The importance of being polarized

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Outline

Polarization and VBS

Polarized cross sections definition

Resonant contributions and approximations

CosΘ* distributions and legendre analysis.

Cuts , interferences and legendre failure

Fit to distributions

A more realistic case: WZ

Next steps

Conclusions

Polarization and VBS

The relevance of weak bosons polarizations effects is documented by

TH studies which start from LEP2 times (Gounaris et al Int.J.Mod.Phys A8(1993))
and continue at LHC e.g. Bern .. Phys.Rev.D84(2011), Stirling..EPJ Web. Conf. 49 (2013), Belyaev.. Jhep 1308(2013), Aguilar..Phys.Rev.D93(2016)

and

by several measurements performed which start at CDF and regard at LHC polarization in W and Z production, ttbar events, WZ, WZ in boson fusion ... (ATLAS and CMS)

Importance of polarization in VBS comes from
gauge cancellations in longitudinal polarized amplitudes

Longitudinal cross sections depend on the way EWSB is realized
Important for searches of
deviations from the SM and hints of New Physics

A quick reminder:

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

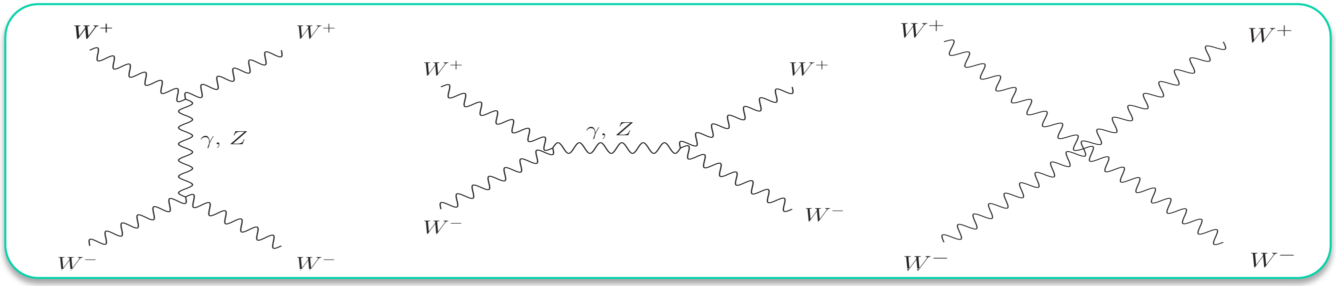
$$\varepsilon^{\mu}_{L/R} = \frac{1}{\sqrt{2}}(0, \mp 1, -i, 0) \quad \varepsilon^{\mu}_{0} = (\kappa, 0, 0, E)/\sqrt{Q^2} \quad E \gg M_W \quad \varepsilon^{\mu}_{0} \approx p^{\mu}_{W}/M_W \quad p^{\mu}_{W} = (E, 0, 0, \kappa)$$

0 = longitudinal

Longitudinal W+W- -> W+W- scattering

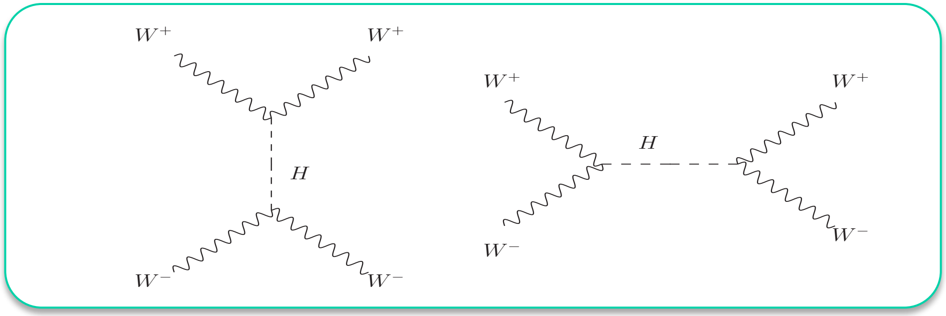
$$\varepsilon_0^{W^+} \cdot \varepsilon_0^{W^-} \propto p^{W^+} \cdot p^{W^-} = s \qquad \Longrightarrow \qquad D_i \propto s^2$$

Longitudinal components: single diagram ∝ s^2



cancellations:

$$\sum \propto s^1$$



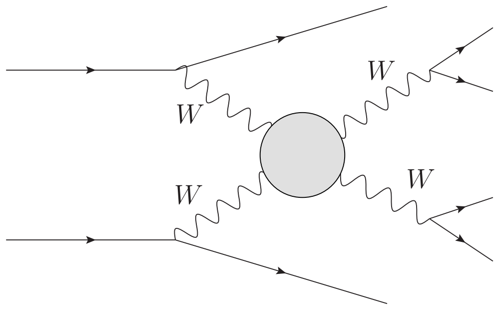
SM Higgs contributions $\sum \propto s^1$

cancellations between the two groups:

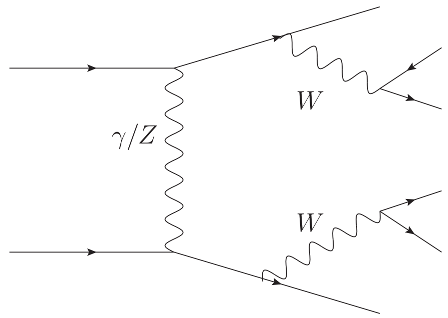
$$\sum_{\text{tot}} \propto s^0$$

The same for other weak bosons, not for ZZ->ZZ

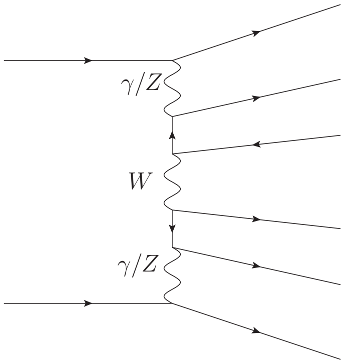
Full process : 3 types of contributions



Resonant signal



Resonant backgroung



Non resonant

$$A_{FULL} = A_{RES} + A_{NONRES}$$

A_{NONRES} Necessary for gauge invariance! Huge cancellations
Numerically relevant in some phase space regions

Boson polarization well defined for on shell W's and Z's (NWA)
But Breit Wigner modulation is lost and difficult to compare with data.

The only alternative: consider only resonant contribution A_{RES}

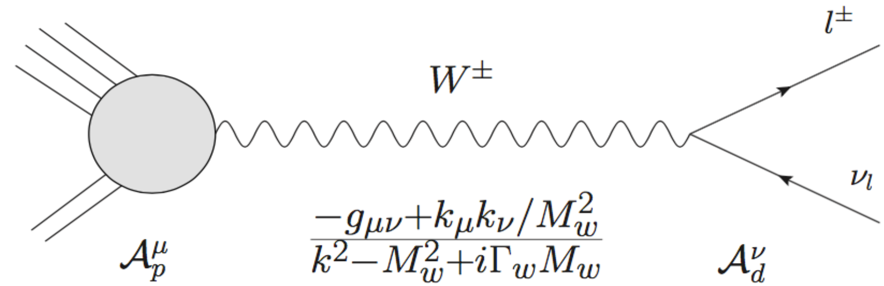
- How to define polarization for off shell vector bosons?
- How to cope with gauge invariance?

In any case polarization defined only in some approximation !

And results depend on the reference system in which you define polarization vectors

Polarization for off shell contributions

The propagator of an off shell decay



can be decomposed in a sum of polarization vectors ε_λ

$$-g^{\mu\nu} + \frac{k^\mu k^\nu}{M^2} = \sum_\lambda \varepsilon_\lambda^\mu \varepsilon_\lambda^{\nu *}$$

The amplitude becomes the sum of polarized amplitudes:

$$\mathcal{A}_f = \sum_\lambda \frac{\mathcal{A}_p^\mu\, \varepsilon_\mu^\lambda \;\; \varepsilon_\nu^{\lambda *} \mathcal{A}_d^\nu}{k^2 - M_W^2 + i\Gamma_W M_W} = \sum_\lambda \mathcal{A}_f^\lambda$$

The substitution: $\sum_\lambda \varepsilon_\lambda^\mu \varepsilon_\lambda^{\nu *} \;\to\; \varepsilon_\lambda^\mu \varepsilon_\lambda^{\nu *}$ defines the various (λ) polarized amplitudes

No need to be on-shell

The cross section contains the sum of polarized amplitudes + interferences

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

Interferences are present also on shell (NWA) !

other methods in MC ?

Resonant contributions and approximations

Considering only resonant contribution may lead to big errors
and violates gauge invariance

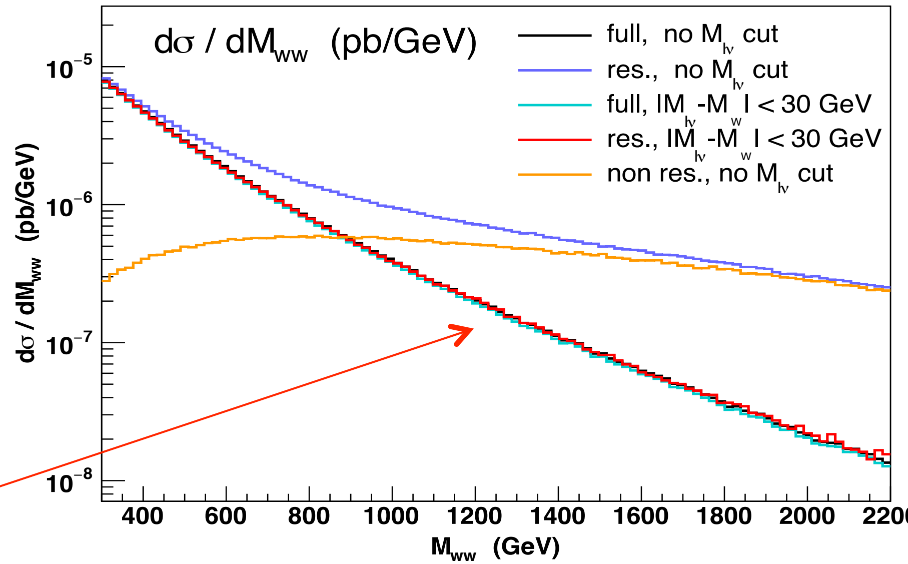
$$pp \to jje^-\bar{\nu}_e\mu^+\nu_\mu \; \mathcal{O}(\alpha^6_{EM})$$

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

$M_{WW} > 300$ GeV

Cuts on invariant mass
of the decay products
seem to solve the problem
as the resonant contibutions
dominate

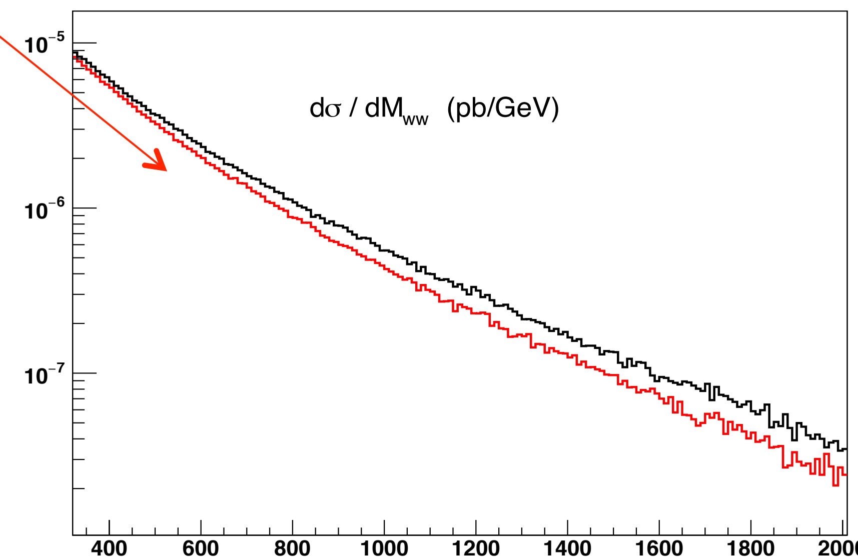
$$|M_{l\nu} - M_w| < 30\ \mathrm{GeV}$$



$$|\eta_j| < 5.5,\; p_t^j > 10\ \mathrm{GeV}$$

But is cut dependent
Differences 5-10% in cross sections

And dangerous in some regions
when cancellations are important



On shell projection (OSP)

In computing the amplitudes of resonant contributions,
one can project (in the numerator) the four momenta of the decay particles on shell

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

kind of On shell production X decay modulated by Breit Wigner
with all exact spin correlations

If applied to both the two bosons (OSP2) the procedure is **gauge invariant** (Ward id.)

provided $\Gamma_W,\,\Gamma_Z \to 0$ in $\mathcal{A}^\mu_{p,RES}$ and $\cos\theta_W,\,\sin\theta_W$ (no complex mass)

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

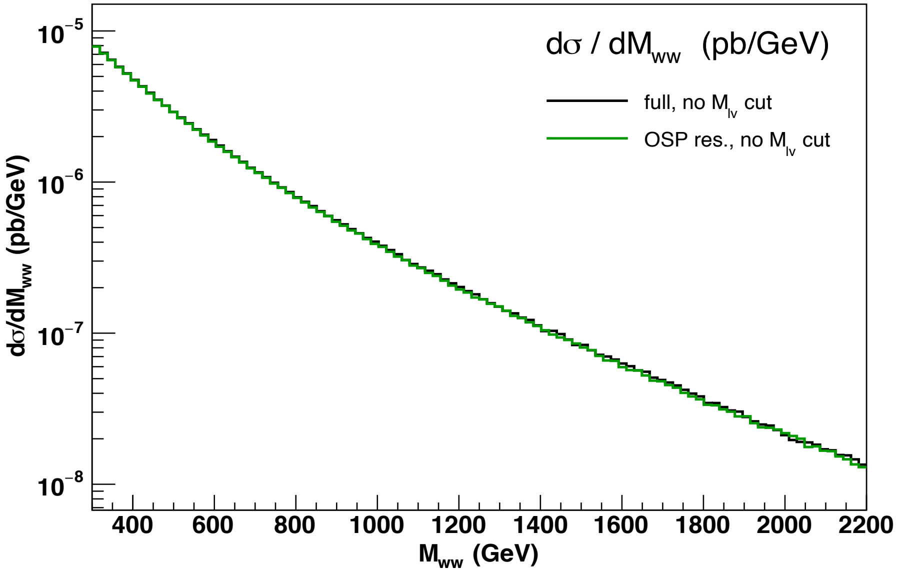
Not uniquely defined. To fully specify Phantom conserves:

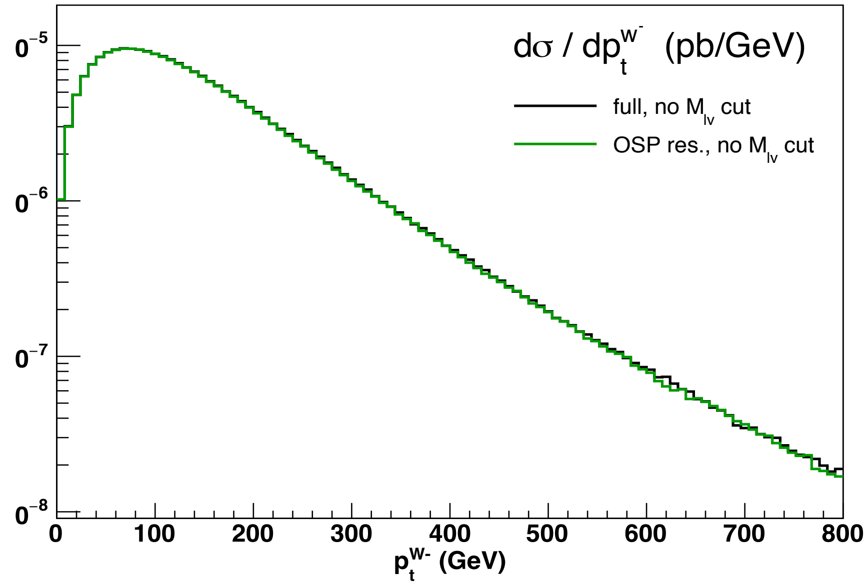
1. the total four–momentum of the WW system;
2. the direction of the two W bosons in the WW center of mass frame;
3. the direction of each charged lepton in his W center of mass frame.

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

Resonant contributions and approximations

OSP2 : excellent agreement for W+W- without cut on decay invariant mass





OSP1 : projection for only one boson. pp->W/Z+X
can be used for single polarization/resonant studies
gives good results but the other boson width ≠ 0 : not gauge invariant

Not uniquely defined: In PHANTOM conserves:
- X four momentum
- WZ 3-mom in lab
- The direction of W/Z decay in W/Z rest frame
- * Modifies initial parton 4-mom to conserve 4-mom

Resonant contributions and approximations

The ZZ case

ZZ -> ZZ processes behave for OSP similar to normal resonant contributions and without cut on $l^+ l^-$ inv. mass are very different from FULL

different cuts around the Z pole

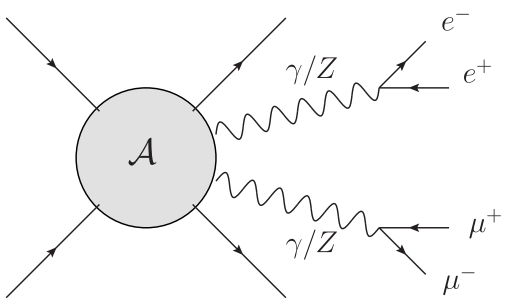
cut	FULL	RES OSP	RES NO OSP
$u\ u \to u\ u\ e^-\ e^+\ \mu^-\ \mu^+$ (4Z)			
no cut	44.79	13.02	13.18
30 GeV	17.76	12.64	12.66
5 GeV	10.09	9.55	9.53

pb^{-8}

$m(l^+ l^-) > 40$ GeV

Contributions missing :

When selecting ZZ resonant diagrams, gamma contributions are discarded



In fact ....

The ZZ case

different cuts around the Z pole

cut	FULL	RES OSP	RES NO OSP
$u\ u \to u\ u\ e^-\ e^+\ \mu^-\ \mu^+$ (4Z)			
no cut	44.79 (13.34)	13.02	13.18
30 GeV	17.76 (12.66)	12.64	12.66
5 GeV	10.09 (9.52)	9.55	9.53

pb^{-8}

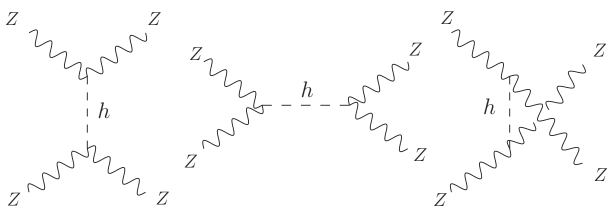
m(l^+ l^-) > 40 GeV

numbers in ( ) obtained with gamma-lepton coupling = 0

OSP2 satisfies Ward Id
Doubts about gauge inv of a theory with Z on shell ?

Similitude between OSP and NO OSP results

ZZ->ZZ has
No unitarity/gauge cancellations
Different from WW->WW WW->ZZ and WZ->WZ



different behaviour for WW-> ZZ

cut	FULL	RES OSP	RES NO OSP
$u\ s \to d\ c\ e^- e^+ \mu^- \mu+$ (2W2Z)			
no cut	267.30	248.60	324.38

pb^{-8}

In practice the above ZZ problem not so relevant as

ZZ production in VBF at LHC includes both

ZZ -> ZZ and WW -> ZZ (largely dominant)

different cuts around the Z pole

cut	FULL	RES OSP	RES NO OSP
$p\,p \to j\ j\ e^-\ e^+\ \mu^-\ \mu^+$			
no cut	6.399 (4Z: 0.075)	5.895 (4Z: 0.030)	7.543 (4Z: 0.030)
30 GeV	5.844 (4Z: 0.036)	5.714 (4Z: 0.029)	5.764 (4Z: 0.029)
5 GeV	4.321 (4Z: 0.023)	4.305 (4Z: 0.022)	4.315 (4Z: 0.022)

pb^{-5}

it is evident that for ZZ final state strong cuts on $l^+\ l^-$ invariant masses are necessary

ZW

pp -> j j e+ e- μ+ ν_μ

$M_{jj} > 500\,\mathrm{GeV},\ |\Delta\eta_{jj}| > 2.5,\ p_t^j > 20\,\mathrm{GeV}, |\eta_j| < 5,\ |M_{\ell^+\ell^-} - M_Z| < 15\,\mathrm{GeV},\ M_{WZ}^{\mathrm{true}} > 250\,\mathrm{GeV}$
no p_t^{miss}, η_ℓ, p_t^ℓ cuts

	SM
full unpol.	3.980
OSP 1 unpol.	3.969
OSP 2 unpol.	3.939

OSP1
single (W) resonant

Cross sections in 10^{-4} pb: a cut on the true M_{WZ} is understood.

$M_{jj} > 500\,\mathrm{GeV},\ |\Delta\eta_{jj}| > 2.5,\ p_t^j > 20\,\mathrm{GeV}, |\eta_j| < 5,\ |M_{\ell^+\ell^-} - M_Z| < 15\,\mathrm{GeV}\ \ M_{WZ} > 250\,\mathrm{GeV},$
$|\eta_\ell| < 2.5,\ p_t^\ell > 20\,\mathrm{GeV},\ p_t^{\mathrm{miss}} > 40\,\mathrm{GeV}$

	SM TRUE	SM RECO
full unpol.	1.364	1.385
OSP 1 unpol.	1.355	1.377
OSP 2 unpol.	1.342	-

RECO :
reconstructed p_Z neutrino
forcing m(μ+ ν_μ) = m_W

different methods.
(for details see Ezio's talk)

Cross sections in 10^{-4} pb: a cut on the M_{WZ} is understood (true or reconstructed).

Good agreement

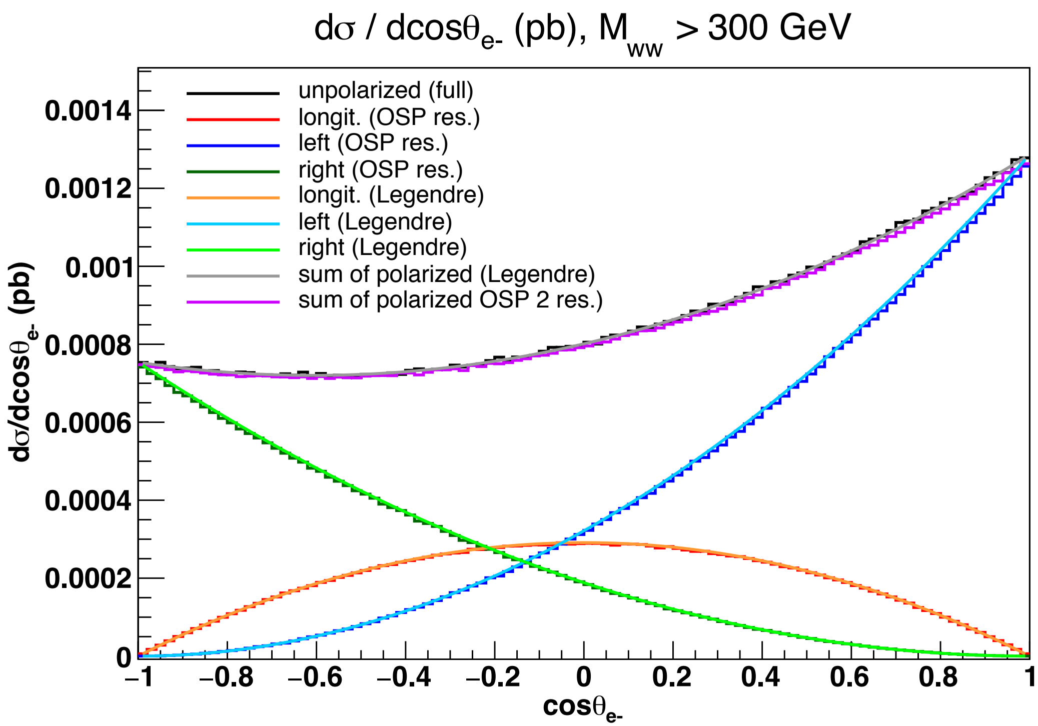
Conclusion: OSP2 for WW cuts for ZZ OSP1 and cut for ZW

Distributions of the decay polarized amplitudes in Boson rest frame angles

0 = longitudinal $\mathcal{A}_d^0 = ig\sqrt{2}E\,\sin\theta$ $\mathcal{A}_d^{R/L} = -ig\,E\,(1\mp\cos\theta)e^{\pm i\phi}$

Integrating over the full Φ range interferences disappear.

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



no lept cuts

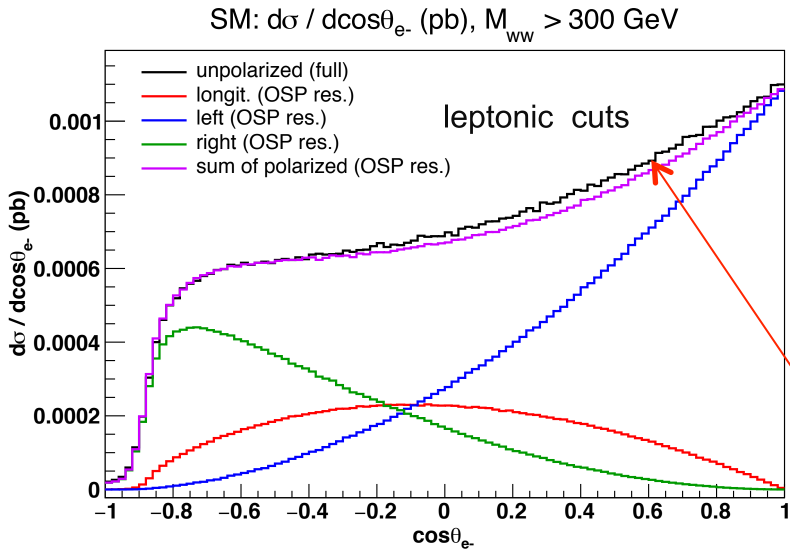
polarized components can be extracted from full differential angular distribution by a projection on first 3 Legendre polynomials

Legendre analysis can be used to test MC

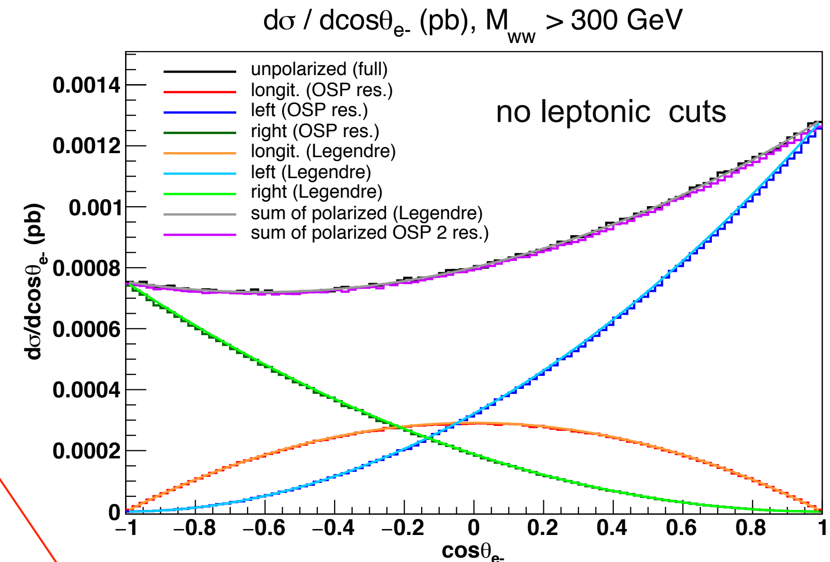
In realistic situation cuts on lepton variables prevent their use for determining polarized components

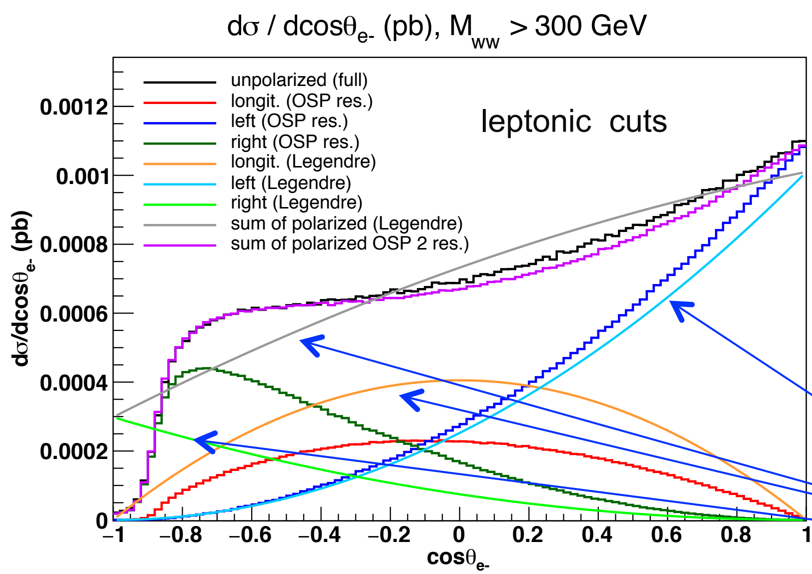
Cuts, interference and legendre failure

lept cuts



no lept cuts





leptonic cuts:

$$p_t^e > 20 \text{ GeV}, \qquad |\eta^e| < 2.5.$$

interferences (small)

Pols are affected differently by cutsMainly at **ϑ=π**

different shapes

failure of legendre method !!

how determine pol xsects from full?

Fit to distributions

Measured angular distribution can be fitted to a linear combination of MC normalized shapes to obtain the various polarizations.

Verified that this procedure works well for the SM:
starting from generated full angular distributions we reproduce well polarized cross sections and angular distributions.

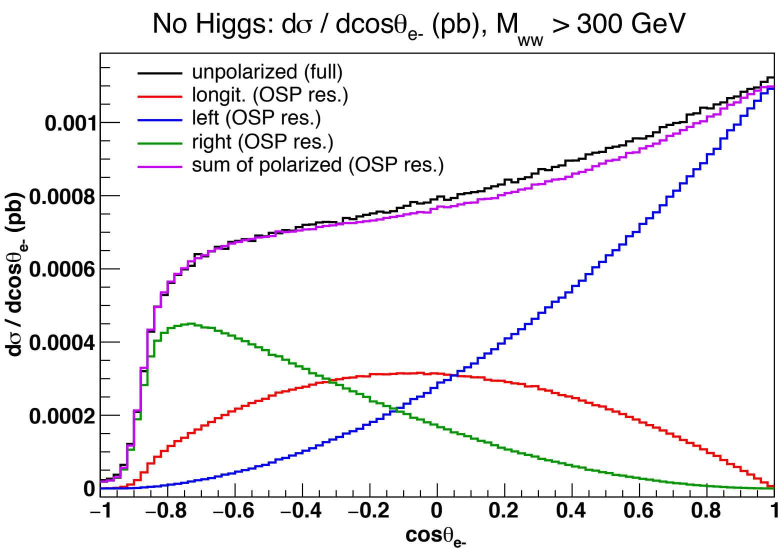
Fitted results are much better if one uses also the shape of the interference.

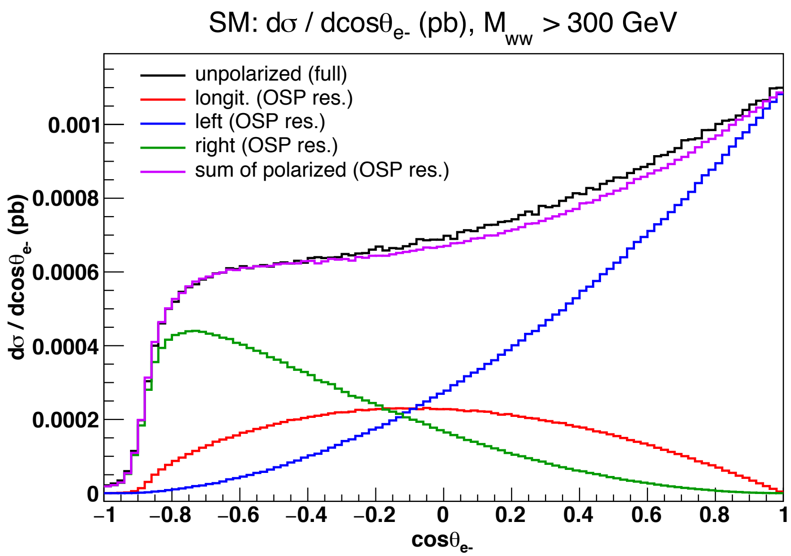
Suppose measured distributions correspond to a BSM diffferent from SM

Do we have to repeat the analysis for each model separately?
Or the shapes are similar for all models and we can trust the fit made with SM ones?
If not, what is the uncertainty of the fit results?

Tested this possibility for WW fitting Higgless model results with SM shapes

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



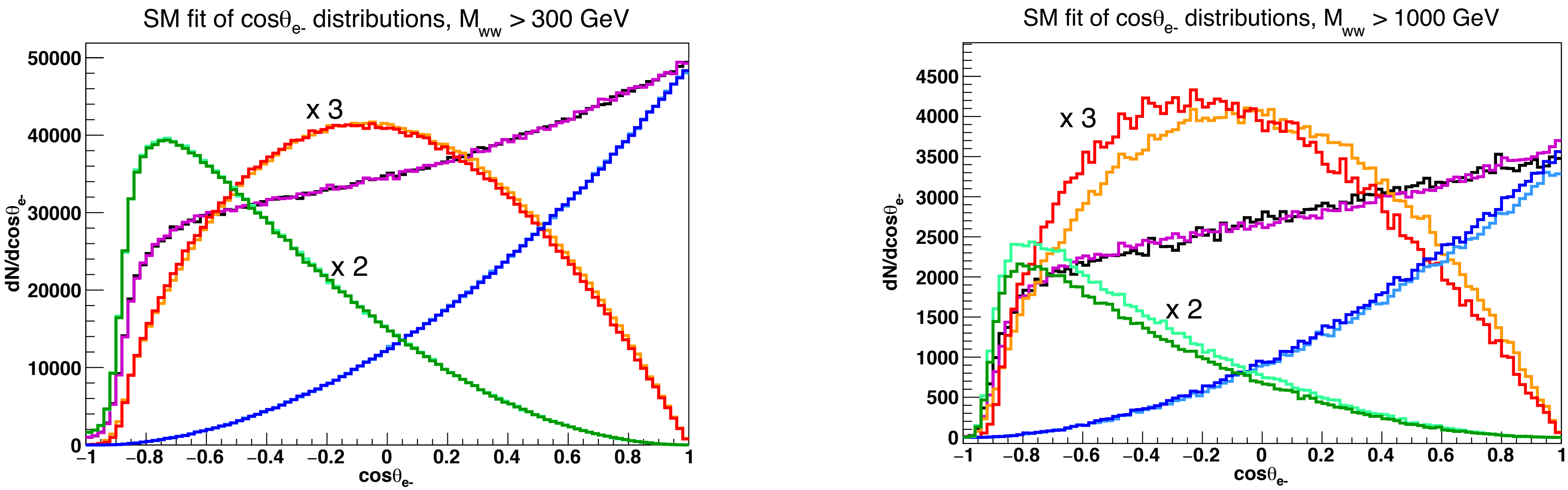


Fit to distributions

W+W-

no ptmiss cut

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



Light colours: singly polarized noH Dark colours: fit of exact noH using SM shapes

red longitudinal green right blue left black unpolarized

	Long.	L	R	Int.
no Higgs	0.266	0.481	0.231	0.022
Fit	0.265	0.481	0.230	0.024
$M_{WW} > 1000$ GeV				
no Higgs	0.347	0.448	0.173	0.031
Fit	0.344	0.467	0.161	0.029

fractions of the various polarizations

Fit uses SM shapes

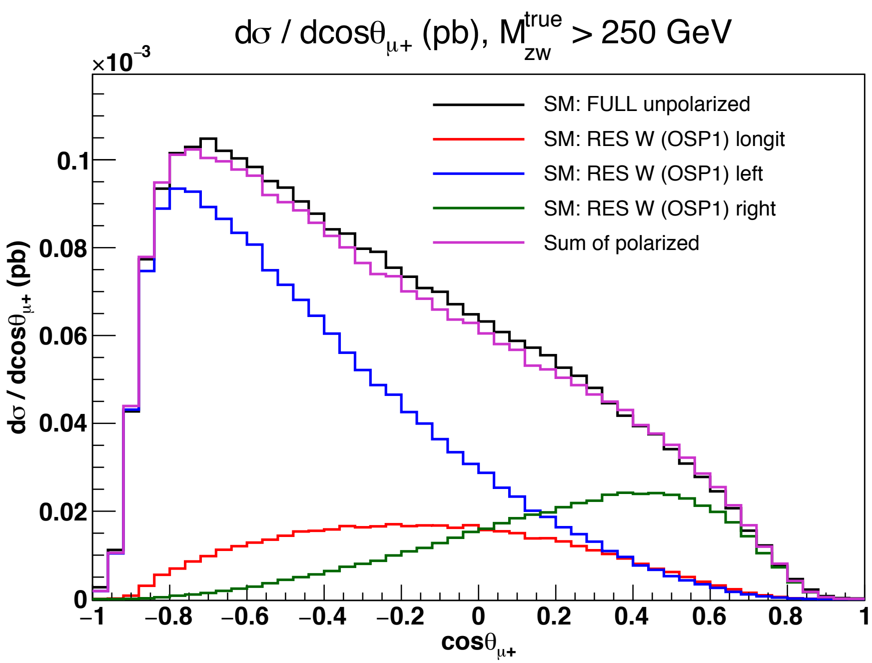
reasonable agreement

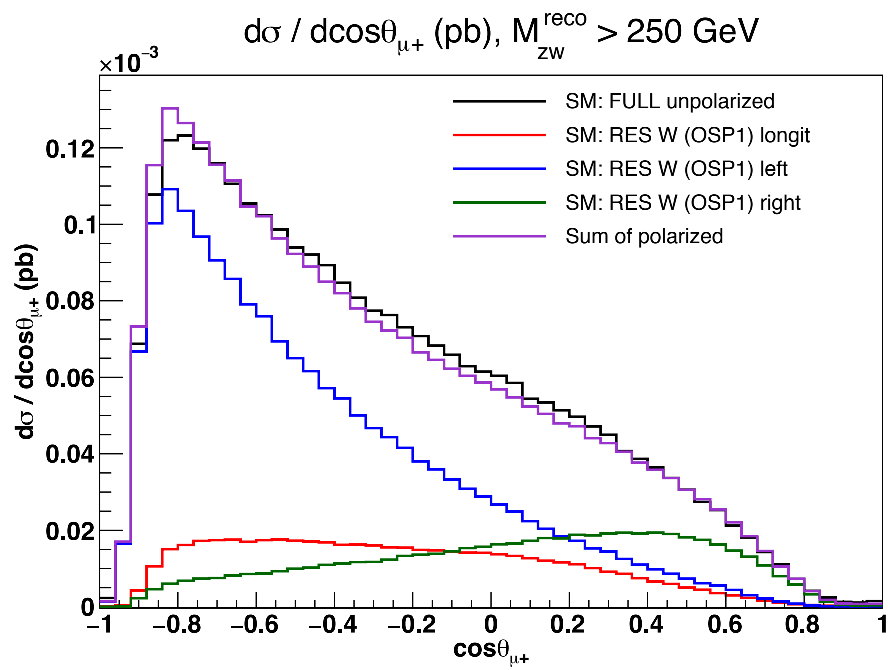
A more realistic case:WZ

A more realistic case: WZ   pp -> j j e+ e- μ+ ν_μ (for ZZ see Ezio's talk)

OSP1 for W resonant   cut m(e+ e-) ± 15 GeV around Z pole

RECO : reconstructed p_Z neutrino   forcing m (μ+ ν_μ) = m_W





red longitudinal   green right   blue left   black unpolarized

true neutrino   neutrino reconstructed

Reconstruction changes the shapes

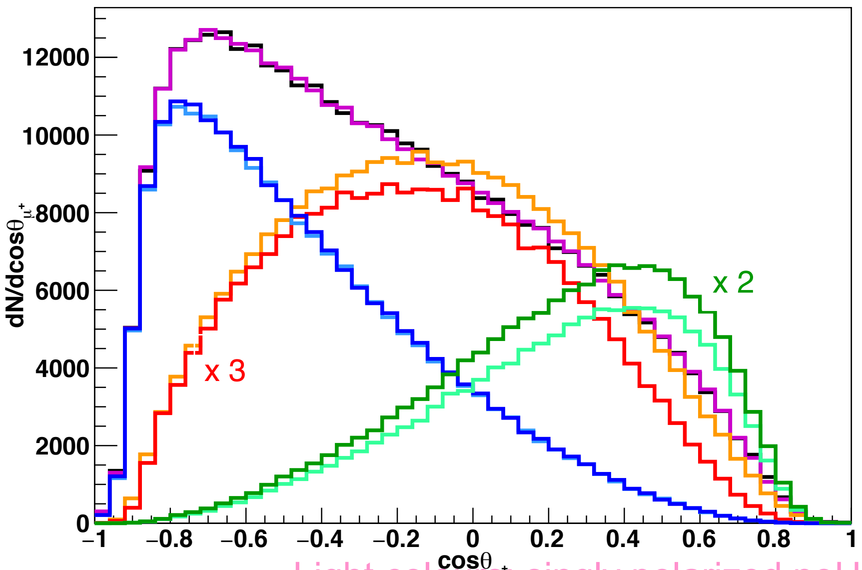
it remains a big difference among polarized distributions

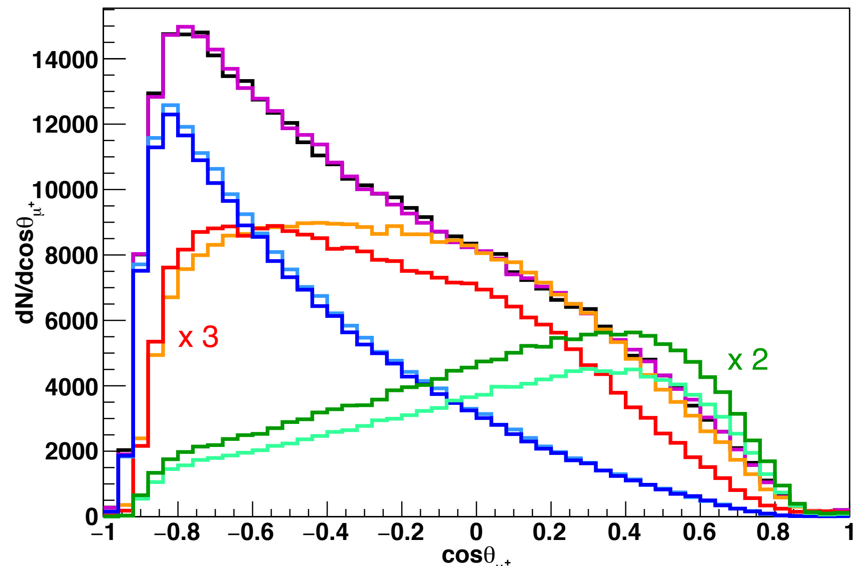
one can still use cos θ for fitting the different contributions from the total.

(it works for SM)

A more realistic case:WZ

model (in)dependence





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	Long.	L	R	Int.
no Higgs	0.256	0.548	0.173	0.024
Fit	0.223	0.552	0.205	0.019

true neutrino

	Long.	L	R	Int.
no Higgs	0.261	0.544	0.179	0.017
Fit	0.231	0.530	0.225	0.015

neutrino reconstructed

Not very accurate: for polarized cross sections errors of ~10%

Is this a superior limit due to extreme no Higgs model?

Not only a neutrino reconstruction problem

Next steps

- Double polarized cross sections
  Double longitudinal cross sections are more sensitive to alternative EWSB
  Fit to 2- dimensional distributions (θ_e θ_μ)
  their (in)dependence on the model to be studied
- Polarization in semi-leptonic cannel
  WW and ZW contributions
- Distributions in leptonic WW events
  reconstructing W rest frame with 2 neutrinos (and θ distributions).
  finding alternative variables which discriminate among polarizations
  several studies ongoing
- **Polarization at $\alpha_s^2\ \alpha_{em}^4 + \alpha_{em}^6$**
  signal or background ? needed in any case
- **Qcd corrections**
  should not be difficult for fully leptonic
  they do not modify the shapes of the distributions
- **EW corrections**
  is it possible? are they relevant given the approximation in the definition?

Conclusions

It is extremely important to define in a consistent way the polarized cross section and to find a method to measure them in a model independent way

A lot of work is ahead of us , both TH and EXP

I hope the present workshop will be the starting point of a true wide collaborations among different groups, TH and EXP for VBS polarization physics.

I am looking forward to tomorrow MC talks because

- The methods employed should be discussed and clarified among MC's authors
- It is essential that the results are validated by several MC's

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e.g. in ttbar, reconstruction of the 2 neutrinos how much does it affect distribtions?
in WZ how is it accounted for possibility ot other models?
how the templates are used for measurement ?
what about "uncut " θ distributions?

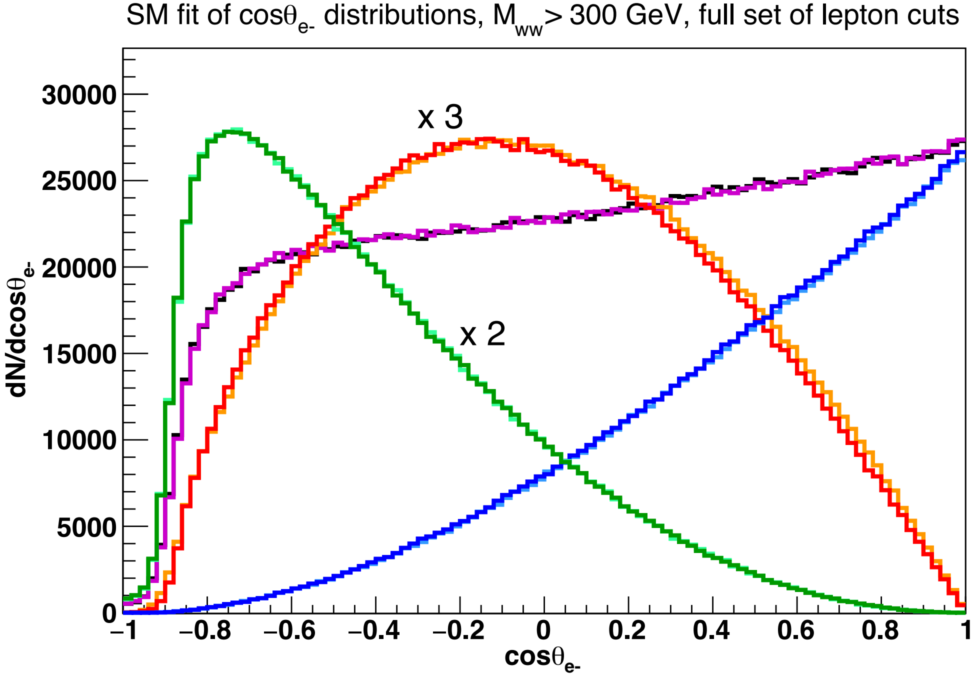
BACKUP

Fit to distributions

W+W-

with ptmiss > 40 GeV

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



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