Triply polarized *WWW* production cross sections at the LHC at LO

Van Cuong LE, Duc Ninh LE

Phenikaa University, Hanoi, Vietnam

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Outlines

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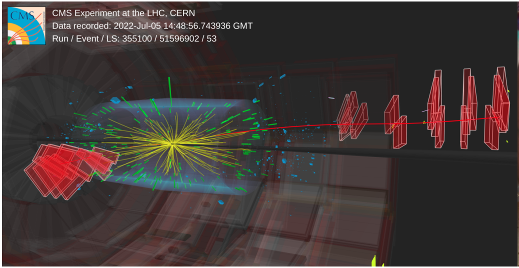
LHC Schedule & Plans



- **7/2022 - 2026:** LHC continues Run 3 at an energy of 13.6 TeV.
- **2028:** High-Luminosity LHC (HL-LHC) will keep the energy unchanged, but increase the luminosity by a factor of 10. [1]
- **2040+:** Future Circular Collider (FCC), developing designs for higher-performance particle accelerators to succeed the LHC.

[1] CERN Yellow Rep. (2015) 1 CERN Yellow Rep. 10/2020 (2020)

Experiment

	Measurement		Prediction		
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV		$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)	f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ	f_{TT}	0.619 ± 0.007	0.646 ± 0.008

Figure: Current Status *WZ*: Experiment vs. Theory (ATLAS)

Experiment [ATLAS,CMS] [2]

- In 2024, ATLAS published experimental results for *WZ* and *ZZ* production processes.
- CMS also published similar measurements on the polarization of the *WZ* process.

Theory [Denner,Pellicciolí,D.N. Le,T.N. Dao,Madgraph,Sherpa,...] [3]

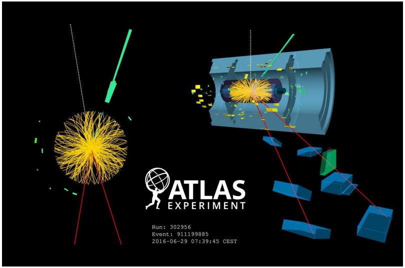
- Polarized cross-sections for diboson processes calculated at NLO QCD and NLO QCD+EW (2020-2025):
- $pp \to WW$, $pp \to WZ$, $pp \to ZZ$
- $pp \to VVjj$

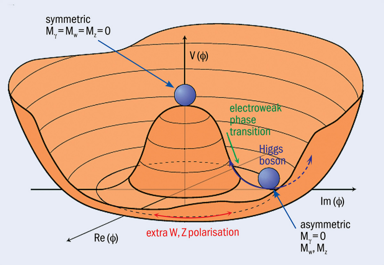
Our focus: Calculating the polarized cross-sections for *VVV* processes (LO for *WWW* in arXiv:2603.02917).

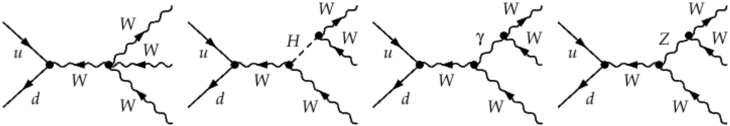
[2] ATLAS, PRL 133 (2024) 101802 CMS, JHEP 07 (2022) 032

[3] T.N. Dao, D.N. Le, EPJC 09 (2020) 164 A. Denner, G. Pellicioli, JHEP 09 (2020) 164 D.N. Le, J. Baglio, EPJC 82 (2022) 917

Physics Motivation







Why study *VVV* processes?

- Highly sensitive to triple and quartic gauge couplings.
- Provides deep insights into the Electroweak Symmetry Breaking (EWSB) mechanism.
- Explores triple polarization effects.

→ **A powerful probe for New Physics Beyond the Standard Model.**

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How to calculate polarized cross sections

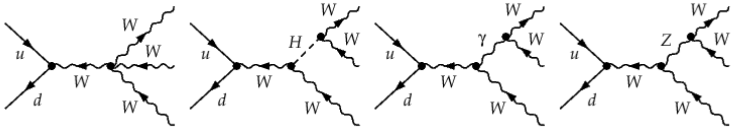

Figure: Typical triple-resonance diagrams at LO for the *WWW* process.

Triple Pole Approximation (TPA):

- Select the triple-resonance Feynman diagrams.
- Factorize the amplitude into production ($\mathcal{A}_P$) and decay ($\mathcal{A}_D$) parts via the polarization summation relation.
- Perform on-shell mapping: $p_i \to \hat{p}_i \implies \mathcal{A}$ (off-shell) $\to \hat{\mathcal{A}}$ (on-shell):
  - Sequential Splitting On-shell Projection (**SSOP**)
  - Simultaneous On-shell Projection (**SOP**)

Narrow Width Approximation (NWA):

- With spin correlation between production and decays
- With mass smearing (Breit-Wigner shapes for the resonaces)

On-Shell Mapping Procedure

Consider the proton-proton scattering process:

$$p(q_1) + p(q_2) \to V_1(k_1) + V_2(k_2) + V_3(k_3) \to \sum_{i=1}^{6} l_i(q_{i+2}) + X, \tag{1}$$

where the intermediate momenta are defined as:

$$k_1 = q_3 + q_4, \quad k_2 = q_5 + q_6, \quad k_3 = q_7 + q_8.$$

Conditions for OS momenta:

$$\hat{q}_i^2 = 0, \ (i = 1, \ldots, 8), \tag{2}$$

$$\hat{k}_1^2 = (\hat{q}_3 + \hat{q}_4)^2 = M_{V_1}^2, \quad \hat{k}_2^2 = (\hat{q}_5 + \hat{q}_6)^2 = M_{V_2}^2, \quad \hat{k}_3^2 = (\hat{q}_7 + \hat{q}_8)^2 = M_{V_3}^2. \tag{3}$$

Constrain on $\hat{k}_i$:

$$\hat{k}_1 + \hat{k}_2 + \hat{k}_3 = k_1 + k_2 + k_3 = q_{VVV} \tag{4}$$

SSOP and SOP mapping

SSOP mapping [4]**:** The idea is to split the *VVV* system into two part: *A* and *B*, while *A* being a single particle and *B* containing two particles.

$$\hat{k}_A^2 = M_{V_i}^2, \ \overline{k}_B^2 = m_B^2 = (k_{V_j} + k_{V_k})^2. \tag{5}$$

Which leads to two conditions:

$$m_{VVV} > M_{V_i} + m_B, \tag{6}$$

$$m_B > M_{V_j} + M_{V_k}. \tag{7}$$

We obtain:

$$\rightarrow \hat{E}_{V_j} = \frac{M_{V_j}^2 - M_{V_k}^2}{2m_B} + \frac{1}{2}M_{V_j}, \ |\hat{k}_{V_j}| = \sqrt{\hat{E}_{V_j}^2 - M_{V_j}^2}, \ \vec{\hat{n}}_{V_j} = \vec{n}_{V_j}. \tag{8}$$

For $\hat{k}_{V_j}$ and $\hat{k}_{V_j}$:

1. Boost k_{V_j}, k_{V_k} into the rest frame of B ($V_j V_k$ c.m.f).
2. Choose the spatial direction of $\hat{k}_{V_j}$ to be the same as that of k_{V_j} in that frame.

SOP mapping [5]**:**

$$f(t) = \sum_{i=1}^{3} \sqrt{M_{V_i}^2 + t\left|\vec{k}_i\right|^2} = m_{VVV} \tag{9}$$

[4] V.C Le, D.N. Le, T.N. Dao, arXiv:2603.02917

[5] A. Denner, D. Lombardi, C. Schwan, arXiv:2406.12301

MulBos [LDN,Dao]

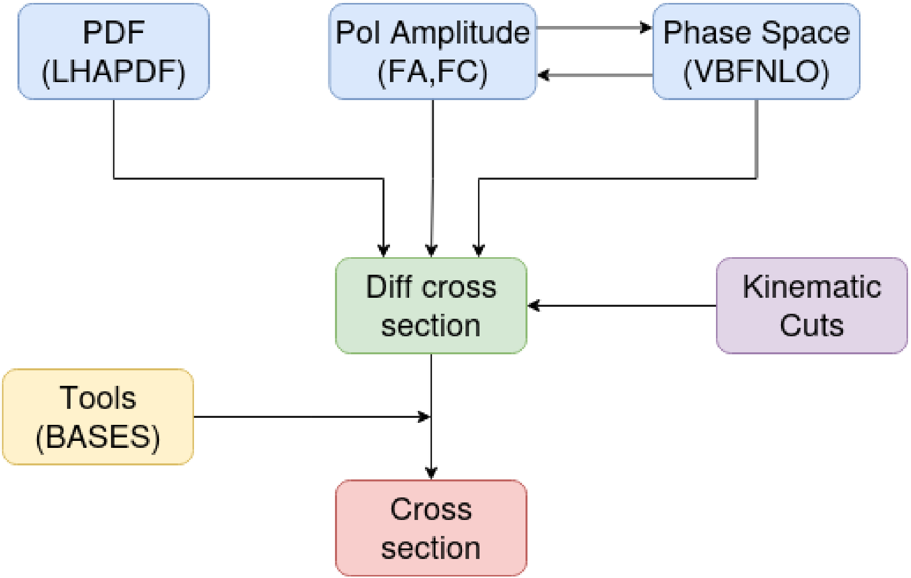

Figure: Algorithm flowchart of MulBos

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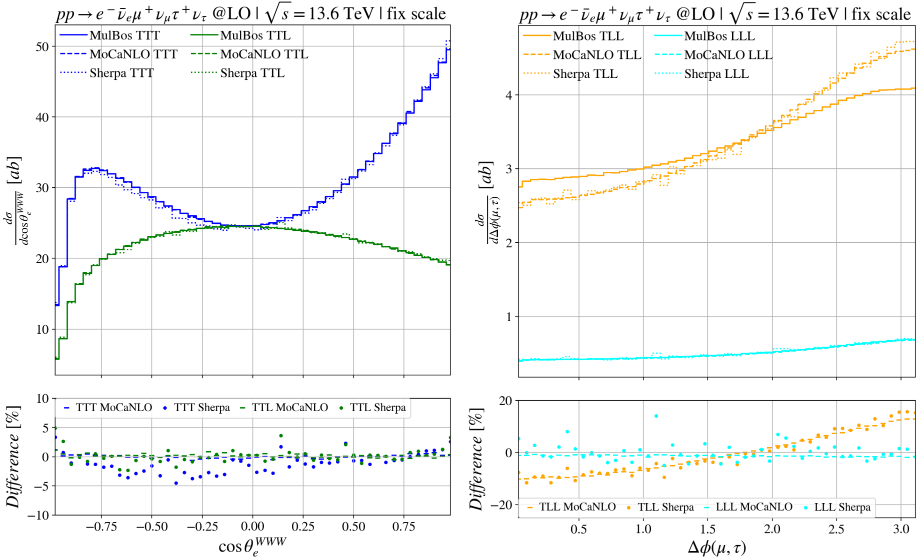
Comparison [6]

	MulBos (SSOP)	MoCaNLO (SOP)	Sherpa (NWA)
Off-shell	122.29(2)	122.32(3)	122.36(2)
Unpol.	118.38(2)	118.53(3)	120.60(7)
TTT	60.75(1)	60.75(1)	60.12(6)
TTL	43.28(1)	43.32(1)	43.29(5)
TLT	10.581(2)	10.613(2)	10.63(2)
LLL	1.5998(4)	1.5781(3)	1.603(7)

Table: Comparisons between MulBos, MoCaNLO, and Sherpa

[6] V.C Le, D.N. Le, T.N. Dao, arXiv:2603.02917

Comparing to Sherpa and MoCaNLO [7]



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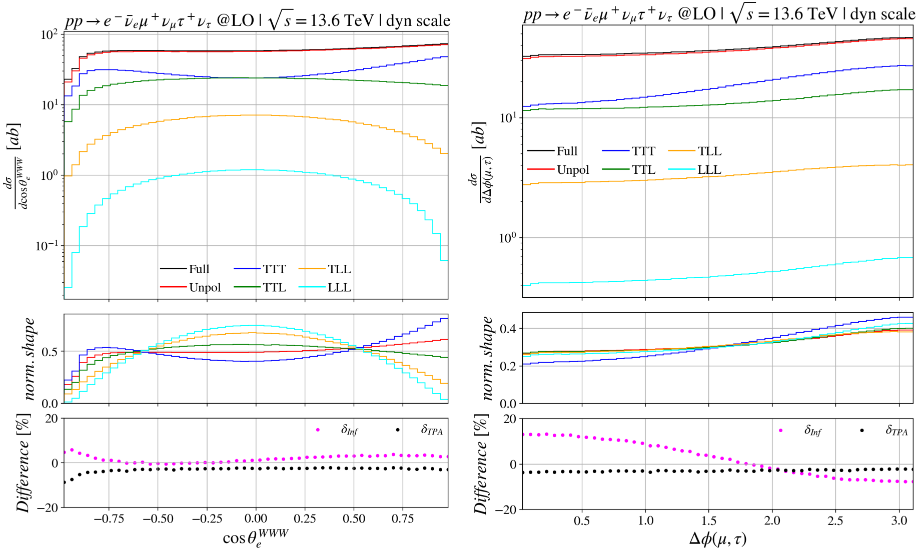
[7] V.C Le, D.N. Le, T.N. Dao, arXiv:2603.02917

Polarized cross-sections [8]

	σ_{fix} [ab]	f_{fix} [%]	σ_{dyn} [ab]	f_{dyn} [%]	δ_σ [%]
Full off-shell	$122.29(2)^{+0.06\%}_{-0.46\%}$		$120.13(2)^{+0.00\%}_{-0.28\%}$		$+1.8$
Unpol, TPA	$118.38(2)^{+0.15\%}_{-0.60\%}$	100	$116.52(2)^{+0.00\%}_{-0.37\%}$	100	$+1.6$
TTT	$60.75(1)^{+0.00\%}_{-0.48\%}$	$51.3^{+0.46\%}_{-0.63\%}$	$59.30(1)^{+0.05\%}_{-0.65\%}$	$50.9^{+0.42\%}_{-0.50\%}$	$+2.4$
TTL	$43.28(1)^{+0.38\%}_{-1.09\%}$	$36.6^{+0.23\%}_{-0.49\%}$	$42.83(1)^{+0.17\%}_{-0.72\%}$	$36.8^{+0.33\%}_{-0.35\%}$	$+1.1$
TLL	$10.581(2)^{+1.26\%}_{-2.16\%}$	$8.9^{+1.10\%}_{-1.57\%}$	$10.578(2)^{+0.97\%}_{-1.82\%}$	$9.1^{+1.13\%}_{-1.45\%}$	$+0.0$
LLL	$1.5998(4)^{+1.41\%}_{-2.27\%}$	$1.4^{+1.25\%}_{-1.69\%}$	$1.5982(4)^{+1.01\%}_{-1.93\%}$	$1.4^{+1.16\%}_{-1.56\%}$	$+0.1$
Interference	$2.176(7)^{+1.66\%}_{-2.16\%}$	$1.8^{+1.51\%}_{-1.58\%}$	$2.182(7)^{+1.39\%}_{-1.63\%}$	$1.9^{+1.54\%}_{-1.26\%}$	-0.3

[8] V.C Le, D.N. Le, T.N. Dao, arXiv:2603.02917

Kinematic distribution [9]



[9] V.C Le, D.N. Le, T.N. Dao, arXiv:2603.02917

Thank you for your listening