Polarization studies with MadGraph5_aMC@NLO

Diogo Buarque Franzosi*,
Olivier Mattelaer, Richard Ruiz, Sujay Shil

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*speaker

Department of Physics, Subatomic and Plasma Physics, Chalmers Univ. Of Technology

Outline

- Introduction
- Implementation and syntax in MadGraph5_aMC@NLO
- Applications:
  1. High energy longitudinal VBS
  2. Decaying weak bosons in VBS
  3. Polarized diboson production at NLO in QCD matched with PS
- Conclusion

Motivation

- Longitudinal weak bosons (W_0) are part of EW symmetry breaking (EWSB) sector
- EW gauge symmetry is chiral $\rightarrow$ *e.g.* left-handed weak bosons (W_L) are enhanced in $q\bar{q} \rightarrow W^+$ production.
- Top-quark mass related to EW sector $y_t \sim 1$, helicity flipping sensitive
- BSM effects can be highly polarization dependent, *e.g.* Right-handed current in extended gauge theories (Beg, Budny, Mohapatra, Sirlin 77), Dynamical EWSB and Composite Higgs couples strongly to W_0,...
- In the EFT framework different operators contribute to different polarizations, *e.g.* in VV polarizations e.g. Liu, Wang, 18 and top-quark physics (Hartland, Maltoni,Nocera, Rojo, Slade, Vryonidou, Zhang 19)
- Huge interest from experimental collaborations

Having each polarization separately described is crucial to understand their contributions to physical processes

Polarization in MadGraph5_aMC@NLO

- MadGraph5_aMC@NLO offers a very flexible and powerful framework to simulate collision events,
  - for "arbitrary" multiparticles in the final state,
  - at NLO in QCD accuracy (via *e.g.* MadLoop and MadFKS),
  - matched to PS,
  - with merged jet multiplicities,
  - for several types of models (UFO format),
  - spin correlated decay via MadSpin or decay chain,
  - interfaced to several analysis frameworks, etc...

In this release: particle polarizations can be specified.

MadGraph5_aMC@NLO implementation

MODE I: Initial/final state particles

- The syntax $\mathcal{P}\{X\}$ is used to define polarization X of particle $\mathcal{P}$, *e.g.*

```
generate p p > t t~{L}
generate e+{L} e- > w+{L} w-{T}
generate p p > w+ w-{T} [QCD]
```

- Implementation: sum and average over helicities done only for the specified polarizations
- Implemented for particles with spin 1/2, 1, 3/2 and 2
- For LO generation we allow the user to choose the *frame* where polarizations are defined in run_card.dat

```
  [1,2]  = me_frame
   ! list of particles to sum-up to define the frame
```

MODE II: Unstable particles in the spin correlated narrow width approximation

- Both decay chain, *e.g.*

```
generate p p > t t~{L}, t~ > b~ w-
generate e+{L} e- > w+{L} w-{T}, w+ > e+ ve, w- > e- ve~
```

- and `MadSpin` on a sample with polarized particles, *e.g.*

```
decay w+ > ta+ vt
```

- Replace propagator numerator with the subset of helicity sum

$$\text{spin 1:} \quad \eta^{\mu\nu} + \frac{p^\mu p^\nu}{m^2} \rightarrow \sum_\lambda \epsilon_\lambda^{\mu^*} \epsilon_\lambda^\nu$$
$$\text{spin 1/2:} \quad \not{p} - m \rightarrow \sum_\lambda u_\lambda \bar{u}_\lambda$$

- Support spin 1/2 and 1
- Gauge dependent pieces at offshell region $\mathcal{O}(\Gamma/M)$
- Implementation does not support interference between different polarizations (this has to be generated with the standard unpolarized ME)

Feature	Unpolarized	Polarized
LO Parton Shower	✓	✓
Merging LO	✓	✓
PS Matching NLO QCD	✓	QCD neutral polarized particles
Merging NLO (FxFx)	✓	QCD neutral polarized particles
Polarized beams	✓	✓
NLO Fixed order	✓	QCD neutral polarized particles
BSM via UFO	✓	✓
`MadSpin` and decay chain	✓	Spin 1/2, 1

Application I: High energy VBS

- If the Higgs has modified couplings to weak bosons (*e.g.* if it is composite)

$$\mathcal{L} \supset m_W^2 W_\mu^+ W^{-\mu} \left(1 + 2a\frac{h}{v} + \cdots\right)$$

the miscancellation of diagrams gives energy growing of longitudinal boson scattering amplitudes at high energies

$$A(W_L W_L \to W_L W_L) \sim (1 - a^2)\frac{s}{v^2}$$

- and affects the prediction in "more physical" observables like VBS, *e.g.*

$$pp \to jjW^+W^-, \quad W \to f\bar{f}$$

- Our framework can be used to predict each polarization component and in particular enrich the longitudinal sample where effects are expected

- We use the Higgs Characterization model (replace X,Y=L,T)

```
import model HC_UFO-CH
generate p p > j j w+{X} w-{Y}  / x1 x2 QCD=0
output VBSCH_pp-wpXwmY
```

- Consider $a = 1$ (SM) and $a = 0.8$, partonic C.M. (pRF) and *WW* C.M. (*WW*RF)
- Cuts: $M(WW) > 300\,\text{GeV}$, $\Delta\eta(jj) > 3.6$, $M(jj) > 600\,\text{GeV}$, $p_T(j) > 20\,\text{GeV}$

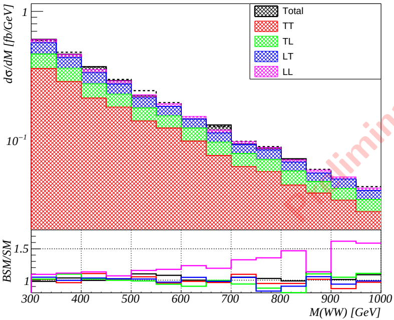
Total cross section

Process	pRF, SM σ [pb]	pRF, SM ε [%]	pRF, $a = 0.8$ σ [pb]	pRF, $a = 0.8$ ε [%]	BSM/SM
jjW^+W^-	0.1526	100	0.1563	100	1.02
$jjW_T^+W_T^-$	0.09552	62.6	0.09641	61.7	1.01
$jjW_L^+W_T^-$	0.02411	15.8	0.02421	15.5	1.00
$jjW_T^+W_L^-$	0.02569	16.8	0.02575	16.5	1.00
$jjW_L^+W_L^-$	0.007912	5.18	0.009539	6.10	1.20

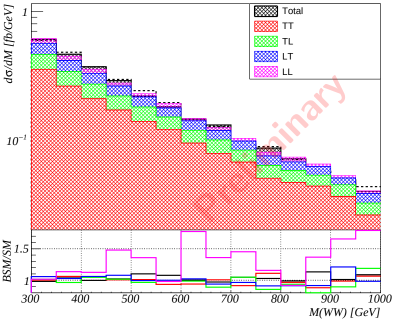
Process	WWRF, SM σ [pb]	WWRF, SM ε [%]	WWRF, $a = 0.8$ σ [pb]	WWRF, $a = 0.8$ ε [%]	BSM/SM
jjW^+W^-	0.1526	100	0.1563	100	1.02
$jjW_T^+W_T^-$	0.09449	61.9	0.09525	60.9	1.01
$jjW_L^+W_T^-$	0.02366	15.5	0.02289	14.6	0.967
$jjW_T^+W_L^-$	0.02569	16.8	0.02556	16.3	0.995
$jjW_L^+W_L^-$	0.00980	6.4	0.01196	7.6	1.22

$M(WW)$ distribution

pRF

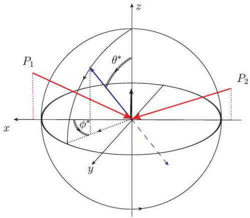


WWRF



Application II: Decaying the W

- Particle polarizations leave their *footprints* in the decay products
- Example: for one W decay, in the W rest frame, the cross section can be written as polarization fractions f_X and the interference terms g_{XY} e.g. Mirkes 92, Stirling, Vryonidou 12, Bern, Diana, Dixon 11



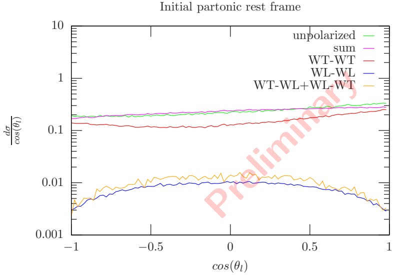
$$\sigma^{-1}\frac{d^2\sigma}{d\cos\theta^*\, d\phi^*} =$$
$$\frac{1}{4\pi}\left\{ f_+ \frac{(1-\cos\theta^*)^2}{2} + f_- \frac{(1+\cos\theta^*)^2}{2} + f_0\,(1-\cos\theta^*)^2 \right.$$
$$+\sqrt{2}g_{+0}\sin\theta^*(1-\cos\theta^*)\cos\phi^* - \sqrt{2}g_{-0}\sin\theta^*(1+\cos\theta^*)\cos\phi^*$$
$$\left. -g_{+-}\sin^2\theta^*\cos(2\phi^*)\right\}$$

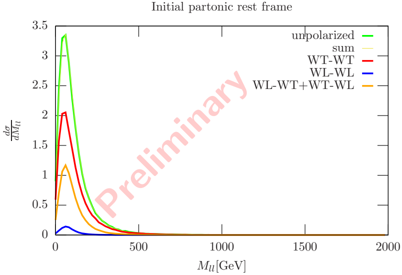
- Interference vanishes for ϕ^* integrated over all phase space.
- Typically measurements of pol. ratios assume integration over ϕ e.g. CMS 1104.3829, but selection cuts "resurrect" them, *e.g.* for W+jets Belyaev, Ross 13 and VBS Ballestrero, Maina, Pellicioli 18

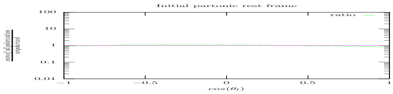
- The polarized samples can be decayed with `MadSpin`

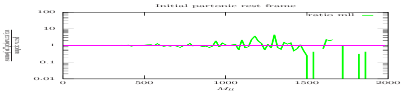
```
decay w+ > mu+ vm
decay w- > e- ve~
```

- Cut: $p_T(j) > 20\,\text{GeV}$
- Independent implementation to PHANTOM Ballestrero, Maina, Pellicciol 18
- We plan to perform a more complete comparison with PHANTOM paper with our implementation of the On-Shell Projection.









Application III: Polarized diboson production

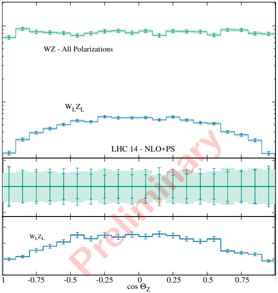
- $q\overline{q'} \to W^{\pm}_{\lambda} Z_{\lambda'}, \quad W^{\pm} \to l^{\pm}\nu_{\ell}, \quad Z \to \tau^{+}\tau^{-}$ production at NLO in QCD with PS matching

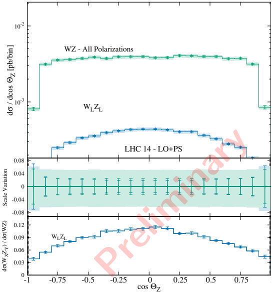
```
import model loop_sm-lepton_masses
define ww = w+ w-
generate p p > ww{T} z{L} [QCD]
decay ww > emu vem
decay  z > ta+ ta-
```

- Fiducial polarization fractions for $W^{+}Z$ production at fixed order NLO in QCD and EW have been computed Baglio, Le Duc 18
- Cuts: $|\eta^{\ell}| < 2.4$, $p_T^{\ell} > 20\,\text{GeV}$, $|m(\tau\tau) - M_Z| < 10\,\text{GeV}$.

$\sqrt{s}$	13 TeV			27 TeV			100 TeV		
Process	σ [pb]	K	ε [%]	σ [pb]	K	ε [%]	σ [pb]	K	ε [%]
WZ	$45.35^{+4.3\%}_{-4.3\%}$	1.62	...	$119.9^{+6.4\%}_{-7.1\%}$	1.77	...	$564.9^{+11.2\%}_{-12.4\%}$	2.07	...
$W_T Z_T$	$32.65^{+3.7\%}_{-3.7\%}$	1.54	(71%)	$86.30^{+5.8\%}_{-6.5\%}$	1.66	(72%)	$406.8^{+9.8\%}_{-11.4\%}$	1.91	(72%)
$W_L Z_T$	$5.396^{+5.8\%}_{-5.7\%}$	2.02	(12%)	$14.55^{+8.6\%}_{-8.9\%}$	2.33	(12%)	$70.67^{+14.5\%}_{-14.7\%}$	2.95	(13%)
$W_T Z_L$	$5.018^{+5.7\%}_{-5.7\%}$	2.08	(11%)	$13.44^{+8.9\%}_{-9.1\%}$	2.40	(11%)	$67.32^{+15.1\%}_{-15.0\%}$	3.08	(12%)
$W_L Z_L$	$2.291^{+3.8\%}_{-4.2\%}$	1.34	(5%)	$5.545^{+4.6\%}_{-6.1\%}$	1.36	(5%)	$23.00^{+6.9\%}_{-9.9\%}$	1.42	(4%)

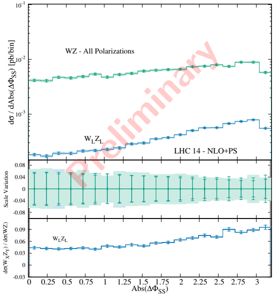
- Amplitude zeros at Born level (Baur, Han, Ohnemus 94) explain large K-factor (Bern et al. 11)
- The larger K at higher energies is led by larger gluon contribution $gq \to fWZ$
- with the TL polarization preferred in this case, a property of the Lorentz structure $gq \sim 3/2, -1/2$, fixing q helicity $1/2$ (massless quarks). V_L is produced by trilinear VVV.
- Notice for an ZZ case, there is suppressed Radiation Zero and no trilinear coupling to produce them. K-factor lower (Baglio, Ninh, Weber 13). Polarization should be checked.

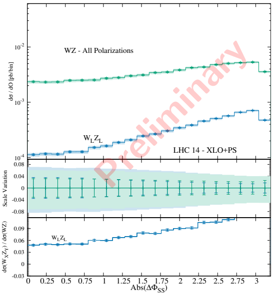




$$\cos\theta_Z = \frac{\vec{p}(\tau\tau)\cdot\vec{\tilde{p}}(\tau^-)}{|\vec{p}(\tau\tau)|\;|\vec{\tilde{p}}(\tau^-)|}$$

τ^- angle w.r.t. W direction in W rest frame





$$|\Delta\Phi_{SS}| = |\phi(\tau^\pm) - \phi(l^\pm)|$$

- Loop induced processes $gg \to W^+_\lambda W^-_{\lambda'}$, $\quad W^\pm \to l^\pm \nu_\ell$

```
generate g g > w+{L} w-{L} [QCD]
```

$\sqrt{s}$ Process	13 TeV σ [pb]	13 TeV ε [%]	14 TeV σ [pb]	14 TeV ε [%]	27 TeV σ [pb]	27 TeV ε [%]	100 TeV σ [pb]	100 TeV ε [%]
	Inclusive $gg \to W^+_\lambda W^-_{\lambda'}$ at LO							
WW	3.031	...	3.504	...	11.19	...	78.28	...
$W_T W_T$	2.794	(92%)	3.2	(91%)	10.16	(91%)	71.76	(92%)
$W_L W_T$	0.1519	(5%)	0.1742	(5%)	0.5589	(5%)	3.81	(5%)
$W_L W_L$	0.1224	(4%)	0.1412	(4%)	0.4292	(4%)	2.906	(4%)
	$p_T(W^\pm) > 250$ GeV							
WW	14.01×10^{-3}	...	17.19×10^{-3}	...	89.86×10^{-3}	...	1.193	...
$W_T W_T$	10.84×10^{-3}	(77%)	13.35×10^{-3}	(77%)	70.06×10^{-3}	(78%)	0.9297	(78%)
$W_L W_T$	0.5661×10^{-3}	(4%)	0.6945×10^{-3}	(4%)	3.549×10^{-3}	(4%)	0.04597	(4%)
$W_L W_L$	2.538×10^{-3}	(18%)	3.107×10^{-3}	(18%)	16.71×10^{-3}	(19%)	0.22	(18%)

Conclusion

- In the `MadGraph5_aMC@NLO` framework we provide the possibility to generate events at LO or NLO accuracy matched to PS for polarized particles
- Having the different polarization contributions separately is useful, for example:
  - in order to estimate distributions more precisely,
  - estimate the effect of new physics in a particular polarization
  - enrich samples of low rate polarization with the correct integration of phase space
  - devise selection cuts to enhance a particular polarization

Backup

spin $\frac{1}{2}$			
	syntax	HELAS equivalent	propagtor
	{L} {+}	+1 (Left)	Yes
	{R} {-}	-1 (Right)	Yes
spin 1			
	syntax	HELAS equivalent	propagtor
	{L} {0}	0 (Longitudinal)	Yes
	{T}	1 and -1 (Transverse)	Yes
	{+}	+1	No
	{-}	-1	No
	{A}		Only for propagators
spin 3/2			
	syntax	HELAS equivalent	propagtor
	{-1}	-1	No
	{1}	1	No
	{3}	3	No
	{-3}	-3	No
spin 2			
	syntax	HELAS equivalent	propagtor
	{-2}	-2	No
	{-1}	-1	No
	{0}	0	No
	{1}	1	No
	{2}	2	No

Beam polarization

process	polbeam1	cross-section	expected
$e^+e^- \to tt$	0	0.1664	
$e^+e^- \to tt$	100	0.2296	
$e^+e^- \to tt$	-100	0.1033	
$e^+e^- \to tt$	25	0.182	0.1822375
$e^+e^- \to tt$	50	0.1983	0.198025
$e^+e^- \to tt$	75	0.2137	0.2138125
$e^+_Le^- \to tt$	0	0.1033	0.1033
$e^+_Le^- \to tt$	100	0	0
$e^+_Le^- \to tt$	-100	0.1036	0.1033
$e^+_Re^- \to tt$	0	0.2293	0.2296
$e^+_Re^- \to tt$	100	0.2296	0.2296
$e^+_Re^- \to tt$	-100	0	0
$e^+_Re^- \to tt$	25	0.143	0.1435
$e^+_Re^- \to tt$	50	0.1719	0.1722
$e^+_Re^- \to tt$	75	0.2008	0.2009