Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

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Polarizations in WZ scattering at the LHC

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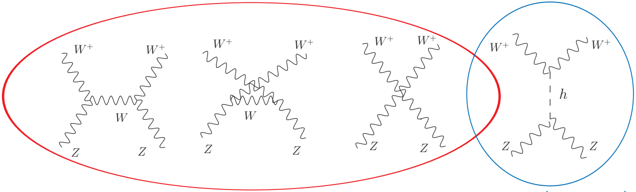
Introduction

Why studying polarizations in the fully-leptonic $W^{\pm}Z$ VBS production ($\ell\ell\ell\nu$)?

- SM amp. for longitudinal bosons: gauge/Higgs required to preserve unitarity



$$\mathcal{A} \propto -\frac{t}{v^2} \qquad \mathcal{A} \propto \frac{1}{v^2}\left(\frac{t^2}{t - M_h^2}\right)$$

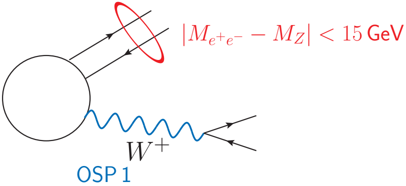
and new physics could interfere in this delicate cancellation.

- a realistic process with only 1 neutrino, differently from WW channel
- a sizeable SM cross-section at LHC@13TeV, much bigger than ZZ channel
- a benchmark for semi-leptonic channel, much bigger σ than fully-leptonic

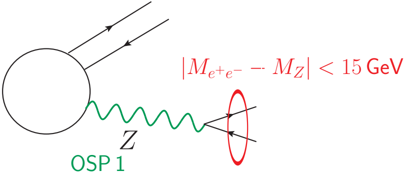
Remark: γ/Z mixing cannot be avoided, $M_{\ell^+\ell^-}$ cut required.

Polarization of WZ bosons and resonant contributions

- For W^+ polarization:



- For Z polarization:



Numerator of W/Z propagator in unitarity gauge
is written as a sum over polarization vectors $\sum_{\lambda'} \varepsilon^{\mu}_{\lambda'} \varepsilon^{\nu\,*}_{\lambda'}$.

To separate polarization modes, perform the substitution:

$$\mathcal{A}^{(W)}_{\text{unpol}} \propto \sum_{\lambda'} \varepsilon^{\mu}_{\lambda'} \varepsilon^{\nu\,*}_{\lambda'} \longrightarrow \varepsilon^{\mu}_{\lambda} \varepsilon^{\nu\,*}_{\lambda} \propto \mathcal{A}^{(W)}_{\lambda}$$

$$\mathcal{A}^{(Z)}_{\text{unpol}} \propto \sum_{\lambda'} \varepsilon^{\mu}_{\lambda'} \varepsilon^{\nu\,*}_{\lambda'} \longrightarrow \varepsilon^{\mu}_{\lambda} \varepsilon^{\nu\,*}_{\lambda} \propto \mathcal{A}^{(Z)}_{\lambda}$$

$|\mathcal{A}_\lambda|^2 \longrightarrow$ polarized cross-sections both for W^+ and Z boson

In a similar fashion as in [Ballestrero, Maina, GP, JHEP03(2018)170]

To cure (at least partially) gauge violation given by the selection of Z/W-resonant diagrams, we perform an On Shell projection of the Z/W boson (OSP1).

Setup of the simulations

$p\,p \to j\,j\,e^+e^-\mu^+\nu_\mu$ at LHC@13TeV.
Parton-level simulations with `PHANTOM_1_5_1_b` at LO EW.

Kinematic cuts: $M_{jj} > 500$ GeV, $|\Delta\eta_{jj}| > 2.5$, $|\eta_j| < 5$, $p_t^j > 20$ GeV, $M_{4\ell} > 200$ GeV, $p_t^\ell > 20$ GeV, $|\eta_\ell| < 2.5$, $p_t^{\text{miss}} > 40$ GeV, $|M_{\ell^+\ell^-} - M_Z| < 15\,$GeV.

Complex-Mass-Scheme, PDF set: `NNPDF30_lo_as_0130`, PDF scale: $\mu = M_{4\ell}/\sqrt{2}$.

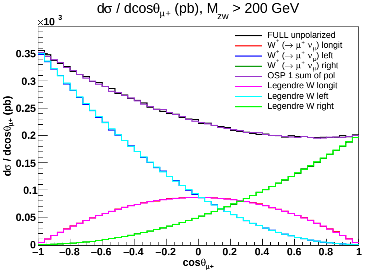
We simulated singly-polarized signals for both polarized W^+ and polarized Z.
In the following we mainly focus on polarized W^+.

Results without lepton cuts

No lepton cuts, no ν reconstruction: validation of the Monte Carlo polarized samples with the analytic results extracted from the full unpolarized $\cos\theta^*_\ell$ distributions.

$$\frac{1}{\sigma}\frac{d\,\sigma}{d\cos\theta*} = \frac{3}{8} f_L \left(1+\cos^2\theta^* - \frac{2(c_L^2-c_R^2)}{(c_L^2+c_R^2)}\cos\theta^*\right) + \frac{3}{8} f_R \left(1+\cos^2\theta^* + \frac{2(c_L^2-c_R^2)}{(c_L^2-c_R^2)}\cos\theta^*\right) + \frac{3}{4} f_0 \sin^2\theta^*$$

c_R, c_L = right/left couplings of fermions to $W^+(Z)$, $f_0+f_L+f_R=1$, θ^* = angle of ℓ^+ in the W^+/Z rest frame.



Very good agreement between MC and analytic results (projection of full over first 3 Legendre poly.'s), both for pol. fractions and distribution shapes (discrep. $\lesssim 2\%$).

Sum of polarized distributions equals the full computation as interferences vanish in the absence of lepton cuts and non-resonant effects are negligible in the fiducial region.

Neutrino reconstruction (1)

Presence of one neutrino in the final state: require $M_{\ell\nu} = M_W$ to determine the longitudinal momentum $p_z^\nu \longrightarrow$ two possible solutions:

$$p_{z\,1,2}^{\nu,\,\mathrm{reco}} = \frac{p_z^\ell\,\xi \pm \sqrt{\Delta}}{{p_\ell^t}^2}\,,$$

where $$\Delta = {p_z^\ell}^2\xi^2 - {p_t^\ell}^2\left[{E^\ell}^2{p_t^\nu}^2 - \xi^2\right]\,, \qquad \xi = \frac{M_W^2}{2} + \mathbf{p}_t^\ell\cdot\mathbf{p}_t^\nu\,.$$

If the transverse mass of the $\ell^+\nu_\ell$ system ($M_t^{\ell\nu}$) is larger than M_W, then $\Delta < 0$, we need to recover a unique real solution. If $M_t^{\ell\nu} < M_W$, then $\Delta > 0$: in such case we need to choose one of the two real solutions.

Several criteria: we investigated how different reconstruction schemes act on unpolarized events, computed with full matrix-elements at LO EW, with VBS cuts.

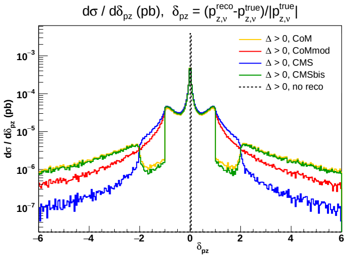
How do we choose the best one? Choose the one which:

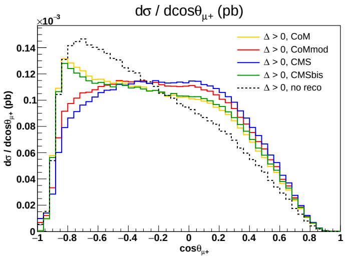
1. minimizes the RMS of $\delta_{p_z} = \frac{p_z^{\nu,\,\mathrm{reco}} - p_z^{\nu,\,\mathrm{true}}}{|p_z^{\nu,\,\mathrm{true}}|}$ (highest central peak, lowest tails)
2. reconstructs $\cos\theta_{\ell^+}^{\mathrm{reco}}$ distributions shapes as similar as possible to $\cos\theta_{\ell^+}^{\mathrm{true}}$ ones

Neutrino reconstruction (2)

$$\delta_{p_z} = \frac{p_z^{\nu,\,\text{reco}} - p_z^{\nu,\,\text{true}}}{|p_z^{\nu,\,\text{true}}|}$$

$\cos\theta_{\ell+}$





Our choice (yellow line):

For $\Delta > 0$:

if $p^{\nu}_{z\,1} \cdot p^{\nu}_{z\,2} < 0$, choose the one such that $p_z^{\ell} \cdot p_z^{\nu,\,\text{reco}} > 0$

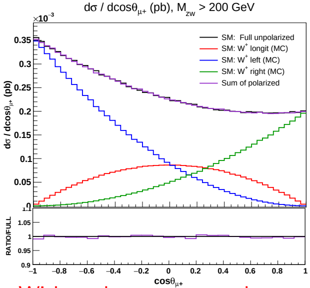
if $p^{\nu}_{z\,1} \cdot p^{\nu}_{z\,2} > 0$, choose the one such that the partonic CoM invariant mass is minimized (natural choice at the LHC, due to PDFs).

For $\Delta < 0$:

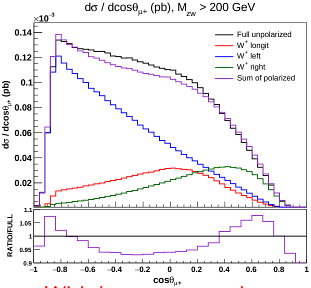
substitute M_W with $M_t^{\ell\nu}$ (this sets $\Delta = 0$), the (unique) solution is $p_z^{\nu} = p_z^{\ell}\,\frac{p_t^{\nu}}{p_t^{\ell}}$

Effects of lepton cuts and neutrino reconstruction

Imposing lepton cuts ($p_t^\ell > 20\,\text{GeV}$, $|\eta_\ell| < 2.5$, $\text{p}_\text{t}^\text{miss} > 40\,\text{GeV}$) and ν reconstruction



Without lepton cuts and ν reco



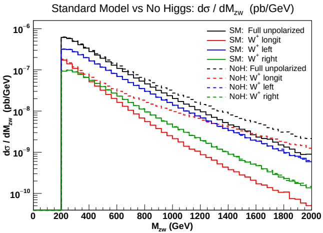
With lepton cuts and ν reco

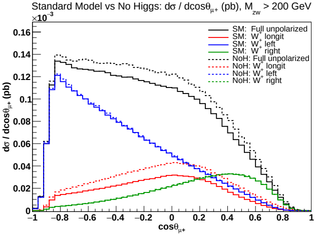
- interferences among different polarization states don't vanish
- neutrino reconstruction affects variables which depend on p_z^ν
- lepton cuts and reco make the discrepancy between full and sum of polarized small but non-negligible (up to 10% in remote regions of phase-space)
- slightly smaller discrepancy for polarized Z (only lepton cut, no reco effects)

Extracting polarization fractions (1)

Simulated Standard Model and No Higgs.

No Higgs (SM, with $M_h \to \infty$): extreme BSM theory (strongly coupled).





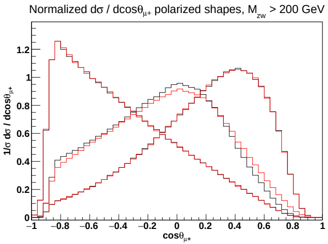
- left and right distributions don't discriminate between SM and NoH (neither in shape, nor in cross-section, $\lesssim$3% discrep.)
- interference is small (a few % of the total) and similar for SM and NoH
- SM longitudinal cross-section is, as expected, much smaller than the NoH one
- longitudinal component shows moderate differences in shapes

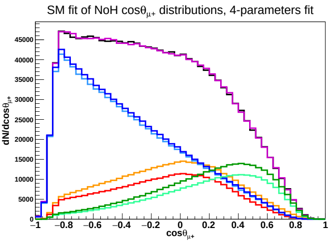
Can we extract the polarized components from the full NoH distributions, employing Standard Model polarized distributions?

Extracting polarization fractions (2)

Fit of full NoH (our "BSM data") with SM templates: longit., left, right, interference.

$$f(\cos\theta)^{\text{noh}}_{\text{full}} = \sum_{\lambda=0,L,R} C_\lambda\, f(\cos\theta)^{\text{sm}}_{\lambda} + C_{\text{I}}\, f(\cos\theta)^{\text{sm}}_{\text{interf}} \qquad \text{(4 free parameters)}$$





Left fig.
- SM shapes
- NoH shapes

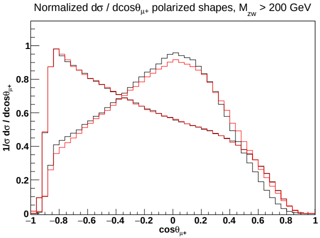
Right fig.
- SM fit (longit.)
- NoH th. (longit.)
- SM fit (left)
- NoH th. (left)
- SM fit (right)
- NoH th. (right)
- SM fit (full)
- NoH th. (full)

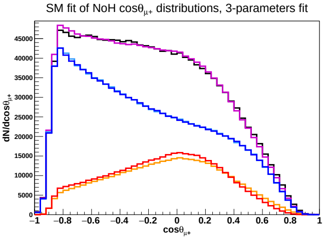
	NoHiggs MC	Fit (4-par.)	δ(%)
longit.	0.260	0.196	-24.6%
left	0.540	0.555	+2.8%
right	0.173	0.215	+24.3%
interf.	0.027	0.034	

Bad fit results: try to substitute L, R with transverse $T = L + R$ (incoherent sum).

$$f(\cos\theta)^{\text{noh}}_{\text{full}} = \sum_{\lambda=0,T} C_\lambda\, f(\cos\theta)^{\text{sm}}_{\lambda} + C_{\text{I}}\, f(\cos\theta)^{\text{sm}}_{\text{interf}} \qquad \text{(3 free parameters)}$$

Extracting polarization fractions (3)



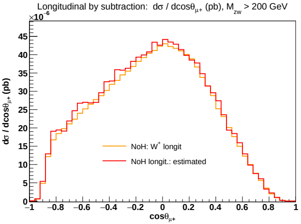


Left fig.
- SM shapes
- NoH shapes

Right fig.
- SM fit (longit.)
- NoH th. (longit.)
- SM fit (transv.)
- NoH th. (transv.)
- SM fit (full)
- NoH th. (full)

Fit with 3 parameters works much better than with 4!

	NoHiggs MC	Fit (3-par.)	$\delta(\%)$
longit.	0.260	0.272	+4.6%
transv.	0.713	0.712	-0.2%
interf.	0.027	0.016	



Subtracting SM transverse and interference from full NoH returns correctly the NoH longitudinal fraction: 0.260 (MC) vs 0.268 (estimated by subtraction).
Transverse are almost equal for SM and NOH.

Monte Carlo VS reweighting (1)

Reweighting approach (often employed by ATLAS/CMS) for cut polarized samples

1. generate the full process without imposing lepton cuts (and no ν reco.)
$M_{jj} > 500$ GeV, $|\Delta\eta_{\mathrm{jj}}| > 2.5$, $\mathrm{p_t^j} > 20$ GeV, $|\eta_\mathrm{j}| < 5$, $|\mathrm{M}_{\ell^+\ell^-} - \mathrm{M_Z}| < 15$ GeV
2. divide the (p_t, η) space of the W^+ in bins *
3. compute pol. fractions $f_0^{(i)}$, $f_L^{(i)}$, $f_R^{(i)}$ in each region i (Legendre expansion)
4. for each event in region i, compute the weights:

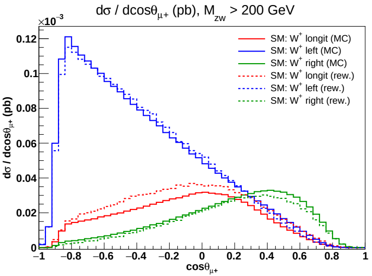
$$w_{0,L,R} = \frac{\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{\mu^+}}\Big|_{0,L,R}}{\frac{3}{4}(\sin\theta_{\mu^+})^2 f_0^{(i)} + \frac{3}{8}(1-\cos\theta_{\mu^+})^2 f_L^{(i)} + + \frac{3}{8}(1+\cos\theta_{\mu^+})^2 f_R^{(i)}}$$

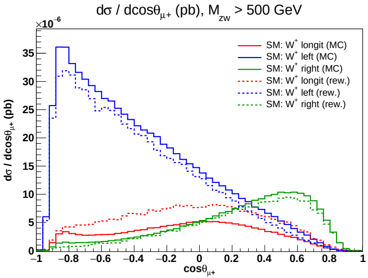
where $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{\mu^+}}\Big|_0 = \frac{3}{4}(\sin\theta_{\mu^+})^2 f_0^{(i)}$, $\quad \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{\mu^+}}\Big|_{L/R} = \frac{3}{8}(1\mp\cos\theta_{\mu^+})^2 f_L^{(i)}$

5. assign to the event a probability w_0 of being a longitudinal event, w_L of being left-handed and w_R of being right-handed event
6. we are left with 3 polarized samples, which one can analyze separately
7. impose lepton cuts and ν reconstruction to obtain cut polarized distributions

* $p_t^W < 30$ GeV, 30 GeV $< \mathrm{p_t^W} < 60$ GeV, 60 GeV $< \mathrm{p_t^W} < 90$ GeV and $p_t^W > 90$ GeV
$|\eta_W| < 1$, $1 < |\eta_W| < 2$, $2 < |\eta_W| < 3$ and $|\eta_W| > 3$.

Monte Carlo VS reweighting (2)





Polarized cross-sections [pb]: $M_{zw} > 200$ GeV

	MC	Reweight.	$\delta(\%)$
longit.	3.3210e-05	4.1023e-05	+23.5 %
left	9.6307e-05	9.5967e-05	-0.35 %
right	3.0926e-05	2.7865e-05	-9.9 %

Polarized cross-sections [pb]: $M_{zw} > 500$ GeV

	MC	Reweight.	$\delta(\%)$
longit.	5.9617e-06	9.9370e-06	+66.7%
left	2.8377e-05	2.5486e-05	-10.2 %
right	9.0614e-06	8.133e-06	-10.3 %

Large disagreement w.r.t. MC polarized signals:

1. rough approximation (average over $\{\eta,\ p_t\}$ regions to extract polarizations)
2. interferences assumed to be vanishing, which is not the case
3. lepton cuts imposed on samples which depend on polarization fractions extracted without lepton cuts: the two procedures don't commute.

Conclusions

We investigated the polarization of vector bosons in fully-leptonic W^+Z scattering at LO EW, including the effects of realistic lepton cuts and neutrino reconstruction.

1. Good description of polarized W/Z bosons in VBS, with PHANTOM: very good agreement ($\lesssim 1\%$) with analytical results (no lepton cuts)
2. Realistic lepton cuts make interferences non-negligible but well under control (difference between full and sum of polarized amounts at a few %).
3. ν reconstruction affects strongly the shape of distributions which depend on p_z^ν.
4. Sizeable differences between SM and NoH only in the longitudinal component (both for W and Z). Remarkable similarities in transverse contributions.
5. Considered 3 different methods to extract NoH polarization fractions with SM shapes ($\cos\theta^*_\ell$) in the presence of lepton cuts and ν reconstruction.
6. Reweighting approach gives bad results: better to use polarized signals computed directly with polarized amplitudes!

Thanks for the attention!

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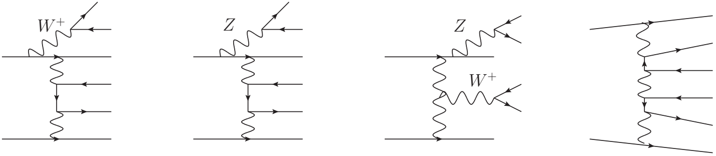
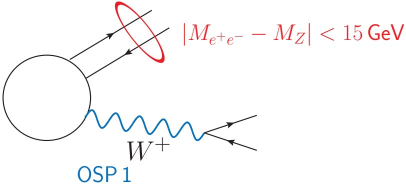
BACKUP SLIDES

Resonant contributions



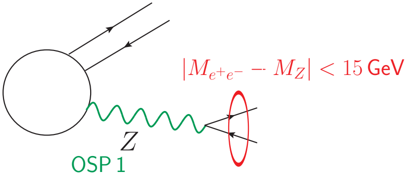
single W res. | single Z res. | double res. | non res.

- For W^+ polarization:



$$\mathcal{A}^{(W)}_{\text{unpol}} \propto \sum_{\lambda'} \varepsilon^{\mu}_{\lambda'} \varepsilon^{\nu\,*}_{\lambda'} \longrightarrow \varepsilon^{\mu}_{\lambda} \varepsilon^{\nu\,*}_{\lambda} \propto \mathcal{A}^{(W)}_{\lambda}$$

- For Z polarization:



$$\mathcal{A}^{(Z)}_{\text{unpol}} \propto \sum_{\lambda'} \varepsilon^{\mu}_{\lambda'} \varepsilon^{\nu\,*}_{\lambda'} \longrightarrow \varepsilon^{\mu}_{\lambda} \varepsilon^{\nu\,*}_{\lambda} \propto \mathcal{A}^{(Z)}_{\lambda}$$

$|\mathcal{A}_\lambda|^2 \longrightarrow$ polarized cross-sections both for W^+ and Z boson

On Shell projections

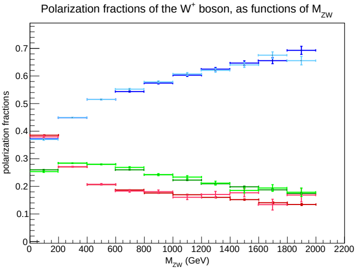
To cure (at least partially) gauge violation given by the selection of Z/W-resonant diagrams, we perform an On Shell projection of the Z/W boson (OSP1).

Details of OSP1: for the process $pp \to V(\to \ell\bar{\ell}) + X$, it conserves X 4-momentum, the V 3-momentum in the lab frame and the ℓ direction in the V rest frame, modifying the initial parton 4-momenta in order to conserve the total 4-momentum.

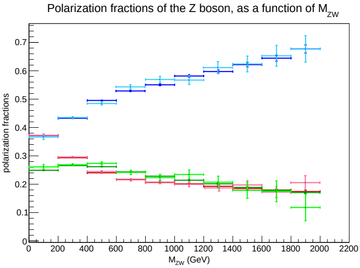
No lepton cuts, no reco: polarization fractions

Polarization fractions as functions of the WZ system invariant mass:

Polarized W^+



Polarized Z



Dark colors: Monte Carlo predictions; light colors: analytic result (Legendre).
Red: longitudinal, blue: left-handed, green: right-handed.

Neutrino reconstruction schemes ($\Delta > 0$)

[DeltaR] If $p^{\nu}_{z\,1} \cdot p^{\nu}_{z\,2} < 0$, choose the one with the same sign as p^{ℓ}_{z}. Otherwise, choose the one which reconstructs the minimum ΔR between neutrino and corrispondent charged lepton [CMS Note AN-2007/05, Ballestrero et al., JHEP 05 (2009) 015]. Note that ΔR has no discriminating power, since the two same-sign solutions feature the same $\Delta\eta_{\ell\nu}$.

[CoM] If $p^{\nu}_{z\,1} \cdot p^{\nu}_{z\,2} < 0$, choose the one with the same sign as p^{ℓ}_{z}. If $p^{\nu}_{z\,1} \cdot p^{\nu}_{z\,2} < 0$, choose the one which reconstructs the minimum partonic center-of-mass invariant mass. The choice of the partonic CoM invariant mass is natural at the LHC (PDFs).

[CoMmod] Choose the one which reconstructs the minimum partonic CoM invariant mass, independently of the relative sign between $p^{\nu}_{z\,1}$ and $p^{\nu}_{z\,2}$. This extends the criterion which is used for same-sign solutions in CoM scheme to events which features opposite-sign solutions.

[CMS] Choose the solution with minimum $|p^{\nu}_{z}|$, independently of the relative sign between $p^{\nu}_{z\,1}$ and $p^{\nu}_{z\,2}$ [CMS Coll., PRL 109 (2012) 141801, ATLAS-CONF-2018-034]. Note that minimizing $|p^{z}_{\nu}|$ is correlated to minimizing the partonic CoM invariant mass.

[CMSbis] If $p^{\nu}_{z\,1} \cdot p^{\nu}_{z\,2} < 0$, choose the one with the same sign as p^{ℓ}_{z}. Otherwise, choose the one with minimum $|p^{z}_{\nu}|$. This reproduces the CMS scheme only for events with two same-sign solutions.

Neutrino reconstruction schemes ($\Delta < 0$)

[poleMw] One possibility [CMS Note AN-2007/05] is to set p_z^ν equal to the real part (which is unique) of the complex solutions.

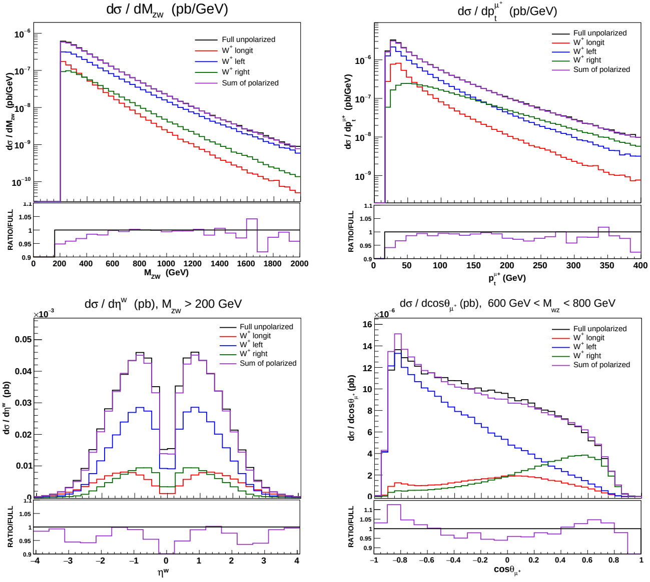
$$p_z^\nu = \frac{p_\ell^z \, \xi}{{p_\ell^t}^2} \qquad (1)$$

[transvMlv] Another possibility [CMS Coll., PRL 109 (2012) 141801] is to substitute the W pole mass M_W with the transverse mass of the lepton-neutrino system in the quadratic equation. This sets $\Delta = 0$, and leads to the following (unique) solution,

$$p_z^\nu = p_\ell^z \, \frac{{M_t^{\ell\nu}}^2 + 2\mathbf{p}_t^\ell \cdot \mathbf{p}_t^\nu}{2{p_t^\ell}^2} = p_z^\ell \, \frac{(2p_t^\ell p_t^\nu - 2\mathbf{p}_t^\ell \cdot \mathbf{p}_t^\nu) + 2\mathbf{p}_t^\ell \cdot \mathbf{p}_t^\nu}{2{p_t^\ell}^2} = p_z^\ell \, \frac{p_t^\nu}{p_t^\ell} \qquad (2)$$

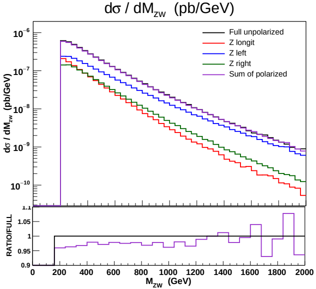
Lepton cuts and ν reco: distributions for polarized W^+

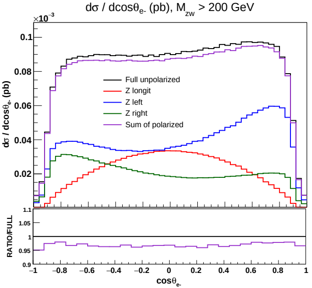
Standard Model distributions

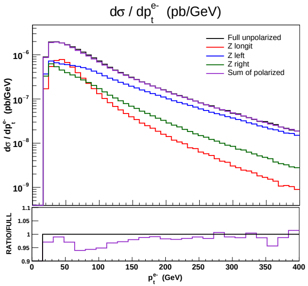


Lepton cuts and ν reco: distributions for polarized Z

Standard Model distributions







Standard Model vs No Higgs: