Polarization observables in WZ production at the LHC in the Standard Model

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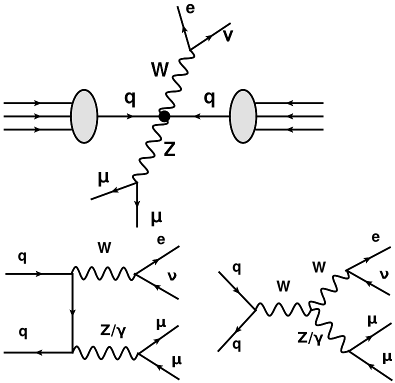
Outline

- Motivation
- Link between polarization observables (angular coefficients) and spin-density matrix
- Reference frames: Collins-Soper and Helicity frames
- How do we (theorists) calculate?
- Results (ATLAS, CMS)
- Summary

Motivation

- The process $pp \to WZ \to 3l + \nu$ is important in the physics program at the LHC.
- Sensitive to triple-gauge couplings
- Background to other processes, new physics searches
- High statistics $\leadsto$ precision!
- To search for hints of new physics: polarization observables can be important
- To find new physics effects: good understanding of theoretical and experimental errors is needed

$W^{\pm}Z$ production at the LHC



- Intial beams: unpolarized
- Only left-handed quarks interact with W (max. asymmetry)
- Z interacts with both left- and right-handed quarks, but with different coupling strength:
  $g_R^f = -(s_W Q_f)/c_W$,
  $g_L^f = (I_f^3 - s_W^2 Q_f)/(s_W c_W)$.
- $\rightsquigarrow$ W and Z produced at the LHC are polarized!

Remark: those polarized W and Z induce an asymmetry in angular distributions of the final-state leptons!

Polarization fractions

Notation: $e = 3$, $\mu^- = 6$, $\theta_i = \angle(\vec{p}'_{l_i}, \vec{z}')$ in the V rest frame

$$\frac{d\sigma}{\sigma d\cos\theta_3} \equiv \frac{3}{8}\left[(1-\cos\theta_3)^2 f_L^{W^+} + (1+\cos\theta_3)^2 f_R^{W^+} + 2\sin^2\theta_3 f_0^{W^+}\right], \quad (1)$$

$$\frac{d\sigma}{\sigma d\cos\theta_6} \equiv \frac{3}{8}\left[(1+\cos^2\theta_6 + 2c\cos\theta_6)^2 f_L^Z + (1+\cos^2\theta_6 - 2c\cos\theta_6)^2 f_R^Z + 2\sin^2\theta_6 f_0^Z\right], \quad (2)$$

$$c = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = \frac{1-4s_W^2}{1-4s_W^2+8s_W^4} \approx 21\% \quad \text{for charged leptons.} \quad (3)$$

Note: $\boxed{f_L + f_R + f_0 = 1}$

- If $f_L = f_R$, the distributions are symmetric in $\cos\theta$.
- For polarized gauge bosons: $f_L \neq f_R \rightsquigarrow$ asymmetry in $\cos\theta$ distributions.
- Values of f_L, f_R, f_0 depend on reference frame and coordinate system.

However, there is more information about polarization.

Spin density matrix (I)

A massive gauge boson (spin = 1) has 3 polarization states!

$$\rho \equiv |\psi><\psi|, \tag{4}$$

$$<A> = <\psi|A|\psi> = \mathrm{Tr}(A\rho), \tag{5}$$

$$|\psi> = \sum_{\lambda=1}^{3} c_\lambda |\lambda>, \tag{6}$$

$$\rho = \sum_{\lambda,\lambda'=1}^{3} \underbrace{c_\lambda c^*_{\lambda'}}_{\rho_{\lambda\lambda'}} |\lambda><\lambda'| \tag{7}$$

- ρ is Hermitian: $\rho^*_{\lambda\lambda'} = \rho_{\lambda'\lambda}$
- Normalization $\mathrm{Tr}(\rho) = 1$
- ρ is positive semidefinite

Thus, ρ is described by 8 real parameters!

Spin density matrix (II)

[Ref. Aguilar-Saavedra, Bernabeu, arXiv:1508.04592, PRD2016]

$$\rho = \frac{1}{3}\mathbb{1} + \frac{1}{2}\sum_{M=-1}^{1} < S_M >^* S_M + \sum_{M=-2}^{2} < T_M >^* T_M, \tag{8}$$

$$S_{\pm 1} = \mp\frac{1}{\sqrt{2}}(S_1 \pm iS_2),\ S_0 = S_3,\ S_i \text{ spin operators}, \tag{9}$$

$$T_{\pm 2} = S_{\pm 1}^2,\ T_{\pm 1} = \frac{1}{\sqrt{2}}(S_{\pm 1}S_0 + S_0 S_{\pm 1}), \tag{10}$$

$$T_0 = \frac{1}{\sqrt{6}}(S_{+1}S_{-1} + S_{-1}S_{+1} + 2S_0^2),\ \text{rank 2 irreducible tensors}$$

$$\rho_{\pm 1 \pm 1} = \frac{1}{3} \pm \frac{1}{2} < S_3 > + \frac{1}{\sqrt{6}} < T_0 >,\ \rho_{00} = \frac{1}{3} - \frac{2}{\sqrt{6}} < T_0 >,$$

$$\rho_{\pm 10} = \frac{1}{2\sqrt{2}}(< S_1 > \mp i < S_2 >) \mp \frac{1}{\sqrt{2}}(< A_1 > \mp i < A_2 >),$$

$$\rho_{1-1} = < B_1 > -i < B_2 >, \tag{11}$$

$$A_1 = \frac{1}{2}(T_1 - T_{-1}),\ A_2 = \frac{1}{2i}(T_1 + T_{-1}),\ B_1 = \frac{1}{2}(T_2 + T_{-2}),\ B_2 = \frac{1}{2i}(T_2 - T_{-2})$$

Complete spin information: 3 vector and 5 tensor modes!

Spin (or polarization) observables: W

[Ref. Gounaris et al IJMPA1993; Aguilar-Saavedra, Bernabeu, arXiv:1508.04592, PRD2016]

Consider the case of $W^*(m) \to l(\lambda_1)\nu_l(\lambda_2)$ decay:

$$|\mathcal{M}|^2 = \sum_{m,m'} \rho_{mm'} \mathcal{M}_{m\lambda_1\lambda_2} \mathcal{M}^*_{m'\lambda_1\lambda_2},$$

$$= \sum_{m,m'} \rho_{mm'} |a_{\lambda_1\lambda_2}|^2 e^{i(m-m')\phi} d^1_{m\lambda}(\theta) d^1_{m'\lambda}(\theta),$$

$$\mathcal{M}_{m\lambda_1\lambda_2} = a_{\lambda_1\lambda_2} e^{im\phi} d^1_{m\lambda}(\theta), \;\; \lambda(W^\pm) = \lambda_1 - \lambda_2 = \pm 1,$$

$$d^1_{11}(\theta) = \frac{1+\cos\theta}{2}, \;\; d^1_{1-1}(\theta) = \frac{1-\cos\theta}{2},$$

$$d^1_{01}(\theta) = \frac{\sin\theta}{\sqrt{2}}, \;\; d^j_{m'm} = (-1)^{m-m'} d^j_{mm'} = d^j_{-m-m'},$$

θ and ϕ are the polar and azimuthal angles of $\vec{p}_e$ in the W boson rest frame.

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta d\phi} = \frac{3}{8\pi}\Big[\frac{1}{2}(1+\cos^2\theta) + <S_3> \cos\theta + (\frac{1}{6} - \frac{1}{\sqrt{6}} <T_0>)(1 - 3\cos^2\theta)$$
$$+ <S_1> \cos\phi\sin\theta + <S_2> \sin\phi\sin\theta - <A_1> \cos\phi\sin 2\theta$$
$$- <A_2> \sin\phi\sin 2\theta + <B_1> \cos 2\phi\sin^2\theta + <B_2> \sin 2\phi\sin^2\theta\Big]$$

This angular distribution contains all W spin information: 8 (pseudo-)observables!

Spin (or polarization) observables: Z

[Ref.1: Aguilar-Saavedra et al, arXiv:1701.03115, EPJC2017]

Similarly, for the case of $Z^*(m) \to l^-(\lambda_1) l^+(\lambda_2)$ decay:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta d\phi} = \frac{3}{8\pi}\Big[\frac{1}{2}(1+\cos^2\theta) - c < S_3 > \cos\theta + (\frac{1}{6} - \frac{1}{\sqrt{6}} < T_0 >)(1 - 3\cos^2\theta)$$
$$- c < S_1 > \cos\phi\sin\theta - c < S_2 > \sin\phi\sin\theta - < A_1 > \cos\phi\sin 2\theta$$
$$- < A_2 > \sin\phi\sin 2\theta + < B_1 > \cos 2\phi\sin^2\theta + < B_2 > \sin 2\phi\sin^2\theta\Big]$$

- The above simple relations between the coefficients of the θ-ϕ distribution and the elements of the spin density matrix were proven at leading order.
- In full calculation, there are also other contributions (e.g. $\gamma^* \to l^- l^+$), interference and radiation effects. The above simple relations hence cannot be true, because they include only the spin information of W or Z.
- However, the form of the θ-ϕ distribution with 8 coefficients is general, same for W and for Z, and will be used for theoretical and experimental calculations.
- Integrating over θ or ϕ, the coefficients $< S_i >$, $< A_i >$, ... can be related to 8 angular asymmetries [Ref.1].

Double Pole Approximation (DPA)

At LO, the amplitude in the DPA is defined as

$$\mathcal{A}^{ab\to V_1V_2\to 4l}_{\text{LO,DPA}} = \sum_{\lambda_1,\lambda_2} \frac{\mathcal{A}^{ab\to V_1V_2}_{\text{LO}} \mathcal{A}^{V_1\to l_1l_2}_{\text{LO}} \mathcal{A}^{V_2\to l_3l_4}_{\text{LO}}}{Q_1Q_2},$$

$$Q_i = q_i^2 - M_{V_i}^2 + iM_{V_i}\Gamma_{V_i}, \quad i = 1,2.$$

Spin-density matrix in DPA, $V = W, Z$:

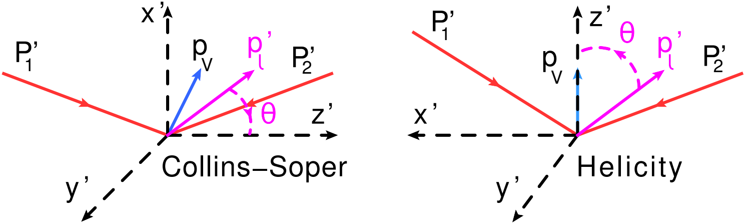
$$\rho^V_{\lambda\lambda'} = C\sum_{s_q,s_l} \mathcal{A}^*_{qq'\to ll'V}(\lambda, s_q, s_l)\mathcal{A}_{qq'\to ll'V}(\lambda', s_q, s_l).$$

- Note: this definition is based on on-shell V production and is independent of V decay.
- In this work, NLOEW corrections are always calculated in DPA. LO and NLOQCD are full calculations.
- FULL NLOEW = FULL LO + NLOEW
- DPA NLOEW = DPA LO + NLOEW.

Polarization observables in two frames

Convention: used by ATLAS and CMS, $l = \mu^-$ for Z, in the V rest frame,

$$\frac{d\sigma}{\sigma d\cos\theta d\phi} = \frac{3}{16\pi}\Big[(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin(2\theta)\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos(2\phi) + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin(2\phi) + A_6\sin(2\theta)\sin\phi + A_7\sin\theta\sin\phi\Big],$$



- Collins-Soper frame [CS, 1977]: z' is the bisector of $\vec{P}'_1$ and $-\vec{P}'_2$, points into the hemisphere of $\vec{p}_V$ (in the lab frame).
- Helicity frame [Bern et al, arXiv:1103.5445]: $z' = \vec{p}_V$.
- Integrating over ϕ gives the above polarization fractions $f_{L,0,R}$.

Calculations

Expectation of an observable $f(\theta, \phi)$:

$$
\begin{aligned}
< f(\theta) > &= \int_{-1}^{1} d\cos\theta f(\theta) \frac{1}{\sigma} \frac{d\sigma}{d\cos\theta}, \\
< f(\theta, \phi) > &= \int_{-1}^{1} d\cos\theta \int_{0}^{2\pi} d\phi f(\theta, \phi) \frac{1}{\sigma} \frac{d\sigma}{d\cos\theta d\phi}, \\
f_L^{W^\pm} &= -\frac{1}{2} \mp < \cos\theta_3 > + \frac{5}{2} < \cos^2\theta_3 >, \\
f_R^{W^\pm} &= -\frac{1}{2} \pm < \cos\theta_3 > + \frac{5}{2} < \cos^2\theta_3 >, \\
f_0^{W^\pm} &= 2 - 5 < \cos^2\theta_3 >, \\
f_L^{Z} &= -\frac{1}{2} + \frac{1}{c} < \cos\theta_6 > + \frac{5}{2} < \cos^2\theta_6 >, \\
f_R^{Z} &= -\frac{1}{2} - \frac{1}{c} < \cos\theta_6 > + \frac{5}{2} < \cos^2\theta_6 >, \\
f_0^{Z} &= 2 - 5 < \cos^2\theta_6 >, \\
A_0 &= 4 - 10 < \cos^2\theta >, \; A_1 = < 5\sin 2\theta\cos\phi >, \; \ldots
\end{aligned}
$$

For distributions independent of p_l: $\sigma \to d\sigma/dp_T^V$. Using bin-averaged method.

Useful relations

Relations between the polarization fractions and angular coefficients:

$$f_L^{W^\pm} = \frac{1}{4}(2 - A_0^{W^\pm} \mp A_4^{W^\pm}), \quad f_R^{W^\pm} = \frac{1}{4}(2 - A_0^{W^\pm} \pm A_4^{W^\pm}), \quad f_0^{W^\pm} = \frac{1}{2}A_0^{W^\pm},$$
$$f_L^Z = \frac{1}{4}(2 - A_0^Z + \frac{1}{c}A_4^Z), \quad f_R^Z = \frac{1}{4}(2 - A_0^Z - \frac{1}{c}A_4^Z), \quad f_0^Z = \frac{1}{2}A_0^Z.$$

- $f_{L,R,0}$ can be calculated from A_0 and A_4.
- $1/c \approx 5$.

Polarization fractions W^+ and Z: best results

13 TeV, ATLAS fiducial:

Method	$f_L^{W^+}$	$f_0^{W^+}$	$f_R^{W^+}$	f_L^Z	f_0^Z	f_R^Z
HE FULL-LO	$0.355(2)^{+2}_{-2}$	$0.513(1)^{+3}_{-3}$	$0.132(2)^{+0.8}_{-0.7}$	$0.222(2)^{+0.8}_{-0.2}$	$0.517(2)^{+1}_{-0.9}$	$0.261(3)^{+1}_{-2}$
HE FULL-NLOQCD	$0.320(3)^{+2}_{-3}$	$0.508(3)^{+2}_{-2}$	$0.172(2)^{+4}_{-3}$	$0.255(8)^{+5}_{-1}$	$0.493(2)^{+2}_{-3}$	$0.252(8)^{+0}_{-3}$
HE FULL-NLOEW	0.355	0.512	0.133	0.217	0.518	0.266
CS FULL-LO	$0.304(3)^{+2}_{-2}$	$0.699(2)^{+2}_{-2}$	$-0.003(1)^{+0.2}_{-0.08}$	$0.227(3)^{+0}_{-0.6}$	$0.627(1)^{+1}_{-0.8}$	$0.145(3)^{+1}_{-0.8}$
CS FULL-NLOQCD	$0.239(3)^{+4}_{-5}$	$0.756(2)^{+4}_{-4}$	$0.004(2)^{+1}_{-0.3}$	$0.211(5)^{+0.1}_{-3}$	$0.634(2)^{+2}_{-3}$	$0.156(7)^{+3}_{-2}$
CS FULL-NLOEW	0.304	0.698	$-0.0023[2]$	0.212	0.629	0.158

- NLOQCD from VBFNLO program, NLOEW in DPA our own code.
- Statistical errors (shown in [] where significant) about 10 times smaller than PDF errors.
- Scale errors are shown for LO and NLOQCD results.
- Central scale $\mu_R = \mu_F = (M_W + M_Z)/2$.
- We use LUXqed17_plus_PDF4LHC15_nnlo_30.
- Polarization fraction can get negative!

Off-shell, NLOEW correction effects

13 TeV, ATLAS fiducial:

Method	$f_L^{W^+}$	$f_0^{W^+}$	$f_R^{W^+}$	f_L^Z	f_0^Z	f_R^Z
HE FULL-LO	$0.355(2)^{+2}_{-2}$	$0.513(1)^{+3}_{-3}$	$0.132(2)^{+0.8}_{-0.7}$	$0.222(2)^{+0.8}_{-0.2}$	$0.517(2)^{+1}_{-0.9}$	$0.261(3)^{+1}_{-2}$
HE DPA-LO	0.355	0.512	0.133	0.263	0.498	0.239
HE DPA-NLOEW-prodV	0.356	0.510	0.134	0.262	0.499	0.240
HE DPA-NLOEW-decayV	0.355	0.512	0.133	0.259	0.498	0.243
HE DPA-NLOEW	0.355	0.510	0.135	0.258	0.499	0.244
CS FULL-LO	$0.304(3)^{+2}_{-2}$	$0.699(2)^{+2}_{-2}$	$-0.003(1)^{+0.2}_{-0.08}$	$0.227(3)^{+0}_{-0.6}$	$0.627(1)^{+1}_{-0.8}$	$0.145(3)^{+1}_{-0.8}$
CS DPA-LO	0.271	0.729	−0.0005[3]	0.242	0.600	0.158
CS DPA-NLOEW-prodV	0.271	0.729	−0.0002[3]	0.240	0.603	0.157
CS DPA-NLOEW-decayV	0.271	0.730	−0.0007[3]	0.228	0.600	0.172
CS DPA-NLOEW	0.271	0.729	−0.0004[3]	0.226	0.603	0.171

- Watch: Full vs. DPA, corrections to production and decays.

W^+ angular coefficients: best results

13 TeV, ATLAS fiducial:

Method	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7
HE FULL-LO	$1.026(3)^{+5}_{-6}$	$-0.286(3)^{+4}_{-3}$	$-1.314(4)^{+2}_{-4}$	$-0.251(3)^{+3}_{-2}$	$-0.446(7)^{+3}_{-3}$	$-0.003(2)^{+0.3}_{-0.2}$	$-0.001(2)^{+0.03}_{-0.01}$	$-0.004(2)^{+0.2}_{-0}$
HE FULL-NLOQCD	$1.016(6)^{+4}_{-3}$	$-0.325(4)^{+3}_{-2}$	$-1.414(8)^{+12}_{-11}$	$-0.230(7)^{+3}_{-0.4}$	$-0.296(9)^{+13}_{-9}$	$-0.001(4)^{+0.6}_{-0.4}$	$0.0004(38)^{+15}_{-6}$	$0.005(8)^{+0.1}_{-2}$
HE FULL-NLOEW	1.023	−0.285	−1.317	−0.252	−0.444	−0.0038[3]	−0.0037[4]	0.0028[3]
CS FULL-LO	$1.397(3)^{+4}_{-5}$	$0.230(3)^{+3}_{-3}$	$-0.944(6)^{+0.8}_{-3}$	$0.003(3)^{+0.1}_{-0.1}$	$-0.613(8)^{+4}_{-4}$	$-0.0005(20)^{+1}_{-1}$	$0.003(2)^{+0.1}_{-0.2}$	$0.004(2)^{+0}_{-0.3}$
CS FULL-NLOQCD	$1.512(5)^{+8}_{-7}$	$0.192(5)^{+1}_{-3}$	$-0.92(1)^{+0.3}_{-0.4}$	$0.061(6)^{+4}_{-4}$	$-0.470(9)^{12}_{-8}$	$-0.0006(41)^{+5}_{-11}$	$0.001(5)^{+0}_{-1}$	$-0.01(1)^{+0.2}_{-0}$
CS FULL-NLOEW	1.397	0.228	−0.945	0.0052[3]	−0.612	0.0007[4]	0.0056[4]	−0.0028[3]

- A_5, A_6, A_7 are very small, but statistically not zero!

W^+ off-shell, NLOEW correction effects on A_i

13 TeV, ATLAS fiducial:

Method	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7
HE FULL-LO	$1.026(3)^{+5}_{-6}$	$-0.286(3)^{+4}_{-3}$	$-1.314(4)^{+2}_{-4}$	$-0.251(3)^{+3}_{-2}$	$-0.446(7)^{+3}_{-3}$	$-0.003(2)^{+0.3}_{-0.2}$	$-0.001(2)^{+0.03}_{-0.01}$	$-0.004(2)^{+0.2}_{-0}$
HE DPA-LO	1.023	−0.326	−1.404	−0.156	−0.445	−0.0001[3]	0.00001[39]	0.0001[3]
HE DPA-NLOEW-prodW^+	1.020	−0.324	−1.406	−0.156	−0.442	−0.0018[4]	−0.0031[4]	0.0067[3]
HE DPA-NLOEW-decayW^+	1.024	−0.326	−1.405	−0.157	−0.443	−0.0001[3]	0.00001[39]	0.0001[3]
HE DPA-NLOEW	1.020	−0.324	−1.407	−0.157	−0.441	−0.0018[4]	−0.0032[4]	0.0067[3]
CS FULL-LO	$1.397(3)^{+4}_{-5}$	$0.230(3)^{+3}_{-3}$	$-0.944(6)^{+0.8}_{-3}$	$0.003(3)^{+0.1}_{-0.1}$	$-0.613(8)^{+4}_{-4}$	$-0.0005(20)^{+1}_{-1}$	$0.003(2)^{+0.1}_{-0.2}$	$0.004(2)^{+0}_{-0.3}$
CS DPA-LO	1.459	0.299	−0.971	−0.073	−0.544	−0.00001[38]	0.00003[38]	−0.0001[3]
CS DPA-NLOEW-prodW^+	1.458	0.297	−0.971	−0.072	−0.543	0.0010[4]	0.0036[4]	−0.0067[3]
CS DPA-NLOEW-decayW^+	1.459	0.298	−0.971	−0.072	−0.544	−0.00002[38]	0.00003[39]	−0.0001[3]
CS DPA-NLOEW	1.458	0.297	−0.971	−0.070	−0.543	0.0010[4]	0.0037[4]	−0.0067[3]

Z angular coefficients: best results

13 TeV, ATLAS fiducial:

Method	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7
HE FULL-LO	$1.035(3)^{+3}_{-2}$	$-0.304(2)^{+0.9}_{-2}$	$-0.705(4)^{+0.7}_{-0.2}$	$0.063(4)^{+0}_{-1}$	$-0.017(2)^{+1}_{-0.6}$	$-0.007(2)^{+0.6}_{-0.3}$	$-0.007(3)^{+0}_{-0.6}$	$0.003(2)^{+0}_{-0.4}$
HE FULL-NLOQCD	$0.985(4)^{+3}_{-5}$	$-0.307(6)^{+5}_{-3}$	$-0.73(2)^{+0}_{-0.8}$	$0.031(4)^{+2}_{-2}$	$0.001(7)^{+3}_{-0.3}$	$-0.005(8)^{+2}_{-0.4}$	$-0.003(5)^{+0.1}_{-2}$	$0.003(5)^{+2}_{-0.9}$
HE FULL-NLOEW	1.035	−0.305	−0.711	0.051	−0.0209[2]	−0.0070[4]	−0.0077[4]	0.0028[3]
CS FULL-LO	$1.255(2)^{+2}_{-2}$	$0.240(2)^{+3}_{-2}$	$-0.488(4)^{+0.3}_{-0.2}$	$-0.061(3)^{+1}_{-0}$	$0.035(3)^{+0.1}_{-0.8}$	$-0.001(3)^{+0.3}_{-0}$	$0.011(2)^{+0.7}_{-0.2}$	$-0.003(2)^{+0.3}_{-0}$
CS FULL-NLOQCD	$1.267(5)^{+4}_{-6}$	$0.220(5)^{+2}_{-1}$	$-0.45(2)^{0.2}_{-0.6}$	$-0.022(6)^{+4}_{-2}$	$0.024(5)^{+0.5}_{-2}$	$-0.001(7)^{+2}_{-0.01}$	$0.006(6)^{+0}_{-1}$	$-0.003(3)^{+1}_{-2}$
CS FULL-NLOEW	1.259	0.235	−0.490	−0.054	0.0232[3]	0.0007[5]	0.0113[3]	−0.0028[3]

- Again, A_5, A_6, A_7 are very small, but statistically not zero!

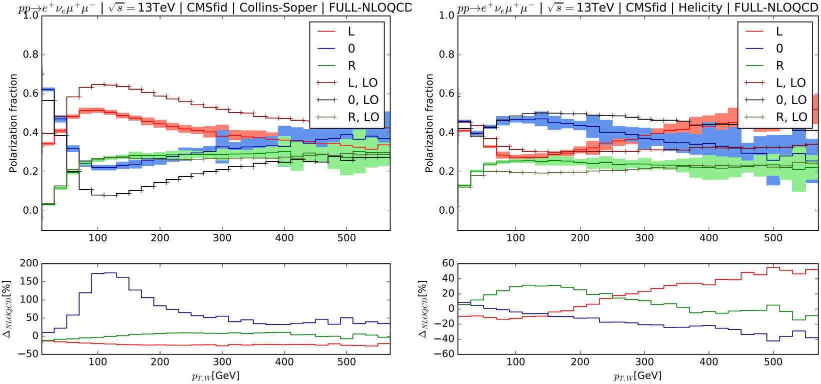
Z off-shell, NLOEW correction effects on A_i

13 TeV, ATLAS fiducial:

Method	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7
HE FULL-LO	$1.035(3)^{+3}_{-2}$	$-0.304(2)^{+0.9}_{-2}$	$-0.705(4)^{+0.7}_{-0.2}$	$0.063(4)^{+0}_{-1}$	$-0.017(2)^{+1}_{-0.6}$	$-0.007(2)^{+0.6}_{-0.3}$	$-0.007(3)^{+0}_{-0.6}$	$0.003(2)^{+0}_{-0.4}$
HE DPA-LO	0.997	−0.265	−0.720	0.039	0.0105[2]	−0.00001[49]	0.00004[41]	0.0001[3]
HE DPA-NLOEW-prodZ	0.997	−0.267	−0.726	0.040	0.0095[2]	−0.0003[5]	−0.0012[4]	−0.0004[3]
HE DPA-NLOEW-decayZ	0.997	−0.265	−0.720	0.026	0.0070[2]	0.000004[441]	0.00005[41]	0.0001[2]
HE DPA-NLOEW	0.997	−0.267	−0.726	0.027	0.0060[2]	−0.0003[5]	−0.0011[4]	−0.0004[2]
CS FULL-LO	$1.255(2)^{+2}_{-2}$	$0.240(2)^{+3}_{-2}$	$-0.488(4)^{+0.3}_{-0.2}$	$-0.061(3)^{+1}_{-0}$	$0.035(3)^{+0.1}_{-0.8}$	$-0.001(3)^{+0.3}_{-0}$	$0.011(2)^{+0.7}_{-0.2}$	$-0.003(2)^{+0.3}_{-0}$
CS DPA-LO	1.200	0.305	−0.519	−0.023	0.036	−0.00005[59]	0.00002[30]	−0.0001[3]
CS DPA-NLOEW-prodZ	1.205	0.301	−0.521	−0.024	0.036	0.0008[6]	0.0011[3]	0.0004[3]
CS DPA-NLOEW-decayZ	1.200	0.305	−0.519	−0.015	0.024	−0.00005[57]	0.00001[27]	−0.0001[2]
CS DPA-NLOEW	1.205	0.301	−0.521	−0.016	0.023	0.0008[5]	0.0011[3]	0.0004[2]

p_T^W distributions: CS vs. HE, NLOQCD effects (CMS)

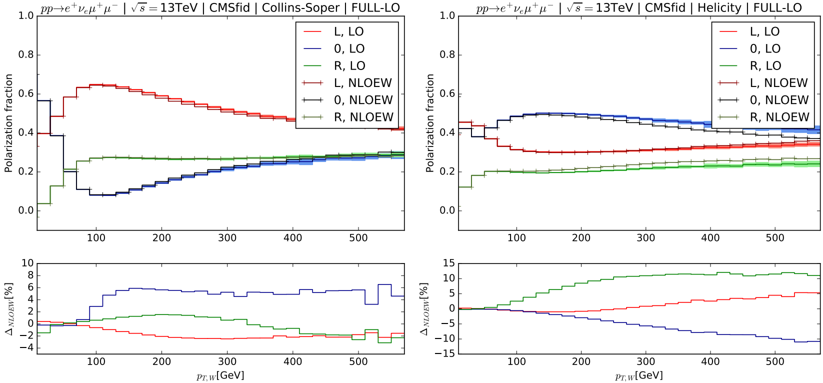
13 TeV, fiducial phase space as in [CMS, Phys. Lett. B766, 268 (2017)]



- Bands show PDF errors, $\Delta_{NLOQCD} = (NLOQCD - LO)/LO$.
- Question to CMS: lepton-photon recombination parameter?

p_T^W distributions: NLOEW effects (CMS)

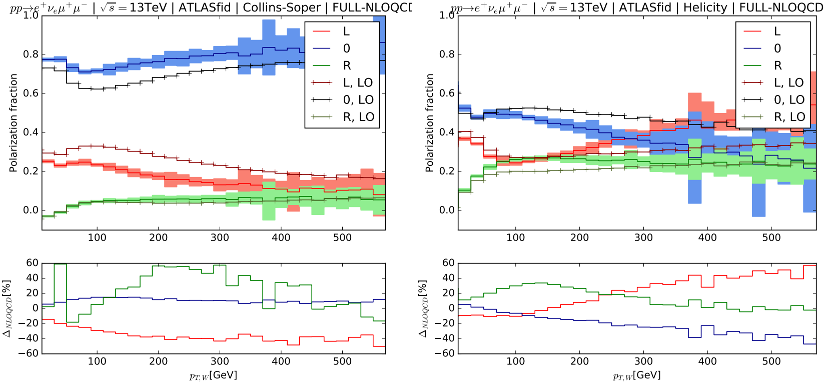
13 TeV, fiducial phase space as in [CMS, Phys. Lett. B766, 268 (2017)]



- Bands show statistical errors, $\Delta_{NLOEW} = (NLOEW - LO)/LO$.

p_T^W distributions: CS vs. HE, NLOQCD effects (ATLAS)

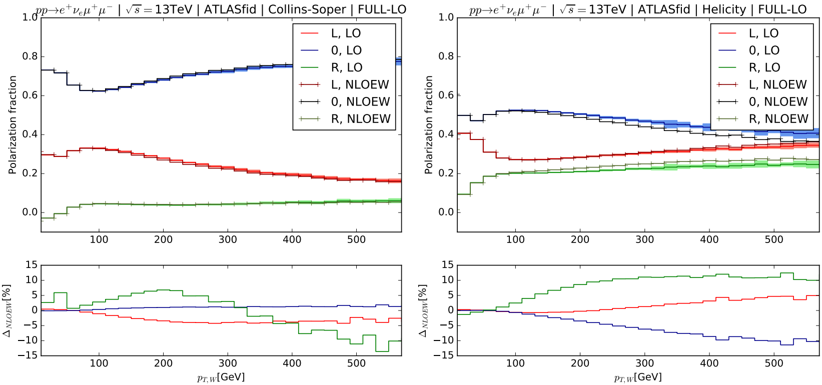
13 TeV, fiducial phase space as in [ATLAS, Phys. Lett. B762, 1 (2016)]



- Bands show PDF errors, rather large at high p_T.

p_T^W distributions: NLOEW effects (ATLAS)

13 TeV, fiducial phase space as in [ATLAS, Phys. Lett. B762, 1 (2016)]



- Bands show statistical errors.

Fiducial cross sections at 13 TeV, $W^{\pm}Z \to l'\nu ll$

ATLAS, one channel:

$$\sigma^{\text{fid.}}_{\text{ATLAS}} = 63.2 \pm 3.2(\text{stat.}) \pm 2.6(\text{sys.}) \pm 1.5(\text{lumi.})\,\text{fb}$$

$$\sigma^{\text{fid.}}_{\text{this work}} = 58.9(\text{NLOQCD}) - 0.4(\text{EW cor.}) \pm 0.7(\text{PDF}) \pm 2.0(\text{scale})\,\text{fb}$$

CMS, four channels (eee, μee, $e\mu\mu$, $\mu\mu\mu$):

$$\sigma^{\text{fid.}}_{\text{CMS}} = 258 \pm 21(\text{stat}) \pm 20(\text{syst}) \pm 8(\text{lumi})\,\text{fb}$$

$$\sigma^{\text{fid.}}_{\text{this work}} = 301.7(\text{NLOQCD}) - 0.2(\text{EW cor.}) \pm 3.4(\text{PDF}) \pm 12.0(\text{scale})\,\text{fb}$$

Agreement with ATLAS within 1.0σ, with CMS 1.3σ.

Summary

- Results for polarization observables (fractions, angular coefficients, distributions) have been obtained at full NLOQCD and NLOEW in DPA for $pp \to WZ \to 3l + \nu$.
- Results for both Collins-Soper and Helicity frames are provided.
- NLOQCD corrections can reach 170% (60%) for p_T^W distributions, CMS (ATLAS) fiducial cuts. NLOEW corrections are within 15%.
- Perfect agreements with ATLAS and CMS for fiducial cross sections. Looking forward to similar comparisons for 8 angular coefficients and distributions.
- Publication in preparation (for both ATLAS and CMS).

Thank you for your attention!

BACKUP

CMS fiducial cut

A charged lepton is combined with a final-state photon if their momenta satisfies the condition of $\Delta R(l,\gamma) \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.1$. The dressed lepton's momentum is the sum of the initial two momenta. After this recombination step, we use the dressed lepton's momentum for kinematical cuts and distributions.

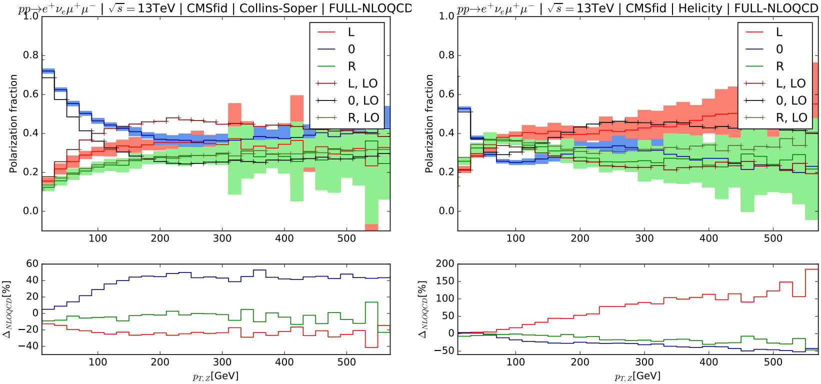
$$p_{T,e} > 20\,\text{GeV}, \quad p_{T,\mu}^{\text{leading}} > 20\,\text{GeV}, \quad p_{T,\mu}^{\text{sub-leading}} > 10\,\text{GeV}, \quad |\eta_l| < 2.5,$$
$$60 < m_{\mu^+\mu^-} < 120\,\text{GeV}.$$

ATLAS fiducial cut

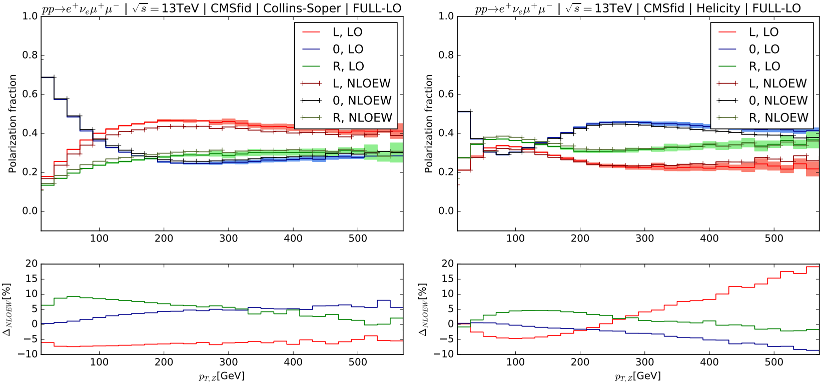
A charged lepton is combined with a final-state photon if their momenta satisfies the condition of $\Delta R(l,\gamma) \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.1$. The dressed lepton's momentum is the sum of the initial two momenta. After this recombination step, we use the dressed lepton's momentum for kinematical cuts and distributions.

$$p_{T,e} > 20\,\text{GeV}, \quad p_{T,\mu} > 15\,\text{GeV}, \quad |\eta_l| < 2.5,$$
$$|m_{\mu^+\mu^-} - M_Z| < 10\,\text{GeV}, \quad \Delta R(\mu^+,\mu^-) > 0.2, \quad \Delta R(e^+,\mu^\mp) > 0.3,$$
$$m_{T,W} = \sqrt{2p_{T,\nu}p_{T,e}[1 - \cos\Delta\phi(e,\nu)]} > 30\,\text{GeV}$$

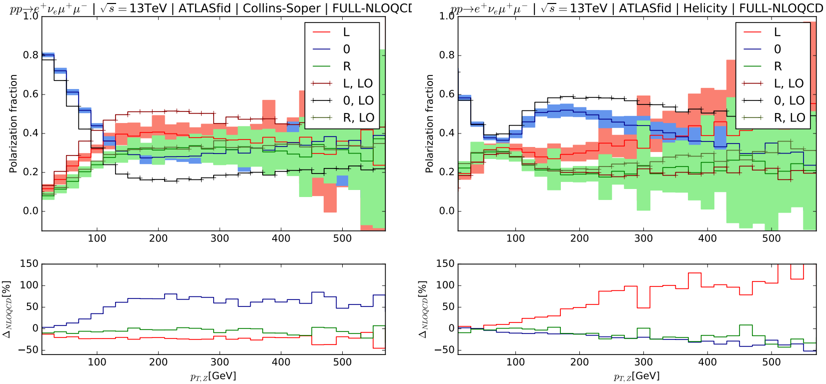
p_T^Z distributions: CS vs. HE, NLOQCD effects (CMS)



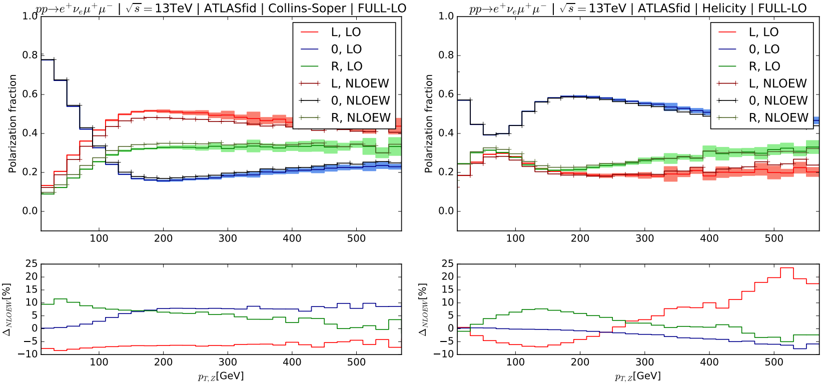
p_T^Z distributions: NLOEW effects (CMS)



p_T^Z distributions: CS vs. HE, NLOQCD effects (ATLAS)



p_T^Z distributions: NLOEW effects (ATLAS)



Results: polarization fractions W^+ and Z

13 TeV, ATLAS fiducial:

Method	$f_L^{W^+}$	$f_0^{W^+}$	$f_R^{W^+}$	f_L^Z	f_0^Z	f_R^Z
HE FULL-LO	$0.355(2)^{+2}_{-2}$	$0.513(1)^{+3}_{-3}$	$0.132(2)^{+0.8}_{-0.7}$	$0.222(2)^{+0.8}_{-0.2}$	$0.517(2)^{+1}_{-0.9}$	$0.261(3)^{+1}_{-2}$
HE FULL-NLOQCD	$0.320(3)^{+2}_{-3}$	$0.508(3)^{+2}_{-2}$	$0.172(2)^{+4}_{-3}$	$0.255(8)^{+5}_{-1}$	$0.493(2)^{+2}_{-3}$	$0.252(8)^{+0}_{-3}$
HE FULL-NLOEW	0.355	0.512	0.133	0.217	0.518	0.266
HE DPA-LO	0.355	0.512	0.133	0.263	0.498	0.239
HE DPA-NLOEW-prodV	0.356	0.510	0.134	0.262	0.499	0.240
HE DPA-NLOEW-decayV	0.355	0.512	0.133	0.259	0.498	0.243
HE DPA-NLOEW	0.355	0.510	0.135	0.258	0.499	0.244
CS FULL-LO	$0.304(3)^{+2}_{-2}$	$0.699(2)^{+2}_{-2}$	$-0.003(1)^{+0.2}_{-0.08}$	$0.227(3)^{+0}_{-0.6}$	$0.627(1)^{+1}_{-0.8}$	$0.145(3)^{+1}_{-0.8}$
CS FULL-NLOQCD	$0.239(3)^{+4}_{-5}$	$0.756(2)^{+4}_{-4}$	$0.004(2)^{+1}_{-0.3}$	$0.211(5)^{+0.1}_{-3}$	$0.634(2)^{+2}_{-3}$	$0.156(7)^{+3}_{-2}$
CS FULL-NLOEW	0.304	0.698	−0.0023[2]	0.212	0.629	0.158
CS DPA-LO	0.271	0.729	−0.0005[3]	0.242	0.600	0.158
CS DPA-NLOEW-prodV	0.271	0.729	−0.0002[3]	0.240	0.603	0.157
CS DPA-NLOEW-decayV	0.271	0.730	−0.0007[3]	0.228	0.600	0.172
CS DPA-NLOEW	0.271	0.729	−0.0004[3]	0.226	0.603	0.171

- NLOQCD from VBFNLO program, NLOEW in DPA our own code.
- Statistical errors (shown in [] where significant) about 10 times smaller than PDF errors.
- Watch: Full vs. DPA, corrections to production and decays.

Results: W^+ angular coefficients

Method	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7
HE FULL-LO	$1.026(3)^{+5}_{-6}$	$-0.286(3)^{+4}_{-3}$	$-1.314(4)^{+2}_{-4}$	$-0.251(3)^{+3}_{-2}$	$-0.446(7)^{+3}_{-3}$	$-0.003(2)^{+0.3}_{-0.2}$	$-0.001(2)^{+0.03}_{-0.01}$	$-0.004(2)^{+0.2}_{-0}$
HE FULL-NLOQCD	$1.016(6)^{+4}_{-3}$	$-0.325(4)^{+3}_{-2}$	$-1.414(8)^{+12}_{-11}$	$-0.230(7)^{+3}_{-0.4}$	$-0.296(9)^{+13}_{-9}$	$-0.001(4)^{+0.6}_{-0.4}$	$0.0004(38)^{+15}_{-6}$	$0.005(8)^{+0.1}_{-2}$
HE FULL-NLOEW	1.023	−0.285	−1.317	−0.252	−0.444	−0.0038[3]	−0.0037[4]	0.0028[3]
HE DPA-LO	1.023	−0.326	−1.404	−0.156	−0.445	−0.0001[3]	0.00001[39]	0.0001[3]
HE DPA-NLOEW-prodW^+	1.020	−0.324	−1.406	−0.156	−0.442	−0.0018[4]	−0.0031[4]	0.0067[3]
HE DPA-NLOEW-decayW^+	1.024	−0.326	−1.405	−0.157	−0.443	−0.0001[3]	0.00001[39]	0.0001[3]
HE DPA-NLOEW	1.020	−0.324	−1.407	−0.157	−0.441	−0.0018[4]	−0.0032[4]	0.0067[3]
CS FULL-LO	$1.397(3)^{+4}_{-5}$	$0.230(3)^{+3}_{-3}$	$-0.944(6)^{+0.8}_{-3}$	$0.003(3)^{+0.1}_{-0.1}$	$-0.613(8)^{+4}_{-4}$	$-0.0005(20)^{+1}_{-1}$	$0.003(2)^{+0.1}_{-0.2}$	$0.004(2)^{+0}_{-0.3}$
CS FULL-NLOQCD	$1.512(5)^{+8}_{-7}$	$0.192(5)^{+1}_{-3}$	$-0.92(1)^{+0.3}_{-0.4}$	$0.061(6)^{+4}_{-4}$	$-0.470(9)^{12}_{-8}$	$-0.0006(41)^{+5}_{-11}$	$0.001(5)^{+0}_{-1}$	$-0.01(1)^{+0.2}_{-0}$
CS FULL-NLOEW	1.397	0.228	−0.945	0.0052[3]	−0.612	0.0007[4]	0.0056[4]	−0.0028[3]
CS DPA-LO	1.459	0.299	−0.971	−0.073	−0.544	−0.00001[38]	0.00003[38]	−0.0001[3]
CS DPA-NLOEW-prodW^+	1.458	0.297	−0.971	−0.072	−0.543	0.0010[4]	0.0036[4]	−0.0067[3]
CS DPA-NLOEW-decayW^+	1.459	0.298	−0.971	−0.072	−0.544	−0.00002[38]	0.00003[39]	−0.0001[3]
CS DPA-NLOEW	1.458	0.297	−0.971	−0.070	−0.543	0.0010[4]	0.0037[4]	−0.0067[3]

Results: Z angular coefficients

Method	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7
HE FULL-LO	$1.035(3)^{+3}_{-2}$	$-0.304(2)^{+0.9}_{-2}$	$-0.705(4)^{+0.7}_{-0.2}$	$0.063(4)^{+0}_{-1}$	$-0.017(2)^{+1}_{-0.6}$	$-0.007(2)^{+0.6}_{-0.3}$	$-0.007(3)^{+0}_{-0.6}$	$0.003(2)^{+0}_{-0.4}$
HE FULL-NLOQCD	$0.985(4)^{+3}_{-5}$	$-0.307(6)^{+5}_{-3}$	$-0.73(2)^{+0}_{-0.8}$	$0.031(4)^{+2}_{-2}$	$0.001(7)^{+3}_{-0.3}$	$-0.005(8)^{+2}_{-0.4}$	$-0.003(5)^{+0.1}_{-2}$	$0.003(5)^{+2}_{-0.9}$
HE FULL-NLOEW	1.035	−0.305	−0.711	0.051	−0.0209[2]	−0.0070[4]	−0.0077[4]	0.0028[3]
HE DPA-LO	0.997	−0.265	−0.720	0.039	0.0105[2]	−0.00001[49]	0.00004[41]	0.0001[3]
HE DPA-NLOEW-prodZ	0.997	−0.267	−0.726	0.040	0.0095[2]	−0.0003[5]	−0.0012[4]	−0.0004[3]
HE DPA-NLOEW-decayZ	0.997	−0.265	−0.720	0.026	0.0070[2]	0.000004[441]	0.00005[41]	0.0001[2]
HE DPA-NLOEW	0.997	−0.267	−0.726	0.027	0.0060[2]	−0.0003[5]	−0.0011[4]	−0.0004[2]
CS FULL-LO	$1.255(2)^{+2}_{-2}$	$0.240(2)^{+3}_{-2}$	$-0.488(4)^{+0.3}_{-0.2}$	$-0.061(3)^{+1}_{-0}$	$0.035(3)^{+0.1}_{-0.8}$	$-0.001(3)^{+0.3}_{-0}$	$0.011(2)^{+0.7}_{-0.2}$	$-0.003(2)^{+0.3}_{-0}$
CS FULL-NLOQCD	$1.267(5)^{+4}_{-6}$	$0.220(5)^{+2}_{-1}$	$-0.45(2)^{0.2}_{-0.6}$	$-0.022(6)^{+4}_{-2}$	$0.024(5)^{+0.5}_{-2}$	$-0.001(7)^{+2}_{-0.01}$	$0.006(6)^{+0}_{-1}$	$-0.003(3)^{+1}_{-2}$
CS FULL-NLOEW	1.259	0.235	−0.490	−0.054	0.0232[3]	0.0007[5]	0.0113[3]	−0.0028[3]
CS DPA-LO	1.200	0.305	−0.519	−0.023	0.036	−0.00005[59]	0.00002[30]	−0.0001[3]
CS DPA-NLOEW-prodZ	1.205	0.301	−0.521	−0.024	0.036	0.0008[6]	0.0011[3]	0.0004[3]
CS DPA-NLOEW-decayZ	1.200	0.305	−0.519	−0.015	0.024	−0.00005[57]	0.00001[27]	−0.0001[2]
CS DPA-NLOEW	1.205	0.301	−0.521	−0.016	0.023	0.0008[5]	0.0011[3]	0.0004[2]