Weak boson scattering from weak boson PDFs

Snowmass on the Zoomissippi: EF04 Group Meeting

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[1] on behalf of many co-signers

the big LoI question

Question: How does the electroweak theory behave at very high energies?

Letter of Interest: EW effects in very high-energy phenomena

C. Arina, G. Cuomo, T. Han, Y.Ma, F. Maltoni, A. Manohar, S. Prestel, R. Ruiz, L. Vecchi, R. Verheyen, B. Webber, W. Waalewijn, A. Wulzer, K. Xie

to be submitted to the Theory Frontier (TF07) and Energy Frontier (EF04)

1 Introduction

Phenomena that take place at multi-TeV scales — high-energy elementary particle scattering or the annihilation/decay of ultra heavy states such as dark matter particles — can give rise to relativistic, final states that are naturally accompanied by additional radiation, that in turn leads to particle showers and final states with large particle multiplicities. In the the Standard Model, the effects of QCD and QED radiation are well understood and treated at various level of sophistication. These range from fixed-order computations at an increasing accuracy to resummed computations via parton showering algorithms and semi-analytic approaches. Even matching/merging between the two while keeping their respective accuracies is available.

In such multi-TeV scales processes typical momentum transfers Q are much larger than the electroweak (EW) scale $m \sim m_Z$, and intial- and final-state EW radiation becomes important. In particular, EW boson emission gives rise to transition rates that grow with logarithms of the type $\log Q/m$. For sufficiently large Q, these logarithms must be resummed in order to recover physically meaningful results. Despite recent progress, a fully exclusive approach that can take care of fixed-order EW corrections, resum large EW logarithms in both inital and final states, systematically account for power corrections, and is implemented in ready-to-use Monte Carlo

Snowmass 21 LoI: SNOWMASS21-TF7_TF0-EF4_EF0-026

Many *fascinating* ways to explore this, e.g., EW parton showers

Summary of output since hiatus

Lots of neat work from the past year! (lots of older work uncited)

- EW boson scattering / fusion at future colliders **(review)**

  ☺ Buarque, et al [2106.01393]

- EW boson PDFs — Han,Ma,Xie [2007.14300; 2103.09844]; ☺ Ruiz, et al [2111.02442]

- EW parton showers — Veryheyen, et al [2002.09248; 2108.10786]

- Spin correlation and interference in parton showers

  Prestel, et al [2109.09706; 2110.05964], Veryheyen, et al [2111.01161]

- Muon collider physics — (many!)

Slide stolen from LoI update on Nov 6 2020!

How the EW theory behaves at very high energies is being explored!

- Exploring polarized matrix elements with `MadGraph5`

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

- Exploring EW VBF with multi-TeV muon colliders

  w/ A. Costantini, F. De Lillo, F. Maltoni, L. Mantani, O. Mattelaer, X. Zhao [2005.10289]

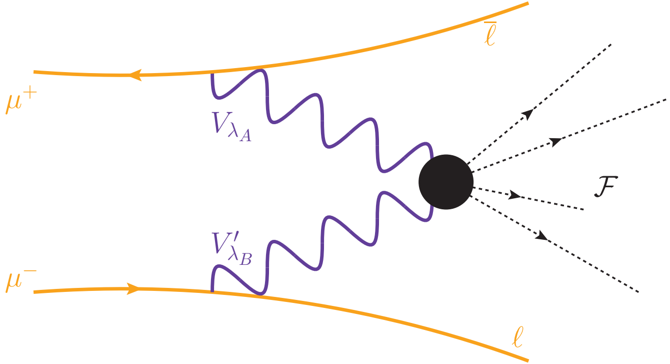
  - Multi-TeV $\ell^+\ell^-$ colliders are "high-luminosity EW boson colliders"

- **NEW!** Exploring the validity of W_λ/Z_λ PDFs

  w/ A. Costantini, F. Maltoni, O. Mattelaer [2111.02442]

  - Support for W_λ/Z_λ PDFs from $\mu^\pm, e^\pm$ beams in `MadGraph5`

Part III: Effective Vector Boson Approximation in High-Energy Muon Collisions



What did we implement into MadGraph5_aMC@NLO?

$$\sigma(\mu^+\mu^- \to \mathcal{F} + X) = f \otimes f \otimes \hat{\sigma} + \text{power-law and log corrections} \quad (1)$$

What did we implement into MadGraph5_aMC@NLO?

$$\sigma(\mu^+\mu^- \to \mathcal{F} + X) = f \otimes f \otimes \hat{\sigma} + \text{power-law and log corrections} \quad (1)$$

$$= \sum_{V_{\lambda_A}, V'_{\lambda_B}} \int_{\tau_0}^{1} d\xi_1 \int_{\tau_0/\xi_1}^{1} d\xi_2 \int dPS_n$$
$$\times \left[f_{V_{\lambda_A}/\mu^+}(\xi_1, \mu_f) f_{V'_{\lambda_B}/\mu^-}(\xi_2, \mu_f) \right] \quad \times \quad \frac{d\hat{\sigma}(V_{\lambda_A} V'_{\lambda_B} \to \mathcal{F})}{dPS_n}$$
$$+ \mathcal{O}\left(\frac{M_V^2}{M_{VV'}^2}\right) + \mathcal{O}\left(\frac{p_T^2}{M_{VV'}^2}\right) + \mathcal{O}\left(\frac{\alpha_W}{M_{VV'}^2} \log \frac{\mu_f^2}{M_{VV'}^2}\right). \quad (2)$$

- Fully differential events for $V_{\lambda_A} V'_{\lambda_B} \to \mathcal{F}$ at lowest order (LO)
- $V_{\lambda_A} \in \{W_\lambda^\pm, Z_\lambda, \gamma_\lambda\}$ with nonzero M_Z, M_W
- $\mathcal{F}$ can be anything (in practice, up to 5-6 legs)
- $f_{V_\lambda/\mu^\pm}(\xi, \mu_f)$ are bare LO PDFs [Dawson('85); Peskin&Schroeder]
- No RG evolution ← important!

W_λ/Z_λ PDFs depend on helicity (λ) of V and $\mu^\pm$

- Subtle but important differences if evolving by q vs p_T

(this can account for some differences between groups!)

- γ_λ PDF (Weizsacker-Williams) also added; kept "Improved WW"

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

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

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

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

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

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

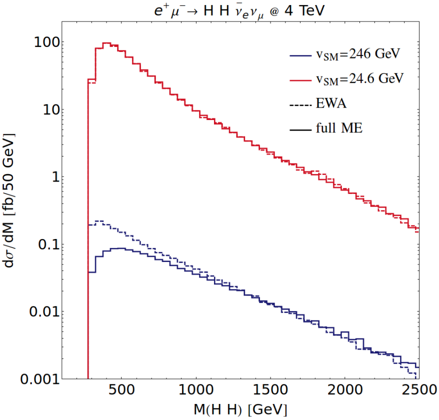
```
c     /* ********************************************************* *
c     EVA (1/6) for f_L > v_+
      double precision function eva_fL_to_vp(gg2,gL2,mv2,x,mu2,ievo)
      implicit none
      integer ievo              ! evolution by q2 or pT2
      double precision gg2,gL2,mv2,x,mu2
      double 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
```

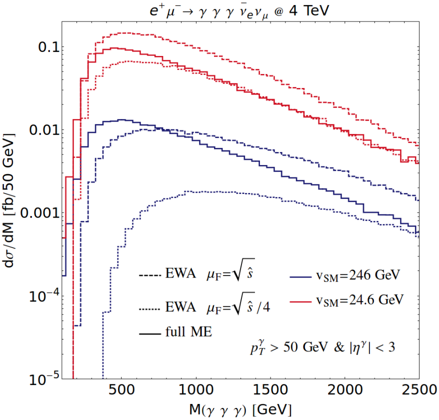
Universal and Quasi-Universal Uncertainties

Spent a lot of time trying to understand when factorization works

- Necessary that $(M_V^2/M_{VV'}^2) \lesssim 0.01$ (just like heavy quark factorization!)

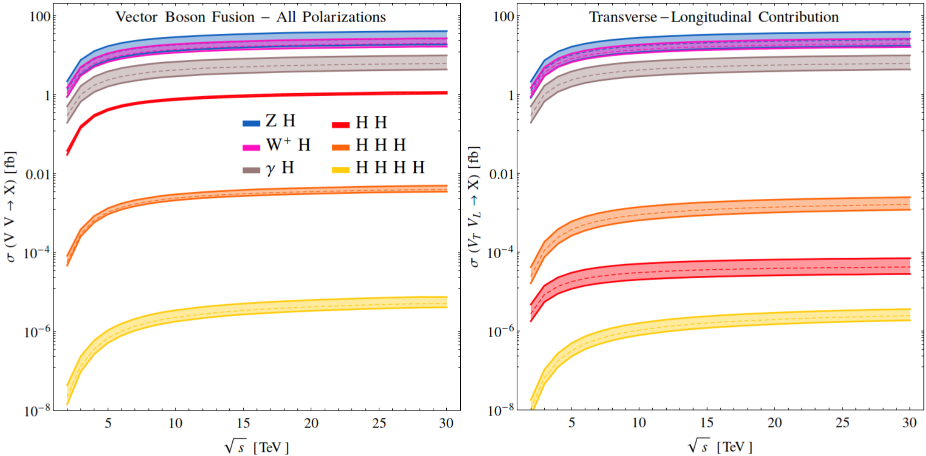
(L) $W_0^+ W_0^- \to HH$ (R) $W_T^+ W_T^- \to \gamma\gamma\gamma$





We then had fun looking into *many* processes

(L) $\sum_{\lambda_A,\lambda_B} V_{\lambda_A} V_{\lambda_B} \to HX$ (R) $V_T V_0 \to HX$



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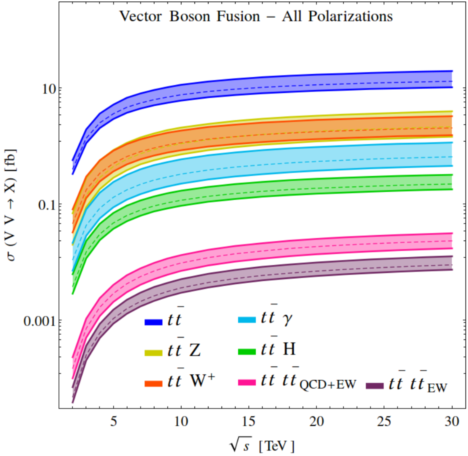
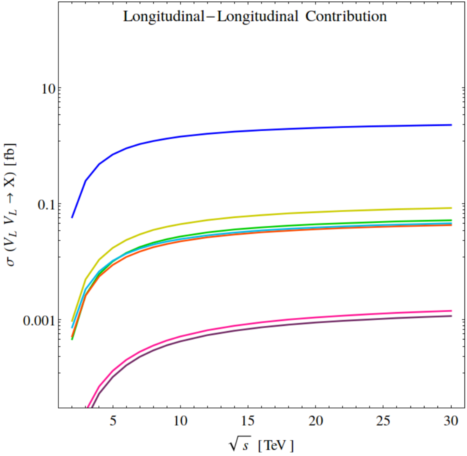
$$\text{(L)} \sum_{\lambda_A,\lambda_B} V_{\lambda_A} V_{\lambda_B} \to t\bar{t}X \qquad \text{(R)} \; V_0 V_0 \to t\bar{t}X$$

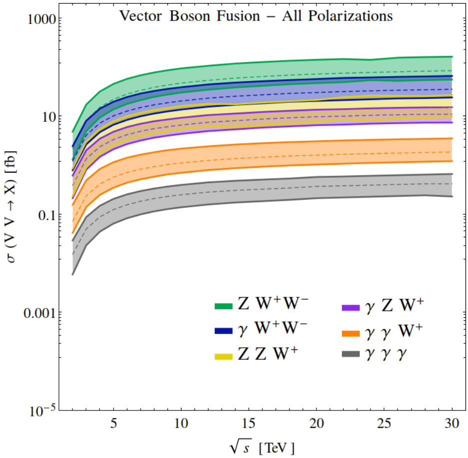


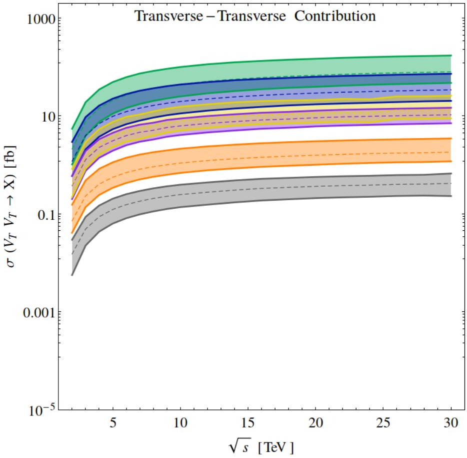


Survey (3/4)

We then had fun looking into *many* processes

(L) $\sum_{\lambda_A,\lambda_B} V_{\lambda_A} V_{\lambda_B} \to 3V$ (R) $V_T V_T \to 3V$





Survey (4/4)

We then had fun looking into *many* processes

	mg5amc syntax	σ [fb] $\sqrt{s}=3$ TeV	$\sqrt{s}=14$ TeV	$\sqrt{s}=30$ TeV
$\sum V_{\lambda_A} V'_{\lambda_B} \to W^+W^-$	`vp vm > w+ w-`	$2.2\cdot10^{2}\,{}^{+98\%}_{-35\%}$	$7.0\cdot10^{2}\,{}^{+91\%}_{-33\%}$	$8.6\cdot10^{2}\,{}^{+88\%}_{-32\%}$
$V_T V'_T \to W^+W^-$	`vp{T} vm{T} > w+ w-`	$2.0\cdot10^{2}\,{}^{+99\%}_{-35\%}$	$6.6\cdot10^{2}\,{}^{+93\%}_{-34\%}$	$8.0\cdot10^{2}\,{}^{+92\%}_{-33\%}$
$V_0 V'_T \to W^+W^-$	`vp{0} vm{T} > w+ w-`	$1.2\cdot10^{1}\,{}^{+54\%}_{-27\%}$	$4.4\cdot10^{1}\,{}^{+50\%}_{-25\%}$	$5.2\cdot10^{1}\,{}^{+49\%}_{-24\%}$
$V_0 V'_0 \to W^+W^-$	`vp{0} vm{0} > w+ w-`	$4.2\cdot10^{-1}$	$1.7\cdot10^{0}$	$2.0\cdot10^{0}$
$\sum V_{\lambda_A} V'_{\lambda_B} \to W^+Z$	`vp vm > w+ z`	$5.3\cdot10^{1}\,{}^{+105\%}_{-40\%}$	$1.8\cdot10^{2}\,{}^{+97\%}_{-37\%}$	$2.2\cdot10^{2}\,{}^{+95\%}_{-37\%}$
$V_T V'_T \to W^+Z$	`vp{T} vm{T} > w+ z`	$5.0\cdot10^{1}\,{}^{+111\%}_{-42\%}$	$1.6\cdot10^{2}\,{}^{+103\%}_{-39\%}$	$2.0\cdot10^{2}\,{}^{+100\%}_{-38\%}$
$V_0 V'_T \to W^+Z$	`vp{0} vm{T} > w+ z`	$3.4\cdot10^{0}\,{}^{+36\%}_{-18\%}$	$1.4\cdot10^{1}\,{}^{+34\%}_{-17\%}$	$1.7\cdot10^{1}\,{}^{+34\%}_{-17\%}$
$V_0 V'_0 \to W^+Z$	`vp{0} vm{0} > w+ z`	$3.9\cdot10^{-2}$	$2.1\cdot10^{-1}$	$2.6\cdot10^{-1}$
$\sum V_{\lambda_A} V'_{\lambda_B} \to ZZ$	`vp vm > z z`	$4.4\cdot10^{1}\,{}^{+164\%}_{-52\%}$	$1.6\cdot10^{2}\,{}^{+144\%}_{-48\%}$	$1.9\cdot10^{2}\,{}^{+143\%}_{-48\%}$
$V_T V'_T \to ZZ$	`vp{T} vm{T} > z z`	$4.0\cdot10^{1}\,{}^{+171\%}_{-54\%}$	$1.4\cdot10^{2}\,{}^{+153\%}_{-50\%}$	$1.7\cdot10^{2}\,{}^{+150\%}_{-49\%}$
$V_0 V'_T \to ZZ$	`vp{0} vm{T} > z z`	$4.2\cdot10^{0}\,{}^{+66\%}_{-33\%}$	$1.8\cdot10^{1}\,{}^{+61\%}_{-30\%}$	$2.2\cdot10^{1}\,{}^{+60\%}_{-30\%}$
$V_0 V'_0 \to ZZ$	`vp{0} vm{0} > z z`	$1.1\cdot10^{-1}$	$6.0\cdot10^{-1}$	$7.2\cdot10^{-1}$
$\sum V_{\lambda_A} V'_{\lambda_B} \to \gamma Z$	`vp vm > a z`	$1.9\cdot10^{1}\,{}^{+169\%}_{-53\%}$	$7.1\cdot10^{1}\,{}^{+149\%}_{-49\%}$	$8.8\cdot10^{1}\,{}^{+145\%}_{-48\%}$
$V_T V'_T \to \gamma Z$	`vp{T} vm{T} > a z`	$1.8\cdot10^{1}\,{}^{+172\%}_{-54\%}$	$6.8\cdot10^{1}\,{}^{+153\%}_{-50\%}$	$8.4\cdot10^{1}\,{}^{+149\%}_{-49\%}$
$V_0 V'_T \to \gamma Z$	`vp{0} vm{T} > a z`	$9.5\cdot10^{-1}\,{}^{+67\%}_{-33\%}$	$4.4\cdot10^{0}\,{}^{+61\%}_{-30\%}$	$5.5\cdot10^{0}\,{}^{+60\%}_{-30\%}$
$V_0 V'_0 \to \gamma Z$	`vp{0} vm{0} > a z`	$5.6\cdot10^{-4}$	$4.5\cdot10^{-3}$	$6.5\cdot10^{-3}$
$\sum V_{\lambda_A} V'_{\lambda_B} \to \gamma W^+$	`vp vm > a w+`	$1.1\cdot10^{1}\,{}^{+111\%}_{-42\%}$	$4.0\cdot10^{1}\,{}^{+101\%}_{-39\%}$	$4.9\cdot10^{1}\,{}^{+99\%}_{-38\%}$
$V_T V'_T \to \gamma W^+$	`vp{T} vm{T} > a w+`	$1.1\cdot10^{1}\,{}^{+111\%}_{-42\%}$	$3.9\cdot10^{1}\,{}^{+102\%}_{-39\%}$	$4.8\cdot10^{1}\,{}^{+100\%}_{-38\%}$
$V_0 V'_T \to \gamma W^+$	`vp{0} vm{T} > a w+`	$1.6\cdot10^{-2}\,{}^{+62\%}_{-31\%}$	$7.3\cdot10^{-1}\,{}^{+56\%}_{-28\%}$	$9.2\cdot10^{-1}\,{}^{+54\%}_{-27\%}$
$V_0 V'_0 \to \gamma W^+$	`vp{0} vm{0} > a w+`	$1.5\cdot10^{-4}$	$1.2\cdot10^{-3}$	$1.7\cdot10^{-3}$
$\sum V_{\lambda_A} V'_{\lambda_B} \to \gamma\gamma$	`vp vm > a a`	$2.1\cdot10^{0}\,{}^{+172\%}_{-54\%}$	$8.5\cdot10^{0}\,{}^{+152\%}_{-50\%}$	$1.1\cdot10^{1}\,{}^{+147\%}_{-48\%}$
$V_T V'_T \to \gamma\gamma$	`vp{T} vm{T} > a a`	$2.1\cdot10^{0}\,{}^{+172\%}_{-54\%}$	$8.5\cdot10^{0}\,{}^{+152\%}_{-50\%}$	$1.1\cdot10^{1}\,{}^{+147\%}_{-48\%}$
$V_0 V'_T \to \gamma\gamma$	`vp{0} vm{T} > a a`	$7.8\cdot10^{-4}\,{}^{+70\%}_{-35\%}$	$3.4\cdot10^{-3}\,{}^{+67\%}_{-34\%}$	$4.2\cdot10^{-3}\,{}^{+67\%}_{-33\%}$
$V_0 V'_0 \to \gamma\gamma$	`vp{0} vm{0} > a a`	$5.8\cdot10^{-4}$	$4.7\cdot10^{-3}$	$6.8\cdot10^{-3}$

How the EW theory behaves at very high energies is being explored!

- Exploring polarized matrix elements with `MadGraph5`

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

- Exploring EW VBF with multi-TeV muon colliders

  w/ A. Costantini, F. De Lillo, F. Maltoni, L. Mantani, O. Mattelaer, X. Zhao [2005.10289]

  - Multi-TeV $\ell^+\ell^-$ colliders are "high-luminosity EW boson colliders"

- **NEW!** Exploring the validity of W_λ/Z_λ PDFs

  w/ A. Costantini, F. Maltoni, O. Mattelaer [2111.02442]

  - Support for W_λ/Z_λ PDFs from $\mu^\pm, e^\pm$ beams in `MadGraph5`

Thank you.

Example Usage

For $V_T V_T \to HH$ at $\sqrt{s} = 3$ TeV in $\mu^+\mu^-$ collisions:

```
 $ ./bin/mg5_aMC
set group_subprocesses false
set gauge Feynman
define vp = w+ z a
define vm = w- z a
generate vp{T} vm{T} > h h
output vtvt_hh
launch
set lpp1 -4
set lpp2 4
set pdlabel eva # calls EVA PDF sets
set fixed_fac_scale false
set dynamical_scale_choice 4 # muf = scalefact * dsqrt(shat)
set scalefact 0.5
set ievo_eva 0 # evolution scheme (0=q2 or 1=pT2)
set ebeam 1500 # GeV
set no_parton_cut
set nevents 1k
set dsqrt_shat 1000 # requirement on M(VV) system
set pt_min_pdg {25:50}
set eta_max_pdg {25:3}
set use_syst true
set nhel 1 # MC sampling over helicities.  must be set to 1
done
```

See appendix B of [2111.02442] for many more details!