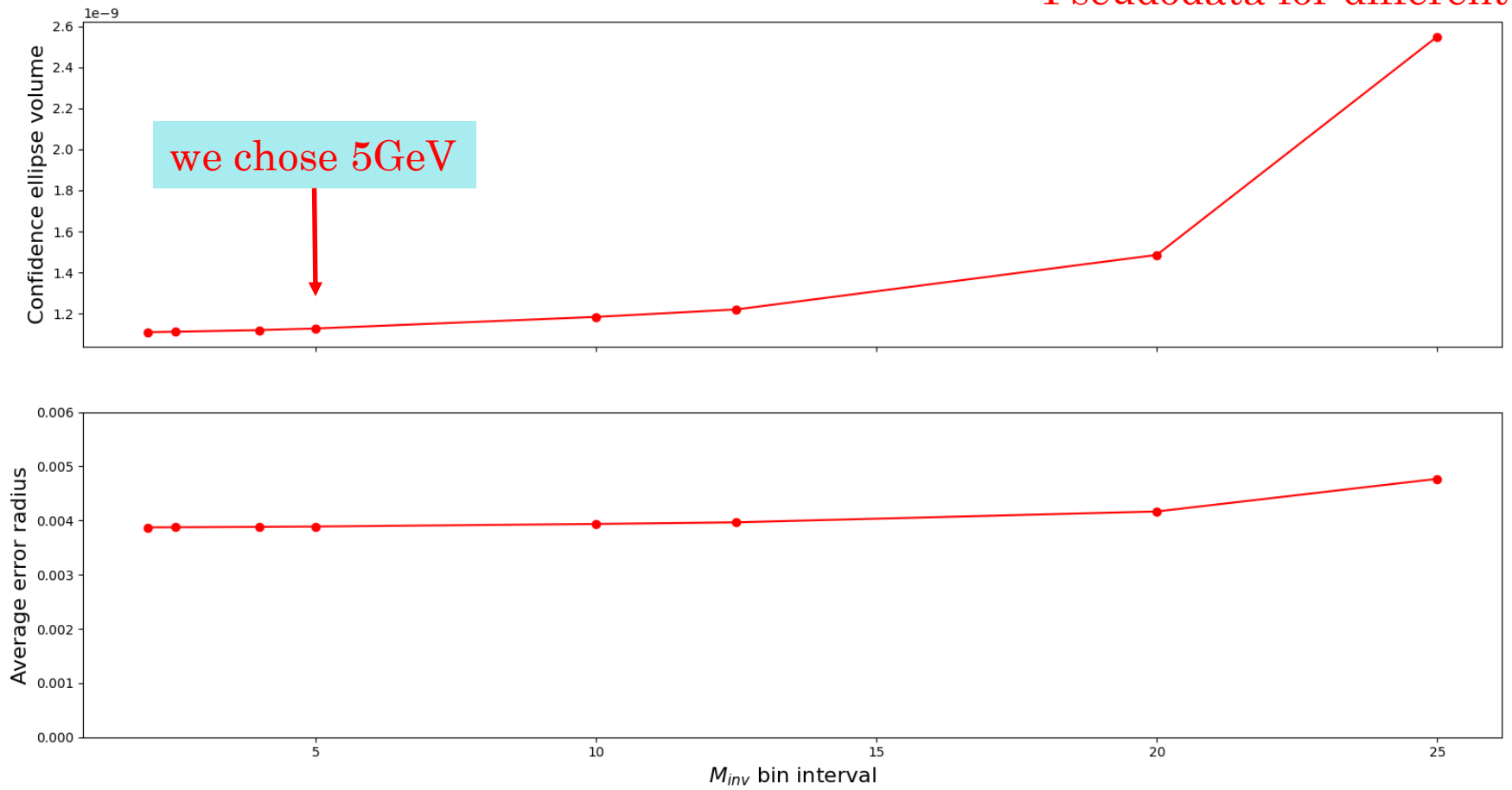
Stat error from HERAPDF20

Introduction of characteristic parameter

4-Elipsoid Volume: $V = \frac{\pi^2}{2}\Delta\delta_{Lu}\Delta\delta_{Ru}\Delta\delta_{Ld}\Delta\delta_{Rd}$

Average volume error: $\langle\Delta\delta\rangle = \left(\frac{2V}{\pi^2}\right)^{1/4}$

Pseudodata for different binning

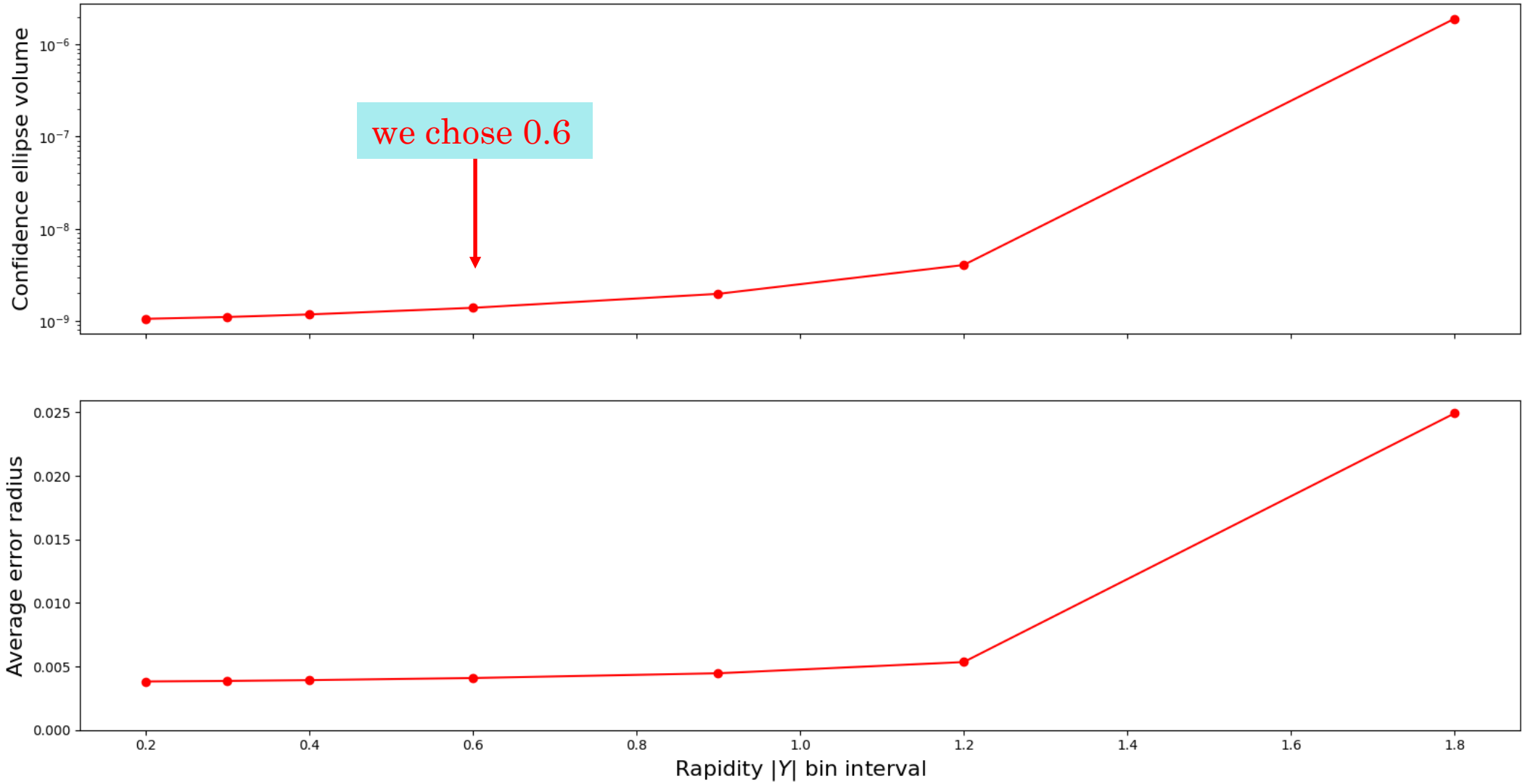


M_{inv} range: 45-145 GeV
Rapidity: 0-3.6

4 rapidity bins

Binning with respect to rapidity $|Y|$

Pseudodata for different binning

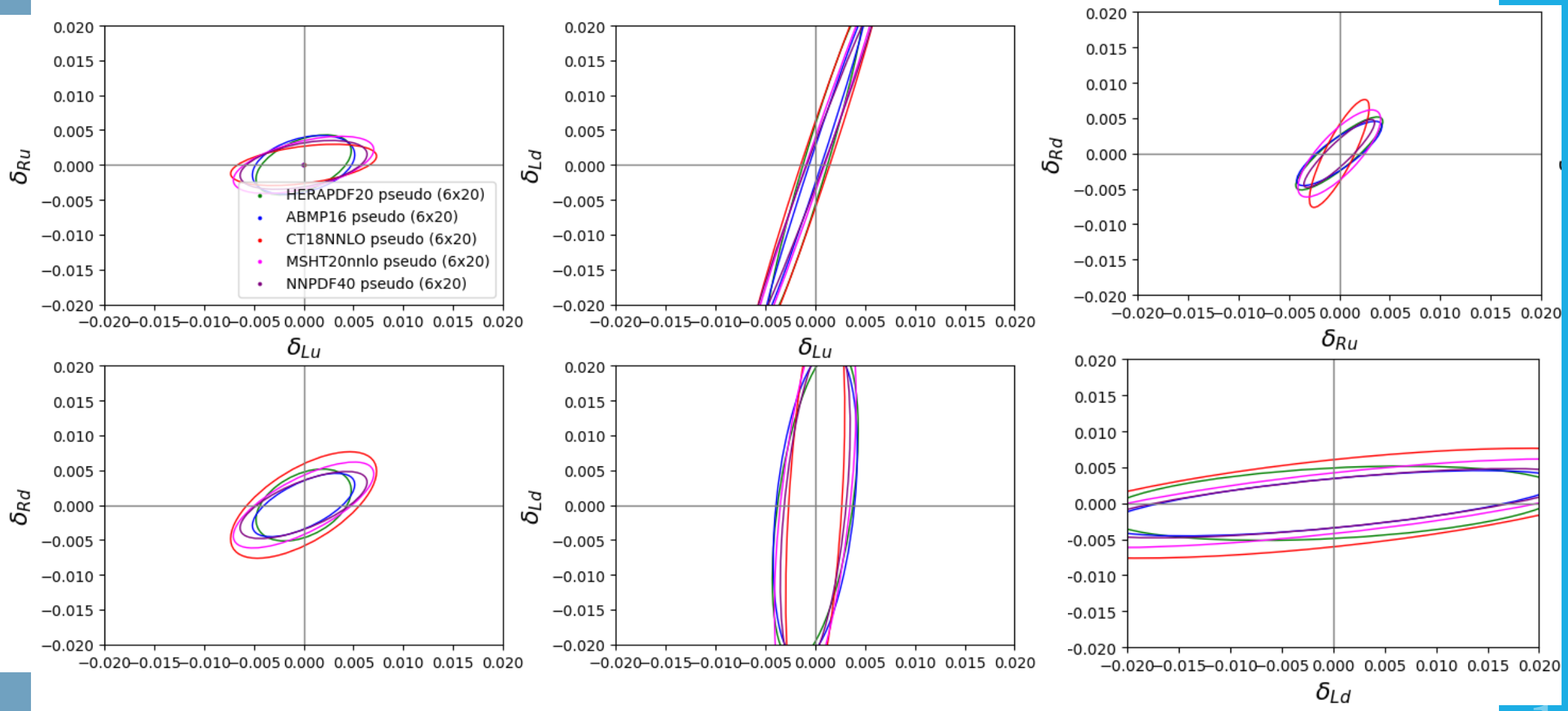


M_{inv} range: 70-125 GeV
Rapidity: 0-3.6

11 M_{inv} bins

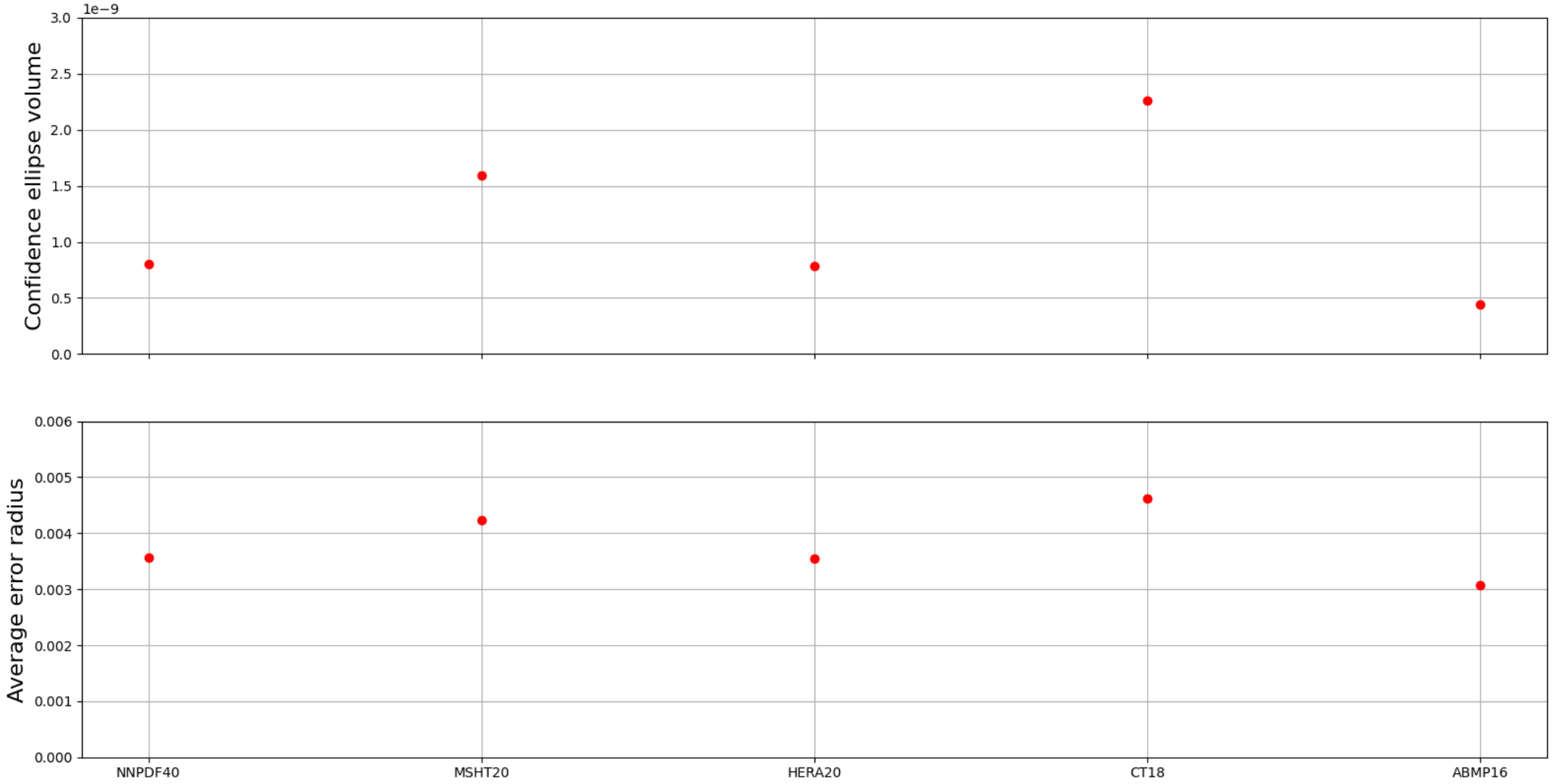
Comparison of different PDFs

M_{inv} range: 45-145 GeV
Rapidity: 0-3.6



Error and correlation of the couplings weakly depend from PDF sets

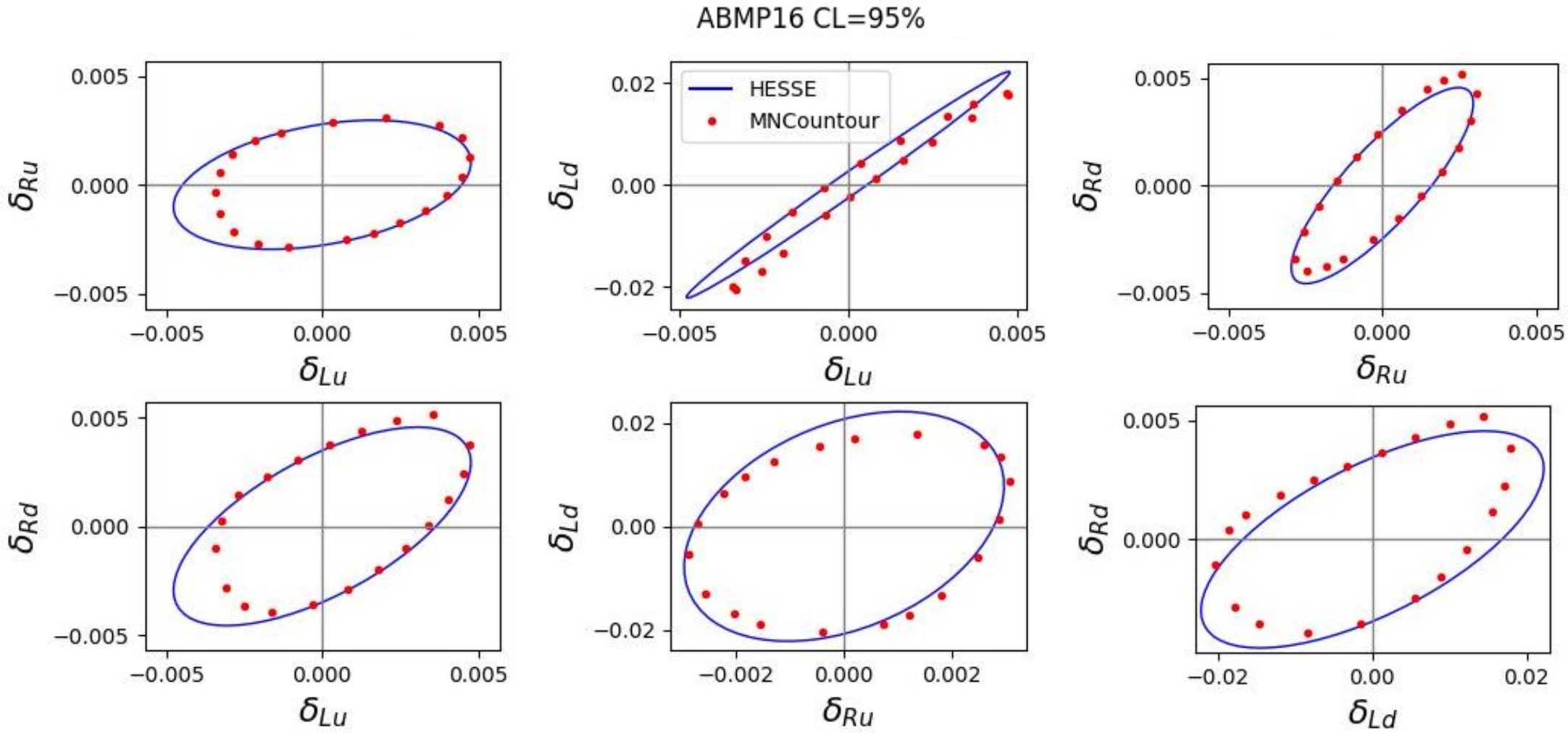
Comparison of different PDFs with Volumes



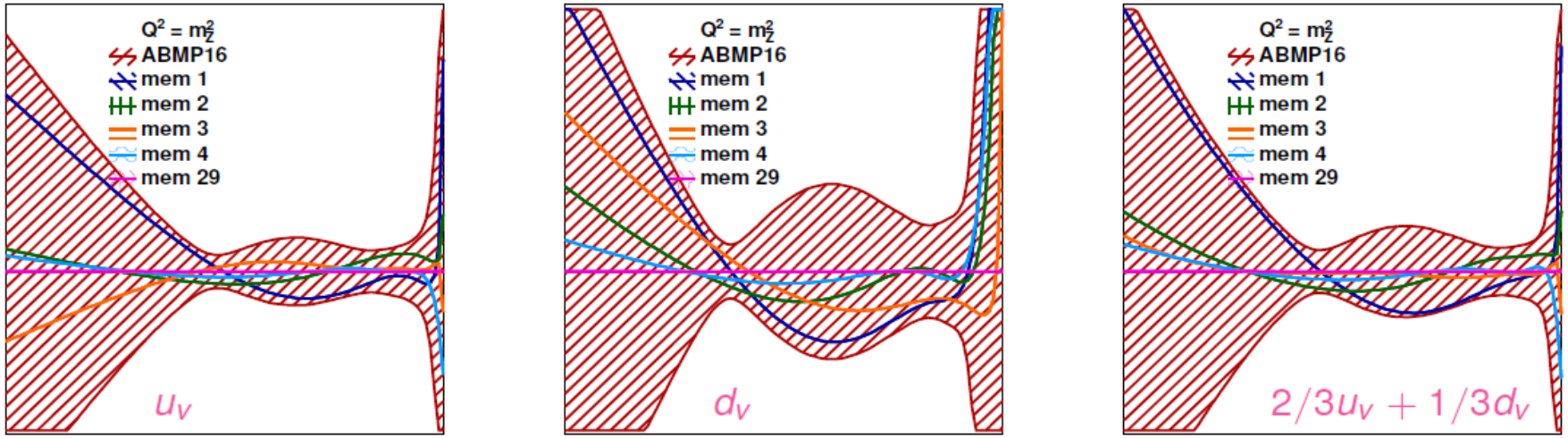
The ratio between average error radii of order $1 \div 1.5$

Comparison of Hesse vs exact variation on $\chi^2 = 1$

Hesse method shows good results compared to the exact calculation by MNContour



PDF rotation (ABMP16)

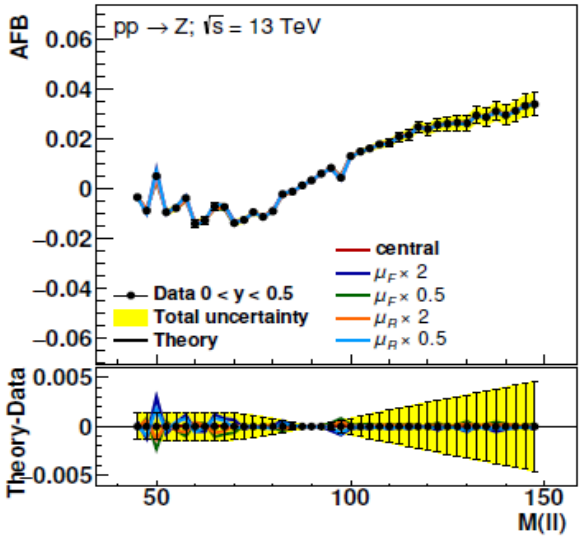


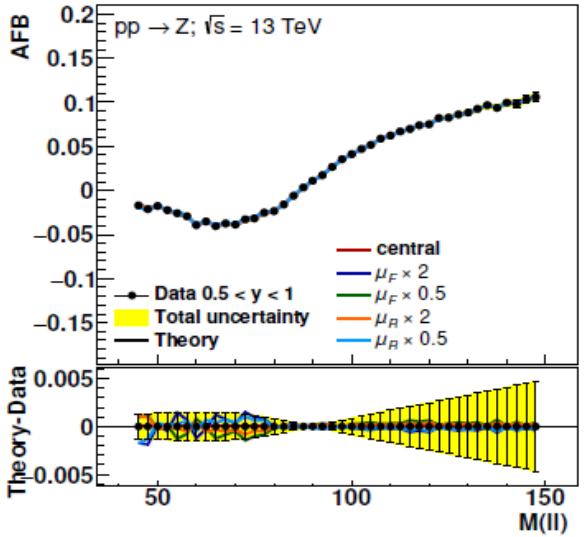
- Used instructions at
  `https://gitlab.cern.ch/fitters/xfitter/-/wikis/PDF%20rotation`
- New 'feature' of `xfitter-draw`: no axis labels... (ROOT Version: 6.28/04)
- Largest impact on $2/3u_V + 1/3d_V$
- 1st eigenvector almost fully determines PDF error band:

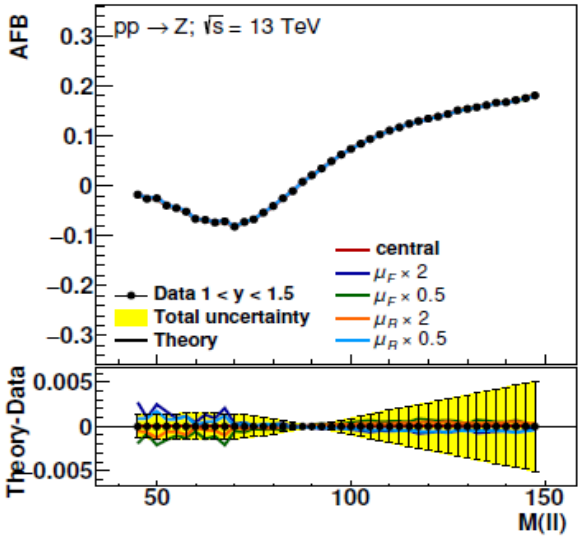
ABMP16_5_nnlo	mem1	mem2	mem3	mem4	mem29
χ^2/dof	878/120	81/120	46/120	4/120	0/120

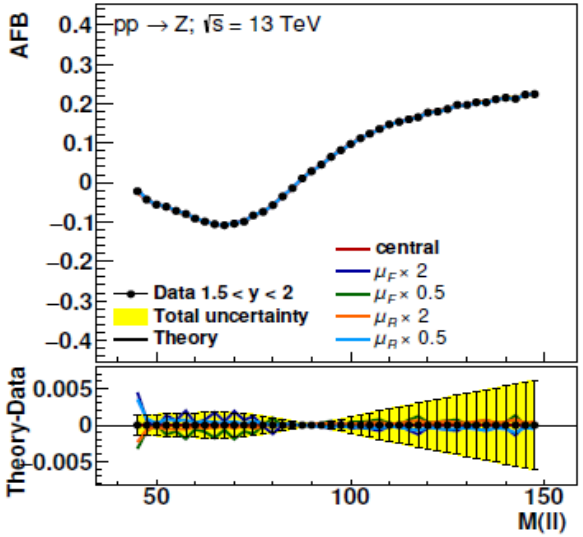
- Consistent with results from arXiv:1907.07727

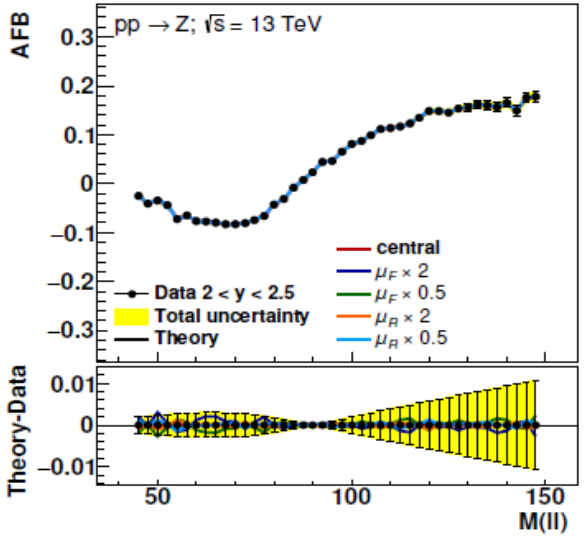
NLO scale variations





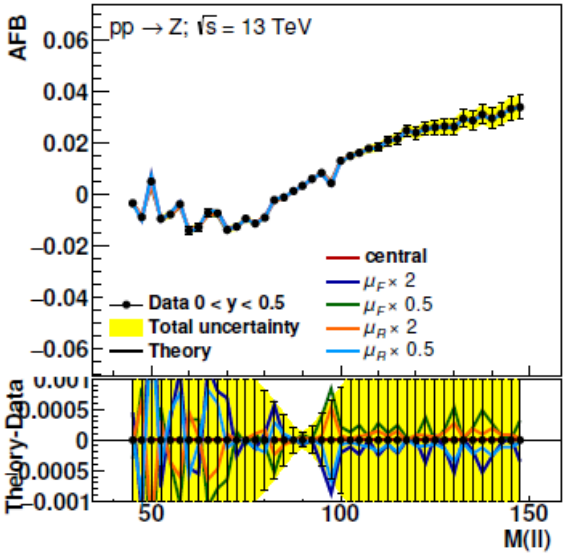


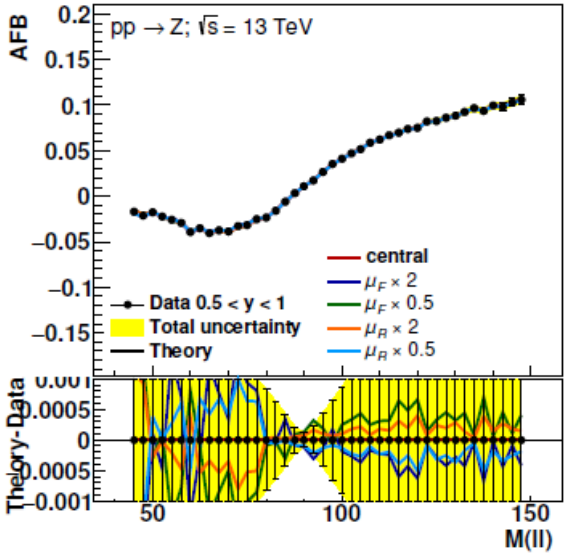


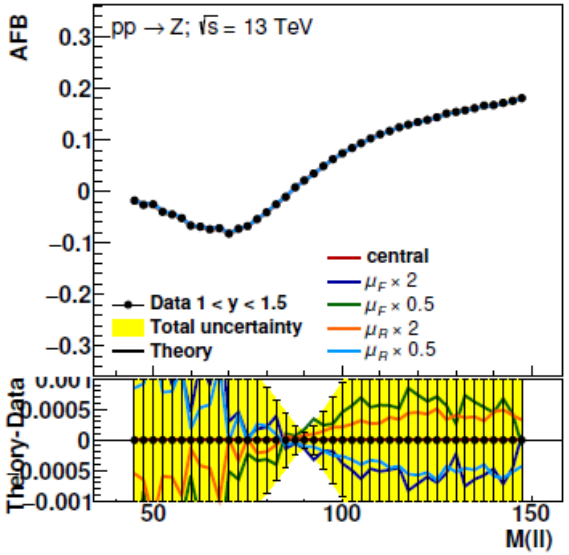


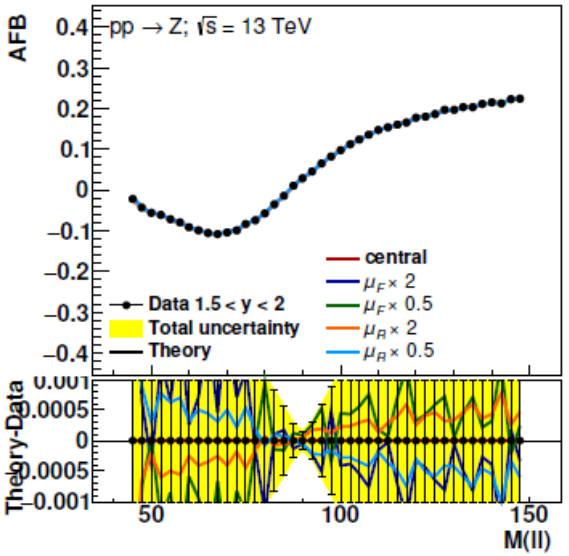
- NLO scale variations are generally smaller than stat. unc. of pseudodata

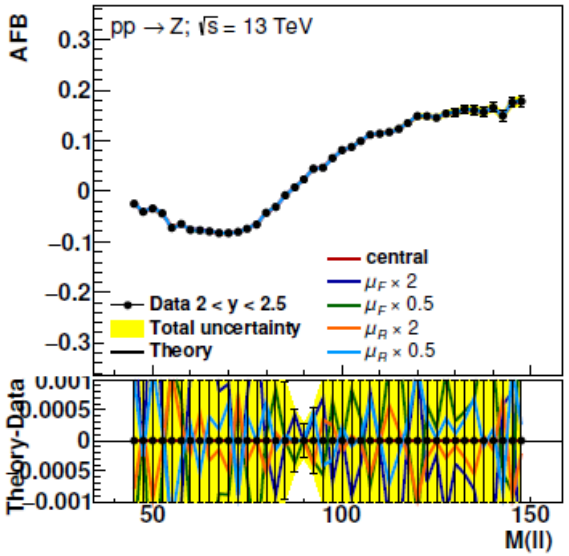
NLO scale variations











- For the future real analysis at NNLO one expects even smaller effect

Running pseudodata with different PDF set

HERAPDF20 pseudodata with ABMP16 (without changes)

```
FCN=   488.4394     FROM CALl fcn  STATUS=RESET          1 CALLS        1 TOTAL
                    EDM= unknown      STRATEGY= 1      NO ERROR MATRIX

 EXT PARAMETER                CURRENT GUESS      PHYSICAL LIMITS
 NO.   NAME         VALUE          ERROR       NEGATIVE      POSITIVE
  1  delta_Z_Ld    0.0000       0.10000
  2  delta_Z_Lu    0.0000       0.10000
  3  delta_Z_Rd    0.0000       0.10000
  4  delta_Z_Ru    0.0000       0.10000
```

HERAPDF20 pseudodata with ABMP16 (with migrad)

```
FCN=   160.0691     FROM HESSE     STATUS=OK            23 CALLS      199 TOTAL
                    EDM=  0.95E-05    STRATEGY= 2      ERROR MATRIX ACCURATE

 EXT PARAMETER                                          INTERNAL      INTERNAL
 NO.   NAME         VALUE          ERROR               STEP SIZE       VALUE
  1  delta_Z_Ld   -0.91099E-02   0.60507E-02          0.17974E-05  -0.91099E-02
  2  delta_Z_Lu    0.32083E-02   0.10986E-02          0.33138E-06   0.32083E-02
  3  delta_Z_Rd    0.75984E-02   0.17967E-02          0.10264E-05   0.75984E-02
  4  delta_Z_Ru    0.68725E-02   0.14078E-02          0.16726E-06   0.68725E-02
```

HERAPDF20 pseudodata with CT18 (without changes)

```
FCN=   68.08138     FROM CALl fcn  STATUS=RESET          1 CALLS        1 TOTAL
                    EDM= unknown      STRATEGY= 1      NO ERROR MATRIX

 EXT PARAMETER                CURRENT GUESS      PHYSICAL LIMITS
 NO.   NAME         VALUE          ERROR       NEGATIVE      POSITIVE
  1  delta_Z_Ld    0.0000       0.10000
  2  delta_Z_Lu    0.0000       0.10000
  3  delta_Z_Rd    0.0000       0.10000
  4  delta_Z_Ru    0.0000       0.10000
```

HERAPDF20 pseudodata with CT18 (with migrad)

```
FCN=   49.39074     FROM HESSE     STATUS=OK            23 CALLS      158 TOTAL
                    EDM=  0.22E-05    STRATEGY= 2      ERROR MATRIX ACCURATE

 EXT PARAMETER                                          INTERNAL      INTERNAL
 NO.   NAME         VALUE          ERROR               STEP SIZE       VALUE
  1  delta_Z_Ld    0.22992E-03   0.77036E-02          0.19912E-05   0.22992E-03
  2  delta_Z_Lu    0.30494E-02   0.19154E-02          0.48711E-06   0.30494E-02
  3  delta_Z_Rd    0.15203E-02   0.31728E-02          0.12172E-05   0.15203E-02
  4  delta_Z_Ru    0.84693E-03   0.18881E-02          0.77681E-06   0.84693E-03
```

HERAPDF20 pseudodata with MSHT20 (without changes)

```
FCN=   249.3247     FROM CALl fcn  STATUS=RESET          1 CALLS        1 TOTAL
                    EDM= unknown      STRATEGY= 1      NO ERROR MATRIX

 EXT PARAMETER                CURRENT GUESS      PHYSICAL LIMITS
 NO.   NAME         VALUE          ERROR       NEGATIVE      POSITIVE
  1  delta_Z_Ld    0.0000       0.10000
  2  delta_Z_Lu    0.0000       0.10000
  3  delta_Z_Rd    0.0000       0.10000
  4  delta_Z_Ru    0.0000       0.10000
```

HERAPDF20 pseudodata with MSHT20 (with migrad)

```
FCN=   116.6972     FROM HESSE     STATUS=OK            23 CALLS      143 TOTAL
                    EDM=  0.35E-05    STRATEGY= 2      ERROR MATRIX ACCURATE

 EXT PARAMETER                                          INTERNAL      INTERNAL
 NO.   NAME         VALUE          ERROR               STEP SIZE       VALUE
  1  delta_Z_Ld   -0.79985E-03   0.51763E-02          0.17101E-05  -0.79985E-03
  2  delta_Z_Lu    0.30990E-02   0.13516E-02          0.45327E-06   0.30990E-02
  3  delta_Z_Rd    0.13714E-01   0.21454E-02          0.12603E-05   0.13714E-01
  4  delta_Z_Ru    0.61700E-02   0.16086E-02          0.97247E-06   0.61700E-02
```

Running pseudodata with different PDF set

HERAPDF20 pseudodata with NNPDF40 (without changes)

```
FCN=   321.3273     FROM CALl fcn  STATUS=RESET          1 CALLS        1 TOTAL
                    EDM= unknown      STRATEGY= 1      NO ERROR MATRIX

 EXT PARAMETER                CURRENT GUESS      PHYSICAL LIMITS
 NO.   NAME         VALUE           ERROR       NEGATIVE      POSITIVE
  1  delta_Z_Ld    0.0000        0.10000
  2  delta_Z_Lu    0.0000        0.10000
  3  delta_Z_Rd    0.0000        0.10000
  4  delta_Z_Ru    0.0000        0.10000
```

HERAPDF20 pseudodata with NNPDF40 (with migrad)

```
FCN=   95.84044     FROM HESSE     STATUS=OK             23 CALLS      161 TOTAL
                    EDM=  0.66E-07    STRATEGY= 2      ERROR MATRIX ACCURATE

 EXT PARAMETER                                          INTERNAL      INTERNAL
 NO.   NAME         VALUE           ERROR              STEP SIZE       VALUE
  1  delta_Z_Ld    0.52608E-02   0.46604E-02          0.11651E-05   0.52608E-02
  2  delta_Z_Lu    0.52660E-02   0.14354E-02          0.38197E-06   0.52660E-02
  3  delta_Z_Rd    0.13051E-01   0.19941E-02          0.62582E-06   0.13051E-01
  4  delta_Z_Ru    0.69733E-02   0.14626E-02          0.51016E-06   0.69733E-02
```

Recheck

MSHT20 pseudodata with CT18 (without changes)

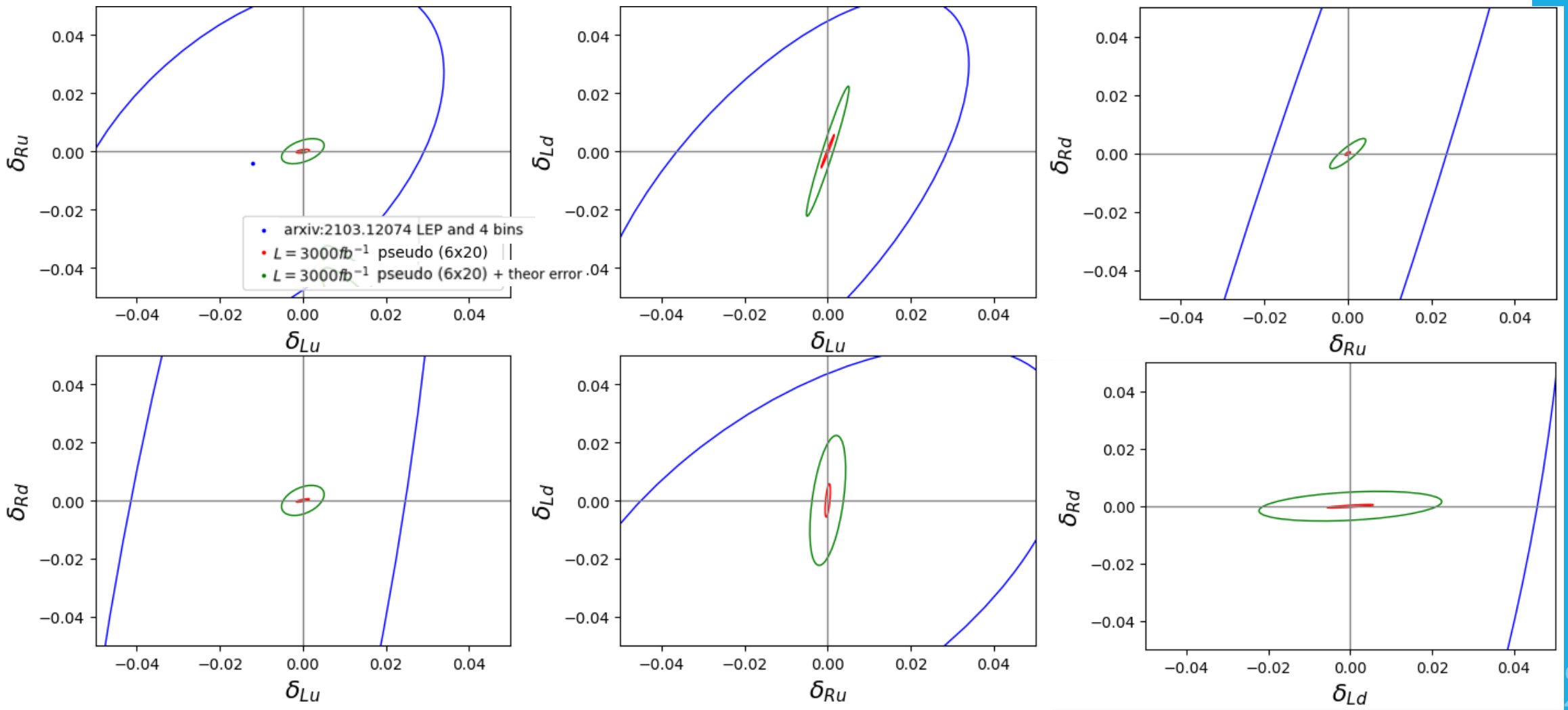
```
FCN=   19.18510     FROM CALl fcn  STATUS=RESET          1 CALLS        1 TOTAL
                    EDM= unknown      STRATEGY= 1      NO ERROR MATRIX

 EXT PARAMETER                CURRENT GUESS      PHYSICAL LIMITS
 NO.   NAME         VALUE           ERROR       NEGATIVE      POSITIVE
  1  delta_Z_Ld    0.0000        0.10000
  2  delta_Z_Lu    0.0000        0.10000
  3  delta_Z_Rd    0.0000        0.10000
  4  delta_Z_Ru    0.0000        0.10000
```

MSHT20 pseudodata with CT18 (with migrad)

```
FCN=   17.20874     FROM HESSE     STATUS=OK             23 CALLS      162 TOTAL
                    EDM=  0.16E-04    STRATEGY= 2      ERROR MATRIX ACCURATE

 EXT PARAMETER                                          INTERNAL      INTERNAL
 NO.   NAME         VALUE           ERROR              STEP SIZE       VALUE
  1  delta_Z_Ld    0.16140E-01   0.12477E-01          0.85399E-06   0.16140E-01
  2  delta_Z_Lu    0.48249E-02   0.40409E-02          0.26004E-06   0.48249E-02
  3  delta_Z_Rd    0.50120E-02   0.40857E-02          0.57853E-06   0.50120E-02
  4  delta_Z_Ru    0.13753E-02   0.22262E-02          0.35630E-06   0.13753E-02
```

The central values don't match for different PDF sets and their pseudodata

Our pseudodata comparing to current constrains



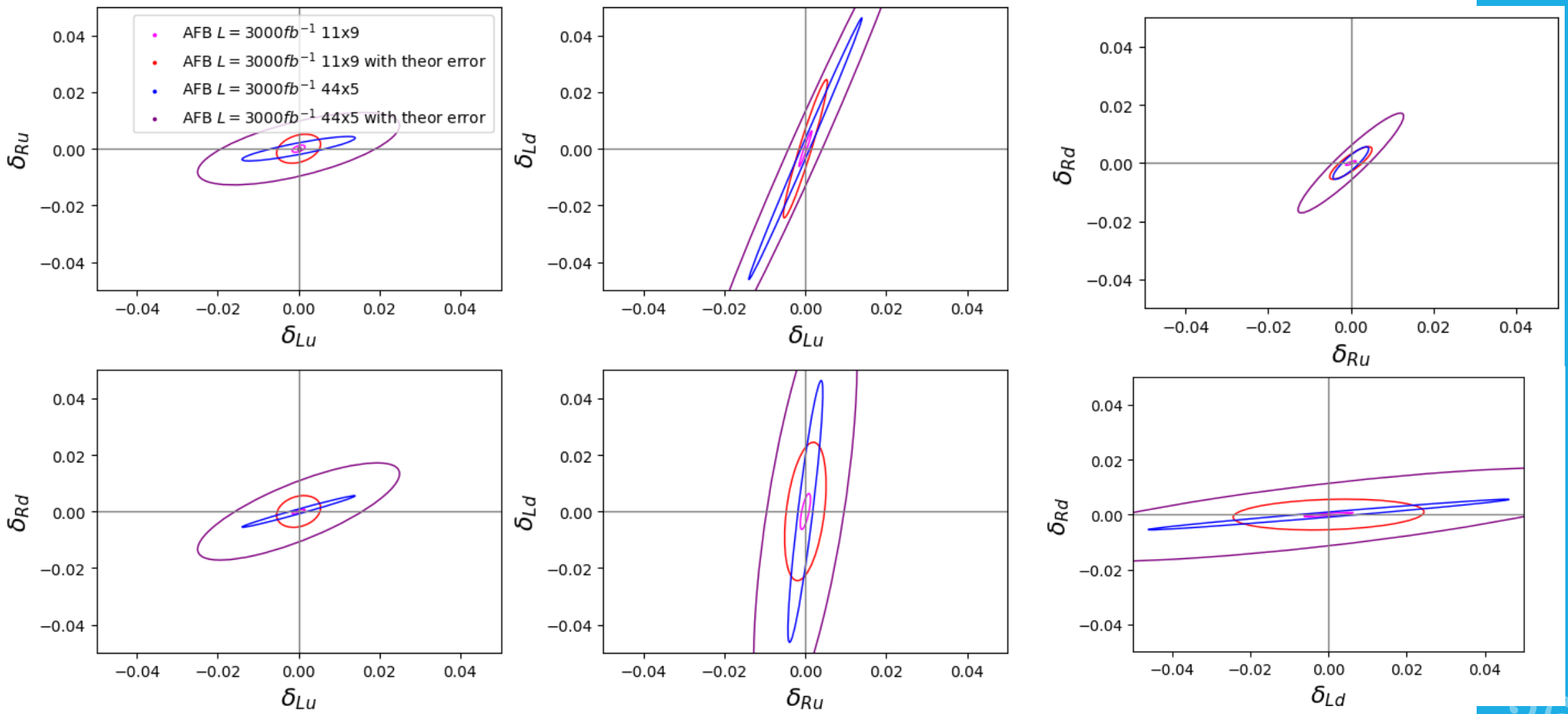
Conclusion!

- Upgrade of xFitter was done
- Constraints on Z couplings using experimental data from ATLAS-CONF-2018-037 were studied
- Different types of pseudodata were generated and explored
- The dependence of constraints from the number of bins for rapidity and invariant mass was obtained
- Comparing different PDF sets using pseudodata was done
- AFB derivatives was studied
- The possibility of significantly constraining Z couplings using HL-LHC data
- The result is ready to be published

Appendix A

Comparison of pseudodata

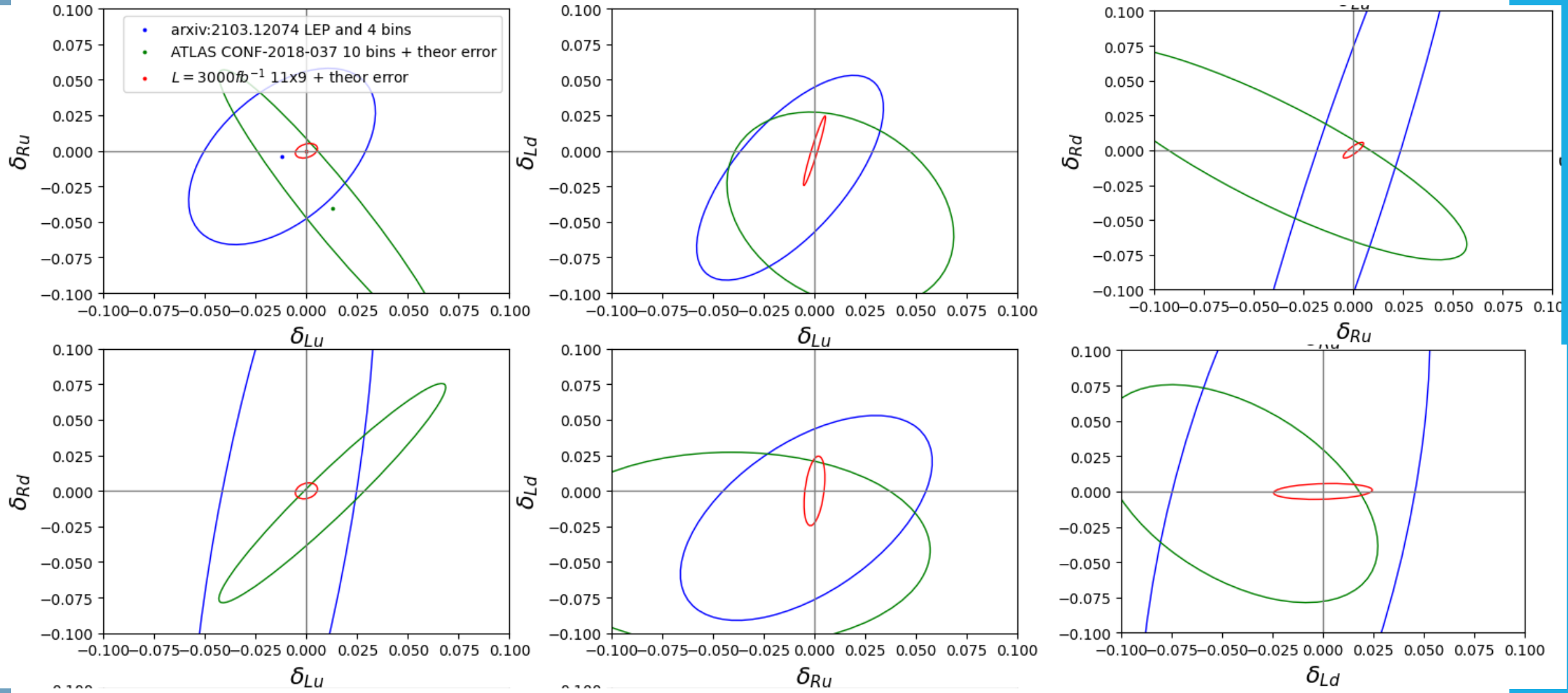
Correction ellipses



Allowed regions (at 95% CL) for four corrections of the Z couplings.

Intermediate result!

Correction ellipses



Allowed regions (at 95% CL) for four corrections of the Z couplings.

Intermediate conclusion

- Current constraints for couplings can be significantly improved with high luminosity data
- Also even current data for 10 bins can additionally constrain deltas
- Found interesting effect with rapidity bins

	$\Delta\delta_{Ru}$	$\Delta\delta_{Lu}$	$\Delta\delta_{Rd}$	$\Delta\delta_{Ld}$
4 bins from [4]	0.031	0.023	0.130	0.036
10 bins from [8]	0.048806	0.027921	0.038547	0.034358
Pseudodata 11x9	0.002563	0.002720	0.002801	0.012219
Pseudodata 44x5	0.006390	0.012492	0.008579	0.039614