Theory Developments in VBS/VBF

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Thank you for the (in-person) invitation! ☺

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High Energy Physics - Phenomenology

[Submitted on 2 Jun 2021 (v1), last revised 15 Apr 2022 (this version, v2)]

Vector Boson Scattering Processes: Status and Prospects

Diogo Buarque Franzosi, Michele Gallinaro, Richard Ruiz, Thea K. Aarrestad, Flavia Cetorelli, Mauro Chiesa, Antonio Costantini, Ansgar Denner, Stefan Dittmaier, Robert Franken, Pietro Govoni, Tao Han, Ashutosh V. Kotwal, Jinmian Li 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, Keping Xie, Rao Zha

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 closely related to the 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, experimental results a theoretical developments of VBS at the Large Hadron Collider, its high luminosity upgrade, and future colliders are presented.

Comments: Journal version with additional discussion and references. 56 pages (including toc and refs.), 71 image files, eight tables, and many references. VBSCan@Snowmass review
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
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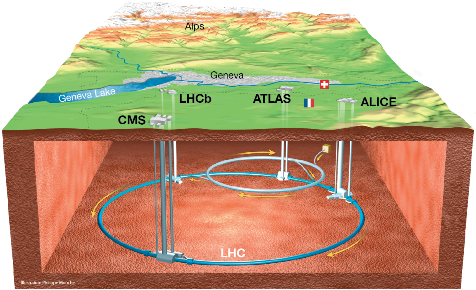
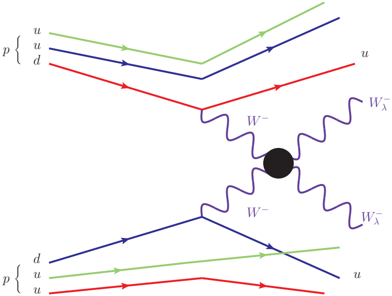
- **VBSCan@Snowmass review:** "state-of-the-art" + (Snowmass) projections for HL-LHC + future colliders (pp, e^+e^-, $\mu^+\mu^-$) [2106.01393]
- **Updates:** follow-up work of Snowmass activities
- **Apologies:** skipping **lots** since only talk is only 15' ☹

Motivation: measuring rare processes, **e.g., vector boson scattering (VBS)**, is part of the **Large Hadron Collider's** long-term program

See review by Buarque (ed.), Gallinaro (ed.), RR (ed.), et al, Rev. Physics ('22) [arXiv:2106.01393]





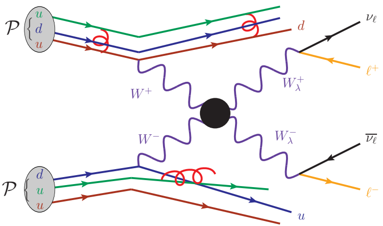
VBS probes spin & charge configurations inaccessible with quarks/gluons

$\Longrightarrow$ **VBS is uniquely sensitive** to Standard Model and new physics!

polarization in vector boson fusion (VBF) / scattering (VBS)

The $W^\pm_\lambda, Z_\lambda$ bosons are massive, spin-1 objects

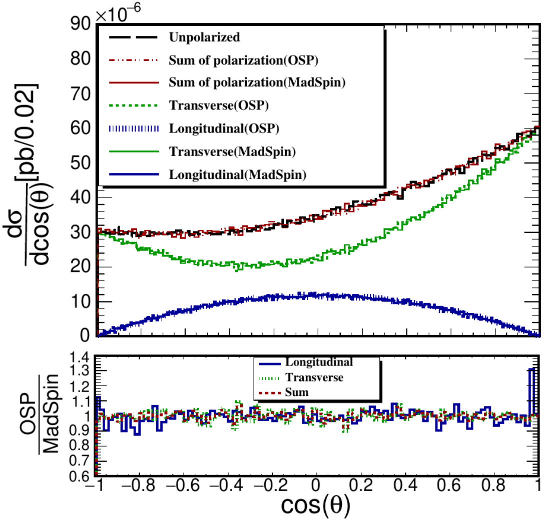
– 2 transverse polarizations (L,R)
– 1 longitudinal polarization (0)



polarizations also imprint on kinematics of decay products!

MadGraph5_aMC@NLO now supports event simulation at LO of particles with fixed helicities

Plotted: angle of outgoing ℓ^- in $pp \to W^+ W^-_\lambda jj \to W^+ \ell^- \overline{\nu_\ell} jj$ via VBS



Buarque Franzosi, Mattelaer, RR, Shil [(JHEP'20)]

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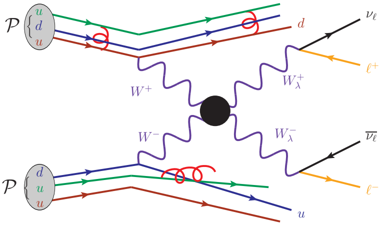

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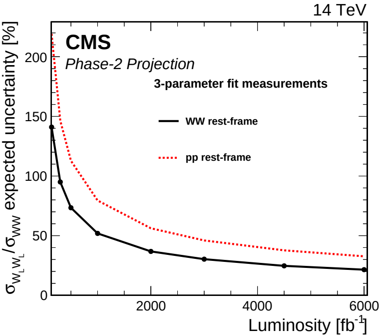
First measurement of polarization in $W^\pm W^\pm$ scattering

CMS (PLB'20)

Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

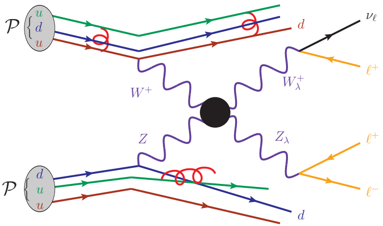
uncertainties sizable but will improve with time



CMS [CMS-PAS-FTR-21-001]

The $W^{\pm}_{\lambda}, Z_{\lambda}$ bosons are massive, spin-1 objects

– 2 transverse polarizations (L,R)
– 1 longitudinal polarization (0)

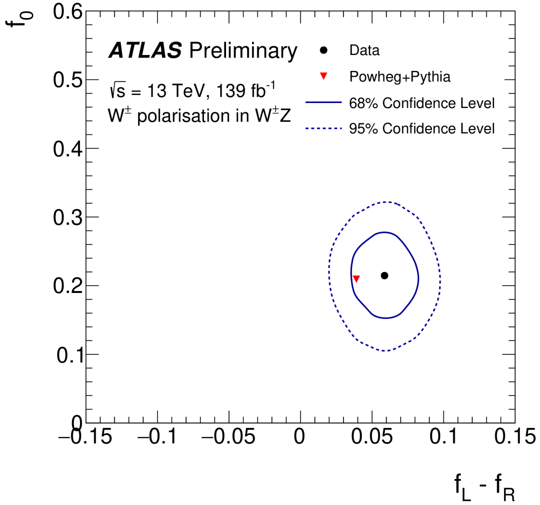


polarizations also imprint on kinematics of decay products!

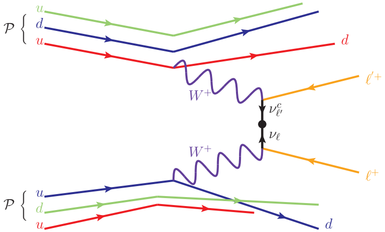
MadGraph5_aMC@NLO now supports event simulation at LO of particles with fixed helicities

First measurement of polarization fractions (f_λ) in $W^{\pm}Z$ scattering

ATLAS ('22) [2211.09435]



violation of lepton number symmetries **(NEW!)**

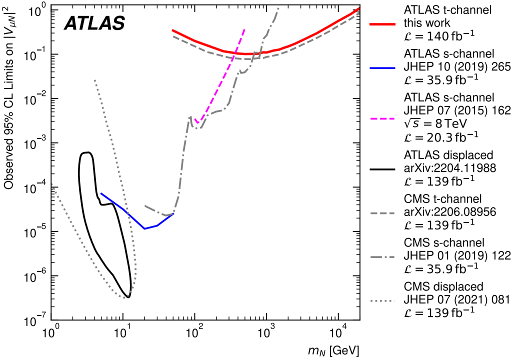


First high-energy constraints on $d = 5$ Weinberg operator

CMS [PRL'22]

$$\Lambda / C_5^{\mu\mu} \gtrsim 5 \text{ TeV}$$

NEW! w/ ATLAS ('23) [EXOT-2020-06]



Fun ideas using **VBS/VBF** to probe **lepton number violation** and **lepton flavor violation**:

– $W\gamma \to 3\ell + X$ or $\ell^\pm\ell^\pm + X$

via heavy neutrinos w/ Alva, Han [1411.7305];

via heavy neutrinos w/ Pascoli, et al [1812.08750]

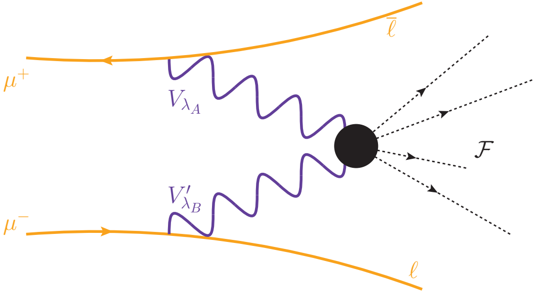
– $W^\pm W^\pm \to \ell^\pm \ell'^\pm$

via heavy neutrinos w/ Fuks, et al [2011.02547]

– $W^\pm W^\pm \to \ell^\pm \ell'^\pm$

via Weinberg operator w/ Fuks, et al [2012.09882]

$\mu^+\mu^-$ collisions at many-TeV[1]

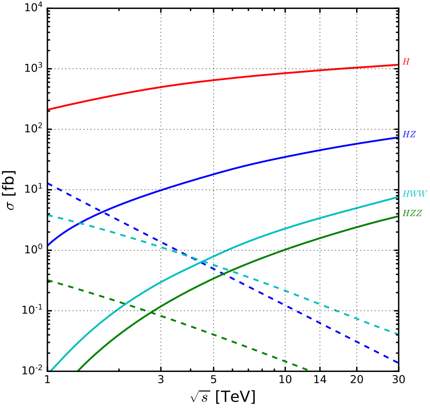


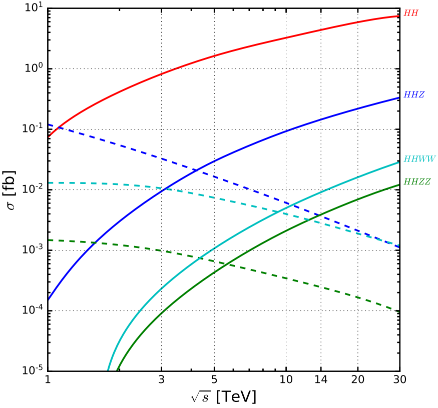
[1] Surge of motivation/interest, e.g., Al Ali, et al. [2103.14043]; R&D progress as reported in the European Strategy Update (Delahaye, et al) [1901.06150], muoncollider.web.cern.ch; Snowmass + US activities

next several slides from w/ A. Costantini, et al [2005.10289]

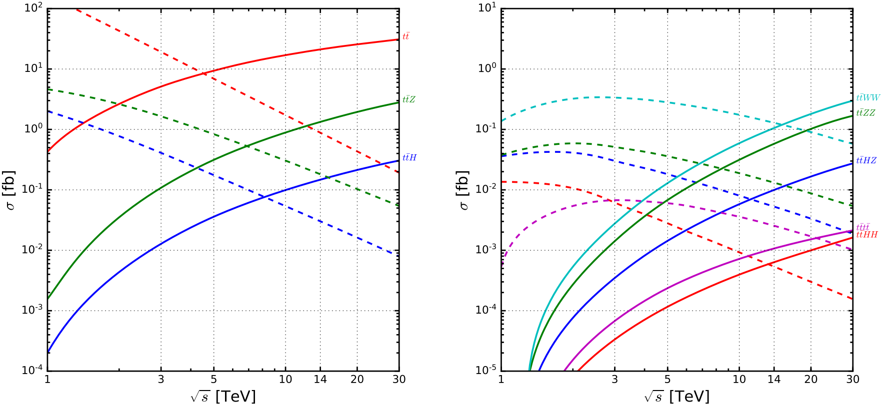
Higgs production

cross sections (σ) vs $\sqrt{s}$ for
s-channel annihilation (dash) vs VBF (solid)



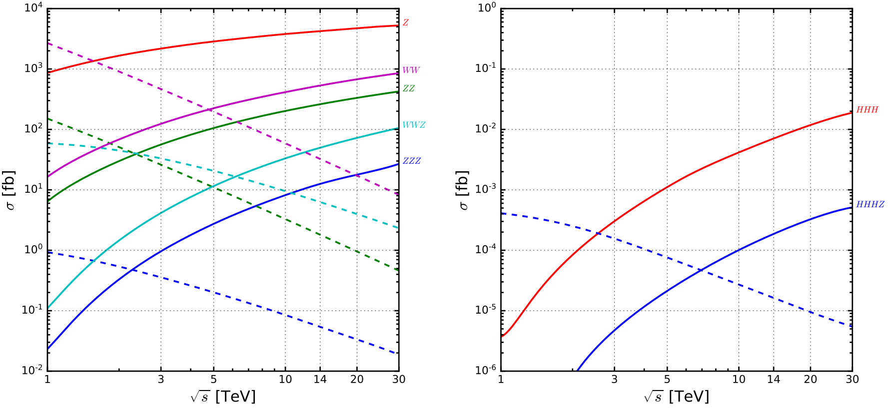


Top production



- Do you notice a pattern?

Many-boson production



- **VBF is the dominant production vehicle for many processes**

Evidence for trend that VBF/S rates will always exceed s-ch. rates

Is this obvious? (not to me at first!) **Is there intuition for this?** (yes!)

w/ A. Costantini, et al [2005.10289]

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Idea: crudely compare the production of X by writing generically

$$\sigma^{s-ch.} \sim \frac{(s-M_X^2)}{(s-M_V^2)^2} \sim \frac{(s-M_X^2)}{s^2} \quad \leftarrow \text{assumes } s \gg M_V^2$$

$$\frac{d\sigma^{VBF}}{dz_1 dz_2} \sim \underbrace{f_V(z_1) f_{V'}(z_2)}_{\text{"}\mu\text{PDFs"}} \underbrace{\frac{(M_{VV'}^2 - M_X^2)}{(M_{VV'}^2 - M_V^2)^2}}_{M_{VV'}^2 = z_1 z_2 s \gg M_V^2} \sim f_V(z_1) f_{V'}(z_2) \frac{(z_1 z_2 s - M_X^2)}{(z_1 z_2)^2} \frac{\sigma^{s-ch.}}{(s-M_X^2)}$$

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PDFs are largest when $z = E_V/E_\mu \ll 1$ but $E_V \sim \sqrt{s} \gg M_V$

$$\implies f_V(z_i) \sim \frac{g_W^2}{4\pi} \frac{1}{z_i} \log\left(\frac{s}{M_V^2}\right) \quad \leftarrow \text{crude approximation}$$

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Observation: $\sigma^{VBF} = \sigma^{s-ch.} \times \int dz_1 dz_2 \ldots$ is solvable for $M_{VV'} \gg M_X$!

Universal behavior: when production of X by VBF and annihilation are driven by same physics, VBF **dominates** when $\sqrt{s}$ satisfies

$$\frac{\sigma^{\rm VBF}}{\sigma^{s-ch.}} \sim \mathcal{S} \left(\frac{g_W^2}{4\pi}\right)^2 \left(\frac{s}{M_X^2}\right) \log^2 \frac{s}{M_V^2} \log \frac{s}{M_X^2} > 1$$

Scaling estimate not so bad if $M_X \gg M_V$. Difference is about $\mathcal{O}(10\%)$

mass (M_X) [TeV]	SZ (Singlet)	H_2Z (2HDM)	$t'\overline{t'}$ (VLQ)	$\tilde{t}\bar{\tilde{t}}$ (MSSM)	$\tilde{\chi}^0\tilde{\chi}^0$ (MSSM)	$\tilde{\chi}^+\tilde{\chi}^-$ (MSSM)	Scaling (Eq. 7.7)
400 GeV	2.1 TeV	2.1 TeV	11 TeV	2.9 TeV	3.2 TeV	7.5 TeV	1.0 (1.7) TeV
600 GeV	2.5 TeV	2.5 TeV	16 TeV	3.8 TeV	3.8 TeV	8.1 TeV	1.3 (2.4) TeV
800 GeV	2.8 TeV	2.8 TeV	22 TeV	4.3 TeV	4.3 TeV	8.5 TeV	1.7 (3.1) TeV
2.0 TeV	4.0 TeV	4.0 TeV	>30 TeV	7.8 TeV	6.9 TeV	11 TeV	3.7 (6.8) TeV
3.0 TeV	4.8 TeV	4.8 TeV	>30 TeV	10 TeV	9.0 TeV	13 TeV	5.3 (9.8) TeV
4.0 TeV	5.5 TeV	5.5 TeV	>30 TeV	13 TeV	11 TeV	15 TeV	6.8 (13) TeV

Table 9. For representative processes and inputs, the required muon collider energy $\sqrt{s}$ [TeV] at which the VBF production cross section surpasses the s-channel, annihilation cross section, as shown in figure 17. Also shown are the cross over energies as estimated from the scaling relationship in equation (7.7) assuming a mass scale M_X ($2M_X$).

Evidence that PDF prescription works quantitatively

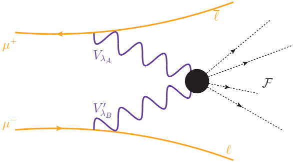
The Effective W/Z Approximation (EWA)[2]

a.k.a. weak boson parton distribution functions

[2] Dawson('84); Kane, et al ('84); Kunszt and Soper ('88)

Idea: one can write the following scattering formula

$$\sigma(\mu^+\mu^- \to \mathcal{F} + \text{ anything}) = f_{i/\mu^+} \otimes f_{j/\mu^-} \otimes \hat{\sigma}_{ij} + \text{uncertainties}$$



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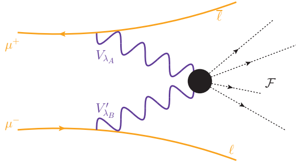


$$= \underbrace{\sum_{V_{\lambda_A}, V'_{\lambda_B}} \int_{\tau_0}^{1} d\xi_1 \int_{\tau_0/\xi_1}^{1} d\xi_2 \int dPS_{\mathcal{F}}}_{\text{sum over all configurations / phase space integral}}$$

$$\times \left[\underbrace{f_{V_{\lambda_A}/\mu^+}(\xi_1, \mu_f)\; f_{V'_{\lambda_B}/\mu^-}(\xi_2, \mu_f)}_{W^+_\lambda/W^-_\lambda/Z_\lambda/\gamma_\lambda \text{ PDFs}} \right] \times \underbrace{\frac{d\hat{\sigma}(V_{\lambda_A} V'_{\lambda_B} \to \mathcal{F})}{dPS_n}}_{\text{"hard scattering" at LO}}$$

$$+ \underbrace{\mathcal{O}\left(\frac{M^2_{V_k}}{M^2_{VV'}}\right) + \mathcal{O}\left(\frac{p^2_{T,V_k}}{M^2_{VV'}}\right)}_{\text{perturbative power-law corrections}}$$

$\leftarrow$ **(appear from expanding $\mu_\lambda \to V_\lambda l$ matrix elements)**

$$+ \underbrace{\mathcal{O}\left(\log \frac{\mu_f^2}{M_V^2}\right)}_{\text{log corrections}}$$

$\leftarrow$ **(μ_f is only an UV regulator here at LO)**

We studied the **red** terms

w/ Antonio Costantini, Fabio Maltoni, Olivier Mattelaer [2111.02442]

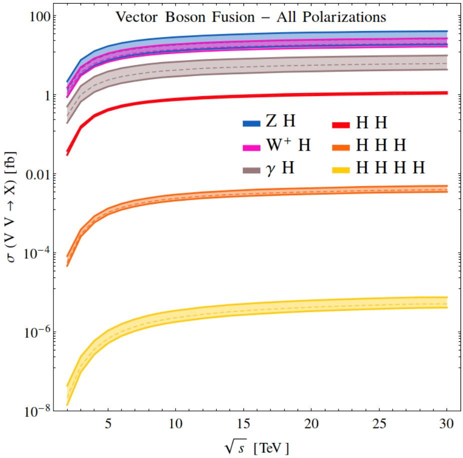
some results on $V_\lambda V'_{\lambda'} \to X$ in $\mu^+\mu^-$ collisions[3]

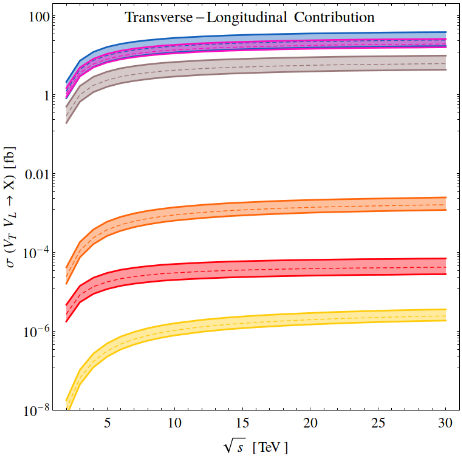
[3] w/ A. Costantini, F. Maltoni, L. Mantani, O. Mattelaer [2111.02442]

Higgs production in EVA

We then had fun looking into *many* processes

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

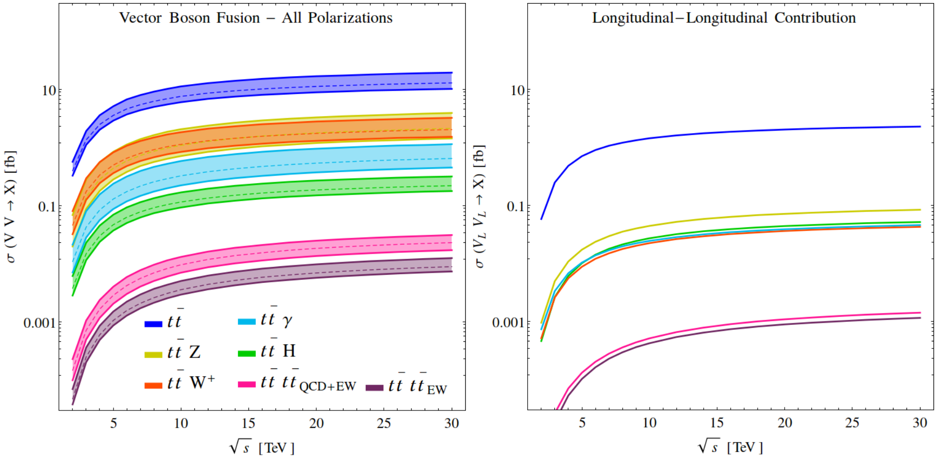




Top production in EVA

... *many* processes

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



Diboson production in EVA

(4 polarization plots + 1 table) × each class of 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-`	$2.2\cdot10^{2}\,^{+98\%}_{-35\%}$	$7.0\cdot10^{2}\,^{+91\%}_{-33\%}$	$8.6\cdot10^{2}\,^{+88\%}_{-32\%}$
$V_TV'_T \to W^+W^-$	`vp{T} vm{T} > w+ w-`	$2.0\cdot10^{2}\,^{+99\%}_{-35\%}$	$6.6\cdot10^{2}\,^{+93\%}_{-34\%}$	$8.0\cdot10^{2}\,^{+92\%}_{-33\%}$
$V_0V'_T \to W^+W^-$	`vp{0} vm{T} > w+ w-`	$1.2\cdot10^{1}\,^{+54\%}_{-27\%}$	$4.4\cdot10^{1}\,^{+50\%}_{-25\%}$	$5.2\cdot10^{1}\,^{+49\%}_{-24\%}$
$V_0V'_0 \to W^+W^-$	`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`	$5.3\cdot10^{1}\,^{+105\%}_{-40\%}$	$1.8\cdot10^{2}\,^{+97\%}_{-37\%}$	$2.2\cdot10^{2}\,^{+95\%}_{-37\%}$
$V_TV'_T \to W^+Z$	`vp{T} vm{T} > w+ z`	$5.0\cdot10^{1}\,^{+111\%}_{-42\%}$	$1.6\cdot10^{2}\,^{+103\%}_{-39\%}$	$2.0\cdot10^{2}\,^{+100\%}_{-38\%}$
$V_0V'_T \to W^+Z$	`vp{0} vm{T} > w+ z`	$3.4\cdot10^{0}\,^{+36\%}_{-18\%}$	$1.4\cdot10^{1}\,^{+34\%}_{-17\%}$	$1.7\cdot10^{1}\,^{+34\%}_{-17\%}$
$V_0V'_0 \to W^+Z$	`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`	$4.4\cdot10^{1}\,^{+164\%}_{-52\%}$	$1.6\cdot10^{2}\,^{+144\%}_{-48\%}$	$1.9\cdot10^{2}\,^{+143\%}_{-48\%}$
$V_TV'_T \to ZZ$	`vp{T} vm{T} > z z`	$4.0\cdot10^{1}\,^{+171\%}_{-54\%}$	$1.4\cdot10^{2}\,^{+153\%}_{-50\%}$	$1.7\cdot10^{2}\,^{+150\%}_{-49\%}$
$V_0V'_T \to ZZ$	`vp{0} vm{T} > z z`	$4.2\cdot10^{0}\,^{+66\%}_{-33\%}$	$1.8\cdot10^{1}\,^{+61\%}_{-30\%}$	$2.2\cdot10^{1}\,^{+60\%}_{-30\%}$
$V_0V'_0 \to ZZ$	`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`	$1.9\cdot10^{1}\,^{+169\%}_{-53\%}$	$7.1\cdot10^{1}\,^{+149\%}_{-49\%}$	$8.8\cdot10^{1}\,^{+145\%}_{-48\%}$
$V_TV'_T \to \gamma Z$	`vp{T} vm{T} > a z`	$1.8\cdot10^{1}\,^{+172\%}_{-54\%}$	$6.8\cdot10^{1}\,^{+153\%}_{-50\%}$	$8.4\cdot10^{1}\,^{+149\%}_{-49\%}$
$V_0V'_T \to \gamma Z$	`vp{0} vm{T} > a z`	$9.5\cdot10^{-1}\,^{+67\%}_{-33\%}$	$4.4\cdot10^{0}\,^{+61\%}_{-30\%}$	$5.5\cdot10^{0}\,^{+60\%}_{-30\%}$
$V_0V'_0 \to \gamma Z$	`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+`	$1.1\cdot10^{1}\,^{+111\%}_{-42\%}$	$4.0\cdot10^{1}\,^{+101\%}_{-39\%}$	$4.9\cdot10^{1}\,^{+99\%}_{-38\%}$
$V_TV'_T \to \gamma W^+$	`vp{T} vm{T} > a w+`	$1.1\cdot10^{1}\,^{+111\%}_{-42\%}$	$3.9\cdot10^{1}\,^{+102\%}_{-39\%}$	$4.8\cdot10^{1}\,^{+100\%}_{-38\%}$
$V_0V'_T \to \gamma W^+$	`vp{0} vm{T} > a w+`	$1.6\cdot10^{-2}\,^{+62\%}_{-31\%}$	$7.3\cdot10^{-1}\,^{+56\%}_{-28\%}$	$9.2\cdot10^{-1}\,^{+54\%}_{-27\%}$
$V_0V'_0 \to \gamma W^+$	`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`	$2.1\cdot10^{0}\,^{+172\%}_{-54\%}$	$8.5\cdot10^{0}\,^{+152\%}_{-50\%}$	$1.1\cdot10^{1}\,^{+147\%}_{-48\%}$
$V_TV'_T \to \gamma\gamma$	`vp{T} vm{T} > a a`	$2.1\cdot10^{0}\,^{+172\%}_{-54\%}$	$8.5\cdot10^{0}\,^{+152\%}_{-50\%}$	$1.1\cdot10^{1}\,^{+147\%}_{-48\%}$
$V_0V'_T \to \gamma\gamma$	`vp{0} vm{T} > a a`	$7.8\cdot10^{-4}\,^{+70\%}_{-35\%}$	$3.4\cdot10^{-3}\,^{+67\%}_{-34\%}$	$4.2\cdot10^{-3}\,^{+67\%}_{-33\%}$
$V_0V'_0 \to \gamma\gamma$	`vp{0} vm{0} > a a`	$5.8\cdot10^{-4}$	$4.7\cdot10^{-3}$	$6.8\cdot10^{-3}$

What about impact of DGLAP/RG evolution?

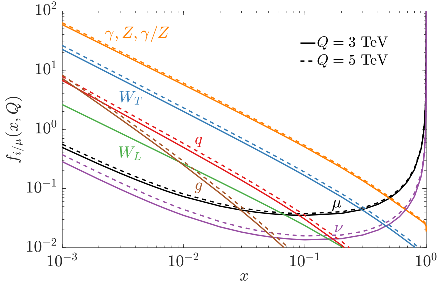
– shift in normalization

– perturbative generation of g, q, t

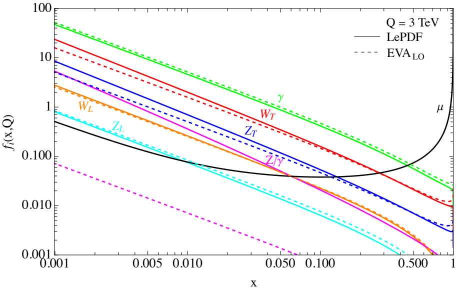
– PDF mixing

– Some PDF tables now public!

– **look out for updates here!**



Han, et al [2007.14300]



Garosi, et al [2303.16964]

Summary and Conclusion

Exploring VBS/VBF is part of LHC's long-term program

See review by Buarque (ed.), Gallinaro (ed.), RR (ed.), et al, Rev. Physics ('22) [arXiv:2106.01393]

- **Helicity-polarized simulations available with `MadGraph5aMC@NLO`**

  up to LO+LL(PS) [1912.01725]; NLO is under dev.; see also Poncelet, et al [2102.13583], + others

- **At high-energies, VBS/VBF eventually becomes leading production mechanism in $\ell^+\ell^-$ collisions** [2005.10289]

  + dedicated updates to support VBS/VBF at higher energies in `mg5amc`, e.g., [2102.00773]

- **Clarity on quantitative success of W/Z PDFs in $\ell^+\ell^-$** [2111.02442]

  EWA@LO in `mg5amc` is now available and plans underway to merge parallel Snowmass efforts

- **EW PDFs at higher orders actively being studied**

  Han, et al [2007.14300], Garosi, et al [2303.16964], +others

Thank you!

backup

Implementing EW boson PDFs in MadGraph5

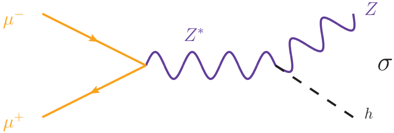
- **NEW: (Polarized) Effective Vector Boson Approx. (EVA)**
  - Bare (LO) PDFs for helicity-polarized $W_\lambda, Z_\lambda, \gamma_\lambda$ from $\ell^\pm_\lambda$
  - Automatically support PDFs for unpolarized W/Z **(EWA)** from $\ell^\pm_\lambda$

- **KEPT: Improved Weizsäcker-Williams approximation (iWWA)**
  - Unpolairzed γ PDF + power corrections from $\ell^\pm$ (Frixione, et al [hep-ph/9310350])

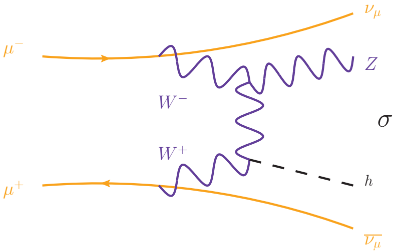
- **Technicalities:**
  - M_W, M_Z always nonzero in PDFs and matrix elements!
  - static and dyamic μ_f
  - n-point μ_f variation
  - Choice of p_T and q as evolution variable **(this gives extra $\log(1-\xi)$ terms in PDFs!)**
  - Also enabled **EVA+DIS** collider configuration

- **Technical appendix** rederiving W_λ, Z_λ PDFs to provide standard reference and mapping between different approaches in the literature
  - Released in v3.3.0 **(Major milestone for lepton colliders; see Frixione, et al [2108.10261])**

s-channel annihilation vs VBF/S



$$\sigma^{s-channel} \sim \frac{g^4}{s}$$



$$\sigma^{VBF} \sim \frac{g^8}{M_{WW}^2} \log^2\left(\frac{M_{WW}^2}{M_W^2}\right)$$

More legs $\implies$ more propagators $\implies$ $\int dk^2/(k^2 - M_W^2) \sim \log(\Lambda^2/M_W^2)$

Larger s $\implies$ larger (M_{WW}^2/M_W^2) $\implies$ collinear V compensate for g

PDFs for $e^\pm, \mu^\pm \to W_\lambda/Z_\lambda/\gamma_\lambda + \ell$ depend on helicities (λ)

- Subtle but important differences if evolving by q^2 of V vs p_T^2 of ℓ

(this can account for some differences in literature!)

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

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

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

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

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

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

```
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
```