W polarization in Vector Boson Scattering at the LHC

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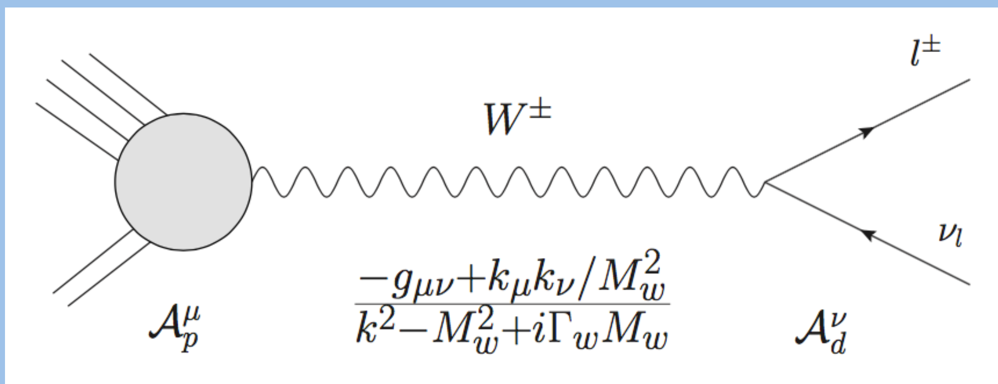
Scattering among longitudinally polarized on-shell VB play a central role in testing EWSB

What are the conceptual issues to be addressed when taking into account VB decay in a realistic environment?

Our proposal for defining and measuring VB polarizations in VBS at the LHC

W polarization vs charged lepton angular distribution



$$\varepsilon^\mu_{L/R} = \frac{1}{\sqrt{2}}(0, \mp 1, -i, 0)$$

$$\varepsilon^\mu_0 = (\kappa, 0, 0, E)/\sqrt{Q^2}$$

$$E \gg M_W \quad \varepsilon^\mu_0 \approx p^\mu_W/M_W$$

$$p^\mu_W = (E, 0, 0, \kappa)$$

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

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

No need to be on-shell

$$\varepsilon^\mu_0 \mathcal{A}^\mu_d = \mathcal{A}^0_d = ig\sqrt{2}E \sin\theta$$

$$\varepsilon^\mu_{R/L} \mathcal{A}^\mu_d = \mathcal{A}^{R/L}_d = -ig\, E\,(1 \mp \cos\theta) e^{\pm i\phi}$$

The substitution:

$$\sum_\lambda \varepsilon^\mu_\lambda \varepsilon^{\nu *}_\lambda \quad \rightarrow \quad \varepsilon^\mu_\lambda \varepsilon^{\nu *}_\lambda$$

defines polarized amplitudes

Single W→ lν differential cross section

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

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

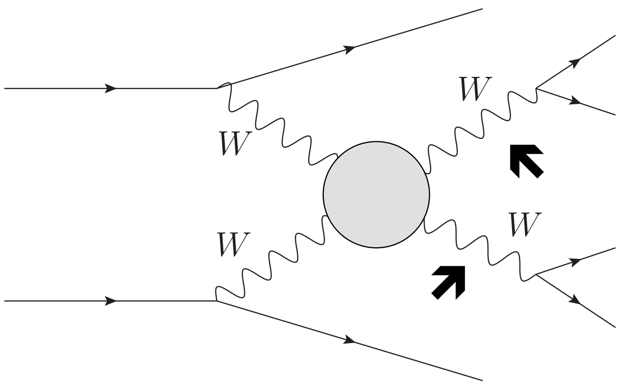
In this case:

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

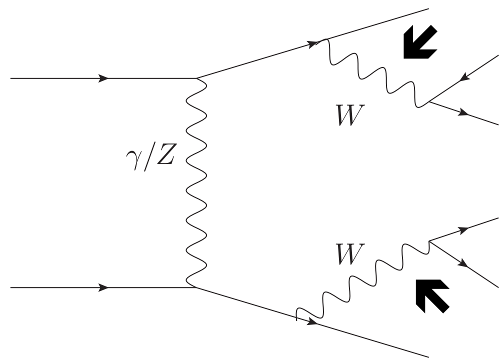
Polarization fractions extracted projecting cosϑ distribution on first 3 Legendre polynomials
Does not work with cuts.

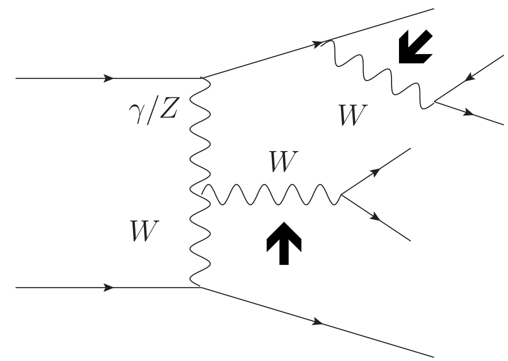
Interference among pols. for any W production channel, even in Narrow Width Approx.

VBS: more vector bosons, more fun



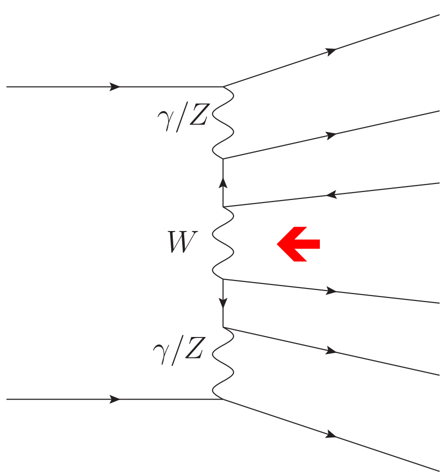
Two resonant W propagators





No resonant propagator.
Cannot be interpreted
as W production.

Necessary for gauge invariance!
Numerically relevant in some phase space regions



$$\mathcal{A}_f = \mathcal{A}_{RES} + \mathcal{A}_{NONRES}$$

To define an amplitude in which a W is polarized an approximation which considers only resonant diagrams is NECESSARY

On Shell Projection (OSP)

Is it possible to devise an APPROXIMATION which
- uses only doubly resonant diagrams
- reproduces well the exact results over most of phase space?

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

Gauge invariant provided $\Gamma_W, \Gamma_Z \to 0$ in $\mathcal{A}^{\mu}_{p,RES}$ and $\cos\theta_W$, $\sin\theta_W$

Similar to DPA Denner,Dittmaier,Roth,Wakeroth NP B587(2000)67

Not uniquely defined. To fully specify conserve:

1. the total four–momentum of the WW system;
2. the direction of the two W bosons in the WW center of mass frame;
3. the direction of each charged lepton in his W center of mass frame.

Applicable only for $M_{WW} > 2\ M_W$

PHANTOM

Unitary gauge, Complex Mass scheme

Can compute singly or doubly polarized amplitudes

Public version in preparation

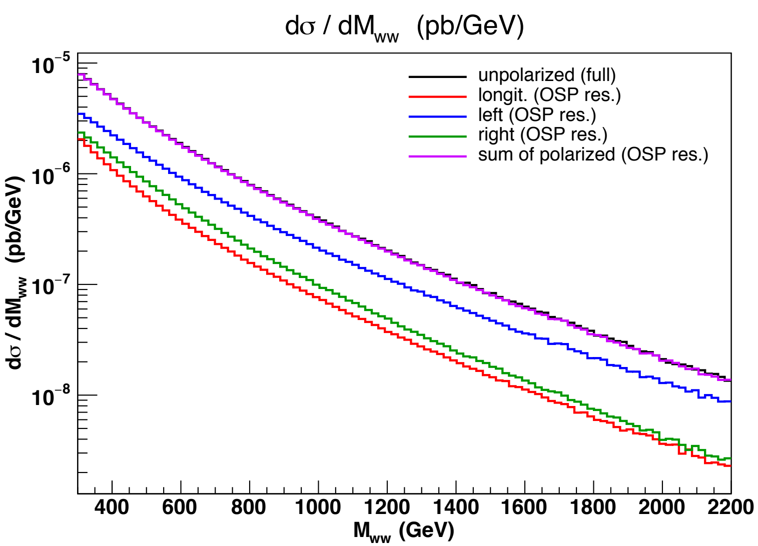
$$pp \rightarrow jje^- \bar{\nu}_e \mu^+ \nu_\mu \ \mathcal{O}(\alpha_{EM}^6)$$

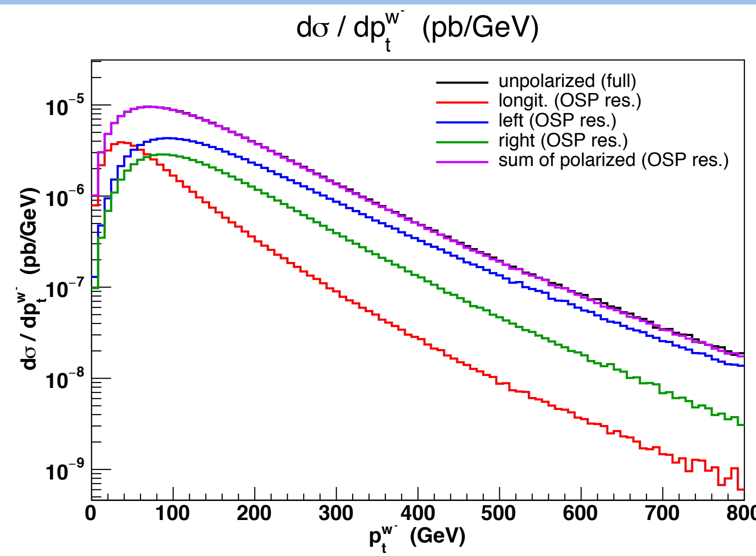
W+W- leptonic   W CM not reconstructable

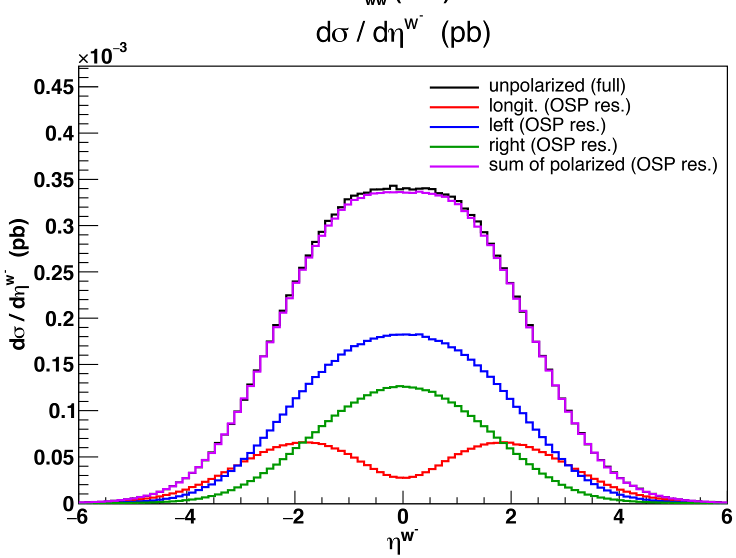
$$|\eta_j| < 5, \ p_t^j > 20\,\mathrm{GeV}, \ M_{jj} > 600\,\mathrm{GeV}, \ |\Delta\eta_{jj}| > 3.6$$

M_{WW} > 300 GeV

Validation and Results







Full L R 0 Sum

W- polarized, W+ unpolarized.

Variables which do not limit the range of φ.

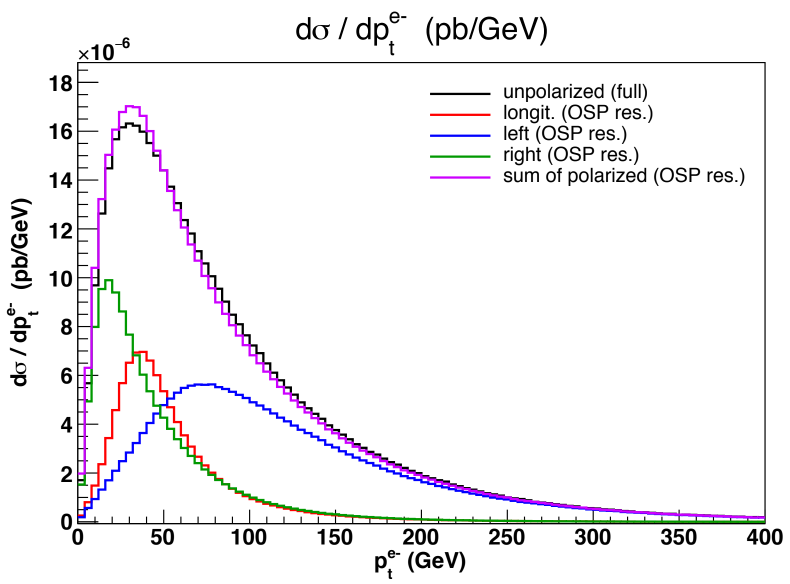
No interference.

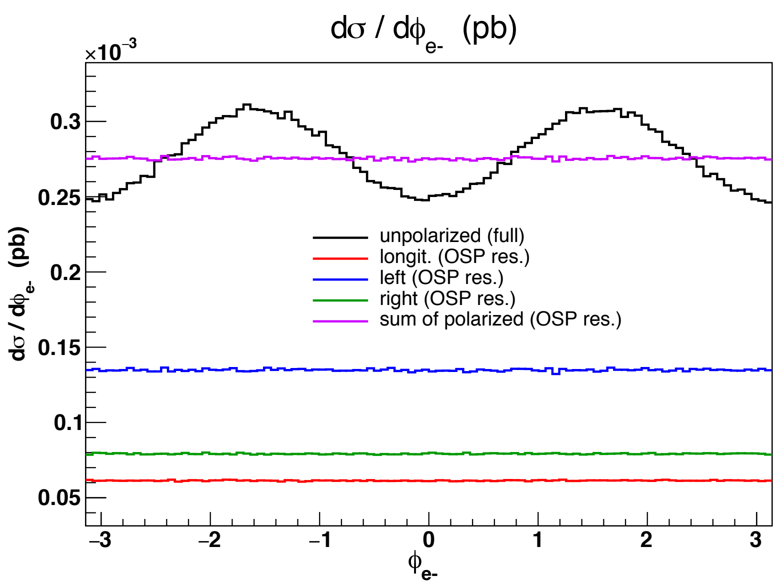
Exact cross section 1.748 fb

Sum of polarized OSP 1.731 fb

Diff ≃ 1%

Validation and Results 2

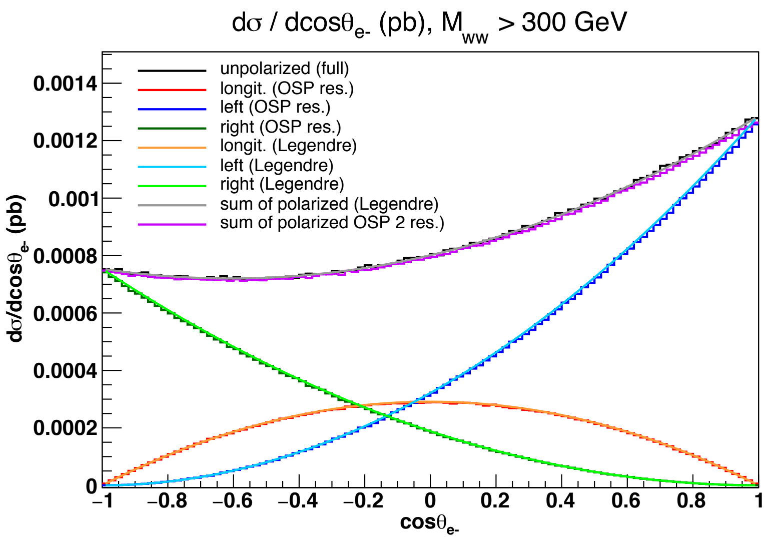


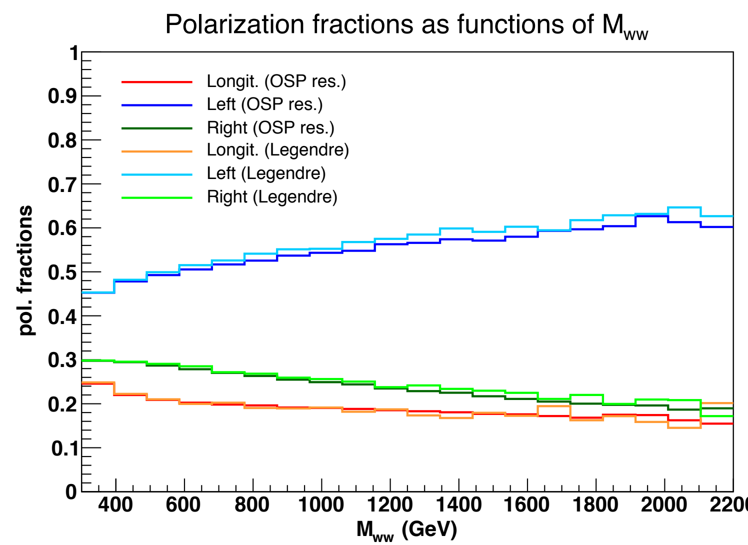


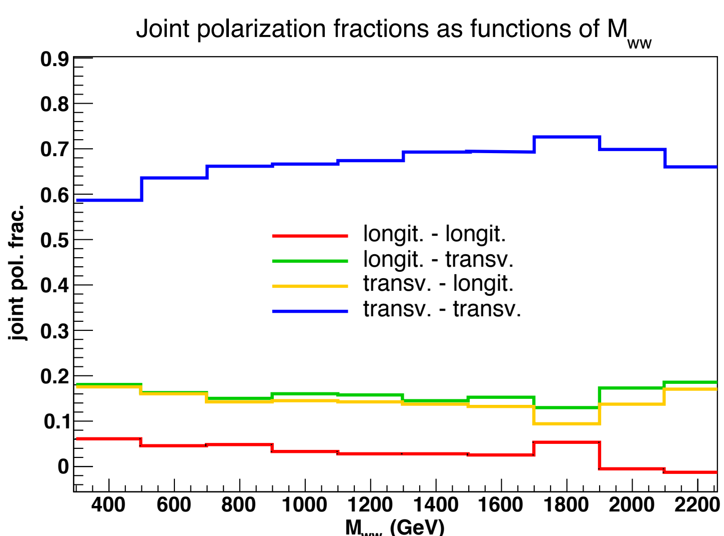
Variables which do limit the range of φ. Interference among polarizations.

Different polarizations have different kinematical distributions

Polarization fractions

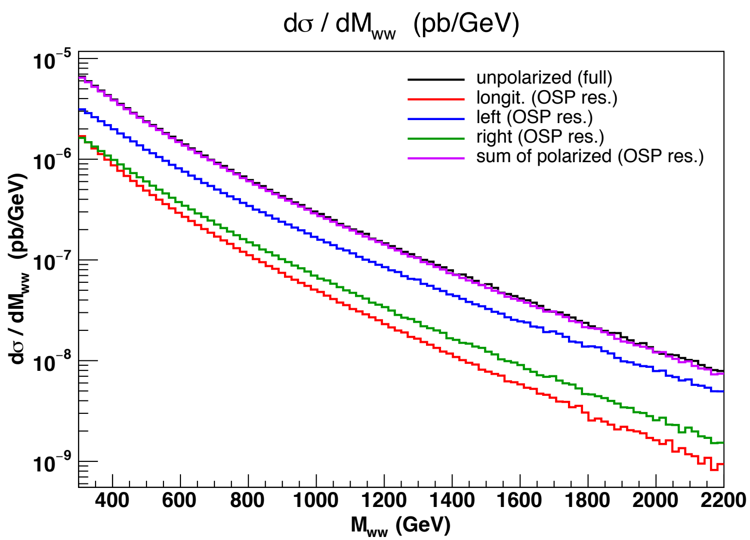


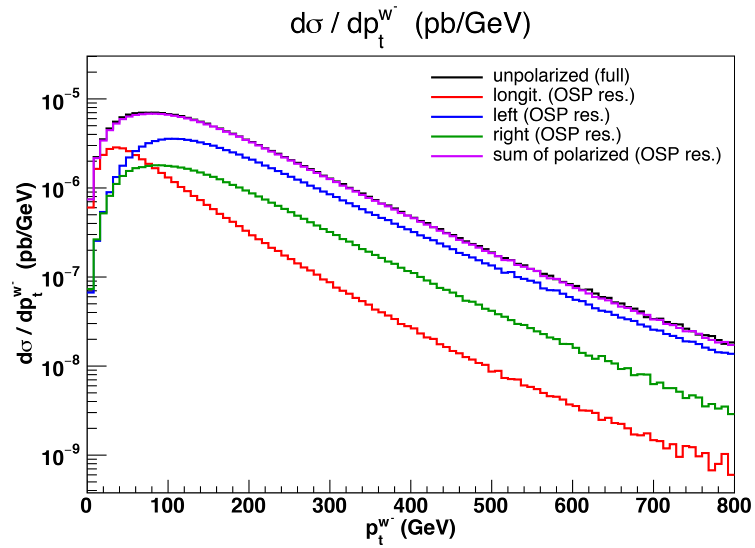


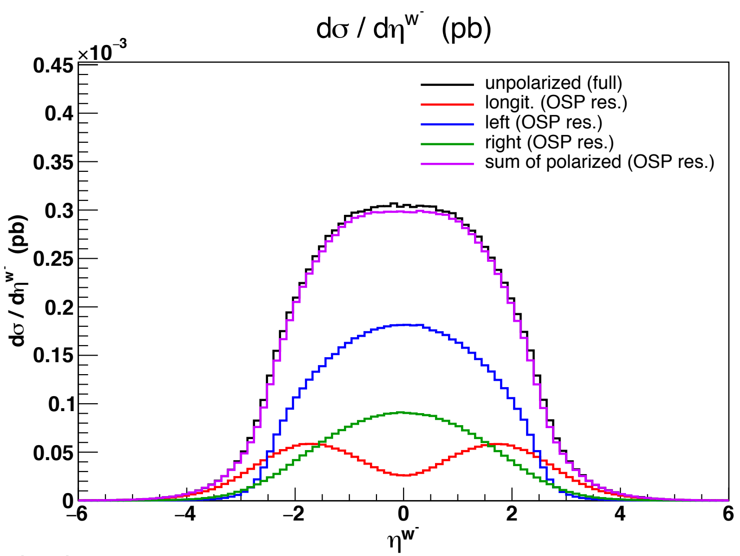


Polarization content through Legendre analysis and through direct computation of polarized cross section agree!
Consistent prediction!

Introducing Lepton Cuts: Results





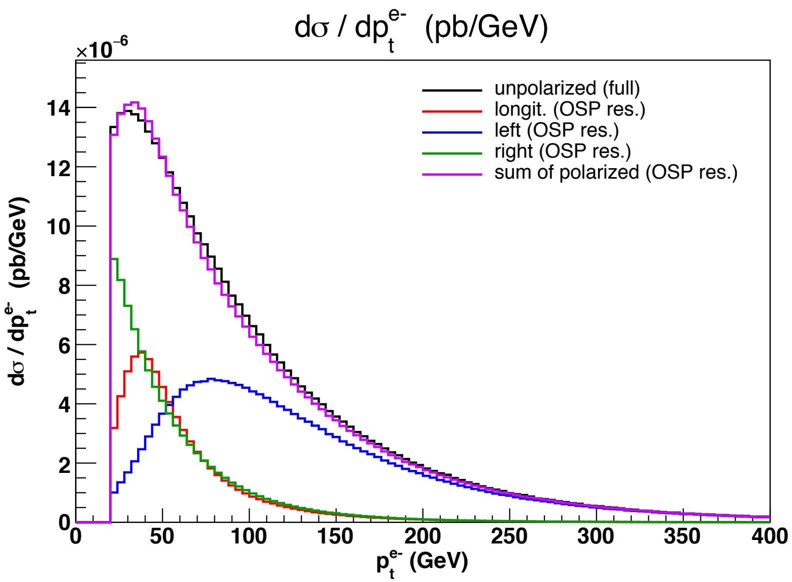


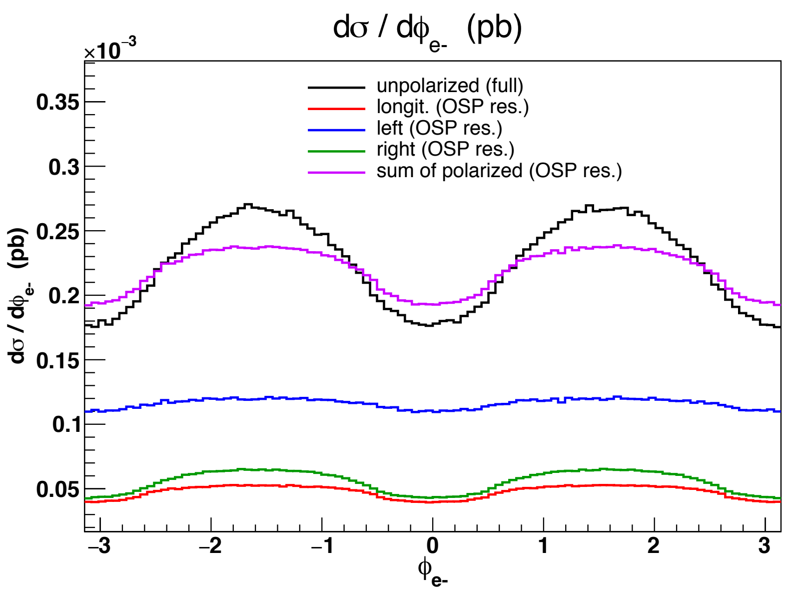
$$p_t^\ell > 20 \text{ GeV}, \ |\eta^\ell| < 2.5$$

Exact cross section	1.412 fb
Sum of polarized OSP	1.378 fb

Diff ≃ 2%

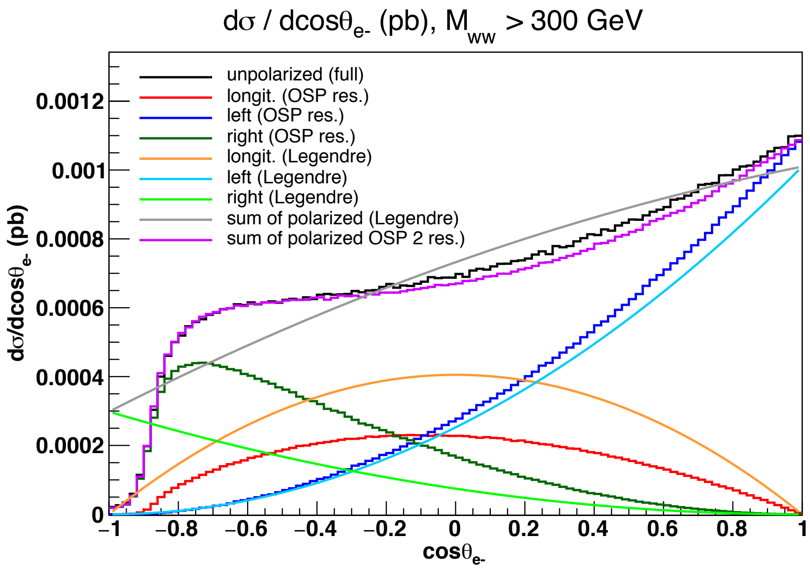
Introducing Lepton Cuts: Results 2

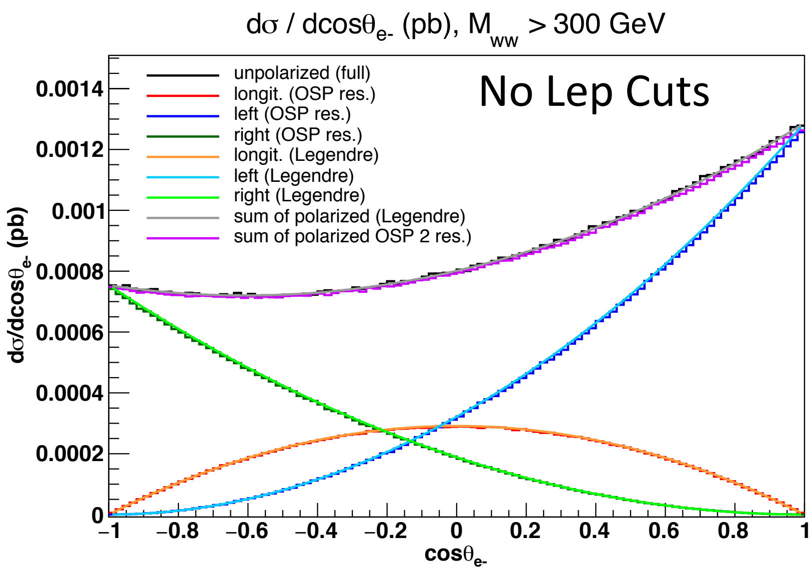




$$p_t^\ell > 20\ \mathrm{GeV},\ |\eta^\ell| < 2.5$$

Polarization fractions with cuts





Pols are affected differently by cuts
Mainly at $\vartheta=\pi$

Legendre expansion fails

Interference among pols is small

Sum of singly polarized distributions reproduces within few % the exact result

Interference terms can be extracted from MC

Different kinematical distributions can be exploited for fit

Conclusions

For the first time we have a consistent framework to describe VB polarizations in VBS

OSP provides a gauge invariant, good approximation to exact VBS which allows to predict Vector Bosons polarization fractions

Works very well for variables which do not restrict the lepton decay angles

Singly polarized distributions provide templates for measuring the polarization fractions of the W's in the presence of reasonable acceptance cuts

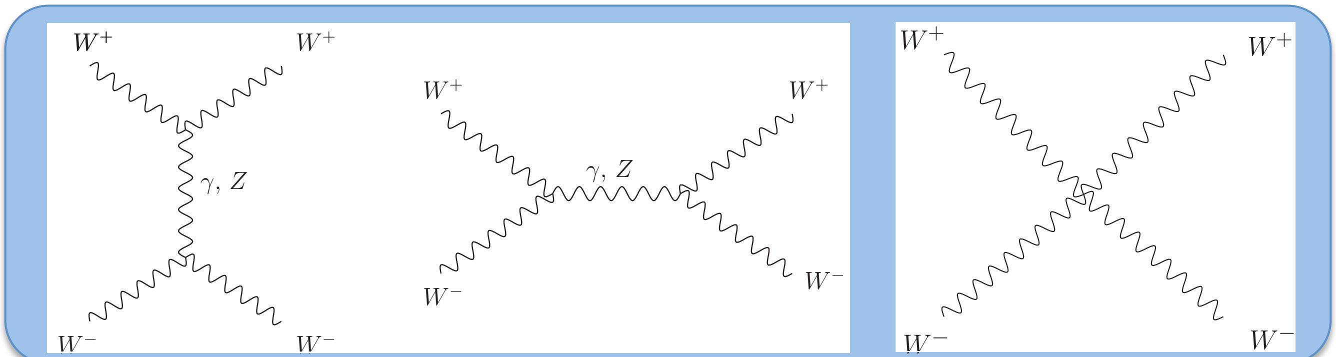
Spares

Longitudinal polarization, gauge invariance, unitarity

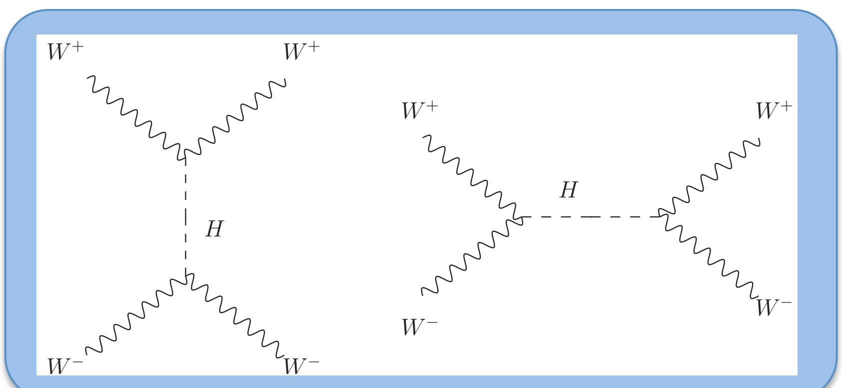
EWSB gives mass to W, Z. Massive vector bosons have three physical polarization states.

$$\varepsilon^\mu_{L/R} = \frac{1}{\sqrt{2}}(0, \mp 1, -i, 0) \quad \varepsilon^\mu_0 = (\kappa, 0, 0, E)/\sqrt{Q^2} \qquad E \gg M_W \quad \varepsilon^\mu_0 \approx p^\mu_W / M_W \qquad p^\mu_W = (E, 0, 0, \kappa)$$

$$\varepsilon_0^{W^+} \cdot \varepsilon_0^{W^-} \propto p^{W^+} \cdot p^{W^-} = s \qquad \Longrightarrow \qquad D_i \propto s^2$$



$$\sum \propto s^1$$



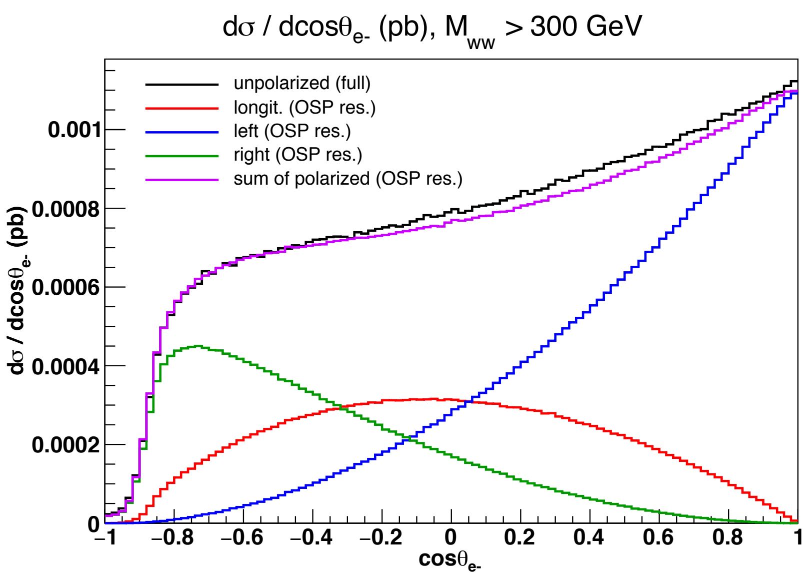
$$\sum \propto s^1$$

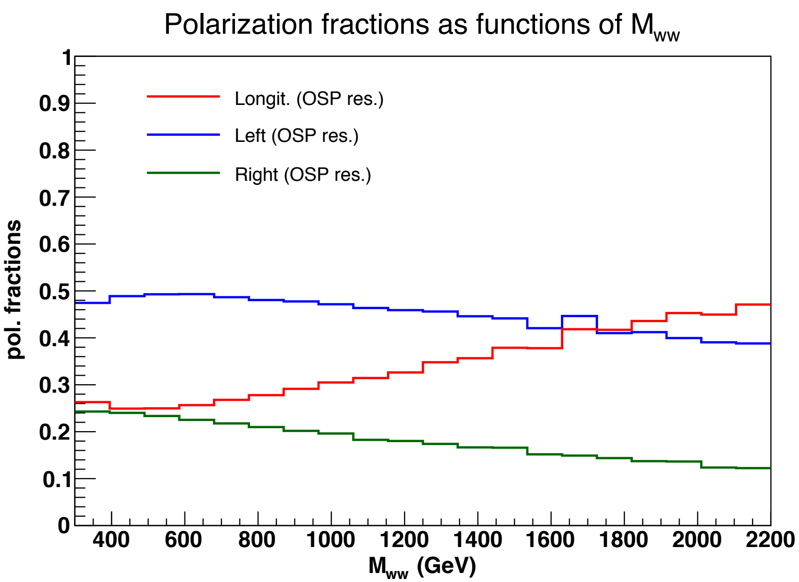
$$\sum \propto s^0$$

Model (in)dependence

Do we have to repeat the analysis for each model separately?

Higgsless model: SM with mh→∞, no cancellation of terms ∝ s in VBS
Unphysical but maximizes differences compared to SM

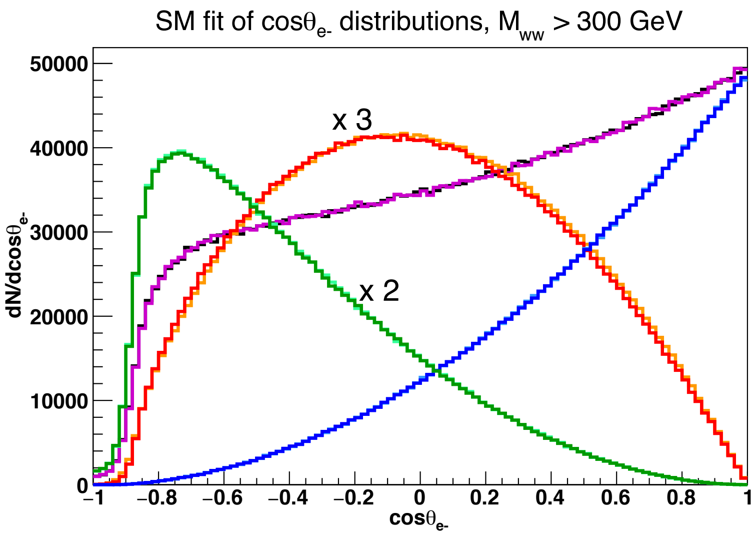


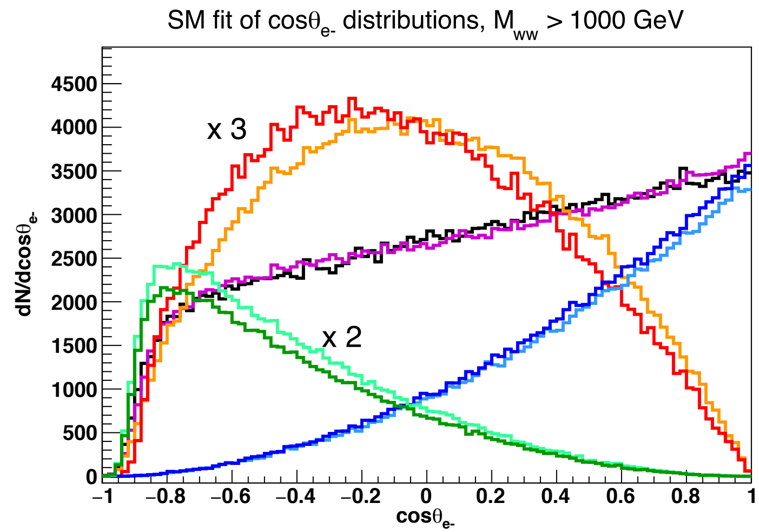


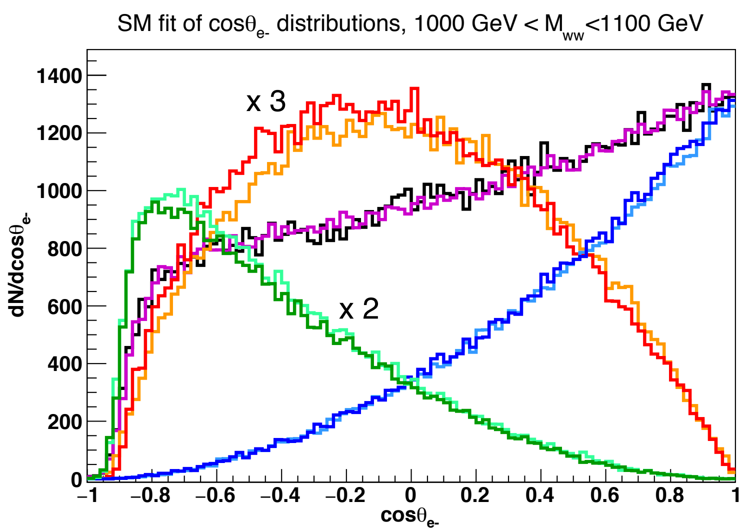
Exact cross section	1.543 fb
Sum of polarized	1.501 fb

$$p_t^\ell > 20\ \text{GeV},\ |\eta^\ell| < 2.5$$

Fitting the noH model using SM shapes







Black: exact noH

Light colours: singly polarized noH

Dark colours: fit of exact noH using SM shapes

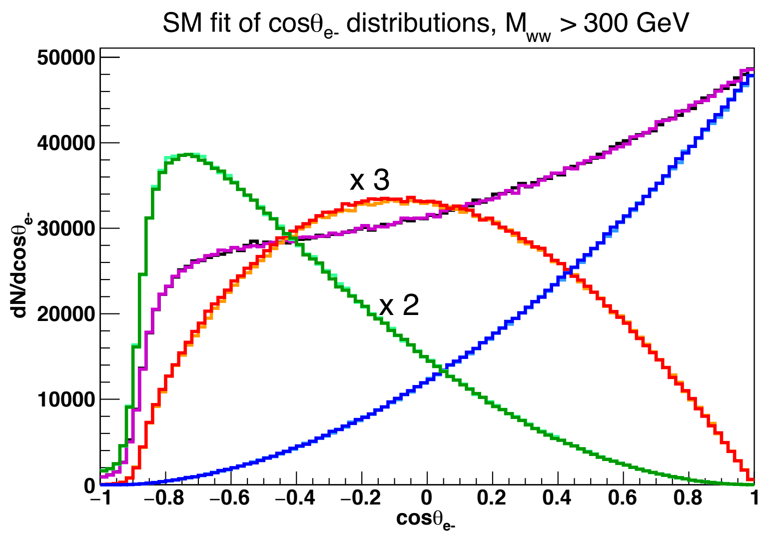
	Long.	L	R	Int.
$M_{WW} > 300$ GeV				
SM	21	52	25	2
no Higgs	27	48	23	2
Fit	26	48	23	2
$M_{WW} > 1000$ GeV				
SM	15	58	22	4
no Higgs	35	45	17	3
Fit	35	47	15	2

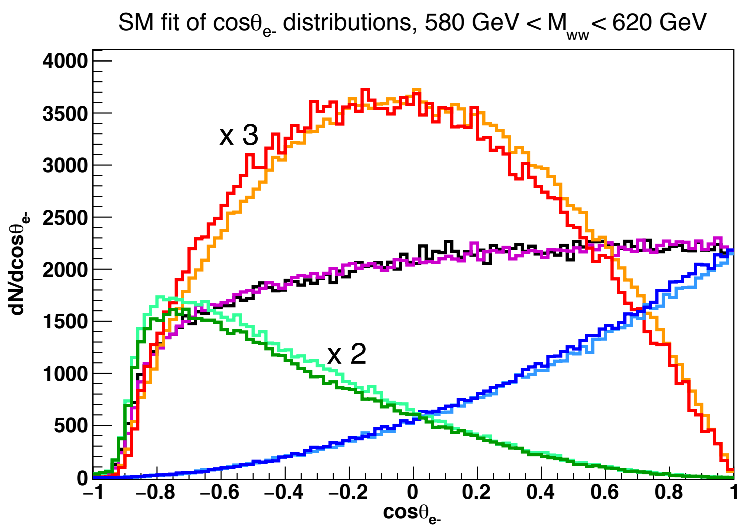
Table 1. Polarization fractions in percent.

Fit uses SM shapes

Fitting the Singlet model using SM shapes

Singlet model: one extra Higgs, mH = 600 GeV, Γ_H = 6.5 GeV, sinα = 0.2





Black: exact Singlet

Light colours: singly polarized Singlet

Dark colours: fit of exact Singlet using SM shapes

W polarization in other processes

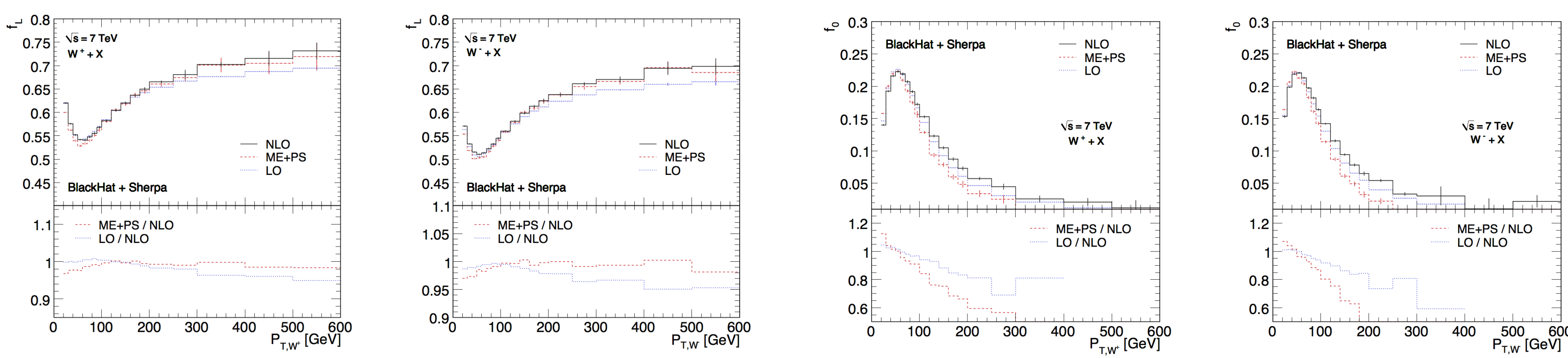
Bern et al., PhysRevD.84.034008; arXiv:1103.5445 W+jets, no lepton cuts

Stirling, Vryonidou, JHEP07(2012)124; arXiv:1204.6427 W+jets , top → W, WW, WZ, WH both with and without lepton cuts

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

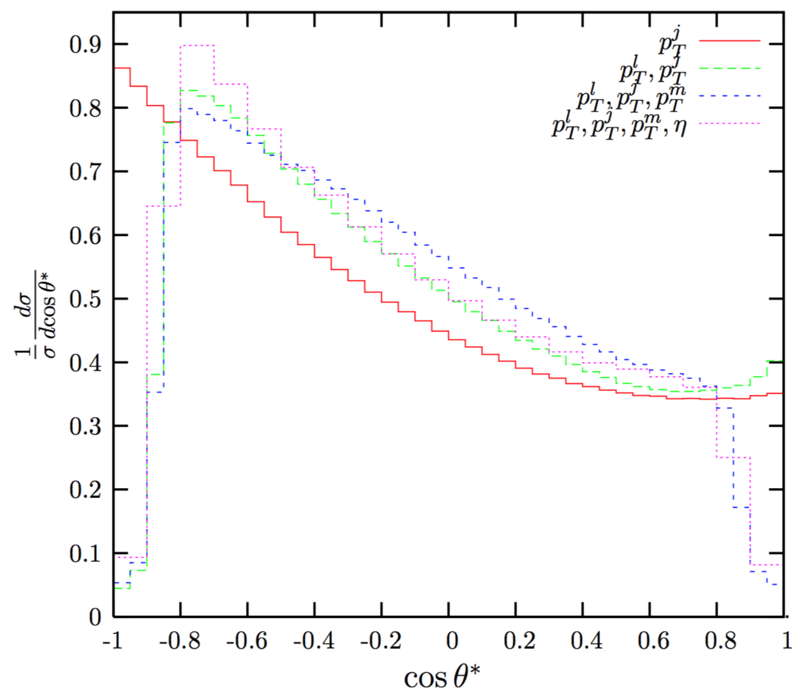
$$\begin{aligned} f_0 &= 2 - 5\langle \cos\theta^{*2}\rangle, \\ f_L &= -\frac{1}{2} - \langle \cos\theta^{*}\rangle + \frac{5}{2}\langle \cos\theta^{*2}\rangle, \\ f_R &= -\frac{1}{2} + \langle \cos\theta^{*}\rangle + \frac{5}{2}\langle \cos\theta^{*2}\rangle. \end{aligned}$$

Bern et al.



W pol with selection cuts in W+Jets

Stirling, Vryonidou



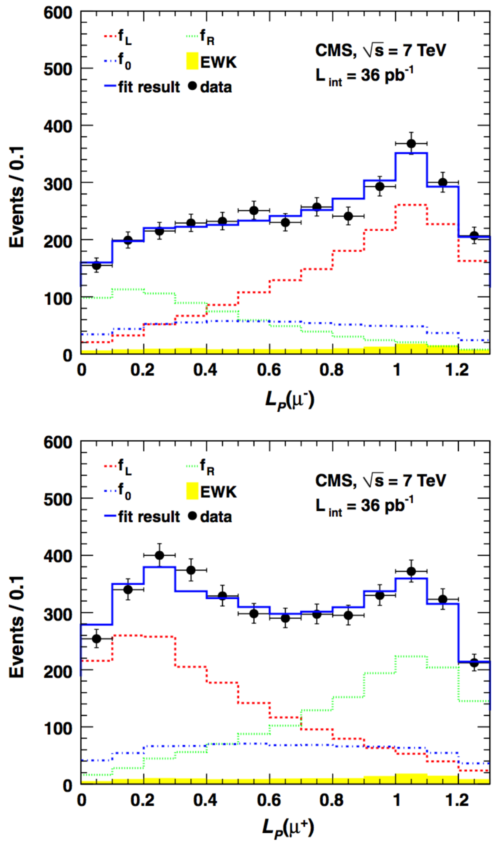
Cuts	"f_0"	"f_L"	"f_R"
$p_T^j > 30$ GeV	0.20	0.56	0.23
$p_T^j > 20$ GeV	0.18	0.59	0.23
$p_T^j > 20$ GeV, $p_T^l > 20$ GeV	0.50	0.35	0.15
$p_T^j > 20$ GeV, $p_T^l > 20$ GeV, $p_T^m > 20$ GeV	0.68	0.29	0.03
$p_T^j > 20$ GeV, $p_T^l > 20$ GeV, $p_T^m > 20$ GeV, $\|\eta_{l,j}\| <2.5$	0.59	0.36	0.05

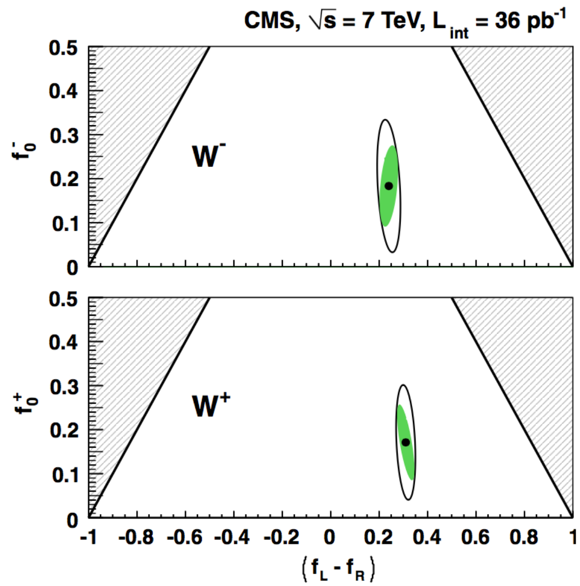
Experimental results CMS

CMS, PhysRevLett.107.021802; arXiv:1104.3829 W+jets, 7 TeV, 35 pb^{-1}

CMS

$$L_P = \frac{\vec{p}_T(\ell)\cdot\vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$





Experimental results ATLAS

ATLAS, Eur.Phys. J. C72(2012)2001; arXiv:1203.2165

W+jets, 7 TeV, 35 pb^{-1}

$$\cos\theta_{2D} = \frac{\vec{p}_{T}^{\,\ell*} \cdot \vec{p}_{T}^{\,W}}{|\vec{p}_{T}^{\,\ell*}|\,|\vec{p}_{T}^{\,W}|}$$