Polarized multiboson production: At the LHC and beyond

LHCP 2021 - Sorbonne Université, Rue de la Zoom

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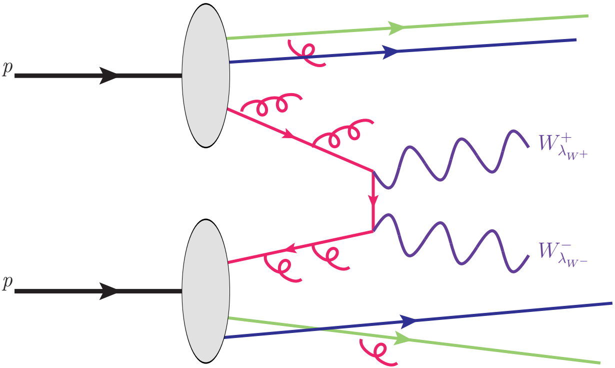
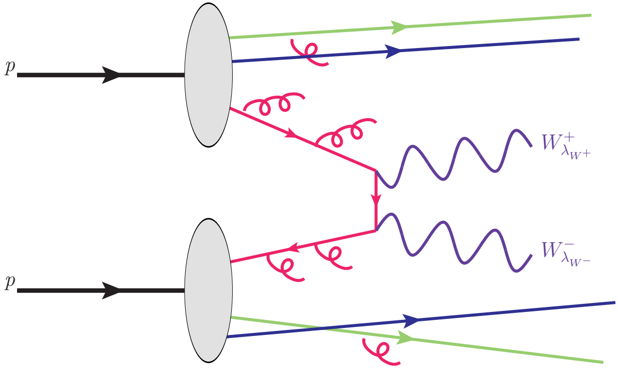
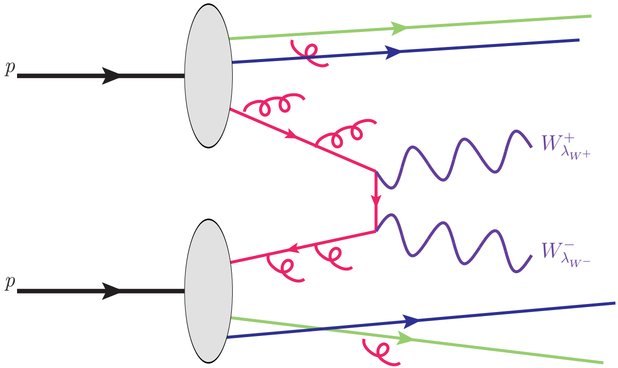
What exactly do I mean by “polarized boson production”?



Intuitively, the production of on-shell EW bosons (V)
in specific helicity eigenstates $(\lambda_V = \pm, 0)$,
defined in a particular frame $(\mathcal{R})$, in spin-averaged proton collisions



In practice, technical details, e.g., def. of $\mathcal{R}$, causes ambiguities when comparing predictions and measurements.



In response, updates on theoretical formalism and event generators (`mg5amc`) to disambiguate things!

WHY?!?!?!?!?!?!?!

Measuring polarized (multi)boson processes is important

Practical Considerations:

- Polarization is excellent test of $V \pm A$ (chiral) structure in (B)SM
- Polarization is excellent test of gauge+unitarity structure in (B)SM

Future Proofing:

- W_0/Z_0 and W_T/Z_T PDFs (needed at $\sqrt{s} \gtrsim 50$ TeV) couple differently to bosons and massles fermions

  Note that rationale studies for $\sqrt{s} = 27 - 100$ TeV are being done today!

- (N)NLO QCD + NLO EW PDFs will eventually be needed to match precision of (N)NLO QCD + NLO EW predictions

  DGLAP evolution for LH/RH quarks is asymmetric $\implies$ polarized PDFs

Important: While formally clear, technical implementation is *difficult* due to relaxing of Lorentz invariance / reference frame independence

So what is new?[1]

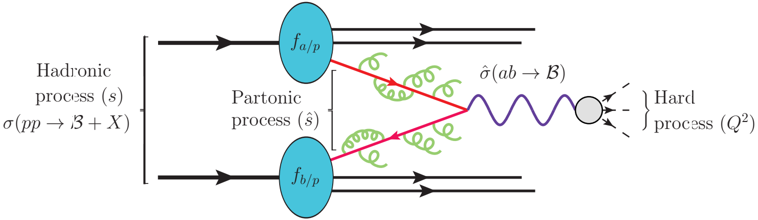
[1] w/ D. Buarque Franzosi, O. Mattelaer, S. Shil [1912.01725]

To get pp scattering rates, one uses the Collinear Factorization Thm

Collins, Soper, Sterman ('85,'88,'89); Collins, Foundations of pQCD (2011)

$$d\sigma(pp \to W\gamma + X) = \sum_{i,j} f_i \otimes f_j \otimes \Delta_{ij} \otimes d\hat{\sigma}(ij \to W\gamma) + \mathcal{O}\left(\Lambda_{\rm NP}^p / Q^{p+2}\right)$$

hadron-level scattering probabilities are the product (convolution) of parton-dist. (PDFs), -emission (Sudakov), and -scattering probs. ($|\mathcal{M}|^2$)



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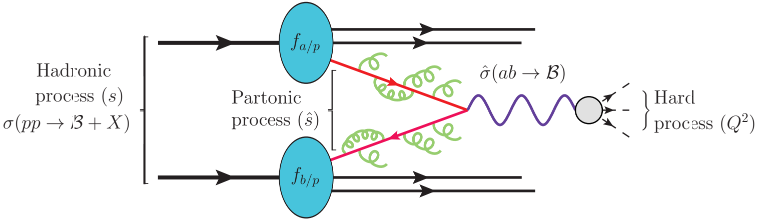

The partonic scattering rate is given by the usual (textbook) expression:

$$d\hat{\sigma}(ij \to W\gamma) = \underbrace{\frac{1}{2Q^2}}_{\text{hard scale}} \quad \underbrace{\overline{|\mathcal{M}(ij \to W\gamma)|^2}}_{\text{dof avg./summed.}}$$

The *unpolarized* external parton scattering rate is given by the dof-averaged[2] (initial states) and dof-summed (final state) matrix element:

$$\overline{|\mathcal{M}(ij \to W\gamma)|^2} = \underbrace{\frac{1}{\mathcal{S}_i \mathcal{S}_j}}_{\text{spin dof}} \underbrace{\frac{1}{N_c^i N_c^j}}_{\text{color dof}} \sum_{\text{dof}} |\underbrace{\mathcal{M}(i_\lambda j_{\lambda'} \to W_{\tilde{\lambda}} \gamma_{\tilde{\lambda}'})}_{\text{ME in helicity basis}}|^2$$

[2]Degrees of freedom = all discrete quantum numbers, e.g., color, spin, electric charge

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For *polarized* scattering, truncate the spin averaging/summing

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The two are related by reintroducing spin averaging/summing

$$\overline{|\mathcal{M}(ij \to W\gamma)|^2} = \underbrace{\frac{1}{\mathcal{S}_i \mathcal{S}_j}}_{\text{spin dof}} \sum_{\lambda,\lambda',\tilde{\lambda}\tilde{\lambda}'} \overline{|\mathcal{M}(i_\lambda j_{\lambda'} \to W_{\tilde{\lambda}} \gamma_{\tilde{\lambda}'})|^2}$$

[2] Degrees of freedom = all discrete quantum numbers, e.g., color, spin, electric charge

Polarized External Parton Scattering (3/3)

Polarized parton scattering in LHC collisions is given by

$$d\sigma(pp \to W_{\tilde{\lambda}}\gamma_{\tilde{\lambda}'} + X)|_{i_\lambda, j_{\lambda'}} = f_{i_\lambda} \otimes f_{i_{\lambda'}} \otimes \Delta_{i_\lambda j_{\lambda'}} \otimes d\hat{\sigma}(i_\lambda j_{\lambda'} \to W_\lambda \gamma_{\tilde{\lambda}'})$$

- f_{i_λ} is the PDF for parton i with helicity λ in *unpolarized proton* p
- $\Delta_{i_\lambda j_{\lambda'}}$ is the parton shower / evolution for i, j with helicities λ, λ'

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Again, unpolarized scattering is recovered by spin averaging/summing

$$d\sigma(pp \to W\gamma + X) = \underbrace{\sum_{i_\lambda, j_{\lambda'}}}_{\text{partons}} \underbrace{\frac{1}{\mathcal{S}_i \mathcal{S}_j}}_{\text{spin dof}} \underbrace{\sum_{\lambda, \lambda', \tilde{\lambda}\tilde{\lambda}'}}_{\text{helicities}} d\sigma(pp \to W_{\tilde{\lambda}}\gamma_{\tilde{\lambda}'} + X)|_{i_\lambda, j_{\lambda'}}$$

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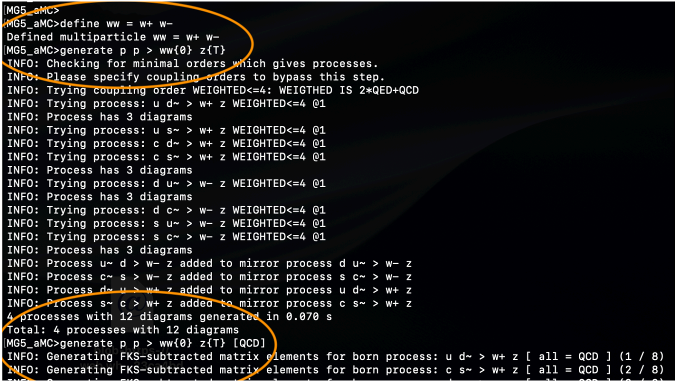
Hence, for unpolarized initial states and polarized final states:

$$d\sigma(pp \to W_{\tilde{\lambda}}\gamma_{\tilde{\lambda}'} + X) = \sum_{i_\lambda, j_{\lambda'}} \underbrace{\frac{1}{\mathcal{S}_i \mathcal{S}_j}}_{\text{spin dof}} \sum_{\lambda, \lambda'} d\sigma(pp \to W_{\tilde{\lambda}}\gamma_{\tilde{\lambda}'} + X)|_{i_\lambda, j_{\lambda'}}$$

Polarized multo-boson production

with `MadGrap5_aMC@NLO` (`mg5amc`)

Generating polarized events at LO in QCD with mg5amc is as difficult as unpolarized computations now (NLO still in developement!)



```
MG5_aMC>
MG5_aMC>define ww = w+ w-
Defined multiparticle ww = w+ w-
MG5_aMC>generate p p > ww{0} z{T}
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying coupling order WEIGHTED<=4: WEIGTHED IS 2*QED+QCD
INFO: Trying process: u d~ > w+ z WEIGHTED<=4 @1
INFO: Process has 3 diagrams
INFO: Trying process: u s~ > w+ z WEIGHTED<=4 @1
INFO: Trying process: c d~ > w+ z WEIGHTED<=4 @1
INFO: Trying process: c s~ > w+ z WEIGHTED<=4 @1
INFO: Process has 3 diagrams
INFO: Trying process: d u~ > w- z WEIGHTED<=4 @1
INFO: Process has 3 diagrams
INFO: Trying process: d c~ > w- z WEIGHTED<=4 @1
INFO: Trying process: s u~ > w- z WEIGHTED<=4 @1
INFO: Trying process: s c~ > w- z WEIGHTED<=4 @1
INFO: Process has 3 diagrams
INFO: Process u~ d > w- z added to mirror process d u~ > w- z
INFO: Process c~ s > w- z added to mirror process s c~ > w- z
INFO: Process d~ u > w+ z added to mirror process u d~ > w+ z
INFO: Process s~ c > w+ z added to mirror process c s~ > w+ z
4 processes with 12 diagrams generated in 0.070 s
Total: 4 processes with 12 diagrams
MG5_aMC>generate p p > ww{0} z{T} [QCD]
INFO: Generating FKS-subtracted matrix elements for born process: u d~ > w+ z [ all = QCD ] (1 / 8)
INFO: Generating FKS-subtracted matrix elements for born process: c s~ > w+ z [ all = QCD ] (2 / 8)
```

- z{T} denotes LH $(-)$ and RH $(+)$ transverse Z bosons
- ww{0} denotes longitudinal $W^{\pm}$ bosons
- **Important**: Just be careful to know in which frame the helicity polarizations are defined

Details and instructions in [1912.01725]

Vector boson scattering at the LHC

Quick advert: new review on VBS/F for (B)SM at the LHC and beyond!

- Covers machine learning, BSM models, EW PDFs/parton showers, SMEFT, muon colliders, ILC, FCC, hardware, and more!

The work of many great people! [2106.01393]

arXiv.org > hep-ph > arXiv:2106.01393

High Energy Physics - Phenomenology

[Submitted on 2 Jun 2021]

Vector Boson Scattering Processes: Status and Prospects

Diogo Buarque Franzosi, Michele Gallinaro, Richard Ruiz, Thea K. Aarrestad, Mauro Chiesa, Antonio Costantini, Ansgar Denner, Stefan Dittmaier, Flavia Cetorelli, Robert Franken, Pietro Govoni, Tao Han, Ashutosh V. I
Lohwasser, Kenneth Long, Yang Ma, Luca Mantani, Matteo Marchegiani, Mathieu Pellen, Giovanni Pelliccioli, Karolos Potamianos, Jürgen Reuter, Timo Schmidt, Christopher Schwan, Michał Szleper, Rob Verheyen, Ke

Insight into the electroweak (EW) and Higgs sectors can be achieved through measurements of vector boson scattering (VBS) processes. The scattering of EW bosons are rare processes that are precisely predicted in the Standard Model (SM) and are
Higgs mechanism. Modifications to VBS processes are also predicted in models of physics beyond the SM (BSM), for example through changes to the Higgs boson couplings to gauge bosons and the resonant production of new particles. In this review,
and theoretical developments of VBS at the Large Hadron Collider, its high luminosity upgrade, and future colliders are presented.

Comments:	53 pages (including toc and refs.), 69 image files, eight tables, and many references. VBSCan@Snowmass review and white paper. Comments to editors are welcome!
Subjects:	**High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)
Report number:	CP3-21-14, DESY-21-064, IFJPAN-IV-2021-8, PITT-PACC-2106, VBSCAN-PUB-04-21
Cite as:	arXiv:2106.01393 **[hep-ph]**
	(or arXiv:2106.01393v1 **[hep-ph]** for this version)

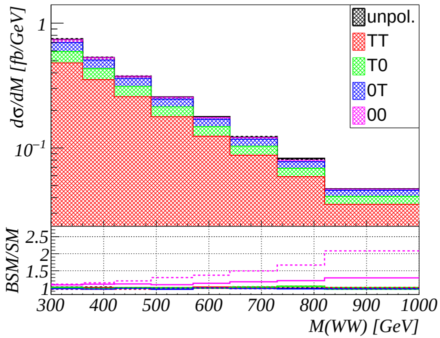
Submission history

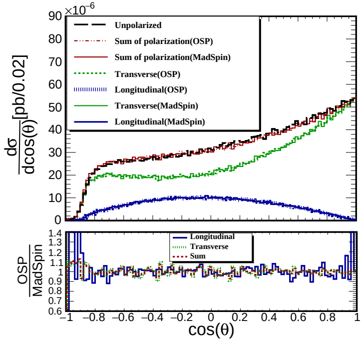
From: Richard Ruiz [view email]
[v1] Wed, 2 Jun 2021 18:00:33 UTC (6,563 KB)

With mg5amc, fully differential events are possible, e.g.,

$$pp \to W^+_{\lambda_{W^+}} W^-_{\lambda_{W^-}} jj \to \ell^+\ell^-\nu\bar{\nu}jj \text{ at } \mathcal{O}(\alpha_W^4)$$

For $(\lambda_{W^+}, \lambda_{W^-})$ defined in the (W^+W^-)-frame and after VBF cuts role of individual polarizations clear

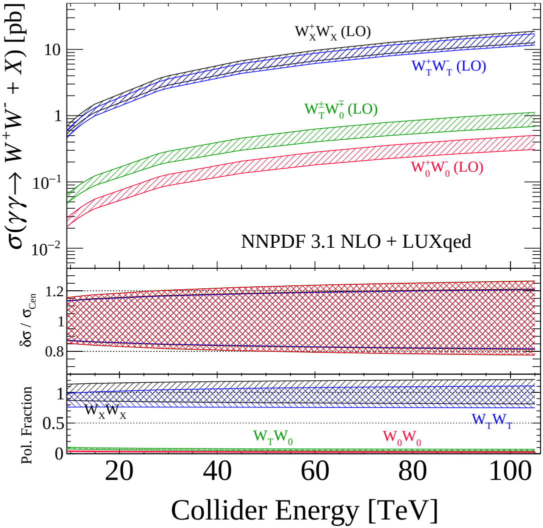




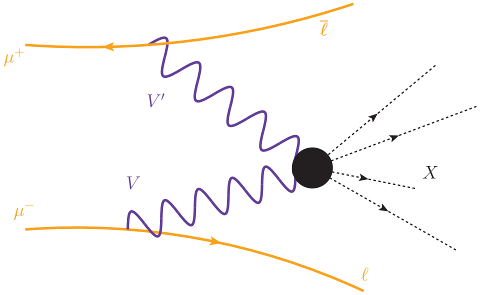
- $(\lambda_{W^+}, \lambda_{W^-})$ can be defined in most any frame [1912.01725]

With mg5amc, on-the-fly uncertainty weights and γ-PDF compability

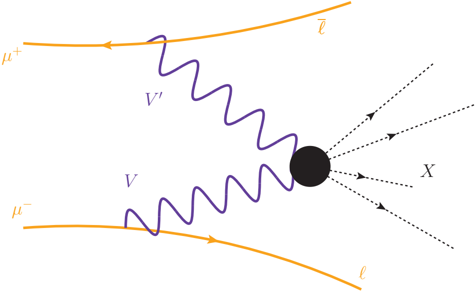
$$\gamma\gamma \to W^+_{\lambda_{W+}} W^-_{\lambda_{W-}}$$



Beyond the LHC



Preliminary Effective Vector Boson Approximation (EVA): EW bosons as partons of the $\mu^{\pm}$ [3]



[3] w/ A. Costantini, F. Maltoni, L. Mantani, O. Mattelaer, et al [soon]

At very high scales $Q \gg M_W, M_Z$, EW bosons can be treated as partons

a.k.a. the Effective W Approximation [Dawson('84); Kane, et al ('84); Kunszt and Soper ('88)]

- Treatment of V_T identical to gluons in QCD; V_0 is novel complication
- W/Z PDFs will be released very soon in `MadGraph5`

$$f_{V_+/f_L}(z,\mu_f^2) = \frac{g_V^2}{4\pi^2}\frac{g_L^2(1-z)^2}{2z}\log\left[\frac{\mu_f^2}{M_V^2}\right],$$

$$f_{V_-/f_L}(z,\mu_f^2) = \frac{g_V^2}{4\pi^2}\frac{g_L^2}{2z}\log\left[\frac{\mu_f^2}{M_V^2}\right],$$

$$f_{V_0/f_L}(z,\mu_f^2) = \frac{g_V^2}{4\pi^2}\frac{g_L^2(1-z)}{z},$$

$$f_{V_+/f_R}(z,\mu_f^2) = \left(\frac{g_R}{g_L}\right)^2 \times f_{V_-/f_L}(z,\mu_f^2)$$

$$f_{V_-/f_R}(z,\mu_f^2) = \left(\frac{g_R}{g_L}\right)^2 \times f_{V_+/f_L}(z,\mu_f^2)$$

$$f_{V_0/f_R}(z,\mu_f^2) = \left(\frac{g_R}{g_L}\right)^2 \times f_{V_0/f_L}(z,\mu_f^2)$$

```
c     /* ******************************************************** *
c     EVA (1/6) for f_L > v_+
      double precision function eva_fL_to_vp(gg2,gL2,mv2,x,mu2,ievo)
      implicit none
      integer ievo                ! evolution by q2 or pT2
      double precision gg2,gL2,mv2,x,mu2
      double precision coup2,split,xxlog,fourPiSq
      data fourPiSq/39.47841760435743d0/ ! = 4pi**2

c      print*,'gg2,gL2,mv2,x,mu2,ievo',gg2 !3,gL2,mv2,x,mu2,ievo
      coup2 = gg2*gL2/fourPiSq
      split = (1.d0-x)**2 / 2.d0 / x
      if(ievo.eq.0) then
         xxlog = dlog(mu2/mv2)
      else
         xxlog = dlog(mu2/mv2/(1.d0-x))
      endif

      eva_fL_to_vp = coup2*split*xxlog
      return
      end
c     /* ******************************************************** *
c     EVA (2/6) for f_L > v_-
      double precision function eva_fL_to_vm(gg2,gL2,mv2,x,mu2,ievo)
      implicit none
      integer ievo                ! evolution by q2 or pT2
      double precision gg2,gL2,mv2,x,mu2
      double precision coup2,split,xxlog,fourPiSq
      data fourPiSq/39.47841760435743d0/ ! = 4pi**2

      coup2 = gg2*gL2/fourPiSq
      split = 1.d0 / 2.d0 / x
      if(ievo.eq.0) then
         xxlog = dlog(mu2/mv2)
      else
         xxlog = dlog(mu2/mv2/(1.d0-x))
      endif

      eva_fL_to_vm = coup2*split*xxlog
      return
      end
```

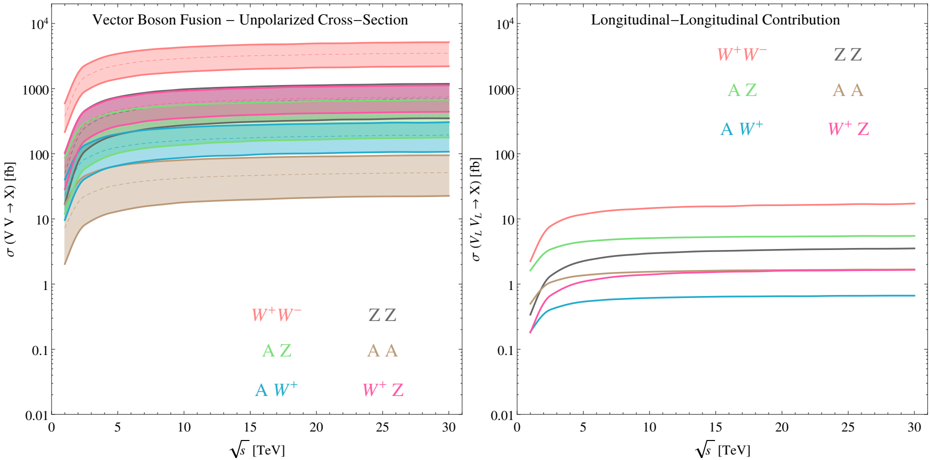
some results on

scattering of polarized EW bosons $V_\lambda V'_{\lambda'} \to X$ [4]

[4] w/ A. Costantini, F. Maltoni, L. Mantani, O. Mattelaer [2105.?????]

Diboson production

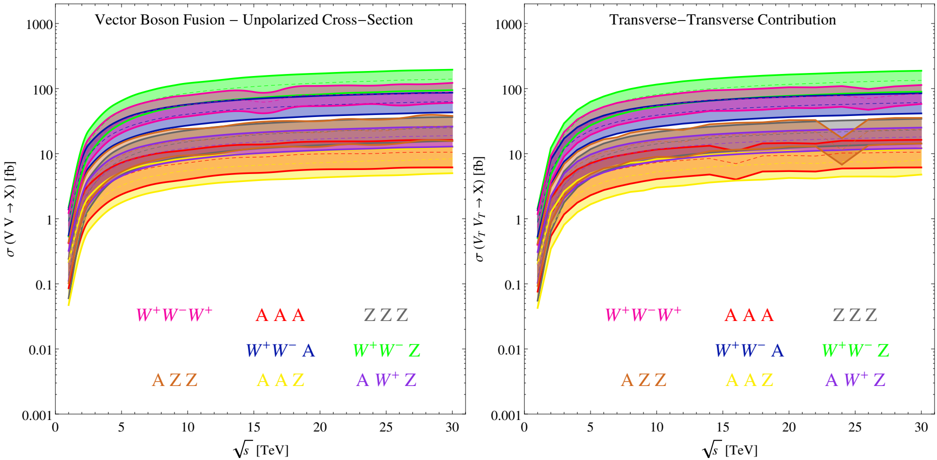
$V_\lambda V'_\lambda \to VV'$: (L) all polarizations (R) $V_0 V_0$



- Only minor role played by $V_0 V'_0$ scattering
- At $\mathcal{L} = 1\ \mathrm{ab}^{-1}/yr \implies 10^6\ WW/yr$ driven by non-Abelian couplings

Triboson production in EVA

$V_\lambda V'_\lambda \to VV'V''$: (L) all polarizations (R) $V_T V_T$



- Major role played by $V_T V'_T$ scattering
- At $\mathcal{L} = 1\ \mathrm{ab}^{-1}/yr \implies 10^3\ VV'V''/yr$

Summary

Searches and measurements of polarized EW bosons remains a powerful probe of SM and BSM physics

- Formalism ready for multiboson, VBF/VBS, etc, tests of (B)SM, in place for future studies and future colliders!

  w/ D. Buarque Franzosi, O. Mattelaer, S. Shil [1912.01725]

- Polarized scattering amplitudes and cross sections now possible with `MadGraph5` simulation framework

  w/ D. Buarque Franzosi, O. Mattelaer, S. Shil [1912.01725]

- Using EVA, $V_\lambda V'_{\lambda'}$ scattering reveal a new picutre of the EW sector at high energies (EVA in `MadGraph5` will be released soon!)

  w/ A. Costantini, F. Maltoni, L. Mantani, O. Mattelaer, et al [soon!]

- Lots not shown: polarization propagation via `MadSpin`, polarization in different reference frames **Stay tuned! New results out soon!**

Thank you for listening!