Overview

Phantom update

How to compute processes with polarized vector bosons with Phantom

Survey of recent results, most of them work in progress,
all in the SM.

Phantom

Two new versions in /afs/cern.ch/work/b/ballest/public/phantom

Phantom_1_3_2 compiles on intel/gfortran as all 1_3 versions

Phantom_1_5_1_b beta version with polarization machinery

Inconsistency between mothers and color flow has been solved.
Integration for processes with initial b and bbar improved

Details of the new features in the readme file
Follow the r.in in the version you are using. Read carefully the comments to every single input variable, especially the new ones. 😉

Phantom capabilities

- All 2 → 6 processes O(α^6) & O($\alpha^4\ \alpha_s{}^2$) exactly in SM
- v. 1_5_1_b computes O(α^6) amplitudes with polarized, resonant, final-state, vector bosons.

$$-g^{\mu\nu} + \frac{k^\mu k^\nu}{M^2} = \sum_\lambda \varepsilon^\mu_\lambda \varepsilon^{\nu *}_\lambda \qquad \Longrightarrow \qquad \mathcal{A}_f = \sum_\lambda \frac{\mathcal{A}^\mu_p\, \varepsilon^\lambda_\mu\ \ \varepsilon^{\lambda *}_\nu \mathcal{A}^\nu_d}{k^2 - M^2_W + i\Gamma_W M_W} = \sum_\lambda \mathcal{A}^\lambda_f$$

$$\mathcal{A}_f = \sum_\lambda \frac{\mathcal{A}^\mu_{p,RES}\,(p,k)\varepsilon^\lambda_\mu\ \ \varepsilon^{\lambda *}_\nu \mathcal{A}^\nu_d(k,q)}{k^2 - M^2_W + i\Gamma_W M_W} + \mathcal{A}_{NONRES} \qquad \Longrightarrow \qquad \sum_\lambda \frac{\mathcal{A}^\mu_{p,RES}\,(p,k_{OSP})\varepsilon^\lambda_{\mu,OSP}\ \ \varepsilon^{\lambda *}_{\nu,OSP} \mathcal{A}^\nu_d(k_{OSP},q_{OSP})}{k^2 - M^2_W + i\Gamma_W M_W}$$

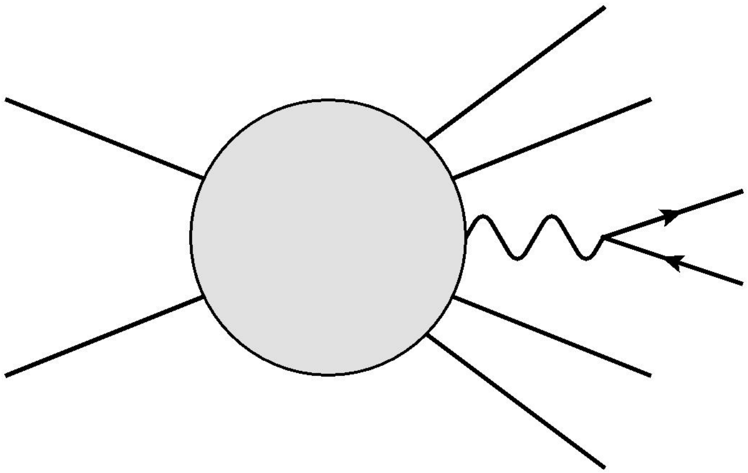
$$\underbrace{\left|\mathcal{A}_f\right|^2}_{\text{coherent sum}} = \underbrace{\sum_\lambda \left|\mathcal{A}^\lambda_f\right|^2}_{\text{incoherent sum}} + \underbrace{\sum_{\lambda \neq \lambda'} \mathcal{A}^{\lambda *}_f \mathcal{A}^{\lambda'}_f}_{\text{interference term}}$$

Selecting resonant contributions

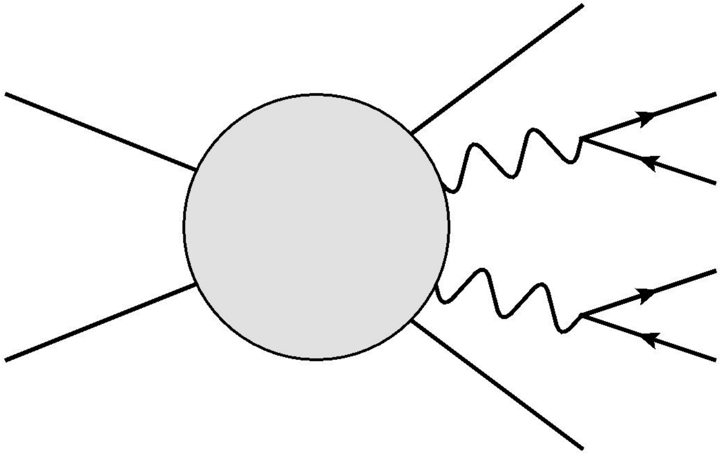
```
*   POLARIZATION MACHINERY REQUIRES  i_pertorder = 1 (alpha_em^6)
*    PARTICLES FROM A RESONANCE MUST BE UNIQUE:
*        Z --> e+e-, W --> mu v OK         Z --> e+e-, W --> e v  NOT OK

*      CALL iread('i_ww',i_ww,1) ! i_ww= 0 full computation
*      i_ww= 1: 1 resonant  w diags,  i_ww= 2: 2 resonant  w diags
 i_ww 1
*       if (i_ww.ge.1) then
*         CALL iread('idw',idw,4)! (four integers must always be given)
*         The first integer in each pair corresponds to the particle
 idw      14  -13  11 -12
*         CALL iread('ipolw',ipolw,2) ! indexes for first/second w
*          They can be:   0 no polarization, 1 longitudinal,
*                                2 left, 3 right , 4 transverse (R+L)
 ipolw 0  0
```

For Z use i_zz, idz, ipolz. For WZ use i_ww= 1, i_zz= 1.



Single Resonant



Double Resonant
(also Single Resonant)

On shell projection

```
*        if (i_ww.ge.1.or.i_zz.ge.1 ) then
*          CALL iread('i_osp',i_osp,1) ! i_osp = 0  no projection
*          i_osp = 1  on shell projection scheme for 1 boson
*          i_osp = 2  on shell projection scheme for 2 bosons
 i_osp 1
 *       if (i_osp.gt.0) then
*          CALL iread('idosp',idosp,4) ! Particles which must
*           be projected. (four integers must always be given)
*           The first integer in each pair corresponds to the particle
 idosp    14 -13   11 -11
```

Channels

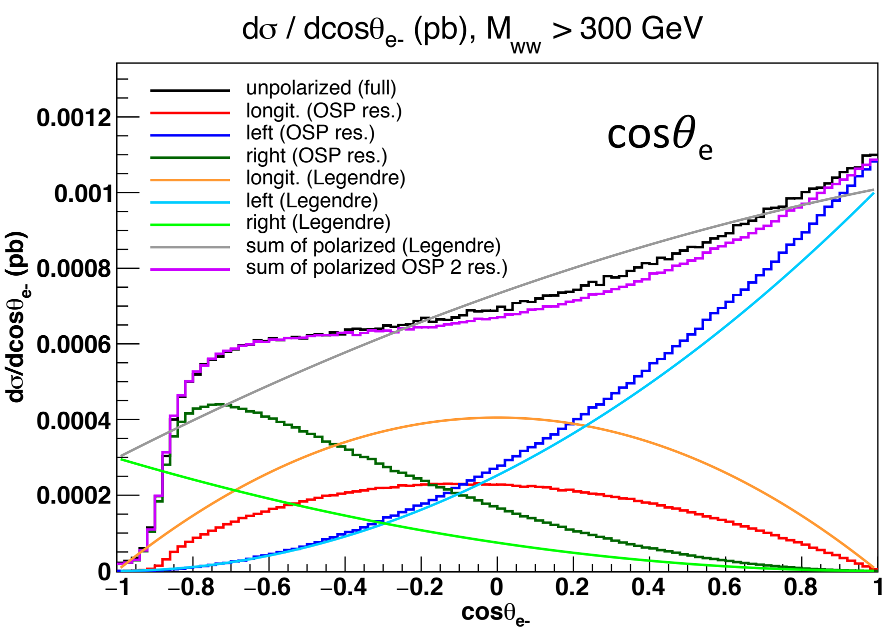
Channel	$\mathcal{O}(\alpha_{EM}^6)$ σ (fb)	$\mathcal{O}(\alpha_{EM}^6)/\mathcal{O}(\alpha_{EM}^4\alpha_S^2)$
$pp \to jje^-\overline{\nu}_e\mu^+\nu_\mu$	1.75	1
$pp \to jje^+\nu_e\mu^+\nu_\mu$	1.40	10
$pp \to jje^+e^-\mu^+\nu_\mu$	0.14	0.5
$pp \to jje^+e^-\mu^+\mu^-$	0.02	1

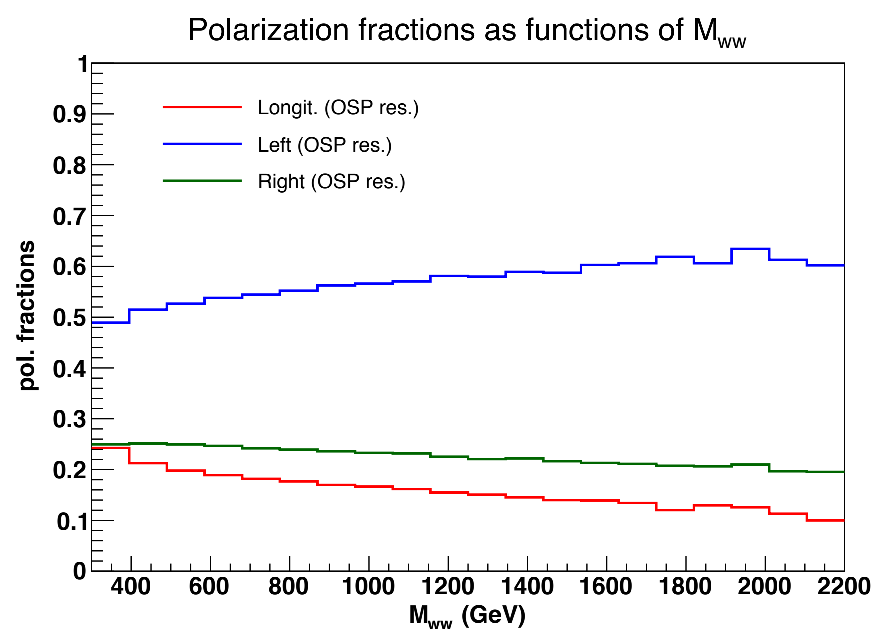
LO only. VBS like cuts, slightly different for different channels. Lepton cuts. No b's in the initial and final state, that is no top contributions.

Factor 4 when summing over all lepton combinations.
All results for LHC@13TeV

$W^+W^- \rightarrow e^-\nu\ \mu^+\nu$ (1)

$$|\eta_j| < 5; \quad p_t^j > 20 \text{ GeV}; \quad M_{jj} > 600 \text{ GeV}; \quad |\Delta\eta_{jj}| > 3.6; \quad \eta_{j_1} \cdot \eta_{j_2} < 0;$$
$$p_t^e > 20 \text{ GeV}; \quad |\eta^e| < 2.5.$$



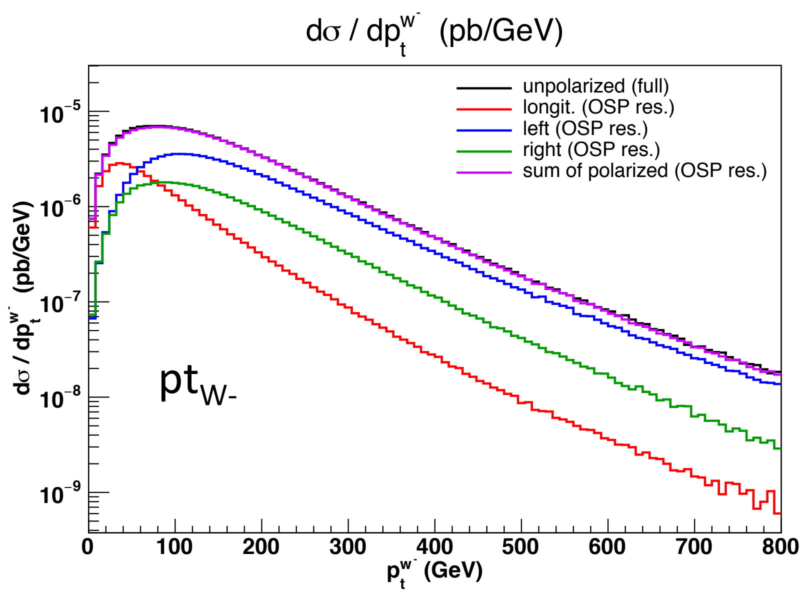


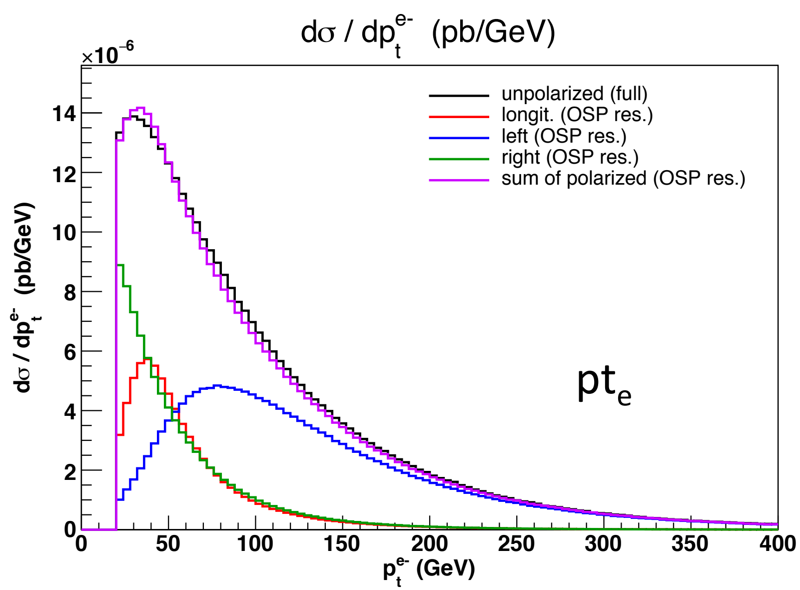
JHEP03(2018)170

Longitudinal fraction decreases at large M_{WW}
Not required by unitarity. All Amps → const.

$W^+W^- \rightarrow e^-\nu\,\mu^+\nu$ (2)

W^- polarized, W^+ unpolarized





Full L R 0 Sum

Longitudinally polarized W's and their decay leptons mainly at low pt. Bad news

$W^+W^+ \rightarrow e^+\nu\ \mu^+\nu$ (1)

$$|\eta_j| < 4.5; \quad p_t^j > 30\ \text{GeV}; \quad M_{jj} > 500\ \text{GeV}; \quad |\Delta\eta_{jj}| > 2.5; \ |\Delta\eta_{j\ell}| > 0.3;$$

$$p_t^e > 20\ \text{GeV}; \quad |\eta^e| < 2.5; \quad \not{p}_T > 40\ \text{GeV}; \quad |\Delta\eta_{\ell\ell}| > 0.3; \quad M_{\ell\nu\ell\nu} > 200\ \text{GeV}.$$

Same as W^+W^+ report
Eur.Phys.J.C.(2018) 78:671

No Reconstruction (?)

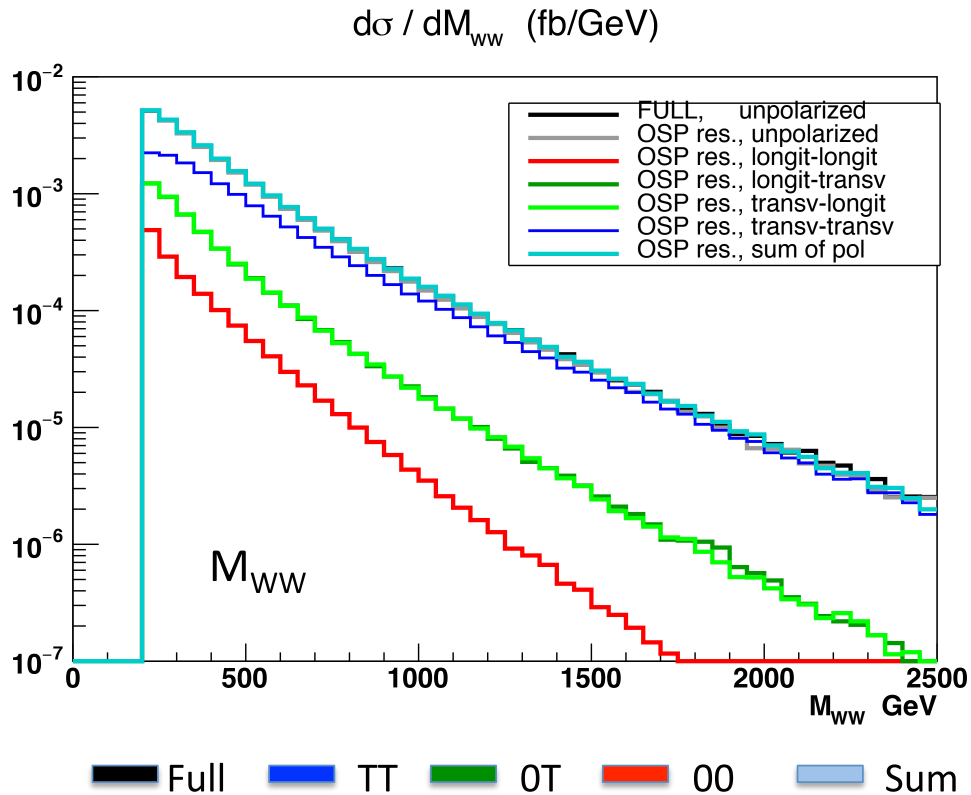
$\sigma_{\text{pol1 pol2}}/\sigma_{\text{tot}}$ full range

00	0.06
0T	0.38
TT	0.57

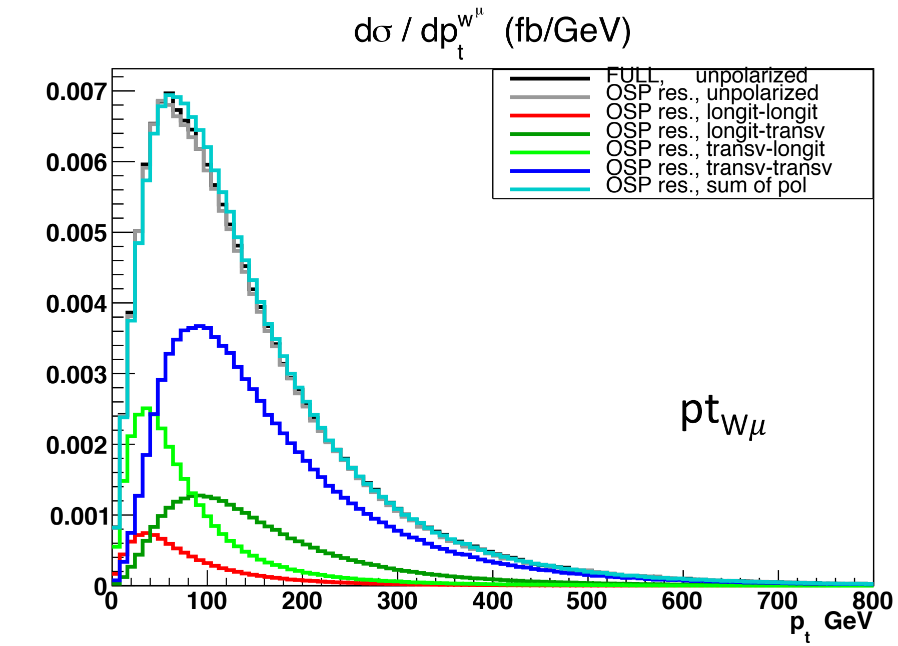
$\sigma_{00}/\sigma_{\text{tot}}$ $\sigma_{0T}/\sigma_{\text{tot}}$ decrease with M_{WW}

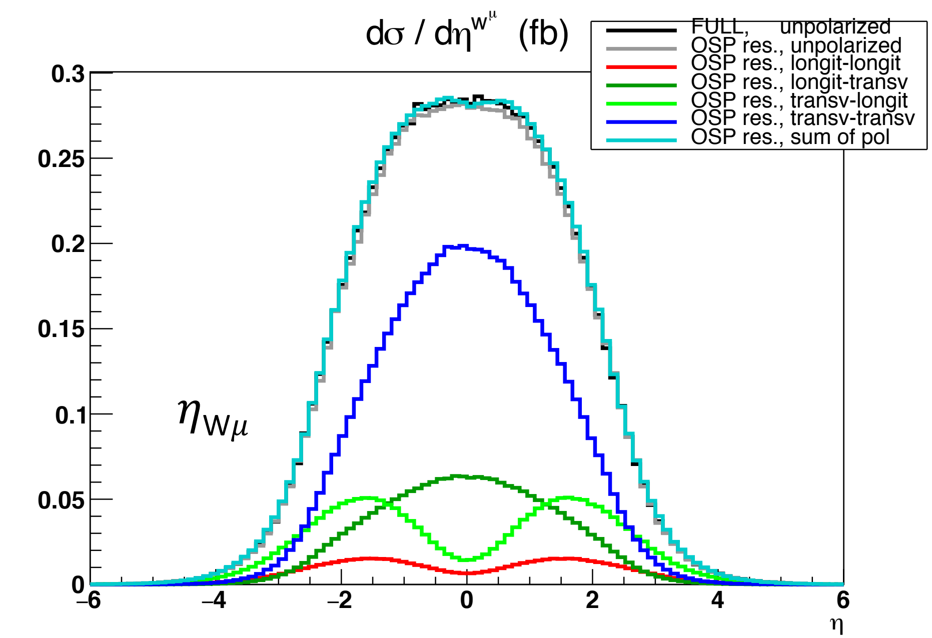
Transverse:

$$-g^{\mu\nu} + \frac{p^\mu p^\nu}{M^2} \rightarrow \varepsilon_R^\mu \varepsilon_R^{*\nu} + \varepsilon_L^\mu \varepsilon_L^{*\nu}$$



$W^+W^+ \rightarrow e^+\nu\ \mu^+\nu$ (2)





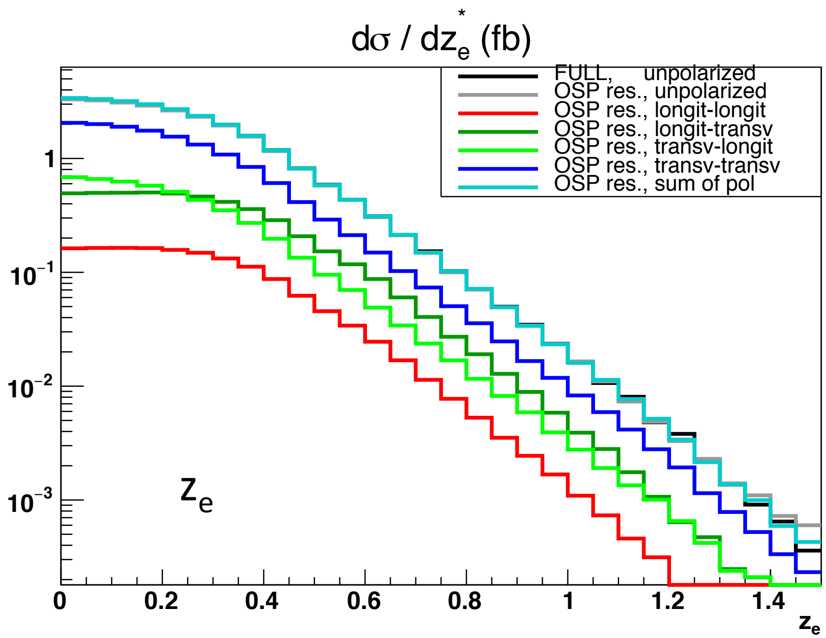
Legends: first polarization refers to $W \rightarrow e\nu$

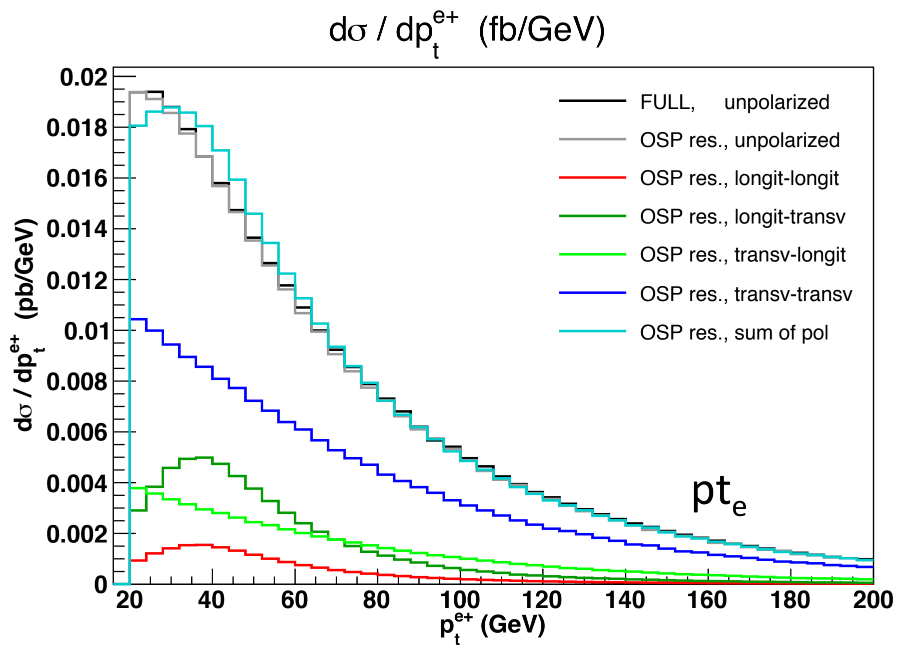
second to $W \rightarrow \mu\nu$

W_e: T W_μ: 0 W_e: 0 W_μ: T

A transverse/longitudinal W has basically the same pt, η distributions, whatever the other W polarization

$W^+W^+ \rightarrow e^+\nu\ \mu^+\nu$ (3)





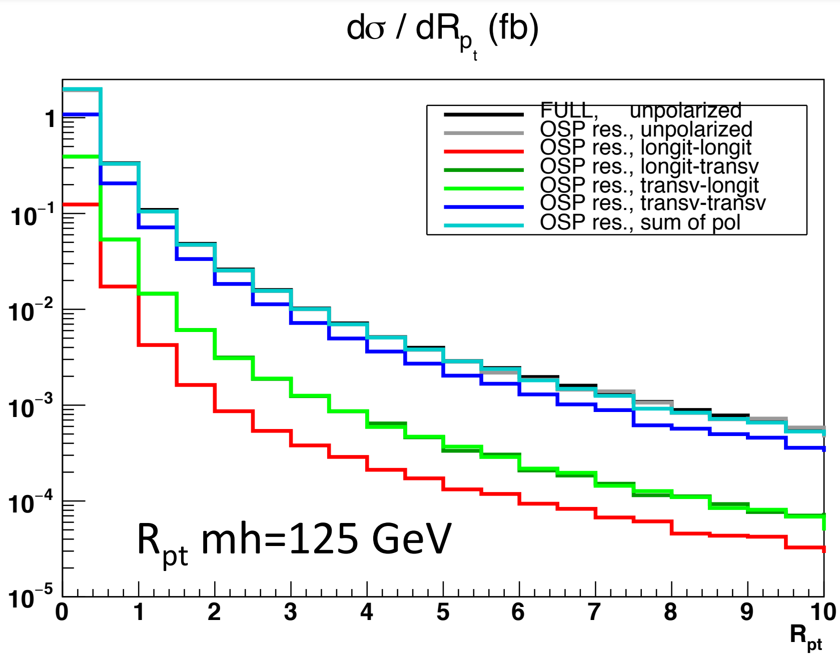
$$z_{e^+} = \frac{y_{e^+} - \frac{y_{j_1}+y_{j_2}}{2}}{|\Delta y_{jj}|}.$$

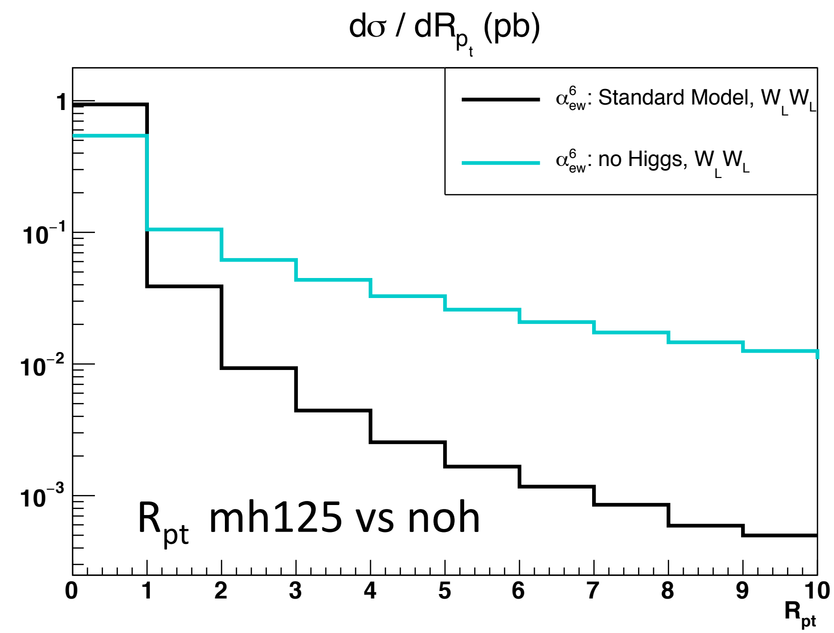
Legends: first polarization refers to W $\rightarrow e\nu$
second to W $\rightarrow \mu\nu$

Zeppenfeld variable

Pt_e not descrbed as well as other variables by the incoherent sum of polarized cross sections

$W^+W^+ \to e^+\nu\ \mu^+\nu$ (4)





$$R_{p_T} = \frac{p_T^{l_1} \cdot p_T^{l_2}}{p_T^{j_1} \cdot p_T^{j_2}}$$

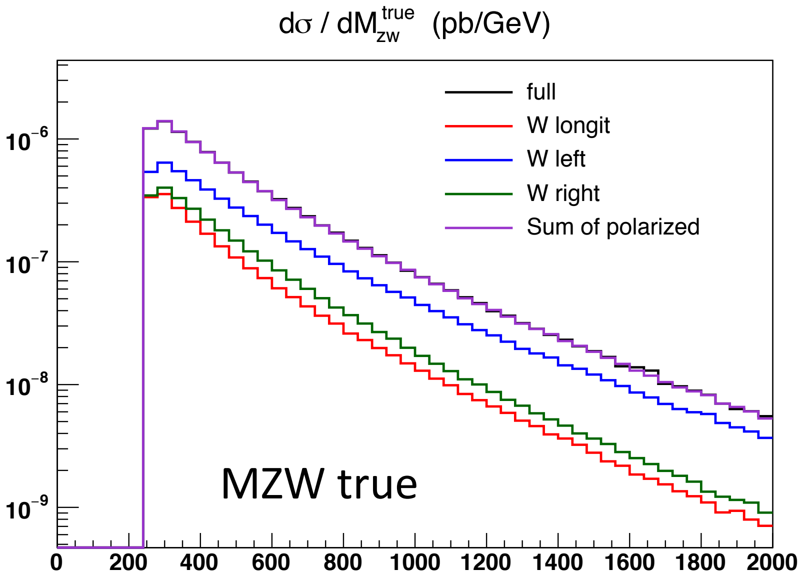
Warsaw variable

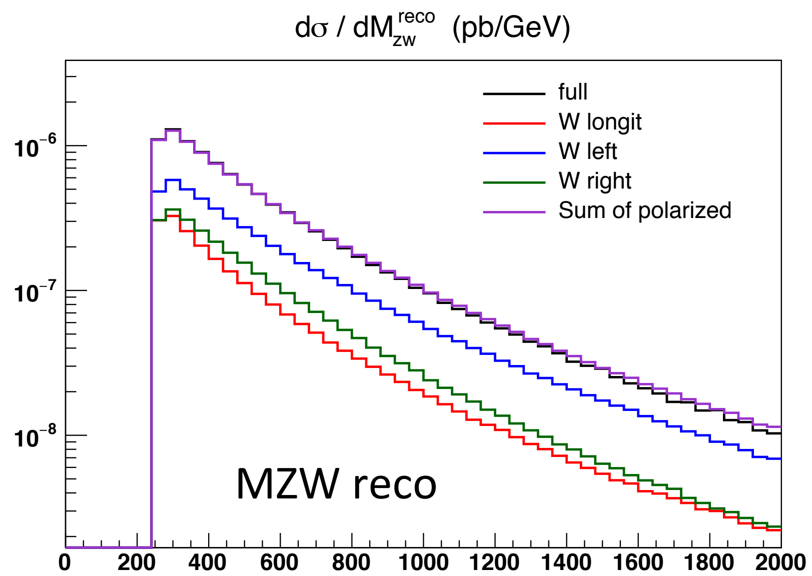
R_{pt} is model dependent
Does not discriminate between longitudinal and transverse polarizations in the SM

Z W$^+$ → e$^+$e$^-$ $\mu^+\nu$ (1)

$$|\eta_j| < 5; \quad p_t^j > 20 \text{ GeV}; \quad M_{jj} > 500 \text{ GeV}; \quad |\Delta\eta_{jj}| > 2.5; \quad \not{p}_T > 40 \text{ GeV};$$

$$p_t^e > 20 \text{ GeV}; \quad |\eta^e| < 2.5; \quad M_{\ell\ell\ell\nu} > 250 \text{ GeV}; \quad |M_{e^+e^-} - M_Z| < 15 \text{ GeV}.$$





$\sigma_{\text{Wpol}}/\sigma_{\text{tot}}$ full range MZ true Z unpolarized OSP 1 W

Long.	0.18	Left	0.61	Right	0.19

Sauvan tomorrow

$P_{z,\nu}$ Reconstruction in single W proc. (1)

$$(p^\mu + p^\nu)^2 = M_W^2$$

Novak tomorrow

$$p_z^\nu = \frac{\alpha p_z^\mu \pm \sqrt{\alpha^2 p_z^{\mu 2} - \left(E^{\mu 2} - p_z^{\mu 2}\right)\left(E^{\mu 2} p_T^{\nu 2} - \alpha^2\right)}}{E^{\mu 2} - p_z^{\mu 2}}$$

$$\alpha = \frac{M_W^2}{2} + p_x^\mu p_x^\nu + p_y^\mu p_y^\nu$$

If $\Delta < 0$ set $\Delta = 0$;

If $\Delta > 0$:

- If the two solutions have opposite sign, select $p_{z,\nu}$ with same sign of $p_{z,e}$
- If the two solutions have same sign, select $p_{z,\nu}$ with smaller $\Delta R(e\nu)$

CMS AN 2007/005

$P_{z,\nu}$ Reconstruction in single W proc. (2)

$$p = (p^+, p^-, \mathbf{p}_\perp), \qquad p^\pm = \frac{E \pm p_z}{\sqrt{2}}, \qquad p \cdot q = p^+ q^- + p^- q^+ - \mathbf{p}_\perp \cdot \mathbf{q}_\perp$$

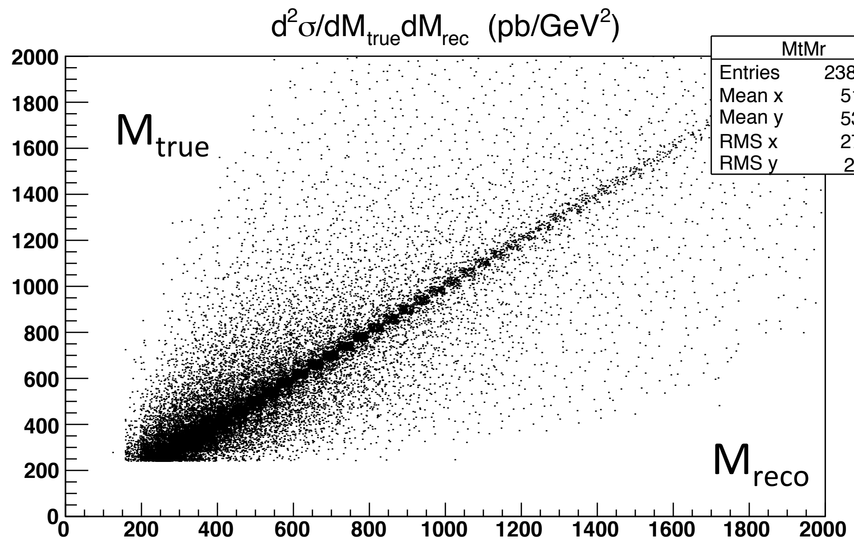
$$p = \left(e^y \sqrt{\frac{m^2 + \mathbf{q}_\perp{}^2}{2}}, e^{-y} \sqrt{\frac{m^2 + \mathbf{q}_\perp{}^2}{2}}, \mathbf{p}_\perp \right)$$

$$\frac{M_W^2}{2} = \sqrt{\frac{\mathbf{p}_{\ell,\perp}{}^2}{2}} \sqrt{\frac{\mathbf{p}_{\nu,\perp}{}^2}{2}} \left(e^{\Delta y} + e^{-\Delta y} \right) - \mathbf{p}_{\ell,\perp} \cdot \mathbf{p}_{\nu,\perp}$$

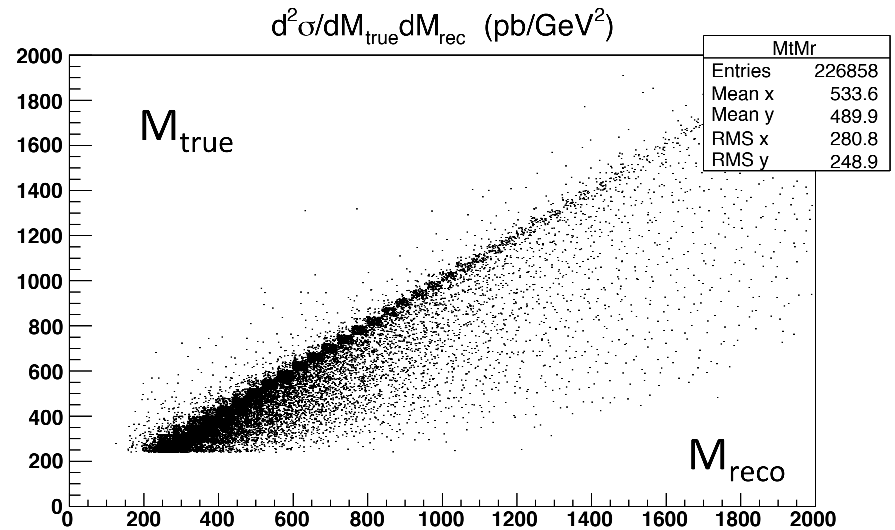
When there are two solutions, they are related by $\Delta y \Leftrightarrow -\Delta y$, $\Delta y = y_l - y_\nu$.
The two ΔR are equal.

Try selecting $p_{z,\nu}$ for which the total mass of the event is smaller.

$P_{z,\nu}$ Reconstruction in single W proc. (3)



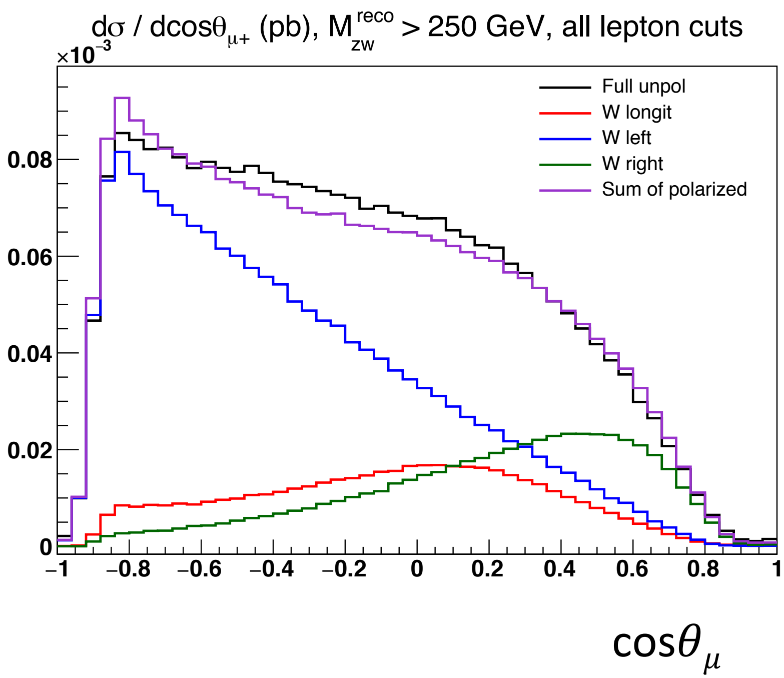
select $p_{z,\nu}$ with smaller ΔR(ev)

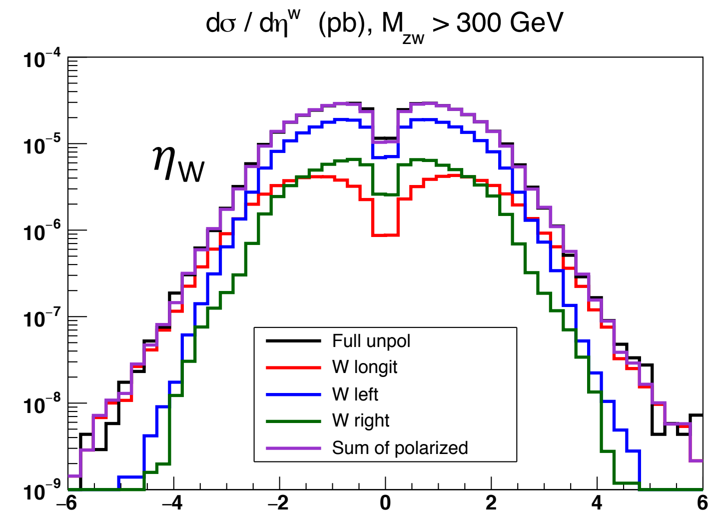


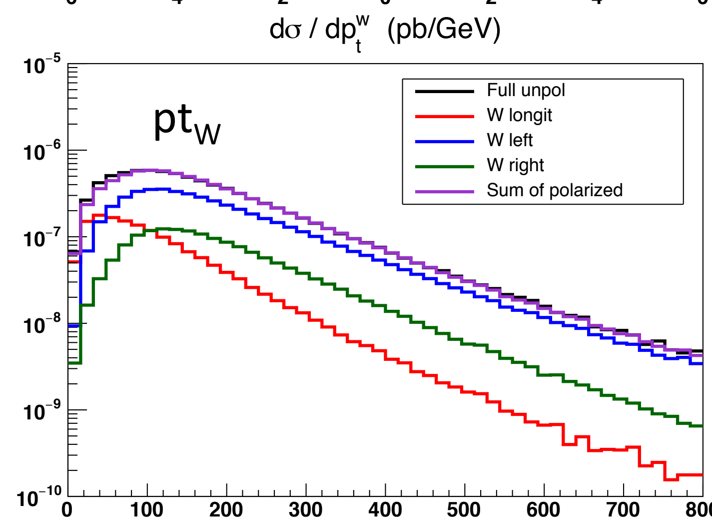
select $p_{z,\nu}$ with smaller event mass

Only events with $\Delta > 0$ and two solutions with same sign

$Z\,W^+ \rightarrow e^+e^-\,\mu^+\nu$ (2)







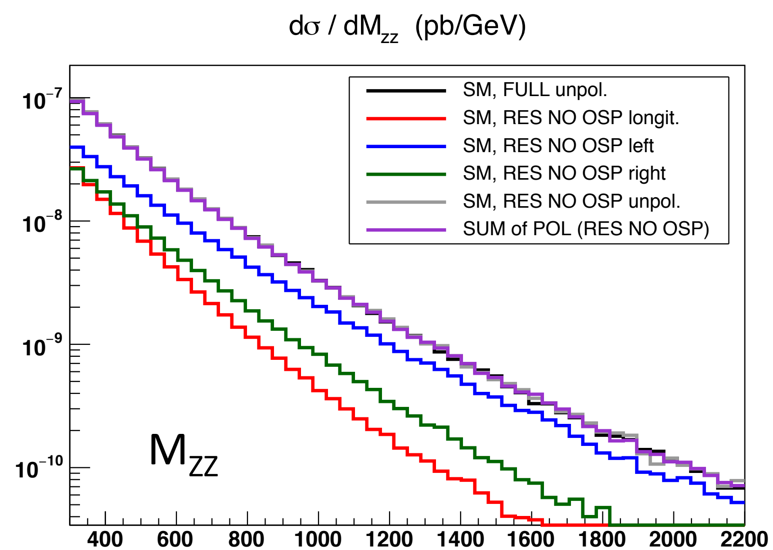
New reco

$ZZ \rightarrow e^+e^- \mu^+\mu^-$ (1)

$$|\eta_j| < 5; \quad p_t^j > 20 \text{ GeV}; \quad M_{jj} > 600 \text{ GeV}; \quad |\Delta\eta_{jj}| > 3.6;$$
$$p_t^e > 20 \text{ GeV}; \quad |\eta^e| < 2.5; \quad M_{\ell\ell\ell\ell} > 300 \text{ GeV}; \quad |M_{\ell^+\ell^-} - M_Z| < 5 \text{ GeV}.$$

Antiparticle decay distribution:

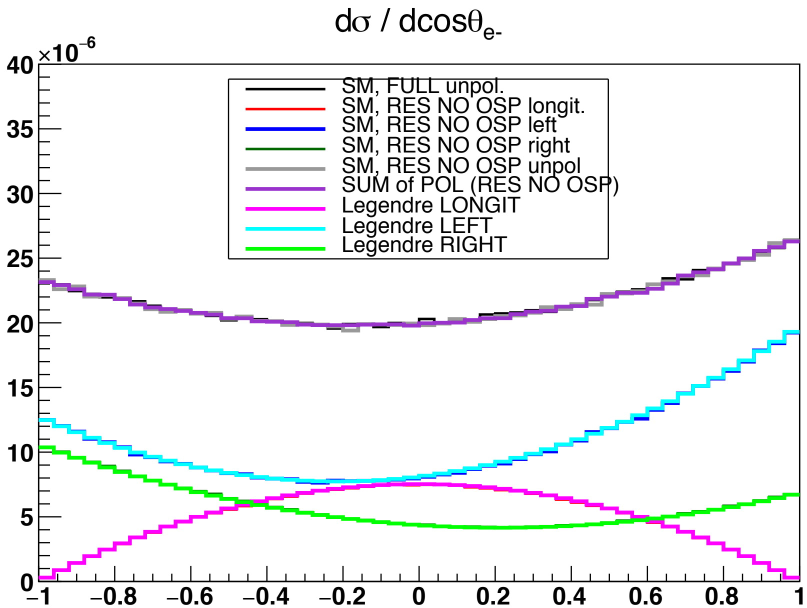
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}\left(1+\cos^2\theta^* - \frac{2(c_L^2 - c_R^2)}{(c_L^2 + c_R^2)}\cos\theta^*\right)f_L + \frac{3}{8}\left(1+\cos^2\theta^* + \frac{2(c_L^2 - c_R^2)}{(c_L^2 - c_R^2)}\cos\theta^*\right)f_R + \frac{3}{4}\sin^2\theta^* f_0,$$



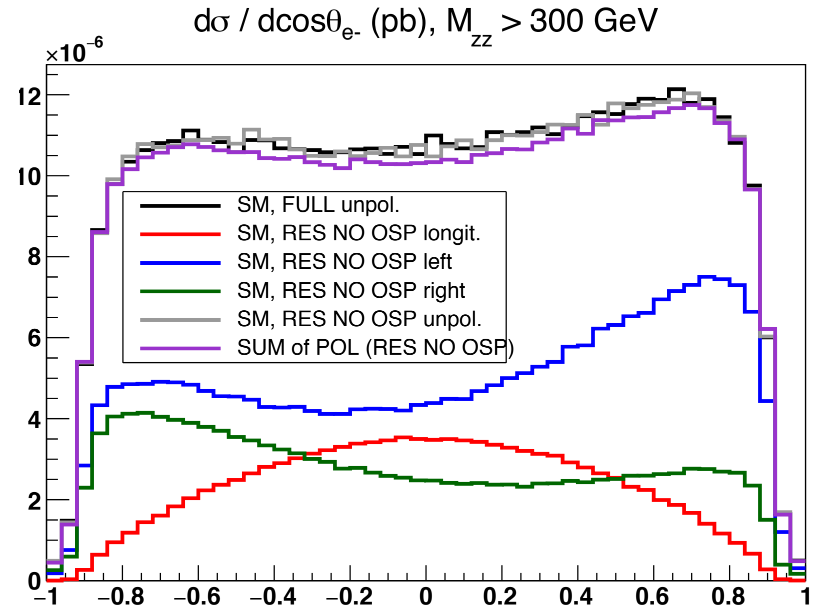
No OSP
Irrelevant after restriction to the Z peak

Charlot tomorrow

$ZZ \rightarrow e^+e^- \mu^+\mu^-$ (2)

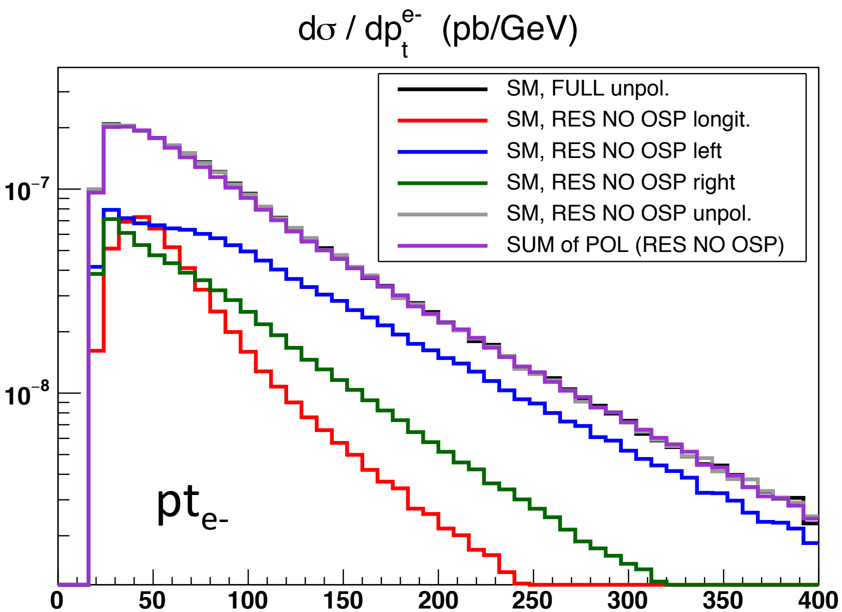


$\cos\theta_e$ no lepton cuts



$\cos\theta_e$ with lepton cuts

$ZZ \rightarrow e^+e^- \mu^+\mu^-$ (3)



pt_{e-}

Conclusions

Full VBS processes are reproduced at the % level by the sum of polarized on shell reactions+decay with Breit-Wigner modulation

Long-Long cross sections are small

Long-Transv are larger

Transv-Transv are largest

Besides decay angles, a number of kinematic distribution help separating the vector polarizations

Phantom provides a flexible and convenient tool for polarization studies in VBS.

Ce n’est qu’un début …

Spares

Single W→ lv differential cross section

$$\frac{d\sigma}{dX\, d\cos\theta\, d\phi} \propto |\mathcal{A}_p^0|^2 \sin^2\theta + |\mathcal{A}_p^R|^2 (1-\cos\theta)^2 + |\mathcal{A}_p^L|^2 (1+\cos\theta)^2$$
$$+2Re(\mathcal{A}_p^R \mathcal{A}_p^{L*} e^{2i\phi})(1-\cos^2\theta) + 2Re(\mathcal{A}_p^R \mathcal{A}_p^{0*} e^{i\phi})(1-\cos\theta)\sin\theta$$
$$+2Re(\mathcal{A}_p^L \mathcal{A}_p^{0*} e^{-i\phi})(1+\cos\theta)\sin\theta$$

INTERFERENCE TERMS cancel ONLY WHEN INTEGRATED OVER ϕ. In practice **NEVER**.

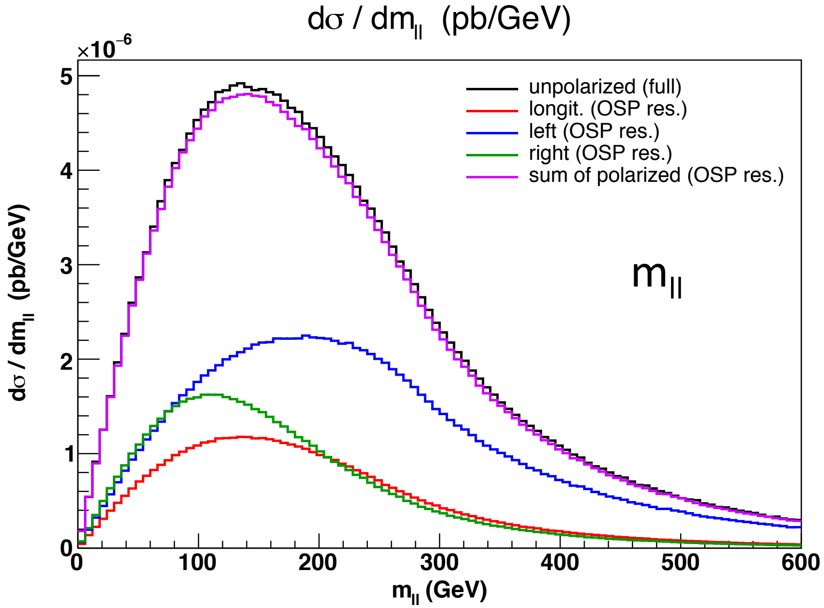
In this case:

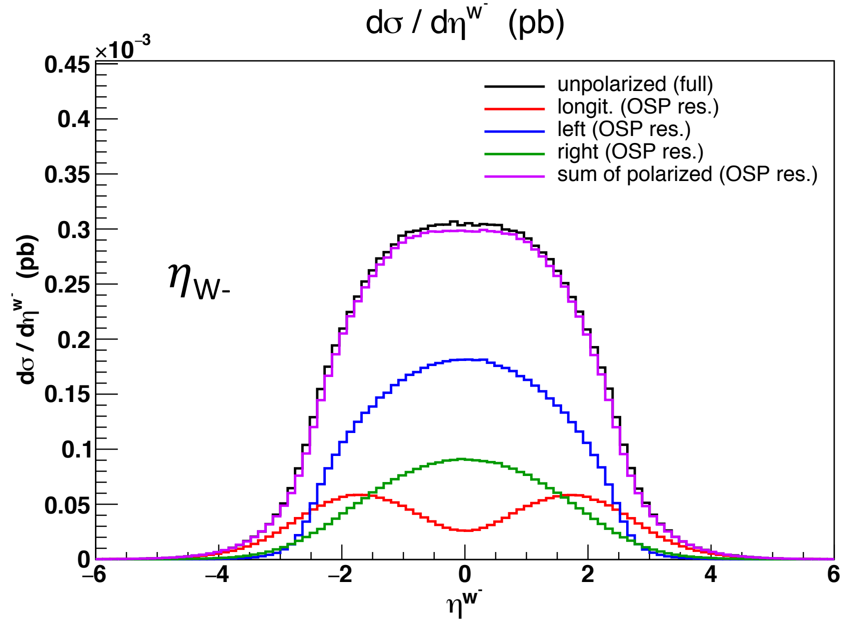
$$\frac{1}{\sigma}\frac{d\sigma}{dX\, d\cos\theta} = \frac{3}{4} f_0(X)\sin^2\theta + \frac{3}{8} f_R(X)(1-\cos\theta)^2 + \frac{3}{8} f_L(X)(1+\cos\theta)^2$$

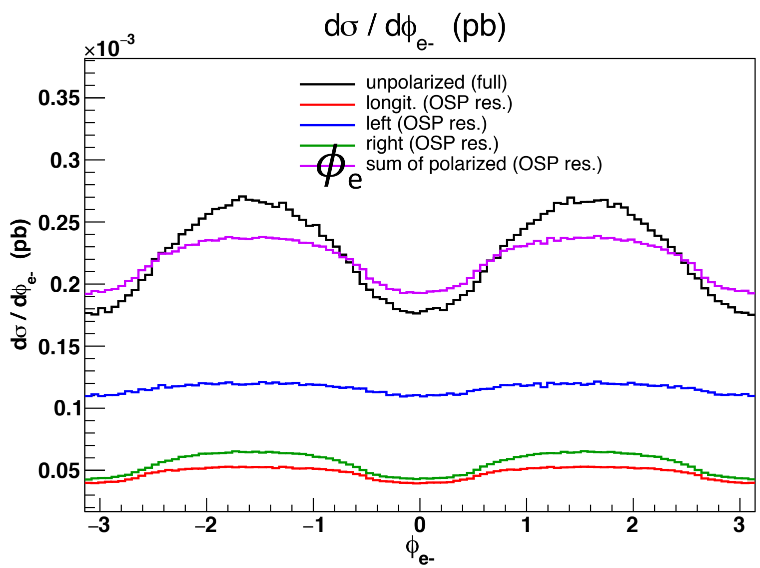
Polarization fractions extracted projecting cosϑ distribution on first 3 Legendre polynomials
Does not work with cuts.

Interference among pols. are present for any W production channel

$W^+W^- \rightarrow e^-\nu\, \mu^+\nu$ (3)







Not all variables are reproduced well

Z. Bern et al.,
Phys. Rev. D 84 (2011) 034008
[arXiv:1103.5445].