Plarised calculations with MulBos

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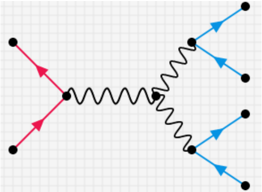
COMETA workshop on vector-boson polarisations,
23 Sep 2024, Toulouse, France

Outline

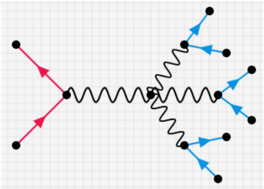
- Why polarization ?
- Massive diboson pairs: ZZ, $W^\pm Z$, W^+W^-
- Definition of polarization
- NLO QCD
- NLO EW
- `MulBos`
- New results: W^+W^-, b-induced processes (tW)
- Summary

Multi-gauge boson production at the LHC

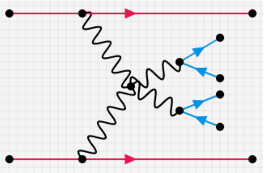
Diboson



Triboson



Vector boson scatterings



Goals:

- Singly polarized differential XS
- Doubly polarized differential XS
- Triply polarized differential XS
- New physics:

  $$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^2}\mathcal{O}_i^{(8)}$$

- Bell inequalities, quantum entanglement, locality of *qutrit* systems: [e.g. arxiv: 2302.00683, 2307.14895, 2307.09675, ...]

W^+, W^-, Z: $\lambda = \pm, 0$

0 mode: from EWSB

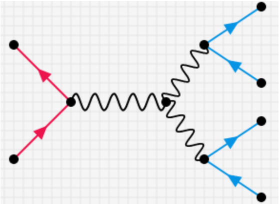
$\sum_\lambda$: Lorentz invariant

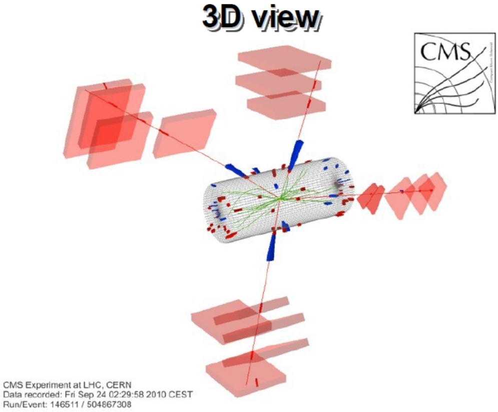
σ_λ: ref. frame dependent

Frame dependence is actually an advantage, as we have various choices !

Polarization in diboson

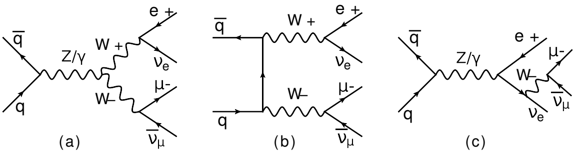
$$pp \to VV' \to 4\,\text{leptons},\ V = W, Z$$





$$\sigma_{4l} = \underbrace{\sigma_{TT} + \sigma_{TL} + \sigma_{LT} + \sigma_{LL}}_{\text{double polarization signals}} + \sigma_{\text{interference}}$$

Polarization definition



Polarized amplitudes are defined using the Double Pole Approximation (DPA):

- Select all diagrams with 2 s-channel resonances: $V_1 \to l_1 l_2$, $V_2 \to l_3 l_4$.
- Factorize the amplitude into production and decay parts.

$$\mathcal{A}_{\mathrm{LO,DPA}}^{\bar{q}q\to V_1V_2\to 4l} = \frac{1}{Q_1Q_2}\sum_{\lambda_1,\lambda_2=1}^{3}\mathcal{A}_{\mathrm{LO}}^{\bar{q}q\to V_1V_2}(\hat{k}_i,\lambda_1,\lambda_2)\mathcal{A}_{\mathrm{LO}}^{V_1\to l_1l_2}(\hat{k}_i,\lambda_1)\mathcal{A}_{\mathrm{LO}}^{V_2\to l_3l_4}(\hat{k}_i,\lambda_2),$$

$Q_j = q_j^2 - M_{V_j}^2 + iM_{V_j}\Gamma_{V_j}$, $m_{4l} > M_{V_1} + M_{V_2}$

- q_j: off-shell momenta.
- $\hat{k}_i$: on-shell mapped momenta (gauge invariance).
- OS mapping DPA$^{(2,2)}$: $\{k_1,\ldots,k_4\} \to \{\hat{k}_1,\ldots,\hat{k}_4\}$.

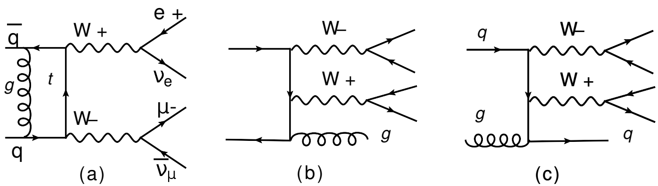
[Denner, Pelliccioli, ZZ, 2107.06579]

- LL: $\lambda_1 = \lambda_2 = 2$.
- LT: $\lambda_1 = 2$, $\lambda_2 = 1,3$.
- TL: $\lambda_1 = 1,3$, $\lambda_2 = 2$.
- TT: $\lambda_1 = 1,3$, $\lambda_2 = 1,3$.

$\sigma_{LT} \propto |A_{21} + A_{23}|^2$ (coherent sum)

NLO QCD corrections

$$\mathcal{A}_{\mathrm{LO,DPA}}^{\bar{q}q\to V_1V_2\to 4l} = \frac{1}{Q_1Q_2}\sum_{\lambda_1,\lambda_2=1}^{3}\mathcal{A}_{\mathrm{LO}}^{\bar{q}q\to V_1V_2}(\hat{k}_i,\lambda_1,\lambda_2)\mathcal{A}_{\mathrm{LO}}^{V_1\to l_1l_2}(\hat{k}_i,\lambda_1)\mathcal{A}_{\mathrm{LO}}^{V_2\to l_3l_4}(\hat{k}_i,\lambda_2),$$



NEW compared to LO:

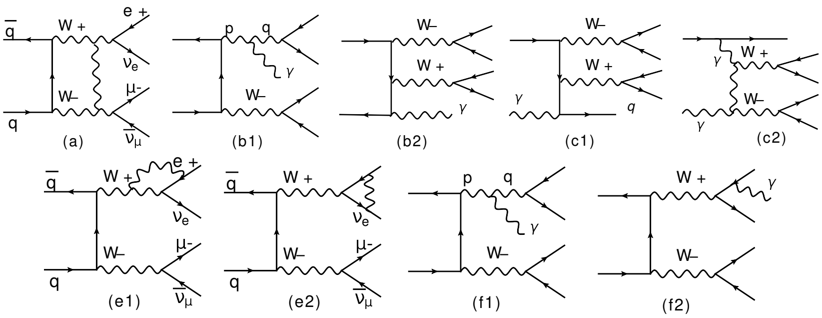
- (a): Virtual corrections.
- (b): Real gluon emission.
- (c): Real quark emission.

Real QCD emission induces a global recoil of the VV system!
QCD corrections only affect the production part.

Calculation details:

- On-shell mapping: DPA$^{(2,2)}$ (same as LO).
- Catani-Seymour-Dittmaier subtraction method (straightforward).
- Details in [Denner, Pelliccioli, ZZ, 2107.06579].

NLO EW corrections (I)



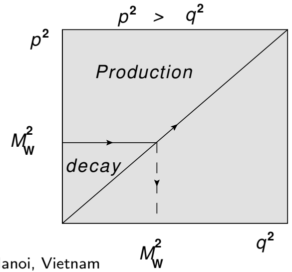
NO double counting: (b1), (f1)

Production (NEW compared to QCD):

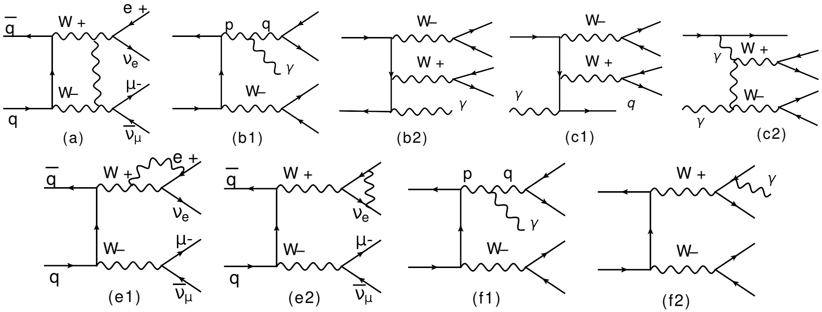
- Real photon emission off an OS W.
- $\gamma\gamma$ induced contribution (LO, Virt, Real).

Decays:

- Virtual corrections.
- Real photon emission off a charged lepton.



NLO EW corrections (II)



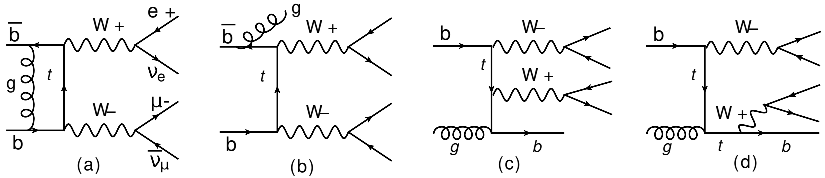
Decays:

- On-shell mapping: DPA$^{(3,2)}$ [Denner, Pellicciolo, ZZ, 2107.06579].
- Subtraction for $W \to e\nu_e\gamma$ [Basso, et al, 1507.04676; DNL, Baglio, Dao, WZ, 2208.09232].

Production: $q\bar{q} \to W^+W^-\gamma$, subtraction term, CS and OS mappings.

- initial emitter, initial spectator: [Denner, Pellicciolo, ZZ, 2107.06579].
- final emitter, initial spectator: [DNL, Baglio, Dao, WZ, 2208.09232].
- final emitter, final spectator: [Denner, Haitz, Pellicciolo, WW, 2311.16031, [DNL, Dao, WW, 2311.17027]

b-induced processes: W^+W^-



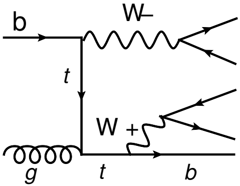
- with top: $t\bar{t}$ dominant
- without top: b-induced is not small ($\sigma^{LO}_{bb}/\sigma_{NLO} \approx 15\%$ for LL; m_t effect); top-interference is unknown (not gauge invariant) and can be sizable.

- non-tW: (a), (b), (c+d)
- tW: (c+d)
- tW interference: (c+d)
- $t\bar{t}$: at NNLO

The best option is to do both !

tW-interference bound: $\hat{\sigma}_{\text{TW-int}} = \sigma_{c+d} - \sigma_{\text{OS-tW}}$

Subtracting OS *tW* @ NLO



$$\not{p} + m_t = \sum_s u(p,s)\bar{u}(p,s)$$

$$\mathcal{A}_{\text{LO,DPA}}^{bg\to tW^-\to 4lb} = \frac{1}{Q_t Q_{W^+} Q_{W^-}} \sum_{\lambda_1,\lambda_2=1}^{3} \Big(\sum_{s_t=1}^{2} [\mathcal{A}_{\text{LO}}^{bg\to tW^-}(\hat{k}_i, s_t, \lambda_2) \mathcal{A}_{\text{LO}}^{t\to W^+ b}(\hat{k}_i, s_t, \lambda_1)] \\ [\mathcal{A}_{\text{LO}}^{W^+\to e^+\nu_e}(\hat{k}_i, \lambda_1) \mathcal{A}_{\text{LO}}^{W^-\to \mu^-\bar{\nu}_\mu}(\hat{k}_i, \lambda_2)] \Big), \quad (1)$$

$$Q_t = p_t^2 - m_t^2 + i m_t \Gamma_t, \quad Q_j = p_j^2 - M_W^2 + i M_W \Gamma_W \ (j = W^+, W^-), \quad (2)$$

OS momenta: $\hat{p}_t^2 = m_t^2$, $\hat{p}_{W^+}^2 = \hat{p}_{W^-}^2 = M_W^2$

1. In the tW^- frame: OS momenta for $bg \to tW^-$.
2. OS momenta for $t(\hat{p}_t) \to e^+(\bar{k}_3)\nu_e(\bar{k}_4)b(\bar{k}_7)$ and $W^-(\hat{p}_{W^-}) \to \mu^-(\hat{k}_5)\bar{\nu}_\mu(\hat{k}_6)$. Note: $(\bar{k}_3 + \bar{k}_4)^2 \neq M_W^2$.
3. Boost to the t-rest frame: $\bar{p}_{W^+} = \bar{k}_3 + \bar{k}_4$, $\bar{p}_b = \bar{k}_7$; then apply an OS mapping to obtain $\hat{k}_3$, $\hat{k}_4$, $\hat{k}_7$.

Theoretical status (VV mainly): very active !

Fixed order calculations (fully leptonic):

- ZZ (NLO QCD+EW) [Denner, Pellicciolі, JHEP (2021)]
- WZ (NLO QCD+EW) [Denner, Pellicciolі, NLO QCD, PLB (2021); DNL, Baglio, Dao, NLO QCD+EW, EPJC (2022)]
- WW (NLO QCD+EW; NNLO QCD) [Denner, Pellicciolі, NLO QCD, JHEP (2020); Poncelet, Popescu, NNLO QCD, JHEP (2021); Denner, Haitz, Pellicciolі, NLO EW, PLB (2024); Dao, DNL, NLO QCD+EW, EPJC (2024), Dao, DNL, NLO QCD+EW, 2409.06396; b-induced]

Other new developments:

- Event generation, parton shower with SHERPA (multi-boson, approx. NLO QCD) [Hoppe, Schönherr, Siegert, JHEP (2024)] and MadGraph5_aMC@NLO [Javurkova, et al, PLB (2024)].
- VV at NLOQCD+PS with POWHEG-BOX-RES [Pellicciolі, Zanderighi, EPJC (2024)]
- Semi-leptonic WZ at NLO QCD [Denner, Haitz, Pellicciolі, PRD (2023)]

and new papers on $VVjj$:

- semi-leptonic: [Denner, Lombardi, Schwan, 2406.12301]
- same-sign W^+W^+jj: [Denner, Haitz, Pellicciolі, 2409.03620]
- ...

MulBos

`MulBos` (**Mul**ti-**Bos**on production): python (run interface), Fortran (source code)

- Feynman diagrams and helicity amplitudes: `FeynArts`, `FormCalc`.
- Loop integrals: in-house `LoopInts` (Fortran).
- Phase-space integration: `BASES` (Monte Carlo method, Fortran); resonance mappings (`VBFNLO-3.0`, arxiv:2405.06990).
- NLO calculations: Catani-Seymour-Dittmaier subtraction method.

Capabilities:

- Polarized ZZ, W^+W^-, WZ at NLO QCD+EW (fully leptonic)
- b-induced processes
- OS tW processes
- Loop induced gg fusion at LO
- $\gamma\gamma$ fusion at LO

Integrated Results (W^+W^-): QCD, EW corrections

Ref. [Dao, DNL, 2311.17027]

	σ_{LO} [fb]	$\sigma_{\text{NLO}}^{\text{QCD}}$ [fb]	$\sigma_{\text{NLO}}^{\text{QCDEW}}$ [fb]	σ_{all} [fb]	$\bar{\delta}_{\text{EW}}$ [%]	$\bar{\delta}_{gg}$ [%]	$\bar{\delta}_{b\bar{b}}$ [%]	$\bar{\delta}_{\gamma\gamma}$ [%]	f_{all} [%]
Unpolarized	$198.14(1)^{+5.3\%}_{-6.5\%}$	$210.91(3)^{+1.6\%}_{-2.2\%}$	$202.90(3)^{+1.3\%}_{-1.9\%}$	$222.41(3)^{+2.2\%}_{-2.5\%}$	-3.80	6.20	1.87	1.18	100
$W_L^+W_L^-$	$12.99^{+6.1\%}_{-7.4\%}$	$14.03^{+1.9\%}_{-2.6\%}$	$13.64^{+1.7\%}_{-2.4\%}$	$16.46^{+4.7\%}_{-5.7\%}$	-2.75	4.08	15.11	0.94	7.4
$W_L^+W_T^-$	$21.67^{+6.3\%}_{-7.5\%}$	$24.86^{+1.8\%}_{-2.6\%}$	$24.28^{+1.7\%}_{-2.5\%}$	$25.75^{+2.6\%}_{-3.5\%}$	-2.32	1.56	3.86	0.50	11.6
$W_T^+W_L^-$	$22.14^{+6.2\%}_{-7.5\%}$	$25.56^{+1.8\%}_{-2.6\%}$	$24.96^{+1.7\%}_{-2.5\%}$	$26.43^{+2.6\%}_{-3.5\%}$	-2.34	1.52	3.75	0.48	11.9
$W_T^+W_T^-$	$140.44^{+4.8\%}_{-6.0\%}$	$144.97(2)^{+1.6\%}_{-1.9\%}$	$138.42(2)^{+1.4\%}_{-1.6\%}$	$152.95(3)^{+2.3\%}_{-1.9\%}$	-4.52	8.32	0.25	1.46	68.8
Interference	0.90(1)	1.50(4)	1.60(4)	0.81(4)	−−	−−	−−	−−	0.4

ATLAS Setup:

$$p_{T,\ell} > 27\,\text{GeV}, \quad p_{T,\text{miss}} > 20\,\text{GeV}, \quad |\eta_\ell| < 2.5, \quad m_{e\mu} > 55\,\text{GeV},$$

jet veto (no jets with $p_{T,j} > 35$ GeV and $|\eta_j| < 4.5$)

Comparison

[Submitted on 28 Nov 2023]

NLO electroweak corrections to doubly-polarized W^+W^- production at the LHC

Thi Nhung Dao, Duc Ninh Le

We present new results of next-to-leading order (NLO) electroweak corrections to doubly-polarized cross sections of W^+W^- production at the LHC. The calculation is performed for the leptonic final state of $e^+\mu_e\mu^-\bar{\nu}_\mu$ using the double-pole approximation in the diboson center-of-mass frame. NLO QCD corrections and subleading contributions from the gg, $b\bar{b}$, $\gamma\gamma$ induced processes are taken into account in the numerical results. We found that NLO EW corrections are small for angular distributions but can reach tens of percent for transverse momentum distributions at high energies, e.g. reaching -40% at $p_{T,e} \approx 300$ GeV. In these high p_T regions, EW corrections are largest for the doubly-transverse mode.

[Submitted on 27 Nov 2023]

NLO EW corrections to polarised W^+W^- production and decay at the LHC

Ansgar Denner, Christoph Haitz, Giovanni Pellliccioli

In this letter we present results for next-to-leading-order electroweak corrections to doubly polarised W^+W^- production at the LHC in the fully leptonic decay channel. We model the production and the decay of two polarised W bosons in the double-pole approximation, including factorisable real and virtual electroweak corrections, and separating polarisation states at amplitude level. We obtain integrated and differential predictions for polarised signals in a realistic fiducial setup.

	$\sigma^{\rm DL}_{\rm LO}$ [fb]	$\sigma^{\rm DHP}_{\rm LO}$ [fb]	$\Delta_{\rm LO}$ [%]	$\sigma^{\rm DL}_{\rm NLO}$ [fb]	$\sigma^{\rm DHP}_{\rm NLO}$ [fb]	$\Delta_{\rm NLO}$ [%]
unpolar. (DPA)	245.6(1)	245.79(2)	−0.07	240.56(3)	241.315	−0.3
LL	18.75(1)	18.752(2)	−0.006	18.497(2)	18.499	−0.01
LT	32.07(2)	32.084(3)	−0.04	31.998(4)	32.032	−0.1
TL	33.21(2)	33.244(5)	−0.09	33.106(4)	33.144	−0.1
TT	182.0(1)	182.17(2)	−0.07	176.93(2)	177.701	−0.4

b-induced effects: YesVeto [Dao, DNL, 2409.06396]

	σ_{NoB} [fb]	σ_{NoTW} [fb]	σ_{YesTW} [fb]	$K_{b\bar{b}}^{\text{LO}}$	K_{NoTW}	K_{YesTW}	$\hat{\delta}_{\text{TW-int}}$ [%]	f_{NoB} [%]	f_{NoTW} [%]	f_{YesTW} [%]
Unpol.	$218.47(3)^{+2.2\%}_{-2.1\%}$	$220.50(3)^{+2.1\%}_{-2.0\%}$	$266.12(3)^{+3.7\%}_{-3.8\%}$	1.02	1.01	1.22	−0.75	100	100	100
$W_L^+W_L^-$	$14.34^{+1.8\%}_{-2.6\%}$	$15.59^{+1.2\%}_{-2.2\%}$	$29.88^{+6.3\%}_{-6.7\%}$	1.15	1.09	2.08	−4.41	6.6	7.1	11.2
$W_L^+W_T^-$	$24.79^{+1.9\%}_{-2.5\%}$	$25.31^{+1.6\%}_{-2.5\%}$	$34.74^{+4.4\%}_{-5.2\%}$	1.04	1.02	1.40	−1.64	11.3	11.5	13.1
$W_T^+W_L^-$	$25.47^{+2.1\%}_{-2.5\%}$	$25.99^{+1.8\%}_{-2.4\%}$	$35.42^{+4.5\%}_{-5.1\%}$	1.04	1.02	1.39	−1.59	11.7	11.8	13.3
$W_T^+W_T^-$	$152.59(3)^{+2.2\%}_{-1.9\%}$	$152.67(3)^{+2.2\%}_{-1.9\%}$	$166.19(3)^{+3.0\%}_{-2.7\%}$	1.00	1.00	1.09	−0.19	69.8	69.2	62.5
Pol-int	1.27(4)	0.93(4)	−0.12(4)	−−	−−	−−	−−	0.6	0.4	−0.0

- NoB: u,d,c,s,gg,$\gamma\gamma$
- YesTW: NoB + b-induced at NLO (tW included)
- NoTW: YesTW − OS tW
- $K_X = \sigma_X/\sigma_{\text{NoB}}$
- $\hat{\delta}_{\text{TW-int}}$: bound of tW-interference (=$\sigma_{bg} - \sigma_{OS-tW}$ for QCD)
- Comparison for δ_{NLOEW} (YesTW): +2.54% (full off-shell; [Denner, Haitz, Pellicioli]) vs. +2.61% (DPA, ours)

b-induced effects: NoVeto [Dao, DNL, 2409.06396]

	σ_{NoB} [fb]	σ_{NoTW} [fb]	σ_{YesTW} [fb]	$K^{\text{LO}}_{b\bar{b}}$	K_{NoTW}	K_{YesTW}	$\hat{\delta}_{\text{TW-int}}$ [%]	f_{NoB} [%]	f_{NoTW} [%]	f_{YesTW} [%]
Unpol.	$327.94(4)^{+5.4\%}_{-4.2\%}$	$334.17(4)^{+5.4\%}_{-4.1\%}$	$620.13(4)^{+8.3\%}_{-6.5\%}$	1.01	1.02	1.89	0.62	100	100	100
$W^+_L W^-_L$	$18.68^{+4.1\%}_{-3.3\%}$	$21.04(1)^{+4.0\%}_{-2.9\%}$	$83.66(1)^{+9.9\%}_{-9.5\%}$	1.11	1.13	4.48	1.04	5.7	6.3	13.5
$W^+_L W^-_T$	$43.33^{+6.0\%}_{-4.9\%}$	$44.86(1)^{+6.1\%}_{-4.8\%}$	$110.18(1)^{+9.5\%}_{-8.1\%}$	1.02	1.04	2.54	1.12	13.2	13.4	17.8
$W^+_T W^-_L$	$44.22(1)^{+6.2\%}_{-4.9\%}$	$45.77(1)^{+6.2\%}_{-4.8\%}$	$111.06(1)^{+9.5\%}_{-8.1\%}$	1.02	1.03	2.51	1.12	13.5	13.7	17.9
$W^+_T W^-_T$	$221.43(3)^{+5.3\%}_{-4.1\%}$	$222.80(3)^{+5.3\%}_{-4.1\%}$	$321.82(3)^{+7.2\%}_{-5.6\%}$	1.00	1.01	1.45	0.43	67.5	66.7	51.9
Pol-int	0.28(5)	−0.30(5)	−6.60(5)	−−	−−	−−	−−	0.1	−0.1	−1.1

tW-interference: from −4% (YesVeto) to +1% (NoVeto) !

b-induced effects: YesVeto/NoVeto [Dao, DNL, 2409.06396]

	σ_{NoB} [fb]	σ_{NoTW} [fb]	σ_{YesTW} [fb]	$K^{\text{LO}}_{b\bar{b}}$	K_{NoTW}	K_{YesTW}	$\hat{\delta}_{\text{TW-int}}$ [%]	f_{NoB} [%]	f_{NoTW} [%]	f_{YesTW} [%]
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$W^+_T W^-_T$	$152.59(3)^{+2.2\%}_{-1.9\%}$	$152.67(3)^{+2.2\%}_{-1.9\%}$	$166.19(3)^{+3.0\%}_{-2.7\%}$	1.00	1.00	1.09	−0.19	69.8	69.2	62.5
Pol-int	1.27(4)	0.93(4)	−0.12(4)	−−	−−	−−	−−	0.6	0.4	−0.0
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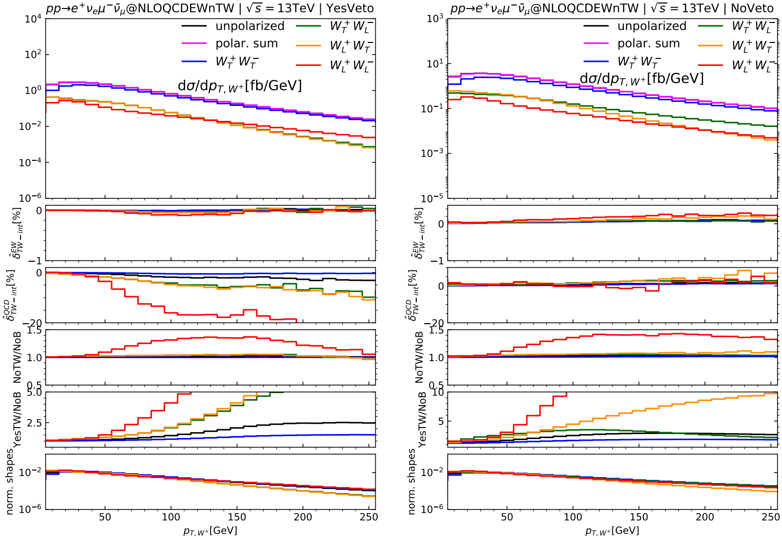
$W^+_T W^-_L$	$44.22(1)^{+6.2\%}_{-4.9\%}$	$45.77(1)^{+6.2\%}_{-4.8\%}$	$111.06(1)^{+9.5\%}_{-8.1\%}$	1.02	1.03	2.51	1.12	13.5	13.7	17.9
$W^+_T W^-_T$	$221.43(3)^{+5.3\%}_{-4.1\%}$	$222.80(3)^{+5.3\%}_{-4.1\%}$	$321.82(3)^{+7.2\%}_{-5.6\%}$	1.00	1.01	1.45	0.43	67.5	66.7	51.9
Pol-int	0.28(5)	−0.30(5)	−6.60(5)	−−	−−	−−	−−	0.1	−0.1	−1.1

tW-interference: YesVeto vs. NoVeto [Dao, DNL, 2409.06396]



Significantly smaller tW-interference for NoVeto !

Summary

- Fixed order results for VV: at least NLO QCD+EW (various tools !)
- W^+W^-: OS tW can be nicely subtracted for individual polarizations.
- W^+W^- measurements: consider both NoTW and YesTW.
- New results for W^+W^-: smaller tW-interference for NoVeto case (relevant for NoTW).

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Thank you for your attention!

b-induced processes: YesVeto/NoVeto [Dao, DNL, 2409.06396]

	σ_b^{LO} [fb]	σ_b^{NoTW} [fb]	σ_b^{YesTW} [fb]	σ_{bg}^{NoTW} [fb]	σ_{bg}^{YesTW} [fb]	$\sigma_{b\gamma}^{NoTW}$ [fb]	$\sigma_{b\gamma}^{YesTW}$ [fb]
Unpol.	3.94	2.03(1)	47.65(1)	−1.62(1)	42.66(1)	−0.01	1.34
$W_L^+W_L^-$	2.12	1.25	15.54	−0.63	13.50	−0.00	0.16
$W_L^+W_T^-$	0.96	0.52	9.95	−0.40	8.84	−0.00	0.17
$W_T^+W_L^-$	0.96	0.52	9.95	−0.40	8.85	−0.00	0.17
$W_T^+W_T^-$	0.36	0.07	13.60	−0.29	12.45	−0.00	0.78
Interf.	−0.46	−0.34(1)	−1.39(1)	0.11(1)	−0.98(1)	0.00	0.04
Unpol.	3.93	6.23(2)	292.19(2)	1.91(2)	278.89(2)	0.13	9.11
$W_L^+W_L^-$	2.12	2.36(1)	64.98(1)	0.18	62.07(1)	0.01	0.75
$W_L^+W_T^-$	0.96	1.53(1)	66.85(1)	0.46(1)	64.62(1)	0.02	1.18
$W_T^+W_L^-$	0.96	1.54(1)	66.83(1)	0.48(1)	64.60(1)	0.02	1.18
$W_T^+W_T^-$	0.36	1.38(1)	100.40(1)	0.88(1)	94.30(1)	0.08	5.68
Interf.	−0.46	−0.58(3)	−6.88(3)	−0.09(2)	−6.70(3)	−0.00	0.31