Polarized W^+W^- pairs at the LHC: Effects from bottom-quark induced processes at NLO QCD+EW

Duc Ninh LE

Phenikaa University, Hanoi, Vietnam

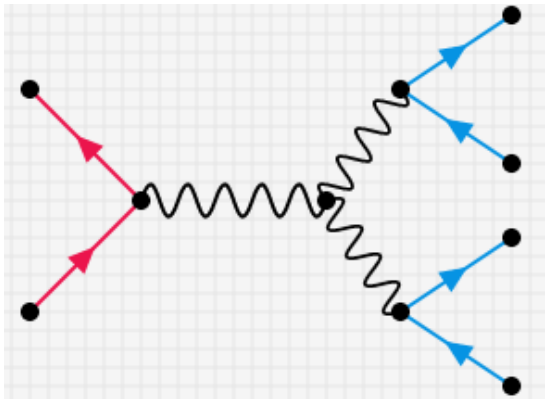
2nd APCTP Workshop on Precision Calculation and Collider Phenomenology, Pohang, 25 November 2025

Outline

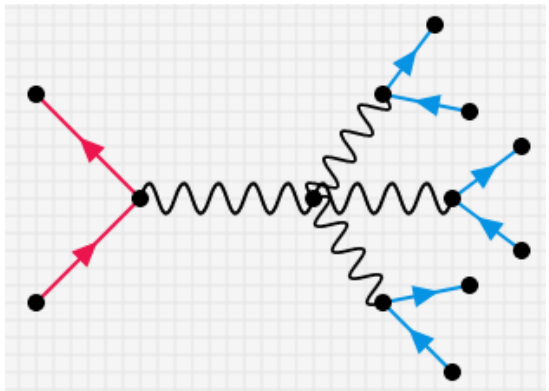
- Motivations for polarization studies in **multi-boson** production.
- Polarization definitions.
- Method of measurement.
- Theoretical Status: fixed order and PS.
- Details of NLO QCD + EW calculations.
- Tool: MulBos (Polarized Multi-Boson production).
- W^+W^-: Subtracting the tW contribution.
- Numerical results.
- Summary.

Multi-gauge boson production at the LHC

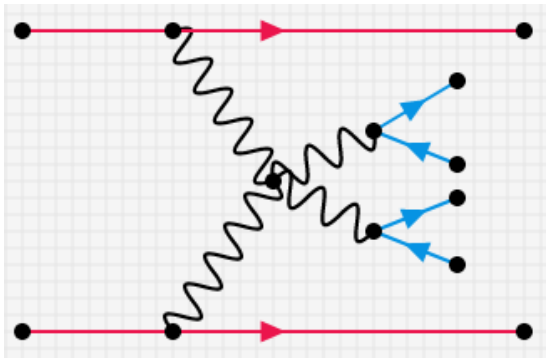
Diboson



Triboson



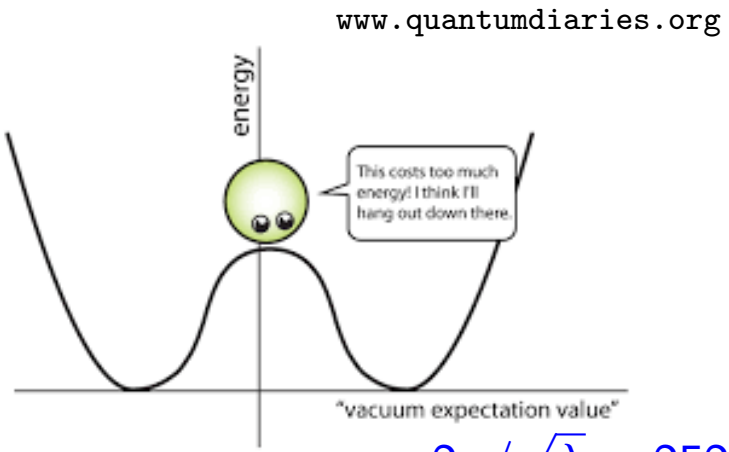
Vector boson scatterings



Physics case:

- sensitive to triple and quartic gauge couplings
- connection to EW symmetry breaking mechanism (EWSB)
- joint polarization
- quantum entanglement

EWSB



$v = 2\mu/\sqrt{\lambda} \approx 252\text{GeV}$

$$\mathcal{L}_H = (D^\mu \Phi)^\dagger (D_\mu \Phi) + \mu^2 \Phi^\dagger \Phi - \frac{\lambda}{4}(\Phi^\dagger \Phi)^2$$

- emergence of the **Higgs**: $M_H = \sqrt{2}\mu \approx 125\text{GeV}$
- emergence of 3 **longitudinal** modes: W^+, W^-, Z at
  - $M_W = g_2 v/2 \approx 80\text{GeV}$
  - $M_Z = \sqrt{g_1^2 + g_2^2}\, v/2 \approx 91\text{GeV}$

Recent measurements

ATLAS 2402.16365	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

Inclusive VV:

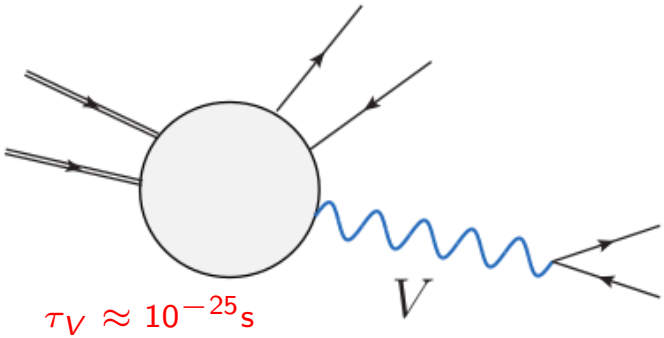
- WZ: ATLAS 2402.16365
- ZZ: ATLAS 2310.04350

$VVjj$:

- Same sign W^+W^+jj: CMS 2009.09429, ATLAS 2503.11317

Polarization measurements: based on polarized-template fits! [more later]

Separation of polarizations for an intermediate V



$\tau_V \approx 10^{-25}$s

$$\mathcal{A} = \mathcal{P}_\mu(k) \frac{-g^{\mu\nu}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu(k),$$

$$g^{\mu\nu} = -\sum_{\lambda=L,\pm} \varepsilon_\lambda^{\mu*}(k)\varepsilon_\lambda^{\nu}(k) + \frac{k^\mu k^\nu}{M_V^2}$$

The $k^\mu k^\nu$ term cancels against the **Goldstone** contribution.

Separation of polarizations:

$$-g^{\mu\nu} \to \sum_{\lambda=L,\pm} \varepsilon_\lambda^{\mu*}(k)\varepsilon_\lambda^{\nu}(k)$$

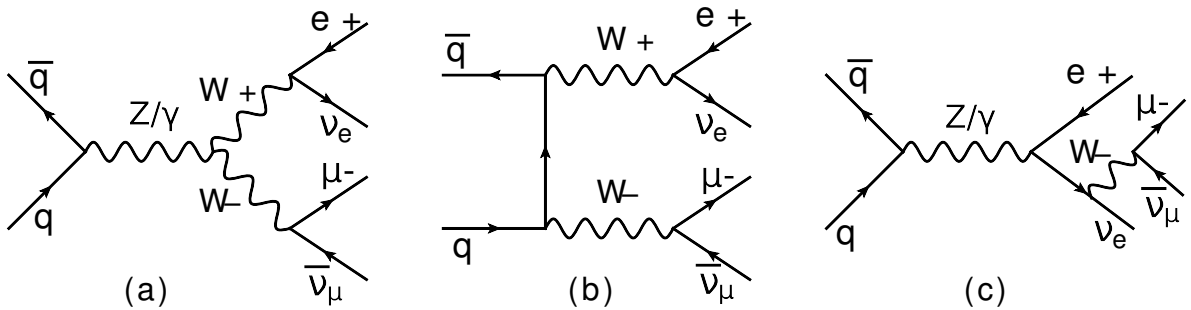
Off-shell amplitude:

$$\mathcal{A} = \frac{1}{k^2 - M_V^2 + iM_V\Gamma_V} \sum_{\lambda=L,\pm} \underbrace{\mathcal{P}_\mu(k)\varepsilon_\lambda^{\mu*}(k)}_{\mathcal{A}_\mathrm{P}} \underbrace{\varepsilon_\lambda^{\nu}(k)\mathcal{D}_\nu(k)}_{\mathcal{A}_\mathrm{D}}, \quad (1)$$

$$= \frac{1}{k^2 - M_V^2 + iM_V\Gamma_V} \sum_{\lambda=L,\pm} \mathcal{A}_\mathrm{P}(\lambda,k)\mathcal{A}_\mathrm{D}(\lambda,k), \quad (2)$$

- Spin **correlations** between production and decay are fully retained.

Methods to define polarizations at LO



1. Select all diagrams with n resonances: $V_i \to ll'$ $(i = 1, n)$.
2. Factorize the amplitude into production and decay parts [pol selection].

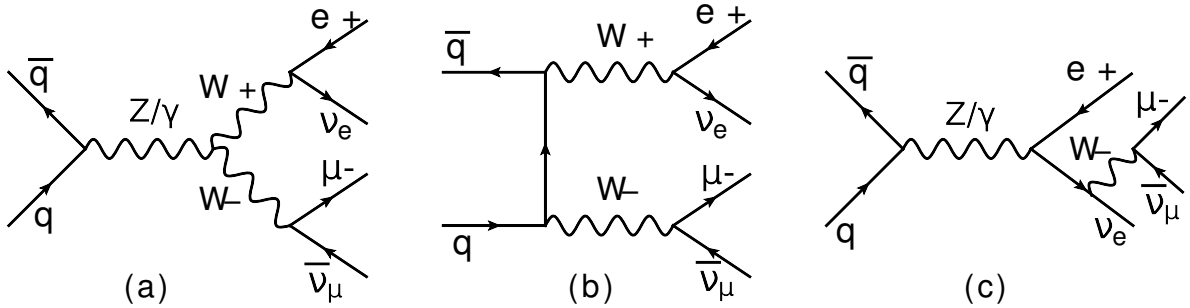
On-shell approximations:

- DPA: OS mappings $(\hat{q}_i^2 = M_i^2)$ [PHANTOM, MoCaNLO, STRIPPER, BBMC, MulBos]
- Narrow-Width Approximation (NWA): [Sherpa, MadGraph]

$$\frac{1}{q^2 - M^2 + iM\Gamma} \to \frac{\pi}{M\Gamma}\delta(q^2 - M^2)$$

[Carrivale et al 2505.09686: Comparison of those programs for polarized ZZ.]

Polarization Templates (DPA)



- Select all diagrams with 2 resonances: $V_1 \to l_1 l_2$, $V_2 \to l_3 l_4$.
- Factorize the amplitude into production and decay parts.
- Perform an on-shell (OS) mapping.

$$\mathcal{A}^{\bar{q}q\to V_1V_2\to 4l}_{\mathrm{LO,DPA}} = \frac{1}{Q_1 Q_2}\sum_{\lambda_1,\lambda_2=1}^{3} \mathcal{A}^{\bar{q}q\to V_1V_2}_{\mathrm{LO}}(\hat{k}_i,\lambda_1,\lambda_2)\mathcal{A}^{V_1\to l_1 l_2}_{\mathrm{LO}}(\hat{k}_i,\lambda_1)\mathcal{A}^{V_2\to l_3 l_4}_{\mathrm{LO}}(\hat{k}_i,\lambda_2),$$

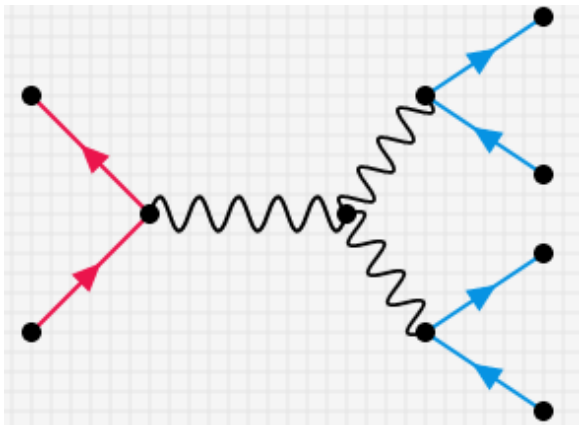
- $Q_j = q_j^2 - M_{V_j}^2 + iM_{V_j}\Gamma_{V_j}$ [off-shell]
- **DP region**: $m_{4l} > M_{V_1} + M_{V_2}$
- OS mapping: [**gauge invariance!**] $\{k_1,\ldots,k_4\} \to \{\hat{k}_1,\ldots,\hat{k}_4\}$.
- $\mathcal{A}_{\lambda_1\lambda_2}$: **Frame** dependence

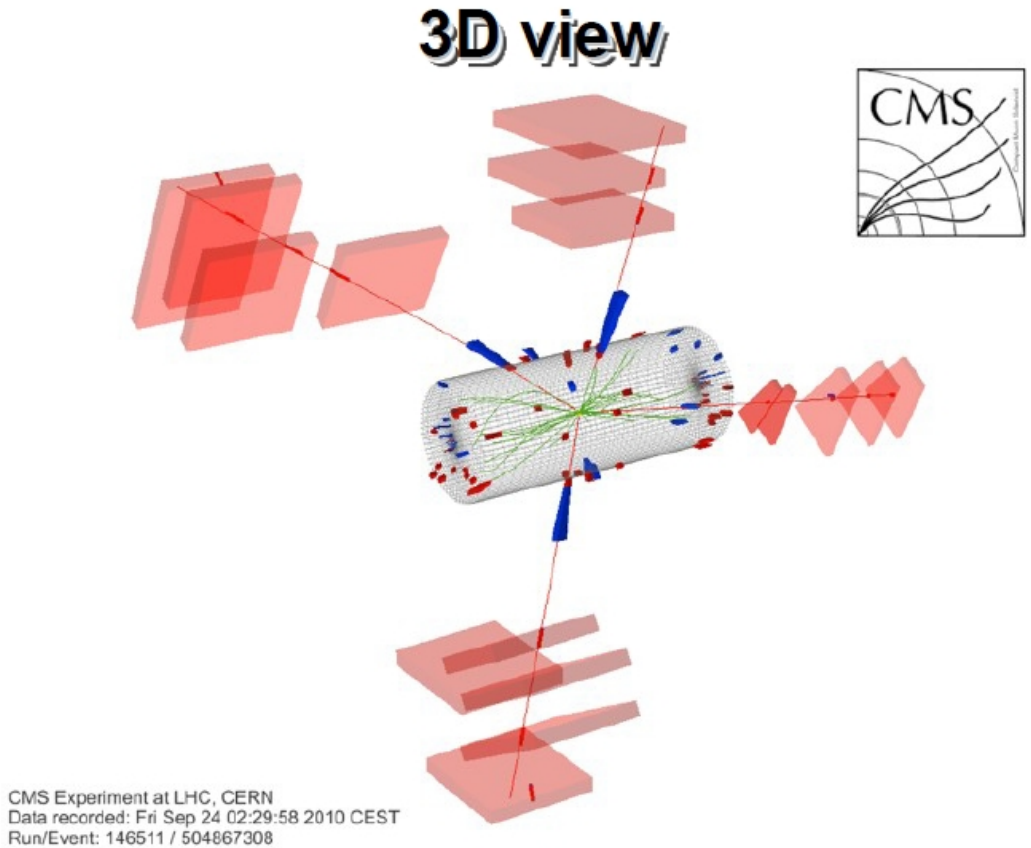
Polarization templates:

- LL: $\lambda_1 = \lambda_2 = 2$.
- LT: $\lambda_1 = 2$, $\lambda_2 = 1, 3$.
- TL: $\lambda_1 = 1, 3$, $\lambda_2 = 2$.
- TT: $\lambda_1 = 1, 3$, $\lambda_2 = 1, 3$.
- Interf: $\sigma_{\mathrm{unpol}} - \sum_{LL,LT,TL,TT} \sigma_{\lambda_1\lambda_2}$

Polarization separation in measurement

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





$$\sigma_{4l} = \underbrace{\sigma_{TT} + \sigma_{TL} + \sigma_{LT} + \sigma_{LL}}_{\text{double polarization signals}} + \underbrace{\sigma_{\text{interf}}}_{\text{small if inc lep cuts}} + \underbrace{\sigma_{\text{off-shell}}}_{\text{small d.t. OS cuts}}$$

Method of measurement

- Select double-resonance region: $m_{4l} > M_{V_1} + M_{V_2}$ and/or suitable cuts
- Generate polarization templates using a SM simulator $[d\hat{\sigma}/dx]$
- A separate template for off-shell contribution $(= \sigma_{\text{full}} - \sigma_{\text{on-shell}})$
- Fit polarized XS: σ_{LL}, σ_{LT}, ...

Example: $x = \Delta\phi_{\ell\ell'}$

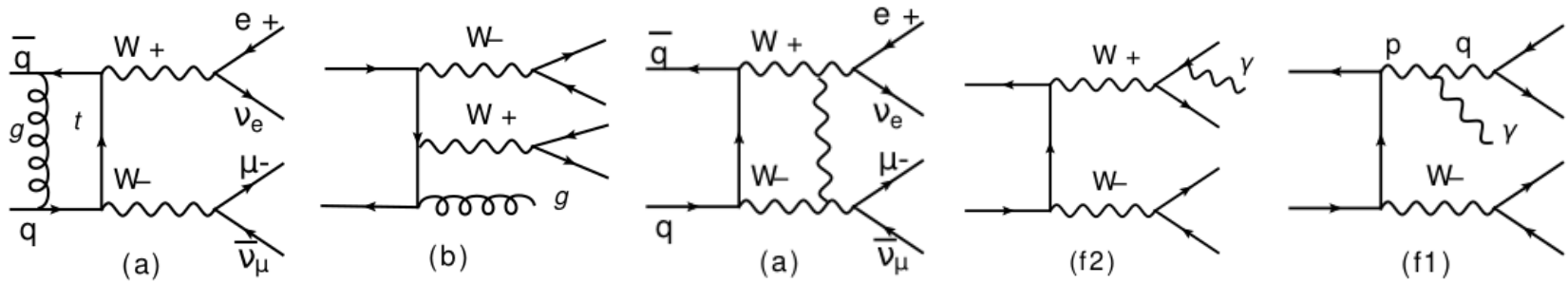
$$\frac{d\sigma_{\text{data}}}{dx} = \frac{d\hat{\sigma}_{\text{LL}}}{dx} + \frac{d\hat{\sigma}_{\text{TL}}}{dx} + \frac{d\hat{\sigma}_{\text{LT}}}{dx} + \frac{d\hat{\sigma}_{\text{TT}}}{dx} + \frac{d\hat{\sigma}_{\text{interf}}}{dx} + \frac{d\hat{\sigma}_{\text{off-shell}}}{dx} + \frac{d\sigma_{\text{bkg. procs}}}{dx}$$

Remarks: ATLAS, CMS measurements

[CMS:2009.09429,ATLAS:2211.09435,ATLAS:2503.11317,...]

- Deep neural network classifier helps to better separate the four polarization states $\rightsquigarrow$ better fit

Higher-order effects: fixed order [Overview]



Fully-leptonic decays:

- (N)NLO QCD: straightforward extension from the LO methods, because QCD corrections affect only the production amplitude (e.g. $q\bar{q} \to VV'$). DPA (NNLOQCD STRIPPER) and NWA (nLO QCD Sherpa).
- NLO EW: succeeded for the DPA. EW corrrections in both production and decay. **Photon radiation off the OS W**. [Denner, Pelliccioli, Haitz, Baglio, Dao, DNL (2020-2023)].

Semi-leptonic decays:

- NLO QCD: $Z(\to \ell^+\ell^-)W(\to jj)$ using DPA. QCD corrections in both production and decay. No gluon radiation off the W. [Denner, Pelliccioli, Haitz (2022)].

Higher-order effects: Parton Shower (PS)

Production:

- POWHEG-BOX: DPA, **NLO QCD** matched to PS.
- Sherpa: NWA, nLO QCD matched and LO **multi-jet merged** to PS.
- MadGraph: LO matched and merged to PS.
- QED ISR: resumming the leading **soft** logarithms to all orders.

Decays (fully leptonic):

- QED FSR: resumming the leading soft logarithms to all orders.

Intermediate on-shell W:

- **Resummation** of QED radiation off W *separately* for production and decay. [NEW for polarization. Not done.]

gg loop-induced (15%, M_t, **overlap** with $q\bar{q}$, qg at higher orders): ZZ, W^+W^-

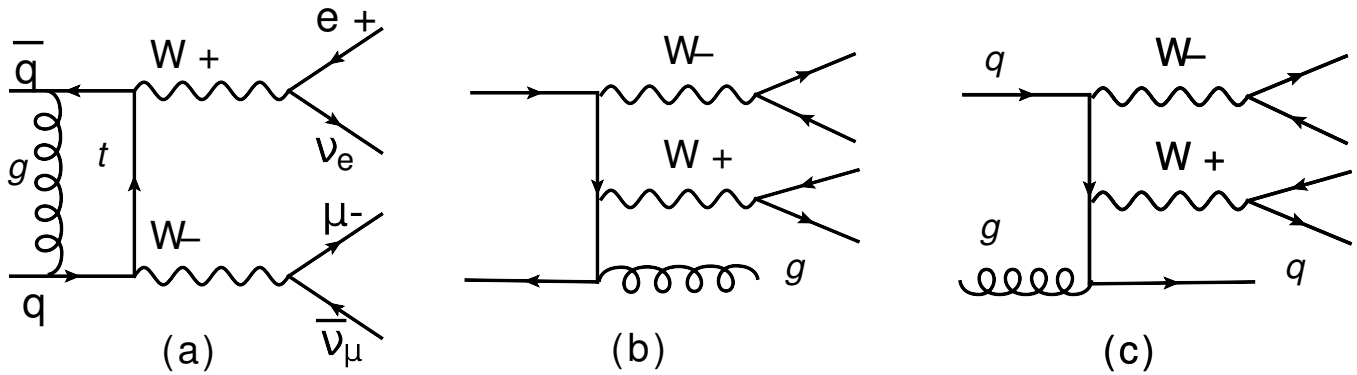
- fixed LO.

Note1: **hadronization** *effects are negligible [VV′, Pelliccioli, Zanderighi, 2023].*

Note2: **unpolarized** *WZ, NNLOQCD + NLOEW matched to PS [MiNNLO, Lindert, Lombardi, Wiesemann, Zanderighi, 2022].*

NLO QCD corrections

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



NEW compared to LO:

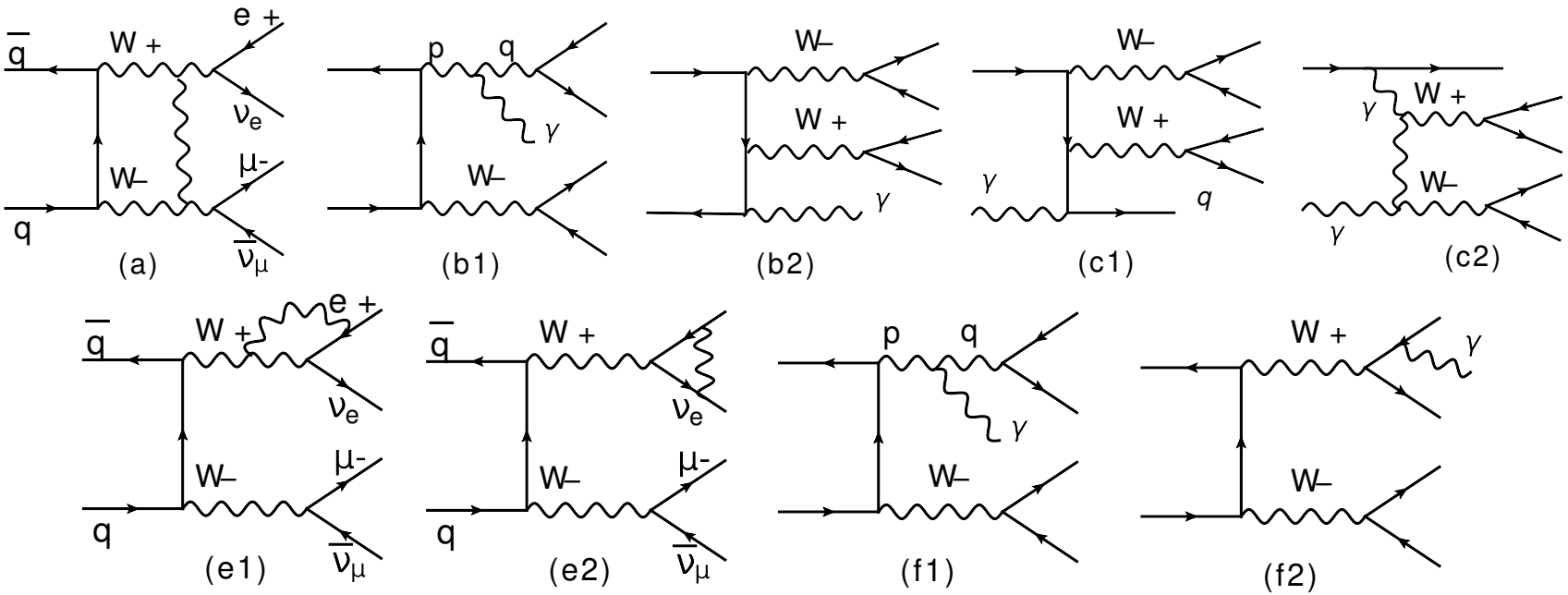
- (a): Virtual corrections.
- (b): Real gluon emission.
- (c): Real quark emission.

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

Calculation details:

- On-shell mapping: same as LO ($\hat{V}\hat{V}'$, $\hat{V}\to 2\hat{l}$).
- Catani-Seymour-Dittmaier subtraction method (straightforward).
- Details in [Denner, Pelliccioli, ZZ, 2107.06579].

NLO EW corrections (I)



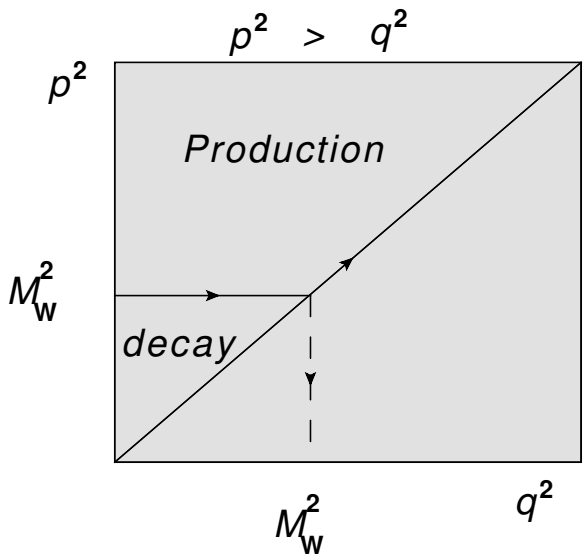
NO double counting: (b1), (f1)

Production (NEW compared to QCD):

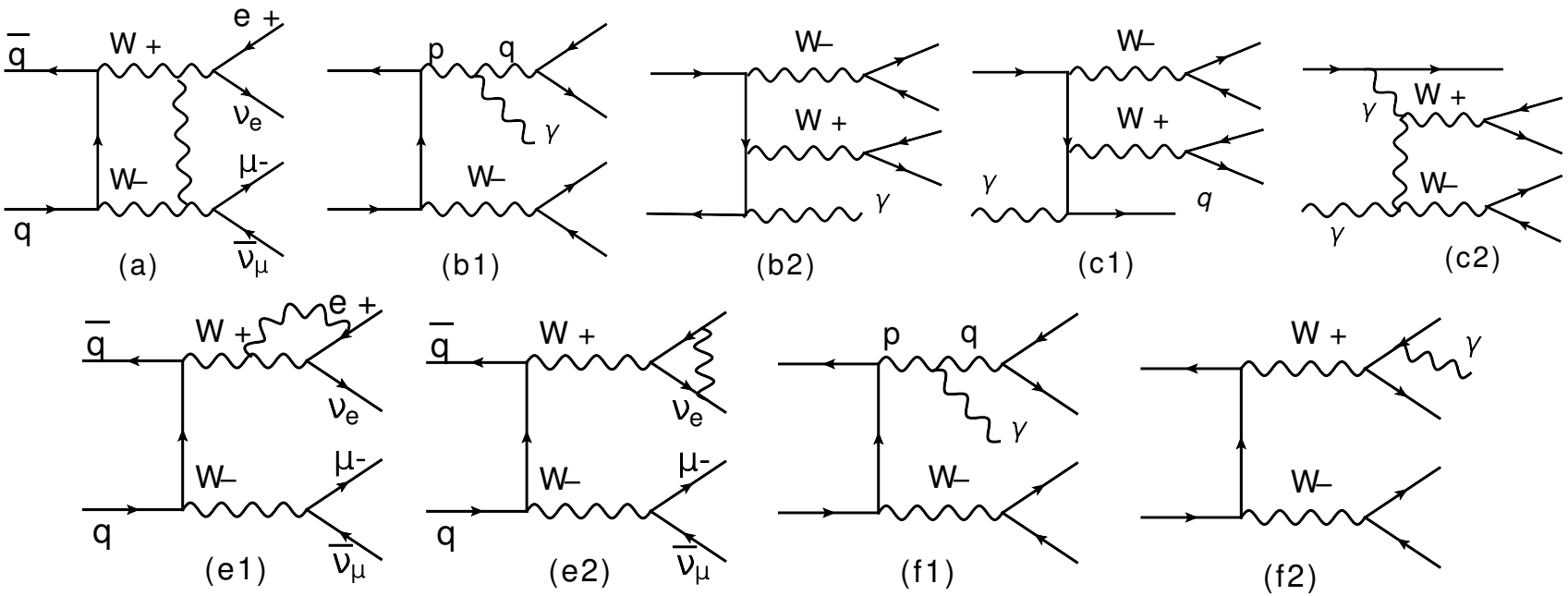
- Real photon emission off an OS W.
- $\gamma\gamma$ induced contribution (LO, Virt, Real).

Decays:

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



NLO EW corrections (II)



Decays:

- On-shell mapping: $\hat{V}\hat{V}'$, $\hat{V} \to 2\hat{l} + \hat{\gamma}$, $\hat{V}' \to 2\hat{l}$ [Denner, Pelliccioli, 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, Pelliccioli, ZZ, 2107.06579].
- final emitter, initial spectator: [DNL, Baglio, Dao, WZ, 2208.09232].
- final emitter, final spectator: [Denner, Haitz, Pelliccioli, WW, 2311.16031; DNL, Dao, WW, 2311.17027]

Theoretical status

Fixed order calculations (fully leptonic):

- ZZ (NLO QCD+EW) [Denner, Pelliccioli, JHEP (2021)]
- WZ (NLO QCD+EW) [Denner, Pelliccioli, NLO QCD, PLB (2021); DNL, Baglio, Dao, NLO QCD+EW, EPJC (2022)]
- WW (NLO QCD+EW; NNLO QCD) [Denner, Pelliccioli, NLO QCD, JHEP (2020); Poncelet, Popescu, NNLO QCD, JHEP (2021); Denner, Haitz, Pelliccioli, NLO EW, PLB (2024); Dao, DNL, NLO QCD+EW, EPJC (2024), Dao, DNL, NLO QCD+EW, 2409.06396; b-induced]
- same-sign W^+W^+jj: NLO QCD+EW [Denner, Haitz, Pelliccioli, 2409.03620]
- $WZjj$: NLO EW [Denner, Franken, Haitz, Lombardi, Pelliccioli, 2510.26462]

Fixed order calculations (semi leptonic):

- WZ at NLO QCD [Denner, Haitz, Pelliccioli, PRD (2023)]
- $VVjj$ LO DPA: [Denner, Lombardi, Schwan, 2406.12301]

Parton showers:

- 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 [Pelliccioli, Zanderighi, EPJC (2024)]
- ZZ: comparisons, NNLOQCD, NLOEW, PS [Carrivale et al 2505.09686]

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

Code publication in progress ...

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

Ref. [Dao, DNL, 2311.17027]

	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}^{\rm QCD}$ [fb]	$\sigma_{\rm NLO}^{\rm QCDEW}$ [fb]	$\sigma_{\rm all}$ [fb]	$\overline{\delta}_{\rm EW}$ [%]	$\overline{\delta}_{gg}$ [%]	$\overline{\delta}_{b\bar{b}}$ [%]	$\overline{\delta}_{\gamma\gamma}$ [%]	$f_{\rm all}$ [%]
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 $p_{T,j} > 35\,\text{GeV}$ and $|\eta_j| < 4.5$)

On-shell cut (simulation of polarization templates):

$$m_{4l} > 2M_W$$

Comparison

	$\sigma_{\rm LO}^{\rm DL}$ [fb]	$\sigma_{\rm LO}^{\rm DHP}$ [fb]	$\Delta_{\rm LO}$ [%]	$\sigma_{\rm NLO}^{\rm DL}$ [fb]	$\sigma_{\rm NLO}^{\rm DHP}$ [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

DL = Dao, Le [2311.17027] vs. DHP = Denner, Haitz, Pelliccioli [2311.16031]

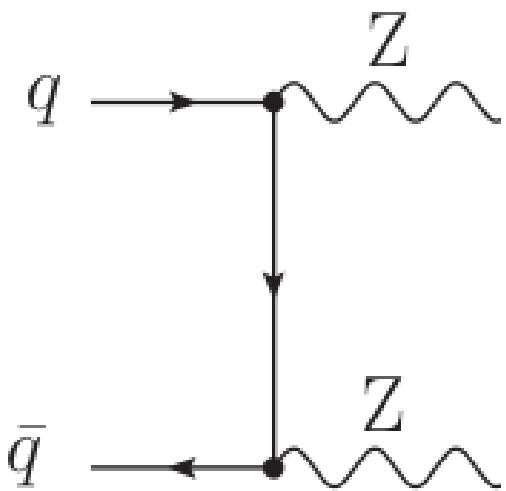
Why the LL fraction is smallest ?

Stable-Z approximation:

$$\varepsilon_-^\mu = \frac{1}{\sqrt{2}}(0, \cos\theta, -i, -\sin\theta),$$

$$\varepsilon_+^\mu = \frac{1}{\sqrt{2}}(0, -\cos\theta, -i, \sin\theta),$$

$$\varepsilon_L^\mu = \frac{1}{M}(p, E\sin\theta, 0, E\cos\theta) \xrightarrow{E \gg M} \frac{p^\mu}{M}$$



$$\frac{d\sigma_{LL}}{d\cos\theta} = \frac{a}{96}\frac{M_Z^4}{s^3}\frac{\cos^2\theta}{\sin^2\theta} + \mathcal{O}\left(\frac{1}{s^4}\right),$$

$$\frac{d\sigma_{LT}}{d\cos\theta} = \frac{a}{12}\frac{M_Z^2}{s^2} + \mathcal{O}\left(\frac{1}{s^3}\right),$$

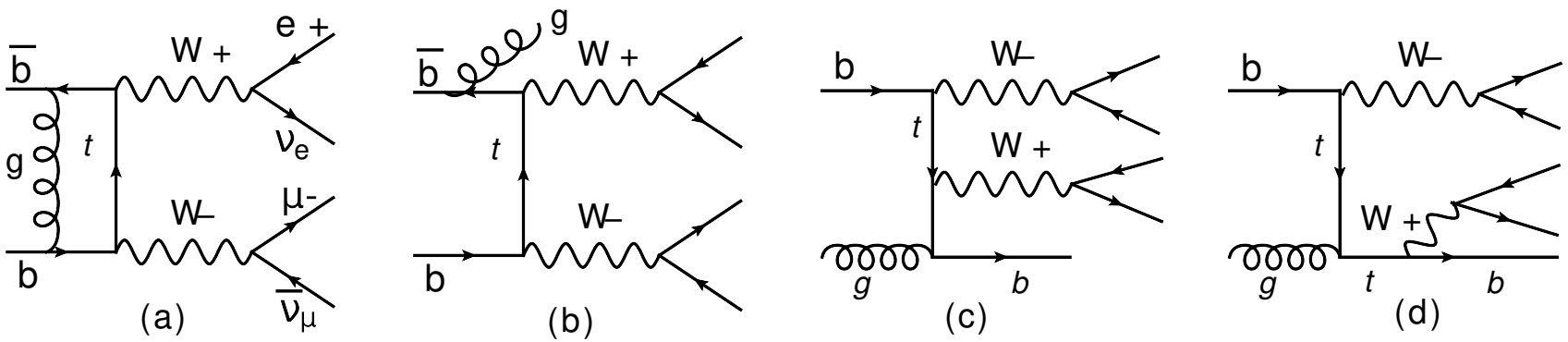
$$\frac{d\sigma_{TT}}{d\cos\theta} = \frac{a}{48}\frac{1}{s}\frac{1+\cos^2\theta}{\sin^2\theta} + \mathcal{O}\left(\frac{1}{s^2}\right)$$

with $a = \pi\alpha^2(c_L^4 + c_R^4)/(s_W^4 c_W^4)$, $\sqrt{s} \in [2M_Z, 13\,\text{TeV}]$

- LL is most sensitive to the mass, but kinematically suppressed !
- Dominant contribution to σ_{LL} comes from the threshold region.

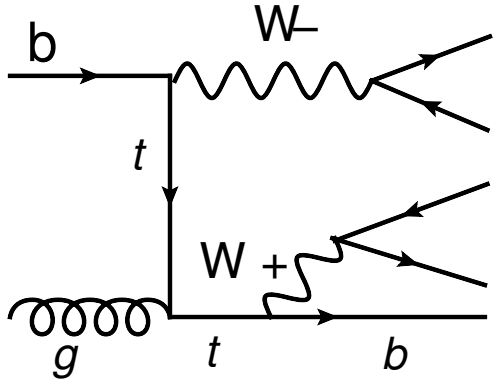
b-quark contribution (W^+W^-)

[Dao, DNL, EPJC 85 (2025) 108]



- $b\bar{b}$ annihilation gives large contribution to LL XS at LO ($\sim M_t$ in the t-channel).
- t resonance(s) occur at NLO (NNLO) $\rightarrow$ t backgrounds.
- b contribution calculated after a proper OS t subtraction $\rightsquigarrow$ largest effects on LL.
- used 5 flavor scheme with $m_b = 0$.

Subtracting OS pol. tW @ NLO [Dao, DNL, EPJC 85 (2025) 108]



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

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

$$Q_t = p_t^2 - m_t^2 + i m_t \Gamma_t, \quad Q_j = p_j^2 - M_W^2 + i M_W \Gamma_W \ (j = W^+, W^-), \qquad (4)$$

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 $\hat{k}_3$, $\hat{k}_4$, $\hat{k}_7$.

b-induced effects: YesVeto [Dao, DNL, EPJC 85 (2025) 108]

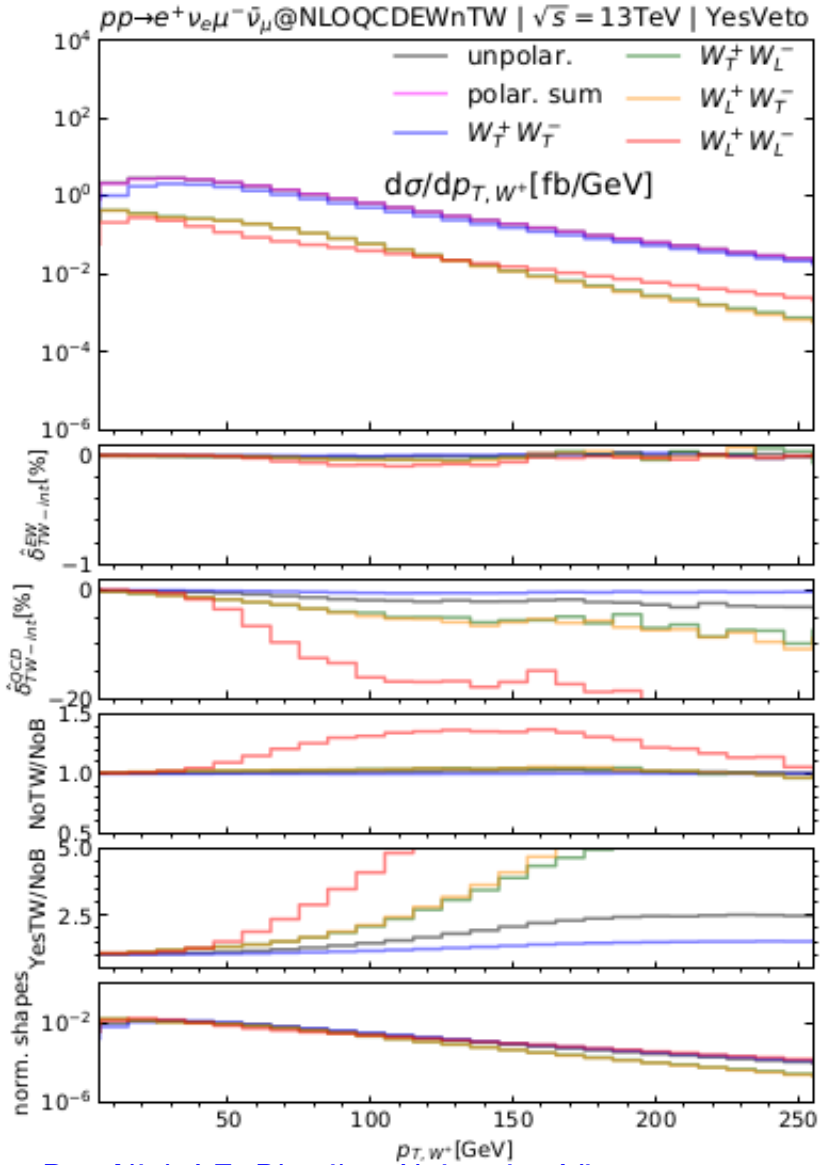
	σ_{NoB} [fb]	σ_{NoTW} [fb]	σ_{YesTW} [fb]	$K_{b\bar{b}}^{\text{LO}}$	K_{NoTW}	K_{YesTW}	$\hat{\delta}_{\text{TW-int}}$ [%]	f_{NoB} [%]	f_{NoTW} [%]	f_{YesTW} [%]
Unpol.	$218.47(3)^{+2.2\%}_{-2.1\%}$	$220.50(3)^{+2.1\%}_{-2.0\%}$	$266.12(3)^{+3.7\%}_{-3.8\%}$	1.02	1.01	1.22	-0.75	100	100	100
$W_L^+W_L^-$	$14.34^{+1.8\%}_{-2.6\%}$	$15.59^{+1.2\%}_{-2.2\%}$	$29.88^{+6.3\%}_{-6.7\%}$	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

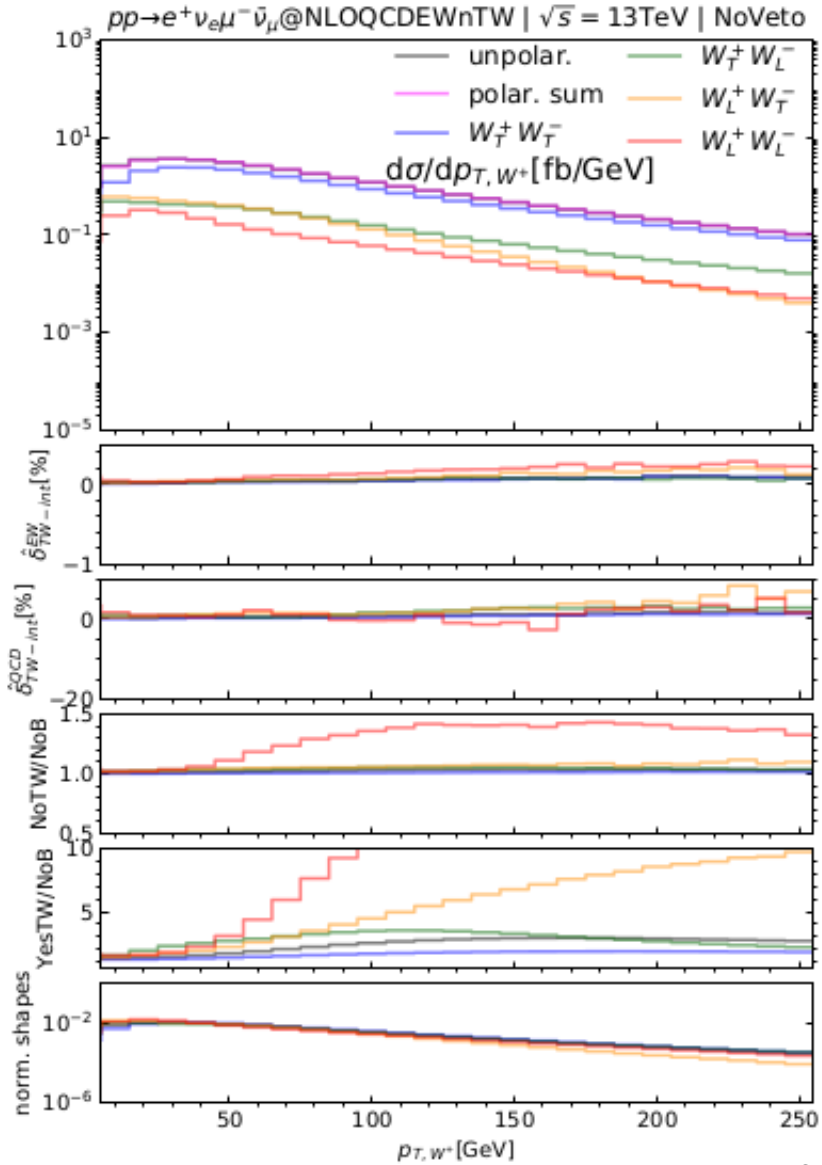
- NoB: u,d,c,s,gg,$\gamma\gamma$
- YesTW: NoB + b-induced at NLO (tW included)
- NoTW: YesTW − OS tW
- $K_X = \sigma_X/\sigma_{\text{NoB}}$
- $\hat{\delta}_{\text{TW-int}}$: bound of tW-interference

W^+W^-: contribution from b-quark

[Dao, DNL, EPJC 85 (2025) 108]

NoTW: OS tW-contribution subtracted at NLO QCD+EW (5FS).





Summary

- Polarization templates for $VVjj$ can be calculated at NLO QCD+EW; inclusive VV at NNLO QCD + NLO EW.
- W^+W^-: b-induced contribution can be large for LL. tW can be subtracted for individual polarizations in the 5FS at NLO.
- Parton showers: soft QED radiation off the W resonance(s), NLO EW matched are still missing.

Acknowledgments:

This work is funded by Phenikaa University under grant number PU2023-1-A-18.

Vietnam School of Physics: Since 1994

32nd Vietnam School of Physics: Particles and Dark Matter

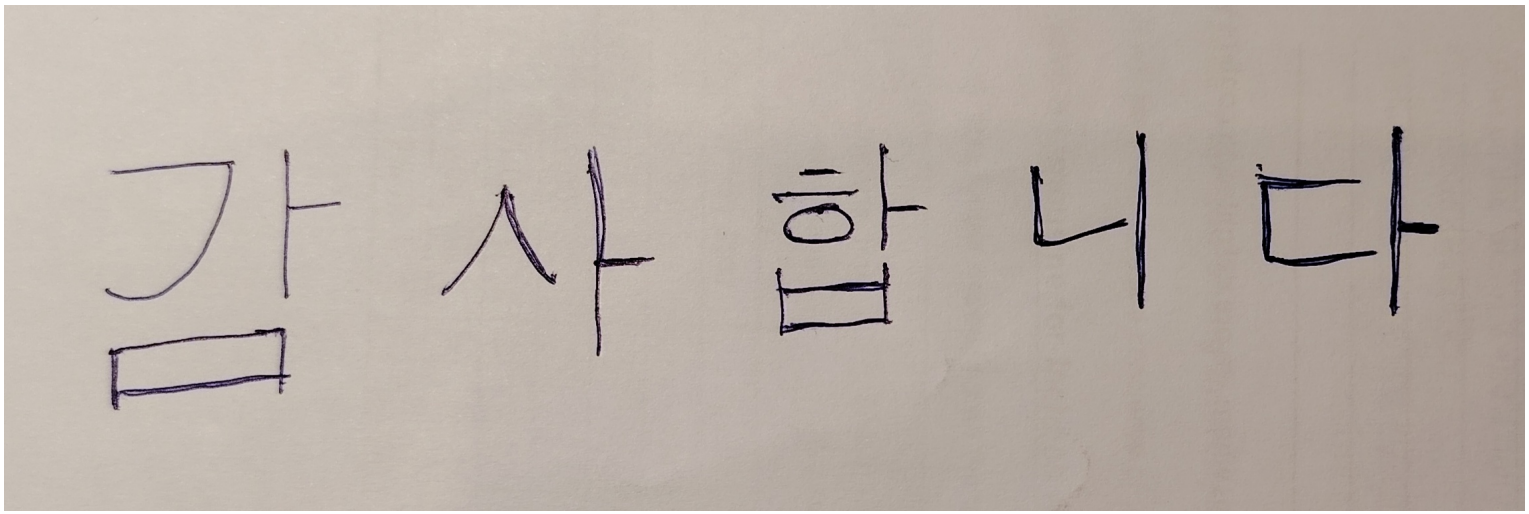
1. Standard Model (TBA)
2. Experimental methods and Statistics at the LHC (Tae Jeong Kim, Hanyang University, Korea)
3. QCD (TBA)
4. Dark matter (TBA)
5. Beyond SM (TBA)
6. Tools and Monte Carlo (Leif Lonnblad, Lund, Sweden – TBC)
7. Machine Learning for particle physicists (Michael Spannowsky, Durham, UK – TBC)

ICISE, Quy Nhon, Vietnam, 13–24 Jul 2026

Web: https://indico.in2p3.fr/event/37344/overview

Many previous schools: supported by the APCTP !

Main organizer and sponsor: Rencontres du Vietnam


감사합니다