Study of W and Z Production at NNLO

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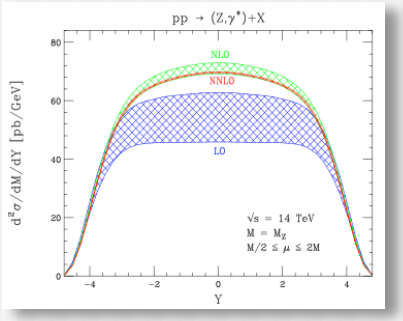
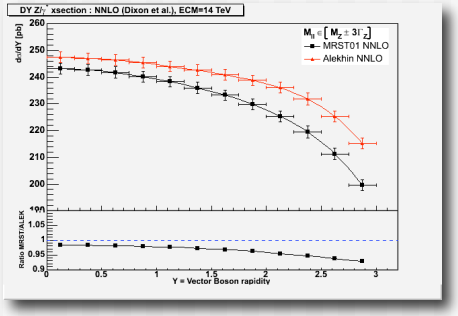
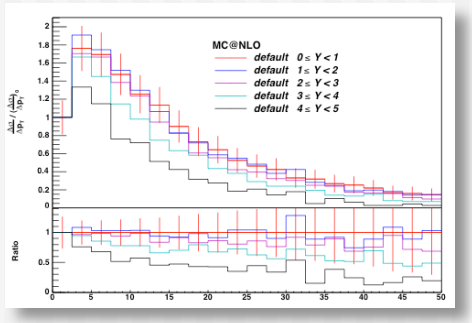
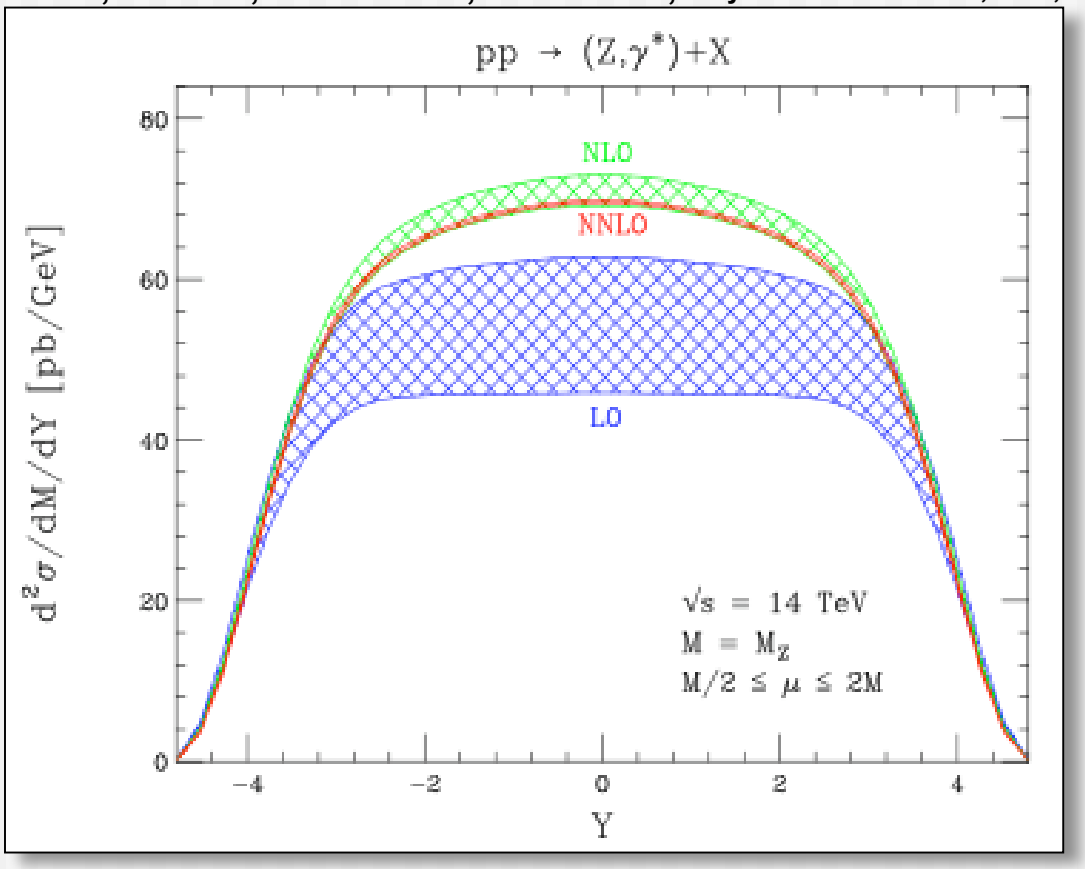






Introduction

- Now known : Vector Boson Production at NNLO (QCD), differential in boson rapidity
  - Anastasiou, Dixon, Melnikov, Petriello, **Phys.Rev.D69:094008,2004; hep-ph/0312266**



Goal of this study

- Apply “selection criteria” as close to exp. reality as possible
- Study theor. systematic uncertainties
- Here shown:
  - “inclusive” cross sections, ie. integrated over experimentally accessible rapidity range
  - differential cross sections
  - for Z, W and high-mass DY (Z/γ^*)

The Program VRAP

courtesy L. Dixon

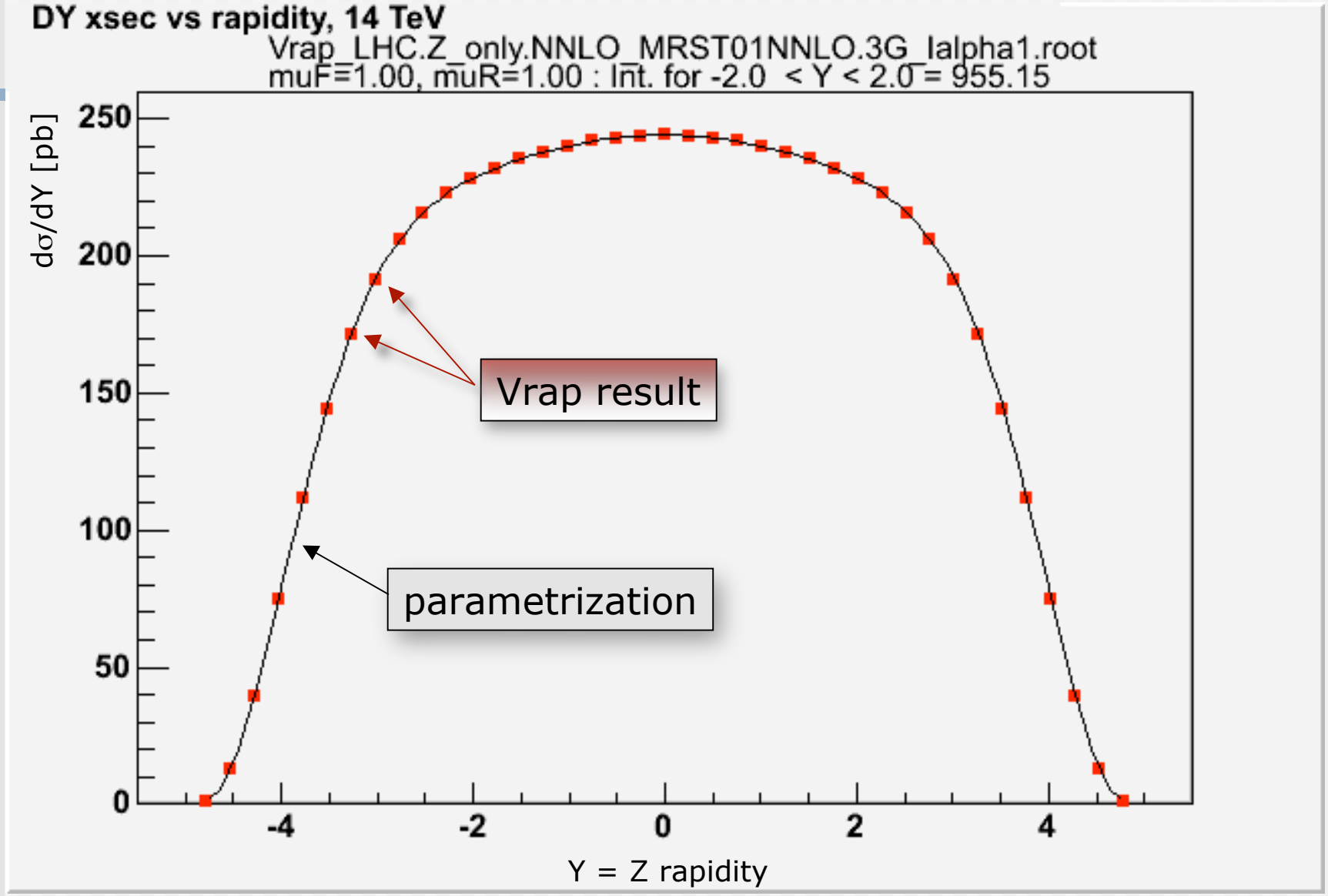
- Possible settings:
  - Collider/Energy : here LHC, 14 TeV
  - Exchanged Boson : γ^*, Z, Z/γ^*, W^+,W^-
  - Scale Q : M_Z, M_W or off-shell (eg. 400 GeV)
  - Renorm. and Factor. Scales
  - Di-lepton invariant mass (fixed or over range)
  - α_{QED} : Fixed (1/128) or $\alpha_{QED}(Q)$
  - Number of light fermions

The Program VRAP...

- Possible settings: PDFs :
  - MRST2001
    - NNLO, mode 1, α_s = 0.1155 : used as nominal set
    - NNLO, mode 4, α_s = 0.121 (fit to jet data, high E_T)
    - NNLO, "fast" evolution, α_s = 0.1155
    - NNLO, "slow" evolution, α_s = 0.1155
    - à la hep-ph/0110215 :
      NNLO x-sec, NLO central PDF, α_s = 0.119
  - ALEKHIN : consistent NNLO set, variable flavour scheme

Method :

- Use VRAP to obtain $d\sigma/dY$ at a fixed number of points in rapidity
- Chosen integration range over dilepton invariant mass:
  - $M_V - 3\Gamma_V < M_V < M_V + 3\Gamma_V$ (for on-shell production)
  - in order to simulate exp. selection of signal region
- Parametrize (Spline)
- With this parametrization:
  - Compute integral over any range in rapidity
  - eg. $|Y| < 2,\ 2.5,\ 3$
  - or integrate over bins in rapidity, as exps. would do by event counting


DY xsec vs rapidity, 14 TeV
Vrap_LHC.Z_only.NNLO_MRST01NNLO.3G_Ialpha1.root
muF=1.00, muR=1.00 : Int. for -2.0 < Y < 2.0 = 955.15
dσ/dY [pb]
250
200
150
100
50
0
-4
-2
0
2
4
Y = Z rapidity
Vrap result
parametrization

Results : Z production

|Y| < 2

ECM=14 TeV, pp (LHC)
alpha_qed = 1/128

M_Z - 3G_Z < M < M_Z + 3G_Z
Z exch only

Channel/Order/Pdf	Integral [pb]	Diff | [pb]	rel Diff | %
PDFs:			
NNLO_MRST01NNLO muF=1 muR=1	**955.151**	**0.000**	**0.000**
NNLO_MRST_HepPh0110215 muF=1 muR=1	968.933	13.782	1.443
NNLO_MRST01NNLO_mode4 muF=1 muR=1	964.815	9.664	1.012
NNLO_MRSTNNLO_fast muF=1 muR=1	954.019	1.132	0.119
NNLO_MRSTNNLO_slow muF=1 muR=1	957.003	1.852	0.194
NNLO_AlekhinNNLO muF=1 muR=1	978.480	23.329	2.442
max difference (abs), rel in %		23.329	2.442
scale variations:			
NNLO_MRST01NNLO muF=0.5 muR=0.5	953.858	1.293	0.135
NNLO_MRST01NNLO muF=2.0 muR=2.0	958.886	3.735	0.391
NNLO_MRST01NNLO muF=1.0 muR=0.5	953.324	1.827	0.191
NNLO_MRST01NNLO muF=1.0 muR=2.0	954.195	0.956	0.100
NNLO_MRST01NNLO muF=0.5 muR=1.0	947.009	8.142	0.852
NNLO_MRST01NNLO muF=2.0 muR=1.0	953.932	1.219	0.128
max difference (abs), rel		8.142	0.852
running of alpha_qed:			
NNLO_MRST01NNLO alpha_qed(Q)	947.987	7.164	0.750
Total theoretical uncertainty (quad. sum of above contr.):		**25.727**	**2.693**

Results : Z production

- For increasing acceptance:

Syst. Uncert. [%]	|Y|<2	|Y|<2.5	|Y|<3
PDF	2.44	2.95	3.57
scale	0.85	0.87	0.90
α_{QED}	0.75	0.75	0.74
Total	**2.69**	**3.16**	**3.76**

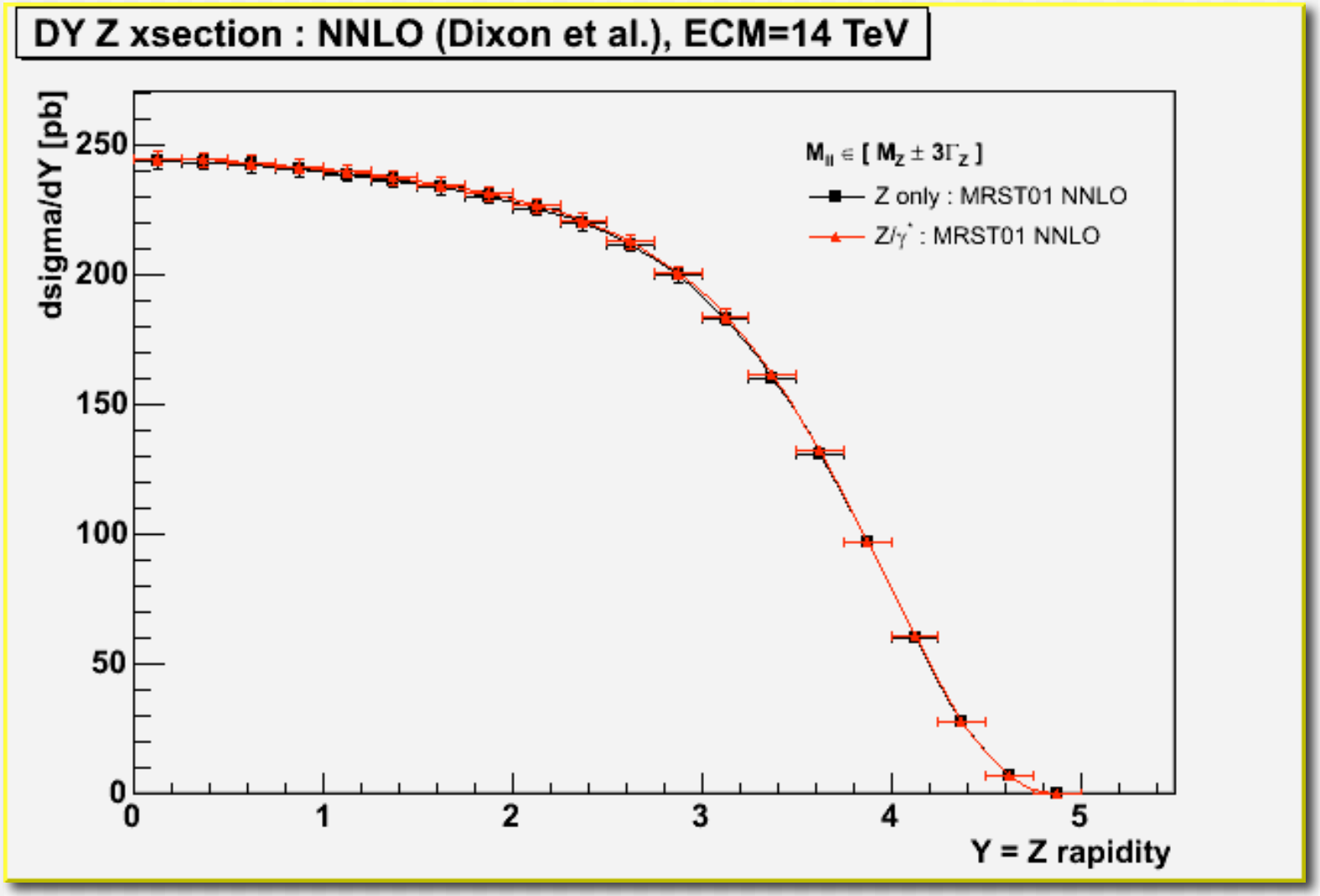
Results : Z production

- **Note** : choice of di-lepton invariant mass range can have large impact

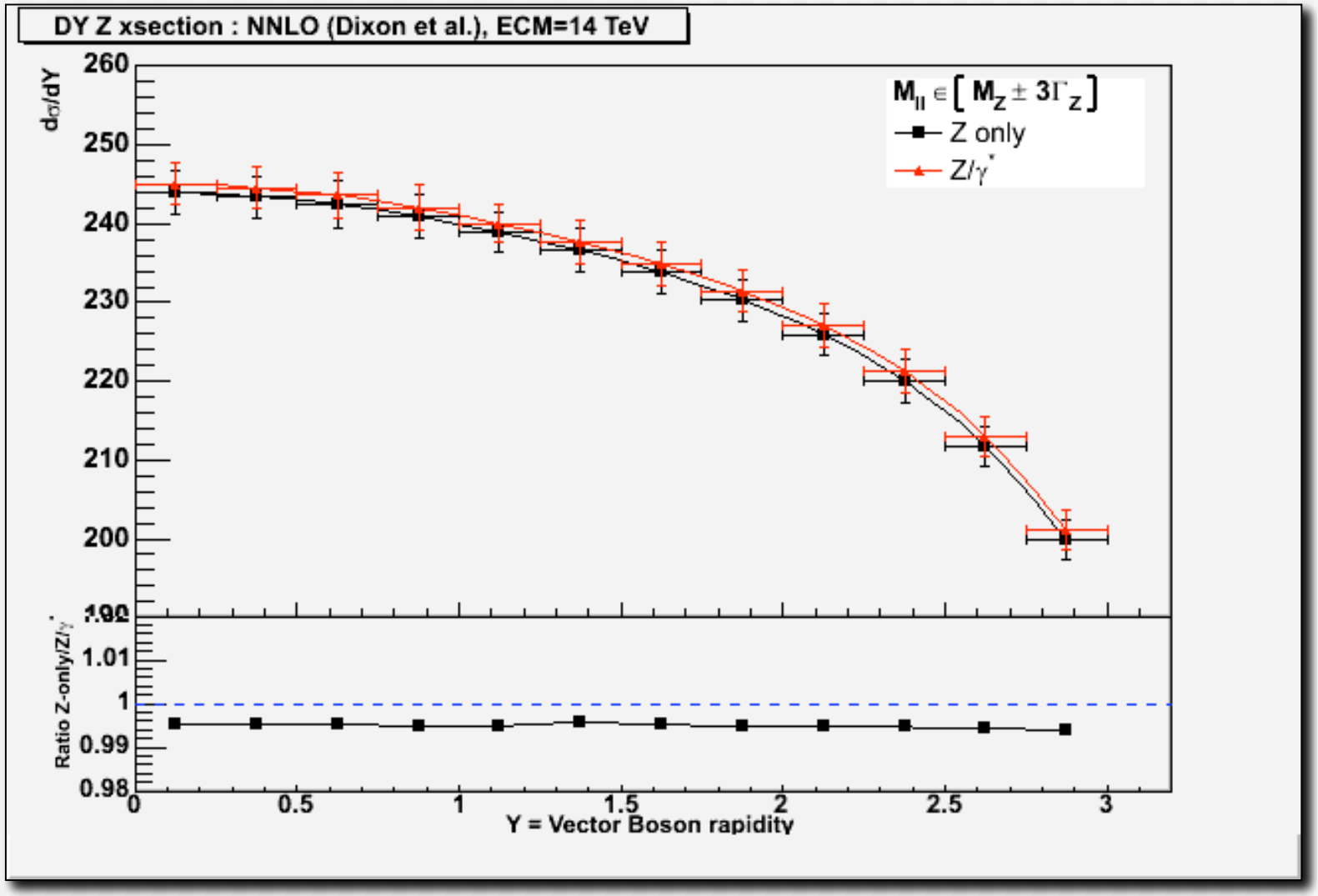
Channel/Order/Pdf	Integral [pb]	| Diff | [pb]	| rel Diff | %
M_Z - 3G_Z < M < M_Z + 3G_Z			
Z exch only			
NNLO_MRST01NNLO muF=1 muR=1	**955.151**	**0.000**	**0.000**
66 < M < 116			
Z exch only			
NNLO_MRST01NNLO muF=1 muR=1	1033.65	78.499	8.218
M_Z - 3G_Z < M < 116			
Z exch only			
NNLO_MRST01NNLO muF=1 muR=1	990.6	35.449	3.711
66 < M < M_Z + 3G_Z			
Z exch only			
NNLO_MRST01NNLO muF=1 muR=1	998.016	42.865	4.488

In fact, simple integration over Lorentzian : $\frac{\int_6^\infty \frac{1}{1+x^2}\,dx}{\int_0^\infty \frac{1}{1+x^2}\,dx}$ ≈10%

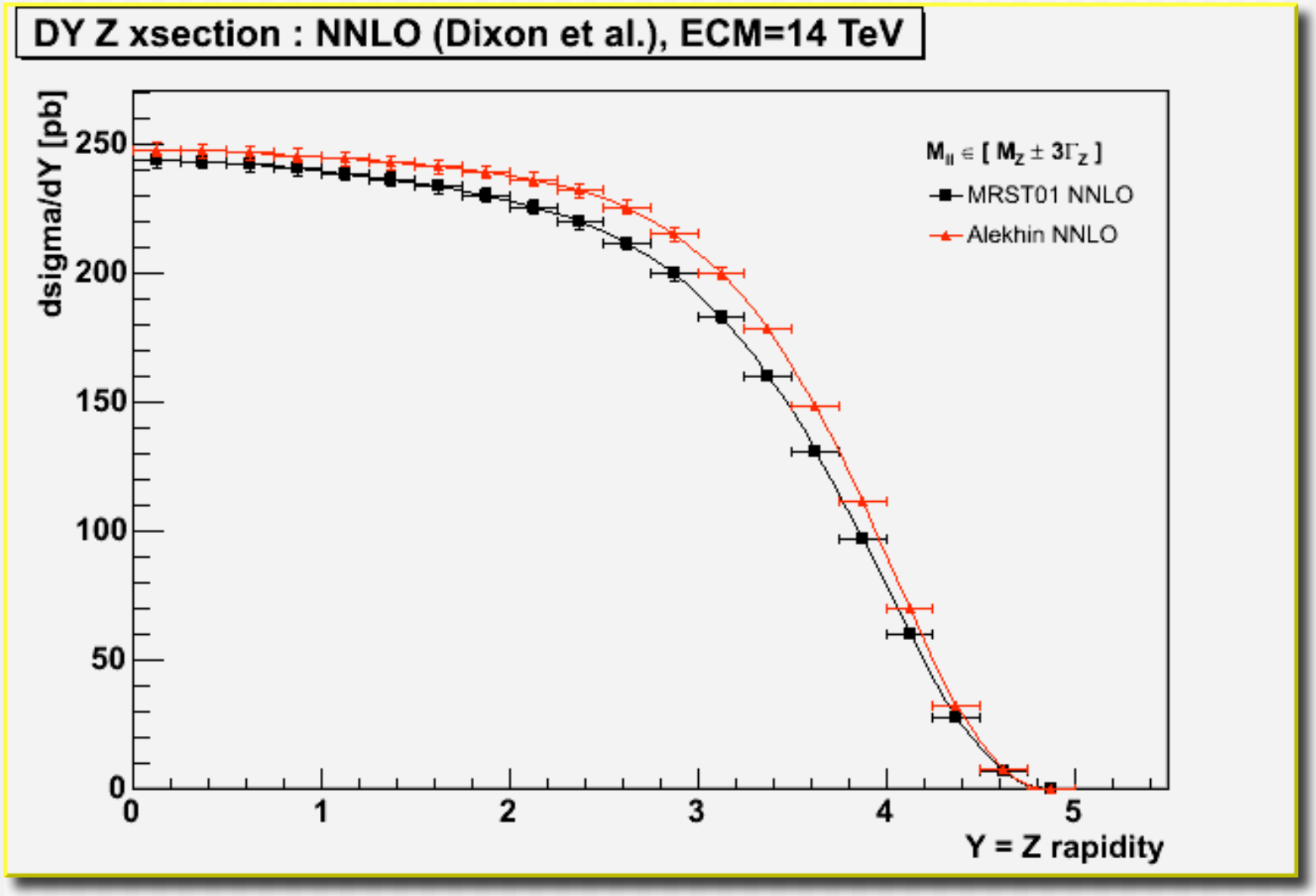
Z rapidity distributions



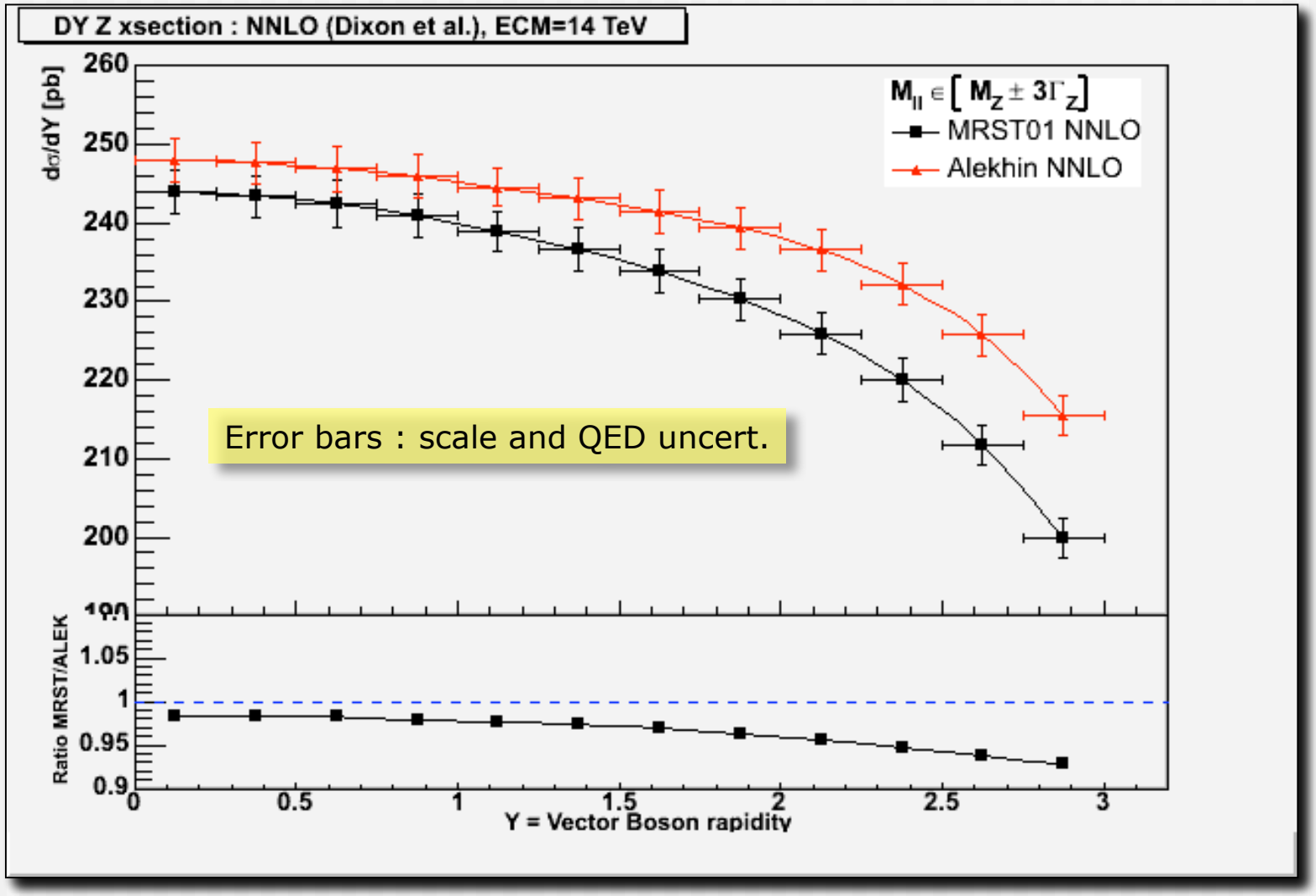
Z rapidity distributions



Z rapidity distributions



Z rapidity distributions



Results : W^+ production

|Y| < 2

ECM=14 TeV, pp (LHC)
alpha_qed = 1/128

M_W - 3G_W < M < M_W + 3G_W

Channel/Order/Pdf	Integral [pb]	| Diff | [pb]	| rel Diff | %
PDFs:			
NNLO_MRST01NNLO muF=1 muR=1	**4937.14**	**0.00**	**0.00**
NNLO_MRST_HepPh0110215 muF=1 muR=1	5015.01	77.87	1.58
NNLO_MRST01NNLO_mode4 muF=1 muR=1	5001.64	64.50	1.31
NNLO_MRSTNNLO_fast muF=1 muR=1	4934.64	2.50	0.05
NNLO_MRSTNNLO_slow muF=1 muR=1	4945.38	8.24	0.17
NNLO_AlekhinNNLO muF=1 muR=1	5197.86	260.72	5.28
max difference (abs), rel in %		260.72	5.28
scale variations:			
NNLO_MRST01NNLO muF=0.5 muR=0.5	4932.24	4.90	0.10
NNLO_MRST01NNLO muF=2.0 muR=2.0	4959.81	22.67	0.46
NNLO_MRST01NNLO muF=1.0 muR=0.5	4930.98	6.16	0.12
NNLO_MRST01NNLO muF=1.0 muR=2.0	4929.20	7.94	0.16
NNLO_MRST01NNLO muF=0.5 muR=1.0	4888.53	48.61	0.98
NNLO_MRST01NNLO muF=2.0 muR=1.0	4936.83	0.31	0.01
max difference (abs), rel		48.61	0.98
running of alpha_qed:			
NNLO_MRST01NNLO alpha_qed(Q)	4893.38	43.76	0.89
Total theoretical uncertainty (quad. sum of above contr.):		**268.80**	**5.44**

Results : W^+ production

- For increasing acceptance:

Syst. Uncert. [%]	|Y|<2	|Y|<2.5	|Y|<3
PDF	5.28	5.68	6.12
scale	0.98	1.03	1.05
α_{QED}	0.89	0.88	0.87
Total	**5.44**	**5.83**	**6.27**

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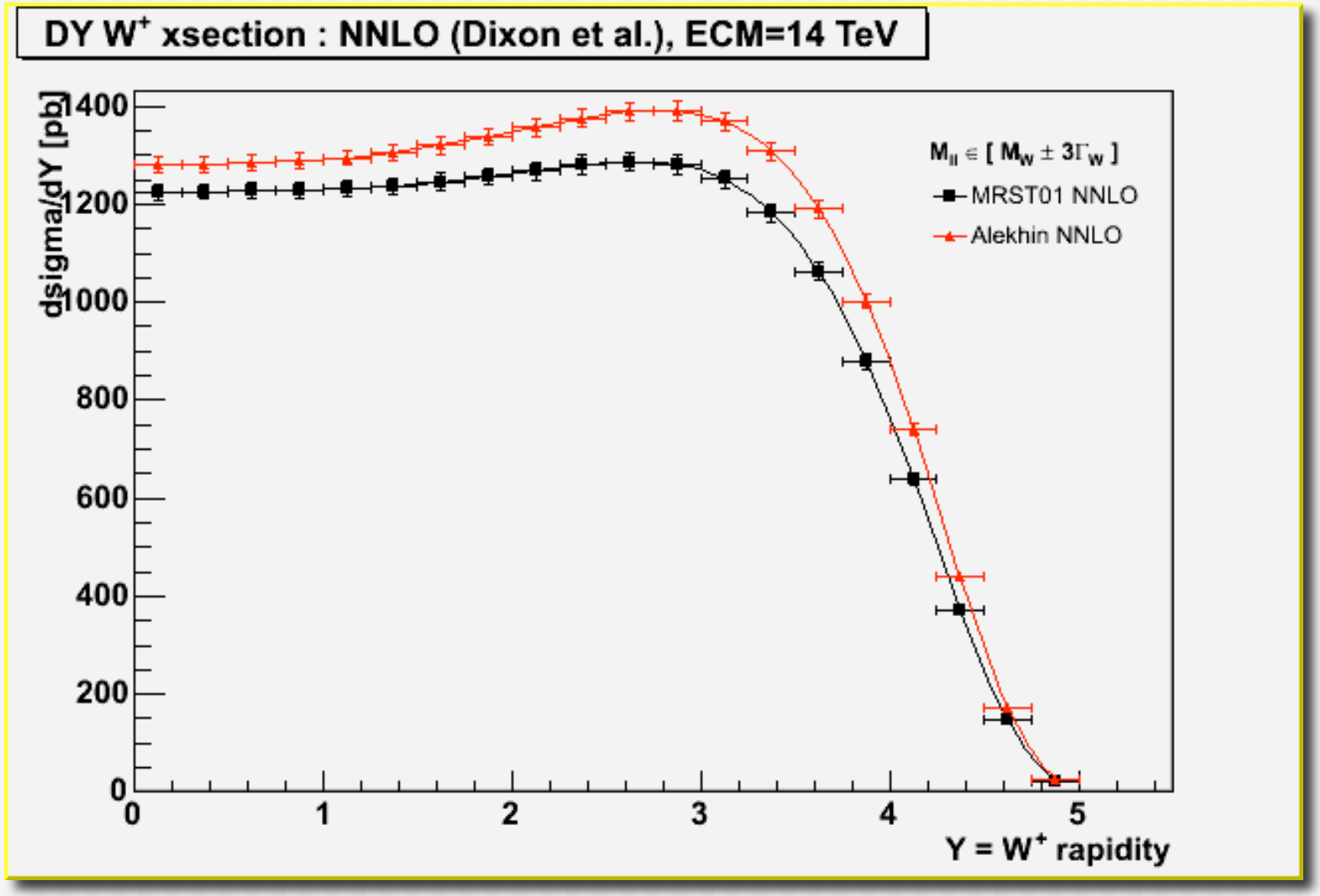
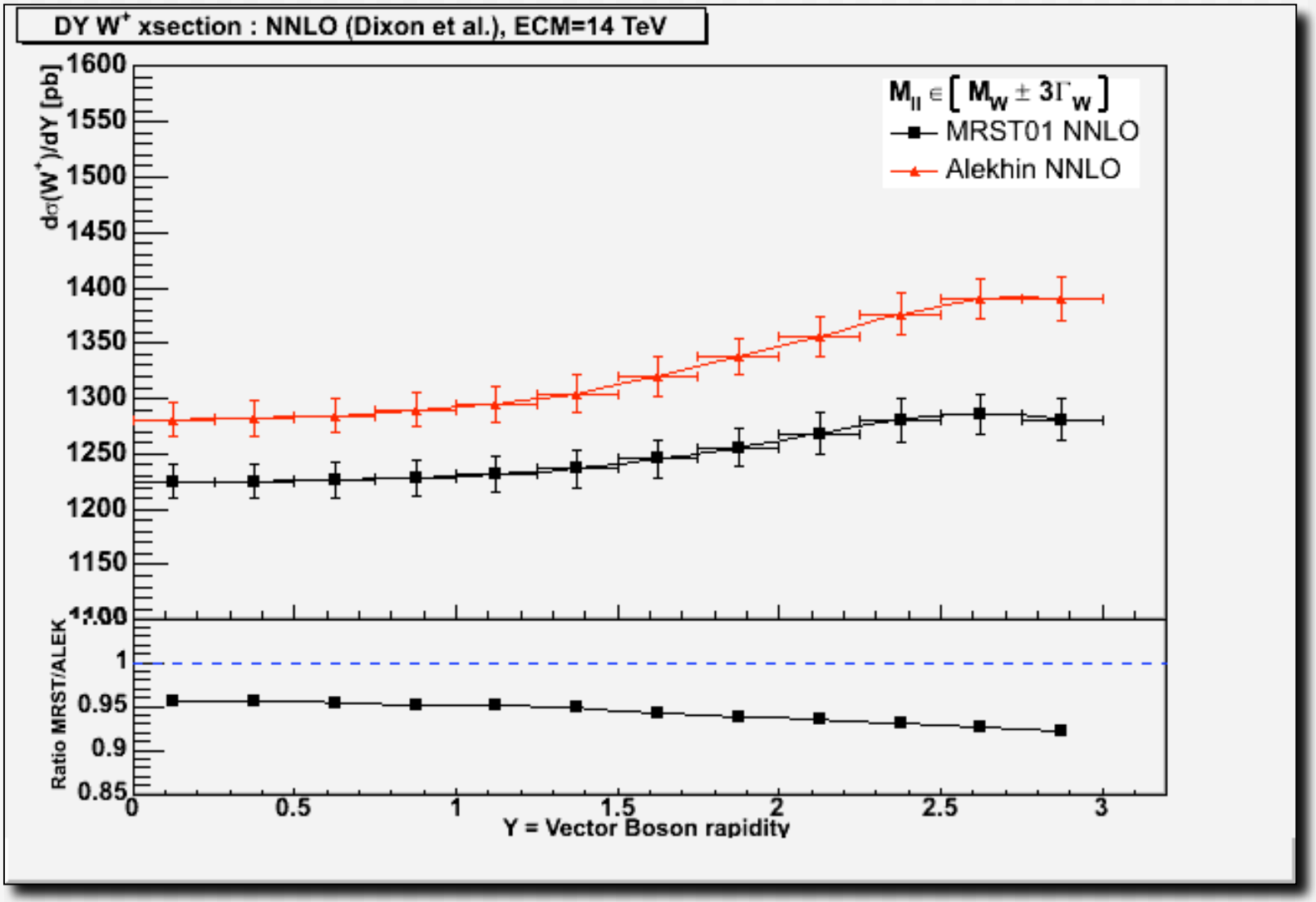
W^+ rapidity distributions



W^+ rapidity distributions



Results : W^- production

|Y| < 2

ECM=14 TeV, pp (LHC)
alpha_qed = 1/128

M_W - 3G_W < M < M_W + 3G_W

Channel/Order/Pdf	Integral [pb]	| Diff | [pb]	| rel Diff | %
PDFs:			
NNLO_MRST01NNLO muF=1 muR=1	**4450.51**	**0.00**	**0.00**
NNLO_MRST_HepPh0110215 muF=1 muR=1	4523.54	73.03	1.64
NNLO_MRST01NNLO_mode4 muF=1 muR=1	4519.18	68.67	1.54
NNLO_MRSTNNLO_fast muF=1 muR=1	4445.19	5.32	0.12
NNLO_MRSTNNLO_slow muF=1 muR=1	4458.74	8.23	0.18
NNLO_AlekhinNNLO muF=1 muR=1	4655.20	204.69	4.60
max difference (abs), rel in %		204.69	4.60
scale variations:			
NNLO_MRST01NNLO muF=0.5 muR=0.5	4441.18	9.33	0.21
NNLO_MRST01NNLO muF=2.0 muR=2.0	4471.27	20.76	0.47
NNLO_MRST01NNLO muF=1.0 muR=0.5	4440.31	10.20	0.23
NNLO_MRST01NNLO muF=1.0 muR=2.0	4446.78	3.73	0.08
NNLO_MRST01NNLO muF=0.5 muR=1.0	4406.26	44.25	0.99
NNLO_MRST01NNLO muF=2.0 muR=1.0	4447.59	2.92	0.07
max difference (abs), rel		44.25	0.99
running of alpha_qed:			
NNLO_MRST01NNLO alpha_qed(Q)	4411.64	38.87	0.87
Total theoretical uncertainty (quad. sum of above contr.):		**213.00**	**4.79**

Results : W^- production

- For increasing acceptance:

Syst. Uncert. [%]	|Y|<2	|Y|<2.5	|Y|<3
PDF	4.60	4.87	5.28
scale	0.99	1.02	1.03
α_{QED}	0.87	0.88	0.88
Total	**4.79**	**5.05**	**5.46**

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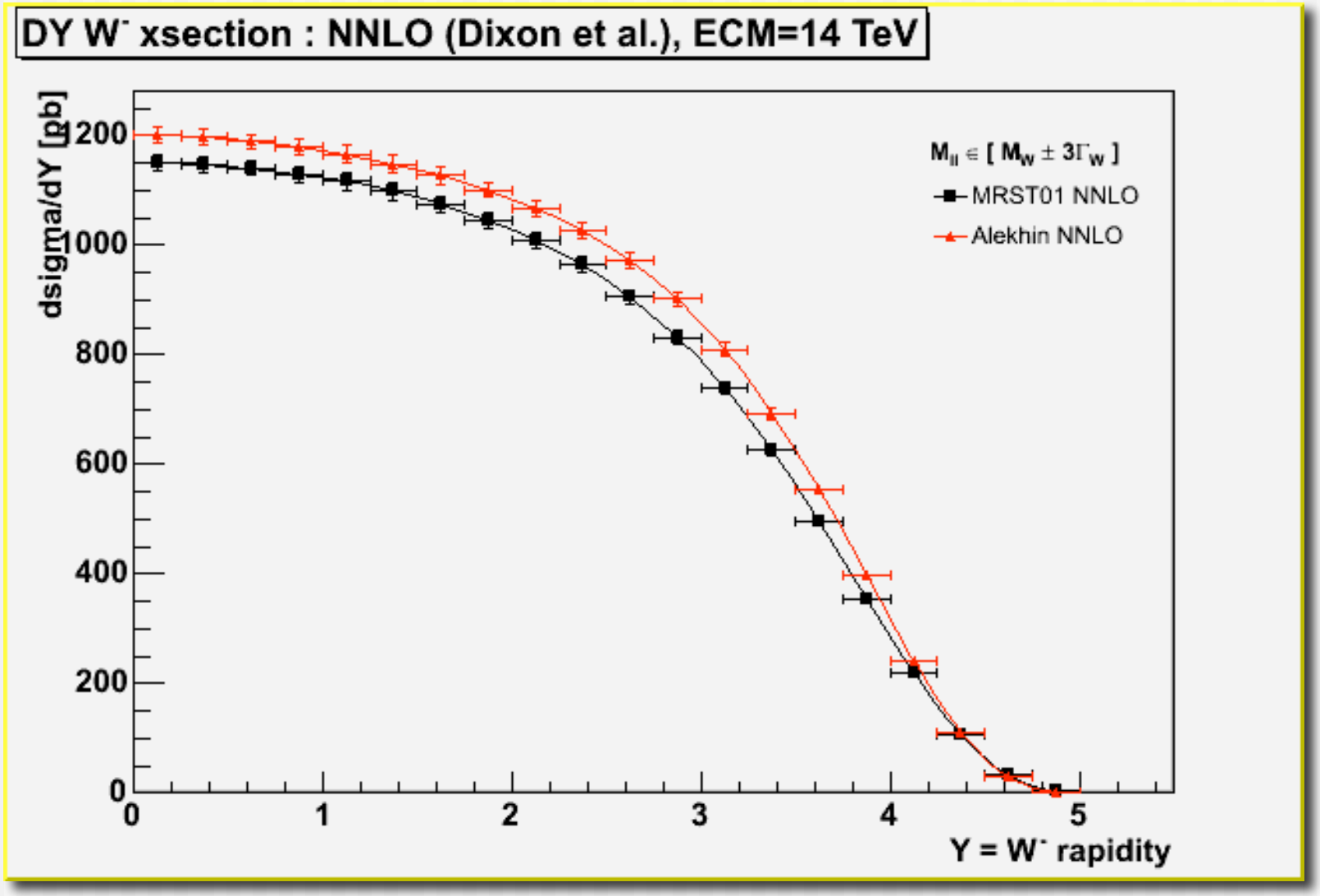
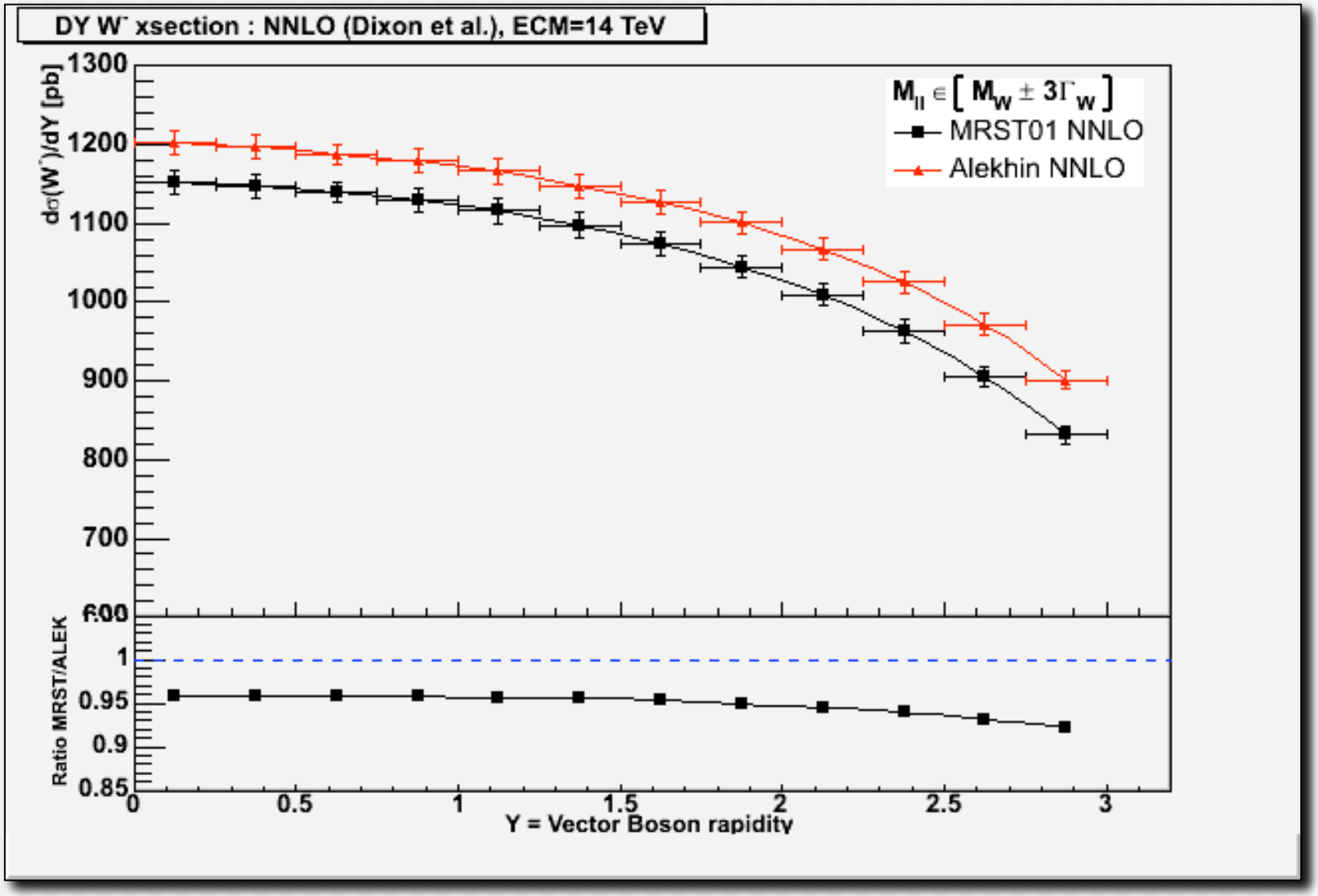
W^- rapidity distributions



W^- rapidity distributions



Results : W^+/W^-

|Y| < 2

ECM=14 TeV, pp (LHC)
alpha_qed = 1/128

M_W - 3G_W < M < M_W + 3G_W

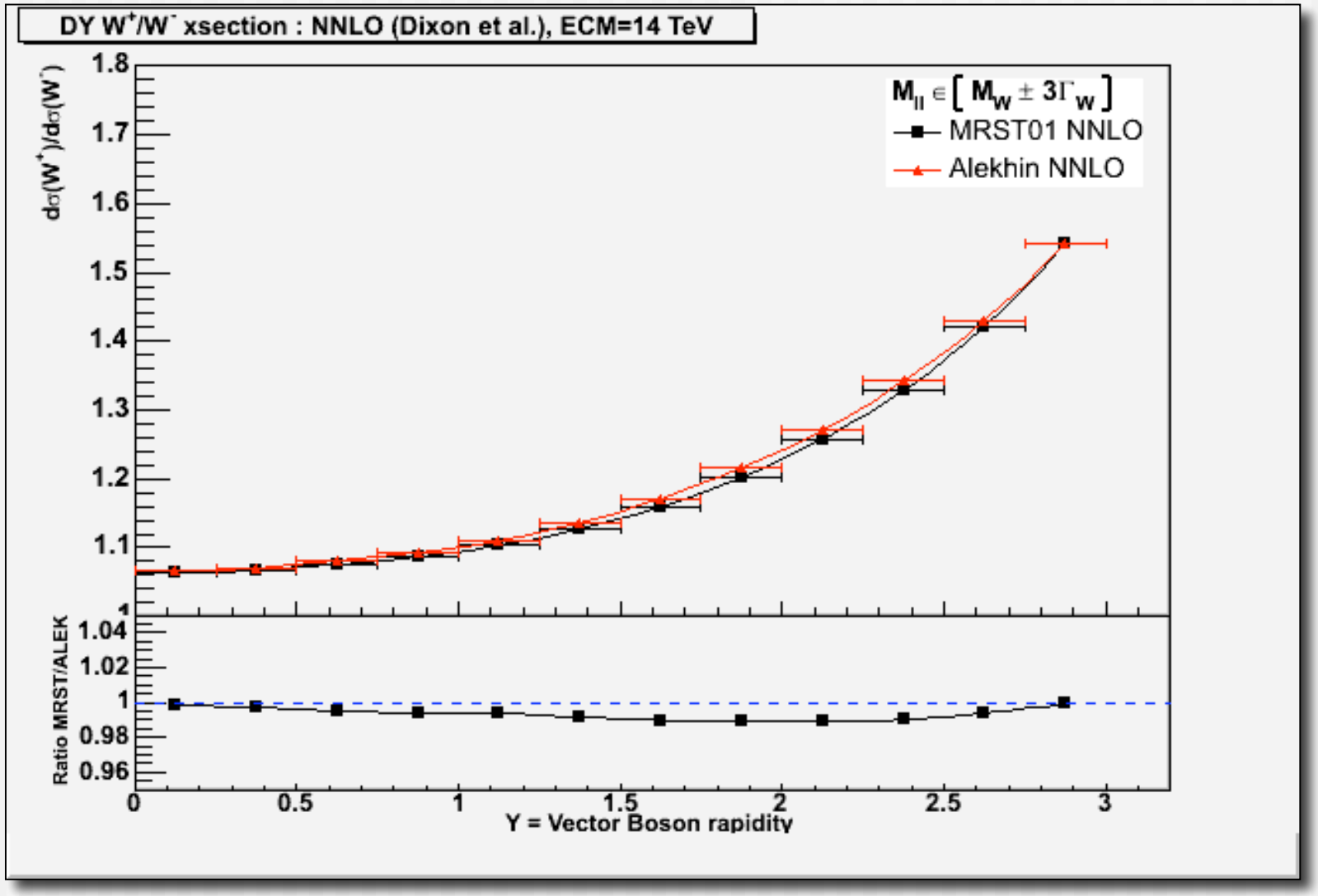
Channel/Order/Pdf	Ratio	| Diff |	| rel Diff | %
PDFs:			
NNLO_MRST01NNLO muF=1 muR=1	**1.109**	**0.000**	**0.000**
NNLO_MRST_HepPh0110215 muF=1 muR=1	**1.109**	0.001	0.063
NNLO_MRST01NNLO_mode4 muF=1 muR=1	**1.107**	0.003	0.233
NNLO_MRSTNNLO_fast muF=1 muR=1	**1.110**	0.001	0.069
NNLO_MRSTNNLO_slow muF=1 muR=1	**1.109**	0.000	0.018
NNLO_AlekhinNNLO muF=1 muR=1	**1.117**	0.007	0.652
max difference (abs), rel in %		0.007	0.652
scale variations:			
NNLO_MRST01NNLO muF=0.5 muR=0.5	**1.111**	0.001	0.111
NNLO_MRST01NNLO muF=2.0 muR=2.0	**1.109**	0.000	0.007
NNLO_MRST01NNLO muF=1.0 muR=0.5	**1.111**	0.001	0.105
NNLO_MRST01NNLO muF=1.0 muR=2.0	**1.108**	0.001	0.077
NNLO_MRST01NNLO muF=0.5 muR=1.0	**1.109**	0.000	0.010
NNLO_MRST01NNLO muF=2.0 muR=1.0	**1.110**	0.001	0.059
max difference (abs), rel		0.001	0.111
running of alpha_qed:			
NNLO_MRST01NNLO alpha_qed(Q)	**1.109**	0.000	0.013
Total theoretical uncertainty (quad. sum of above contr.):		**0.007**	**0.661**

Results : W^+/W^-

- For increasing acceptance:

Syst. Uncert. [%]	|Y|<2	|Y|<2.5	|Y|<3
PDF	0.652	0.766	0.791
scale	0.111	0.128	0.161
α_{QED}	0.013	0.003	0.011
Total	**0.661**	**0.777**	**0.808**

W^+ / W^- rapidity distributions



Results : W production

|Y| < 2

ECM=14 TeV, pp (LHC)
alpha_qed = 1/128

M_W - 3G_W < M < M_W + 3G_W

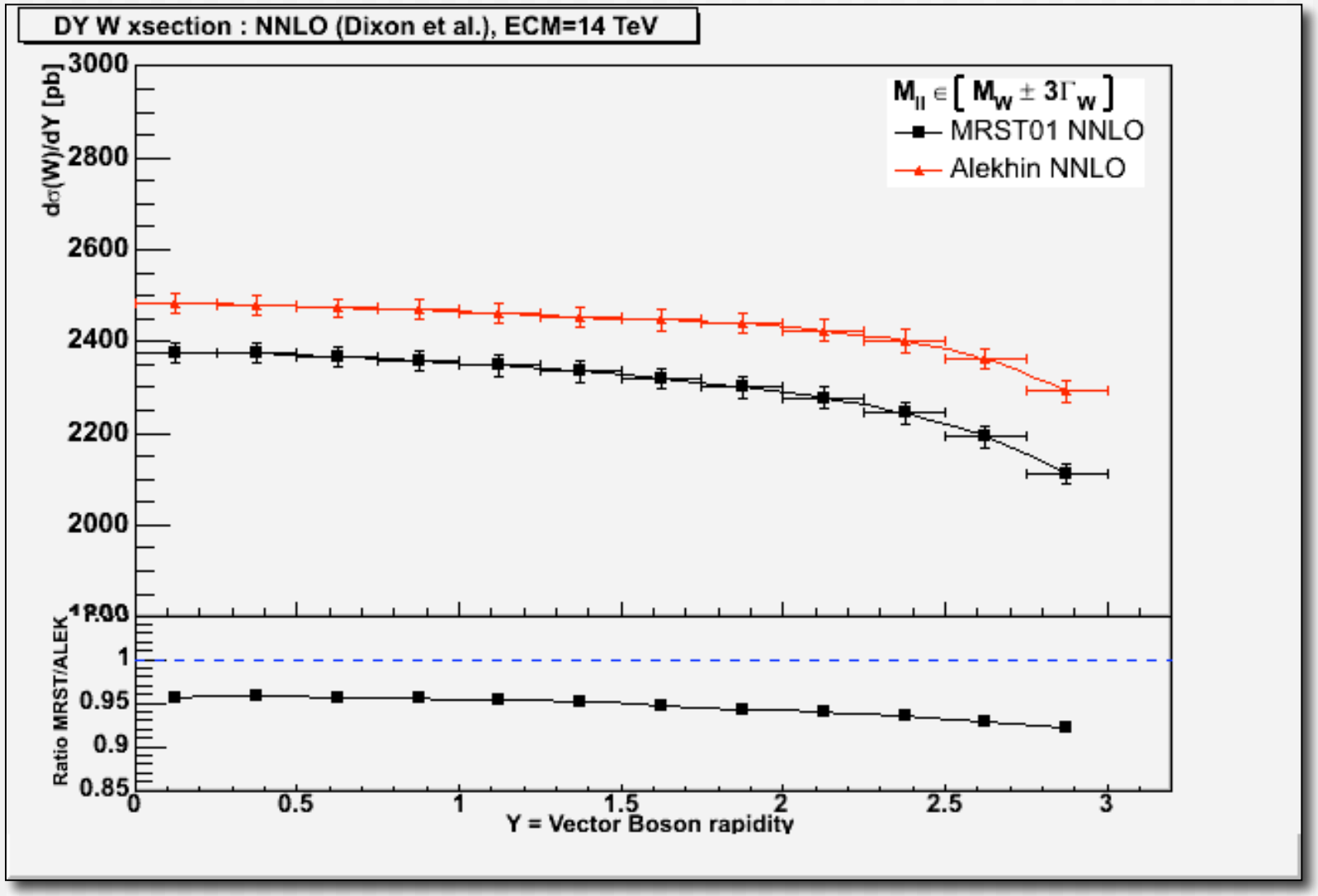
Channel/Order/Pdf	Integral [pb]	| Diff | [pb]	| rel Diff | %
PDFs:			
NNLO_MRST01NNLO muF=1 muR=1	**9387.65**	**0.00**	**0.00**
NNLO_MRST_HepPh0110215 muF=1 muR=1	9538.55	150.90	1.61
NNLO_MRST01NNLO_mode4 muF=1 muR=1	9520.82	133.17	1.42
NNLO_MRSTNNLO_fast muF=1 muR=1	9379.83	7.82	0.08
NNLO_MRSTNNLO_slow muF=1 muR=1	9404.12	16.47	0.18
NNLO_AlekhinNNLO muF=1 muR=1	9853.06	465.41	4.96
max difference (abs), rel in %		465.41	4.96
scale variations:			
NNLO_MRST01NNLO muF=0.5 muR=0.5	9373.42	14.23	0.15
NNLO_MRST01NNLO muF=2.0 muR=2.0	9431.08	43.43	0.46
NNLO_MRST01NNLO muF=1.0 muR=0.5	9371.29	16.36	0.17
NNLO_MRST01NNLO muF=1.0 muR=2.0	9375.98	11.67	0.12
NNLO_MRST01NNLO muF=0.5 muR=1.0	9294.79	92.86	0.99
NNLO_MRST01NNLO muF=2.0 muR=1.0	9384.42	3.23	0.03
max difference (abs), rel		92.86	0.99
running of alpha_qed:			
NNLO_MRST01NNLO alpha_qed(Q)	9305.02	82.63	0.88
Total theoretical uncertainty (quad. sum of above contr.):		**481.72**	**5.13**

Results : W production

- For increasing acceptance:

Syst. Uncert. [%]	|Y|<2	|Y|<2.5	|Y|<3
PDF	4.96	5.30	5.74
scale	0.99	1.02	1.05
α_{QED}	0.88	0.88	0.87
Total	**5.13**	**5.47**	**5.90**

W rapidity distributions



Results : W/Z

|Y| < 2

ECM=14 TeV, pp (LHC)
alpha_qed = 1/128

M_W - 3G_W < M < M_W + 3G_W

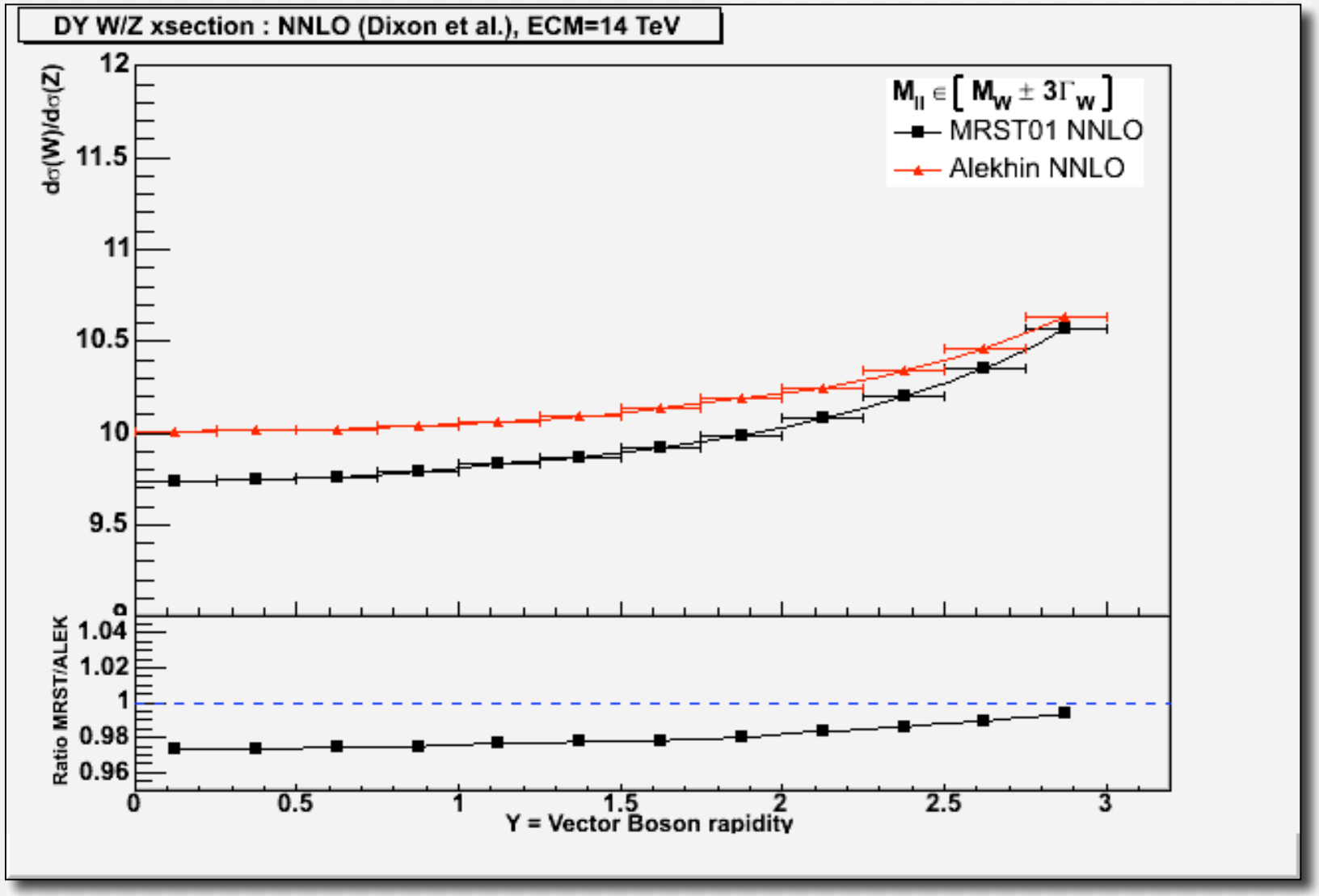
Channel/Order/Pdf	Ratio	| Diff |	| rel Diff | %
PDFs:			
NNLO_MRST01NNLO muF=1 muR=1	**9.83**	**0.00**	**0.00**
NNLO_MRST_HepPh0110215 muF=1 muR=1	**9.84**	0.02	0.16
NNLO_MRST01NNLO_mode4 muF=1 muR=1	**9.87**	0.04	0.40
NNLO_MRSTNNLO_fast muF=1 muR=1	**9.83**	0.00	0.04
NNLO_MRSTNNLO_slow muF=1 muR=1	**9.83**	0.00	0.02
NNLO_AlekhinNNLO muF=1 muR=1	**10.07**	0.24	2.46
max difference (abs), rel in %		0.24	2.46
scale variations:			
NNLO_MRST01NNLO muF=0.5 muR=0.5	**9.83**	0.00	0.02
NNLO_MRST01NNLO muF=2.0 muR=2.0	**9.84**	0.01	0.07
NNLO_MRST01NNLO muF=1.0 muR=0.5	**9.83**	0.00	0.02
NNLO_MRST01NNLO muF=1.0 muR=2.0	**9.83**	0.00	0.02
NNLO_MRST01NNLO muF=0.5 muR=1.0	**9.81**	0.01	0.14
NNLO_MRST01NNLO muF=2.0 muR=1.0	**9.84**	0.01	0.09
max difference (abs), rel		0.01	0.14
running of alpha_qed:			
NNLO_MRST01NNLO alpha_qed(Q)	**9.82**	0.01	0.13
Total theoretical uncertainty (quad. sum of above contr.):		**0.24**	**2.46**

Results : W/Z

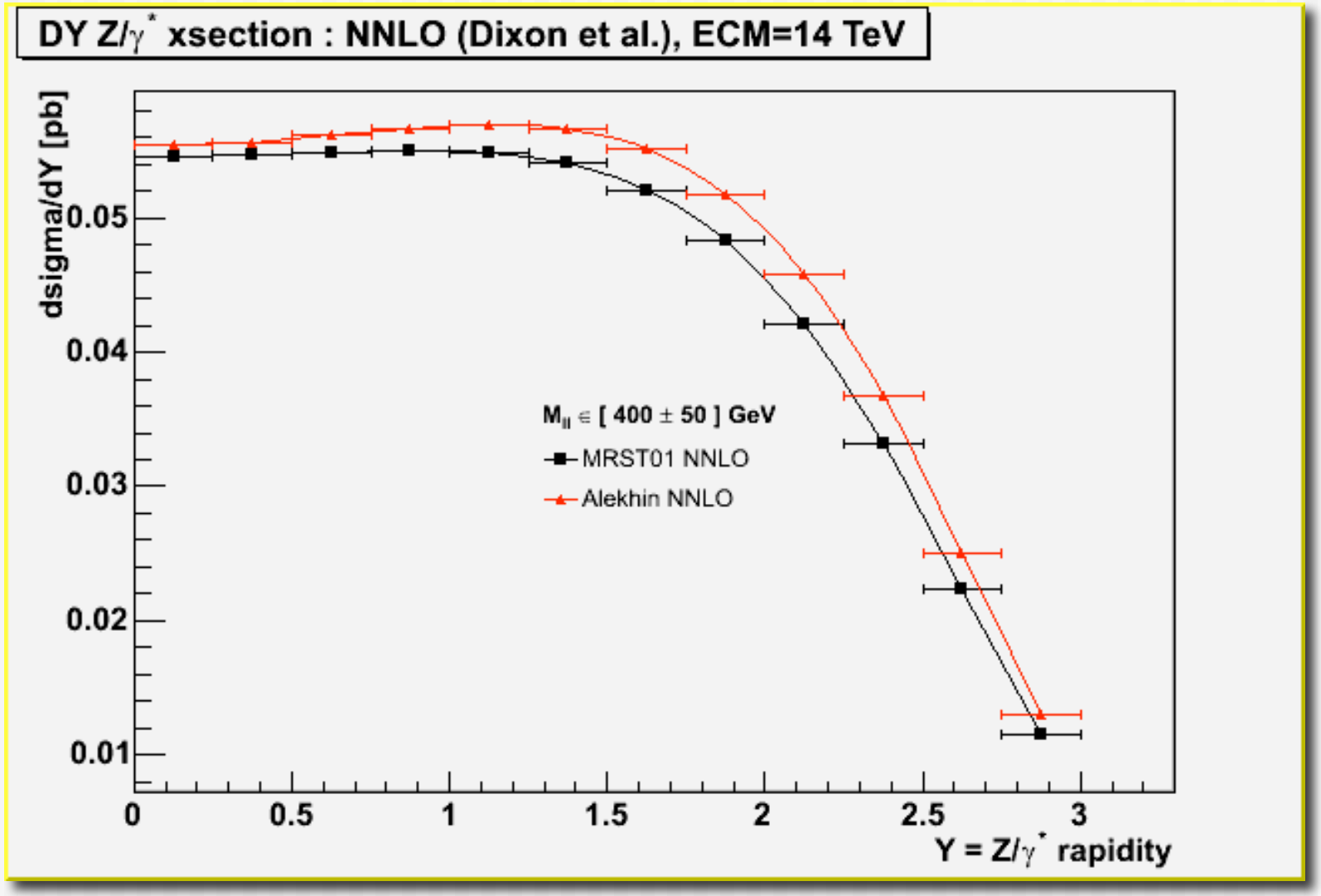
- For increasing acceptance:

Syst. Uncert. [%]	|Y|<2	|Y|<2.5	|Y|<3
PDF	2.46	2.29	2.09
scale	0.14	0.15	0.15
α_{QED}	0.13	0.13	0.13
Total	**2.46**	**2.29**	**2.10**

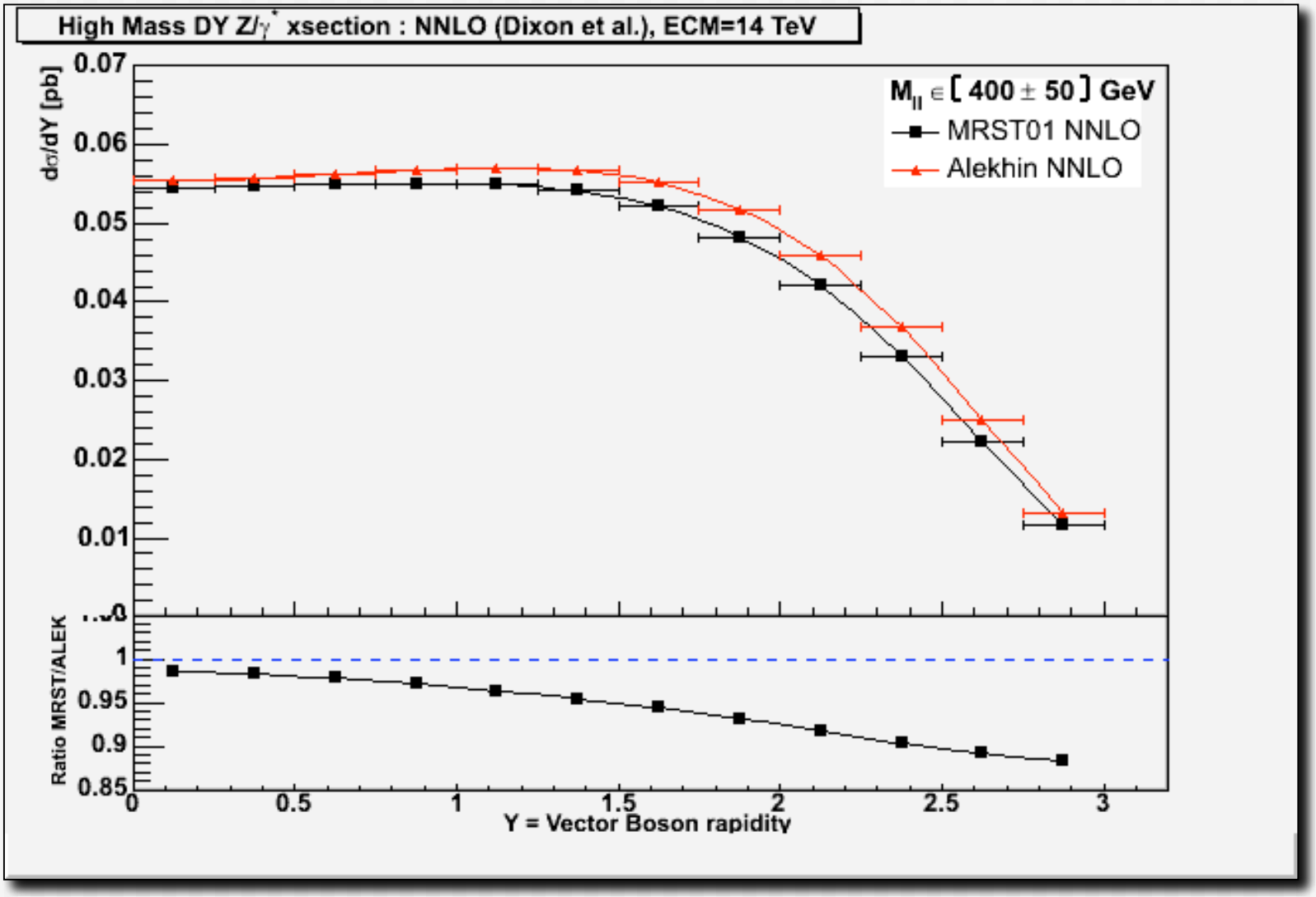
W/Z rapidity distributions



High Mass DY : Z/γ*, Q=400 GeV

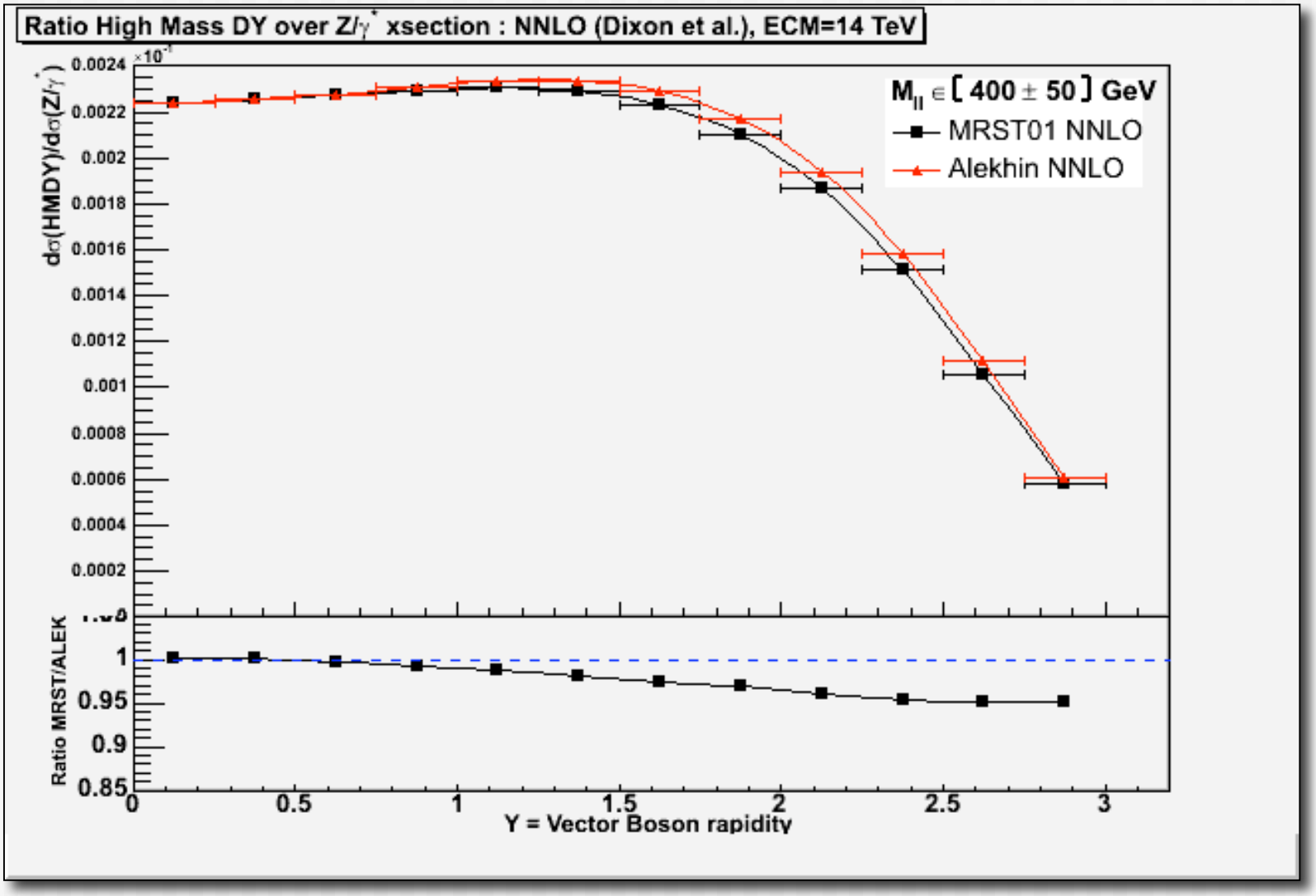


High Mass DY : Z/γ*, Q=400 GeV



High Mass DY : Z/γ*, Q=400 GeV

DY : Z/γ*, Q = M_Z



High Mass DY prod.

- For increasing acceptance:

Syst. Uncert. [%]	|Y|<2	|Y|<2.5	|Y|<3
ΔPDF= MRST-ALEKHIN: Q=400 GeV	3.73	4.64	5.13
ΔPDF= MRST-ALEKHIN: Q=M_Z	2.50	3.00	3.63
ΔPDF= MRST-ALEKHIN: Ratio	1.21	1.59	1.46
Δscale= $0.5Q < \mu_R, \mu_F < 2Q$: Q=400 GeV	0.19	0.16	0.19
Δscale= $0.5Q < \mu_R, \mu_F < 2Q$: Q=M_Z	0.40	0.43	0.47
Δscale= $0.5Q < \mu_R, \mu_F < 2Q$: Ratio	0.54	0.55	0.58

Ongoing Work

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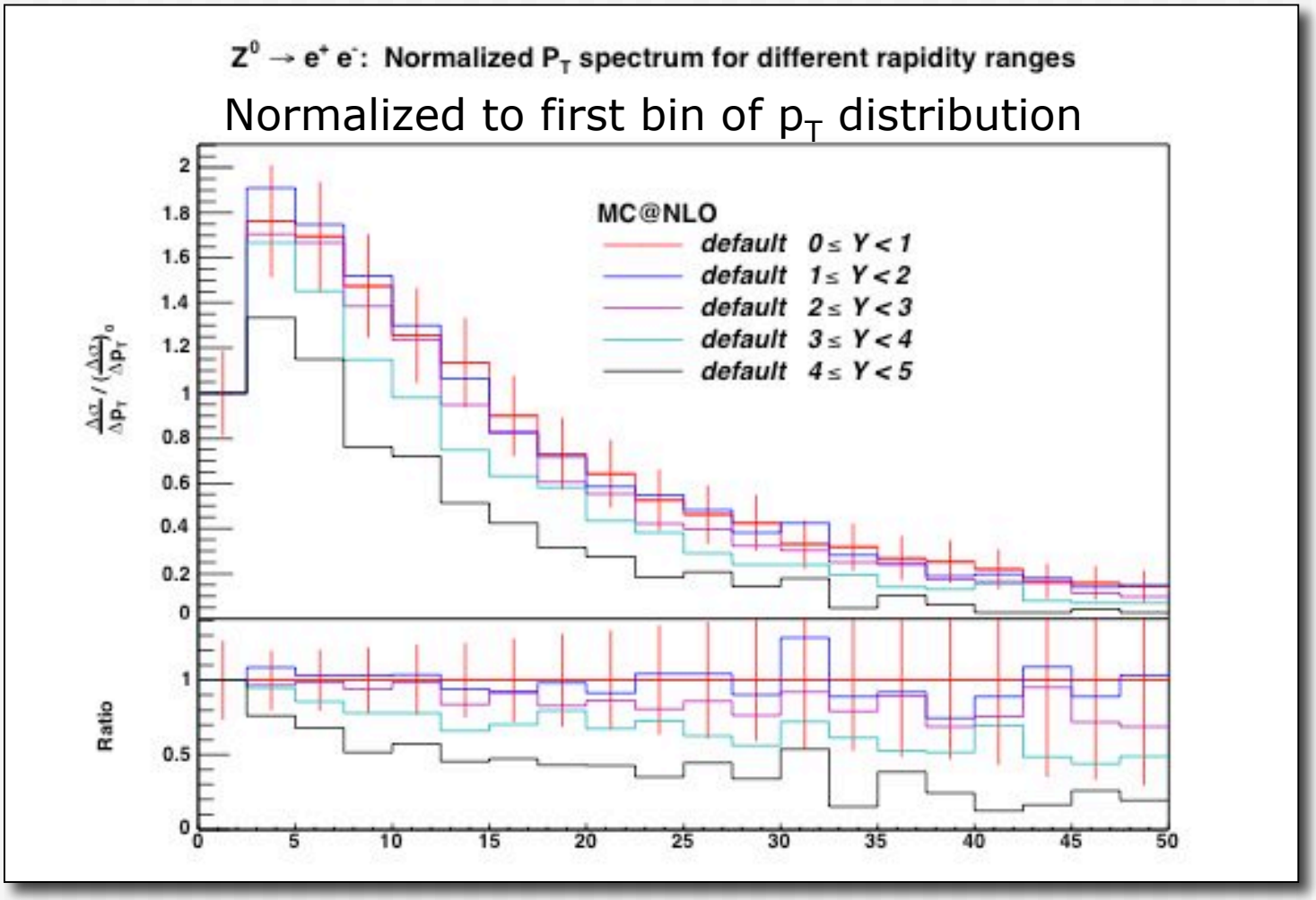
- Similar studies also with various MC generators
  - PYTHIA, HERWIG, MCatNLO
  - With many different PDF sets
  - Almost completed
- Not only in rapidity, but also p_T
- A question among others:
  - How much does the shape of the p_T distribution change for various rapidity regions?
  - Interesting if we want to reweight MC with NNLO calculations

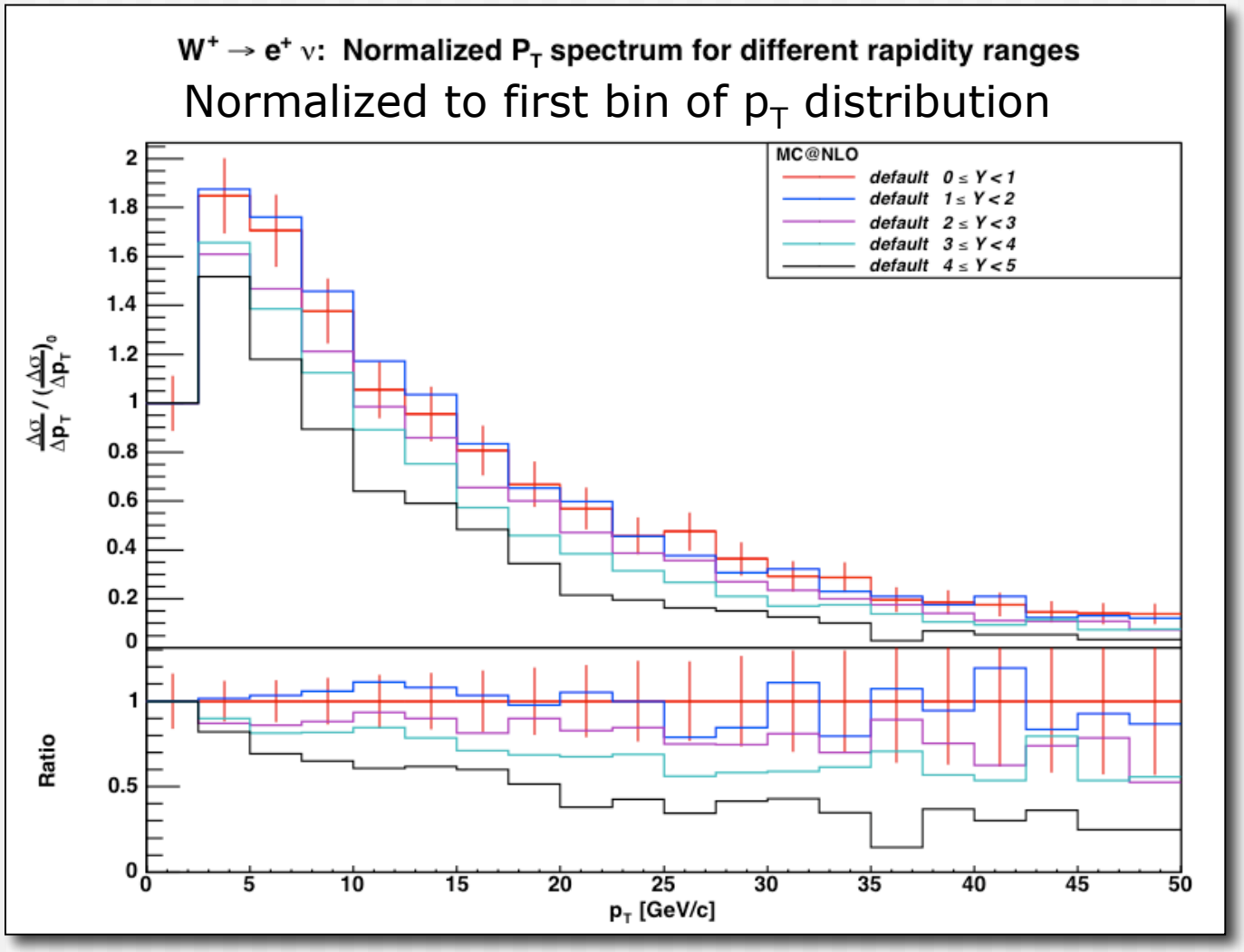
MCatNLO : Z p_T at LHC



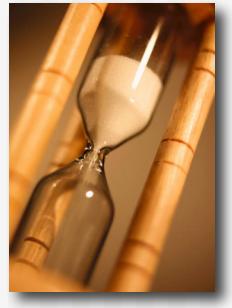
Normalized to first bin of p_T distribution

p_T of Z boson

MCatNLO : W p_T at LHC



Conclusions



- Study of W and Z production at LHC using new NNLO QCD predictions
  - for integrals over exp. acceptance in rapidity
  - differential in rapidity
- Uncertainties
  - difference from PDFs (MRST, ALEKHIN) dominant, but around or below 5%
  - Can be reduced by taking ratios of cross sections
  - renorm. and factor. scale : =< 1%
  - inclusion of full EW corrections seems necessary
- Further studies with MC generators, including boson p_T, close to completion

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