(Non)Polarization interference in weak boson production at high energies

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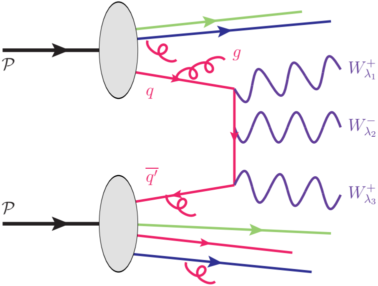
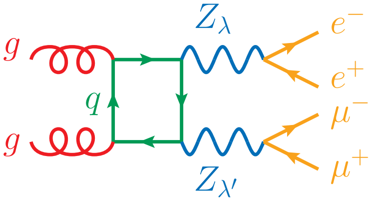
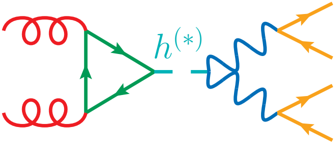
many thanks for the invitation!

Spin correlation and **helicity polarization** in **multiboson processes** probe the structure of gauge theory itself, including:

- longitudinal polarization $(\lambda = 0)$ of W/Z bosons
- gauge charges of gauge bosons
- spin and charge configurations not accessible in q/g scattering
- (mis)cancelations between gauge and gauge-symmetry-breaking sectors







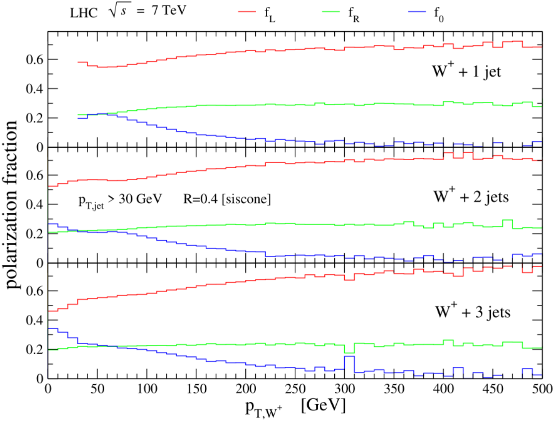
theory vs data

historically, compute full matrix element analytically and identify $V \mp A$ structure

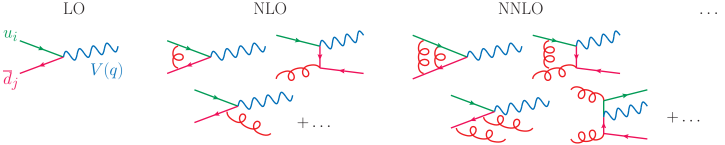
Collins & Soper ('77); Ellis, et al ('96); others

Bern, et al ('11) →

drawback: difficult for multiboson processes

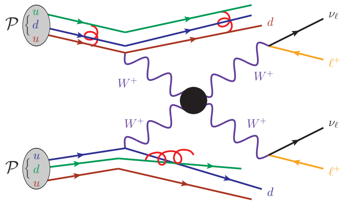


$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}(1\mp\cos\theta^*)^2 f_L + \frac{3}{8}(1\pm\cos\theta^*)^2 f_R + \frac{3}{4}\sin^2\theta^* f_0$$



Modern paradigm: use completeness to build up polarized matrix element

care needed due to loss of Lorentz invariance, unphysical dofs, etc!

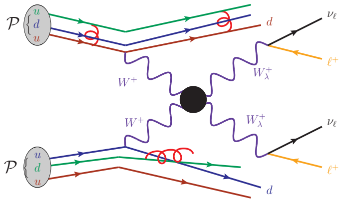


$$\Pi^V_{\mu\nu}(q) = \frac{-i\left(g_{\mu\nu} - q_\mu q_\nu/(M_V^2 - iM_V\Gamma_V\right)}{q^2 - M_V^2 + iM_V\Gamma_V}$$

$$= \sum_{\lambda\in\{0,\pm1,S\}} \eta_\lambda \left(\frac{-i\varepsilon_\mu(q,\lambda)\ \varepsilon^*_\nu(q,\lambda)}{q^2 - M_V^2 + iM_V\Gamma_V}\right)$$

key step: truncate the sum over helicities **"polarized propagator"**

Ballestrero, Maina, & Pellicciolii [1710.09339,1907.04722]



$$\Pi^V_{\mu\nu}(q,\lambda) = \frac{-i\varepsilon_\mu(q,\lambda)\ \varepsilon^*_\nu(q,\lambda)}{q^2 - M_V^2 + iM_V\Gamma_V}$$

Different generators, different implementation but good agreement

COMETA stress test [2505.09686]

- **helicity-truncated propagator + on-shell projection (DPA)**

  Aeppli, et al ('93,'94); Denner, et al ('00); Denner, Pellicciioli [JHEP('21)]; Pellicciioli, et al (`PowHEG`) [2311.16031]

- **helicity-truncated propagator + full Breit-Wigner**

  w/ Buarque-Franzosi, et al (`MadGraph`) [JHEP('20)]; w/ Javurkova, et al [PLB('24)]; w/ Basu [2512.10015] (**new!**)

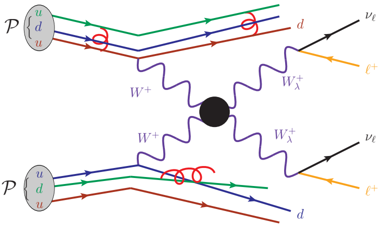
- **narrow width approx.** **(unpol. rate)** **+ spin-density matrix** **(pol. fraction)**

  Hoppe, et al (`Sherpa`) [2310.14803]

Pol. fractions in $W^\pm W^\pm$ scattering

CMS (PLB'20)

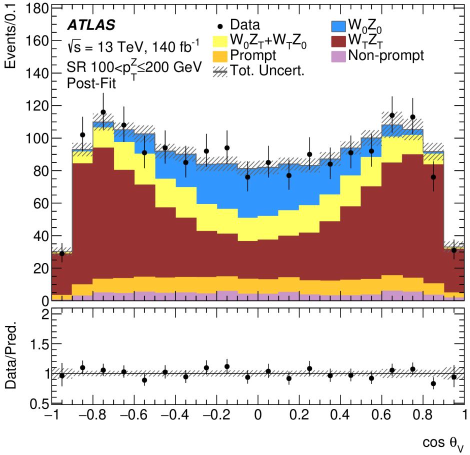
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

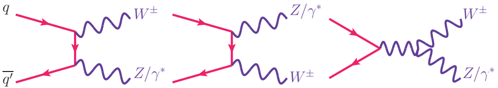


polarization paradigm works really well!

Pol. fractions in $W^\pm Z$ production

ATLAS [PLB('23); PRL('24)]





LHC data is well described by sum of squared amplitudes $|\mathcal{M}_\lambda|^2$

$$|\mathcal{M}_{\rm unpol}|^2 = \underbrace{\sum_{\lambda\in\{\pm1,0,S\}} |\mathcal{M}_\lambda|^2}_{\text{diagonal pol.}} + \underbrace{\sum_{\lambda\neq\lambda'} \mathcal{M}_\lambda \mathcal{M}^*_{\lambda'}}_{\text{pol interference}} \leftarrow \text{ numerically small}$$

why is polarization interference small? when is it large?

pol. interference driven by helicity inversion and nonzero masses

so assume $\frac{m_f}{E_V}, \frac{m_{f'}}{E_V} \to 0$**, then** $V \to f\overline{f'}$ **current is conserved,** $q \cdot J = 0$

$\Longrightarrow$ **T/0 polarization of** $V(q)$ **only sees T/0 part of** $f\overline{f'}$ **current** J^μ

$\Longrightarrow$ **T-0 interference is odd-symmetric in kinematics of** $f, \overline{f'}$

$\Longrightarrow$ **T-0 interference is small after integrating over phase space**[1]

[1] **w/ T. Basu [2512.10015, 2605.xxxxx]**

how to show this?

Step 1: treat the "polarized" propagator itself as a **Feynman rule**

w/ Javurkova, et al (PLB'24) [2401.17365]

$$\frac{-i\ \varepsilon_\mu(q,\lambda)\ \varepsilon^*_\nu(q,\lambda)}{q^2-M_V^2} =$$

$V_\lambda(q)$

BRST invariance: $\lambda = 0$ polarization should not be treated in isolation, but on same level as $\lambda = S$ polarization, Goldstones, and F.P. ghosts

't Hooft ('71), BRS('74,'75), T('75)

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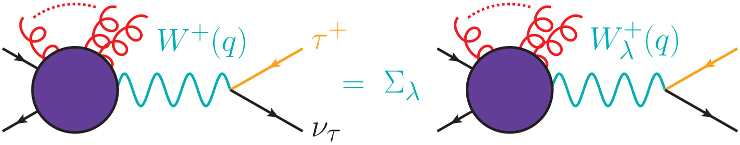
Step 2: treat each "polarized" diagram as **separate subamplitude**

$4\times$ **increase in diagram multiplicity in Unitary gauge**



Step 3: realize that polarized propagators have **simple analytical forms**

given momenta $q^\mu = (E_V, \vec{q})$ with arbitrary q^2, one can always build:

$$\hat{q}^\mu_\perp \quad , \; \hat{q}^\mu_{T\perp} \quad , \; n^\mu = (1, -\hat{q})$$

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transverse polarizations:

$$\sum_{\lambda=\pm1} \eta_\lambda \varepsilon_\mu(q,\lambda)\varepsilon^*_\nu(q,\lambda) = \hat{q}_{\perp\mu}\hat{q}_{\perp\nu} + \hat{q}_{T\perp\mu}\hat{q}_{T\perp\nu}$$

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longitudinal polarization (off-shell polarization vector needed for exact cancellations):

$$\eta_{\lambda=0}\varepsilon_\mu(q,\lambda=0)\varepsilon_\nu(q,\lambda=0) \; = \; \Theta_{\mu\nu} \; + \; \frac{q_\mu q_\nu}{q^2}$$

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scalar polarization in R_ξ gauge:

$$\eta_{\lambda=S}\varepsilon_\mu(q,\lambda=S)\varepsilon_\nu(q,\lambda=S) \ = \ -\left(\frac{q_\mu q_\nu}{q^2} + \frac{(\xi-1)\ q_\mu q_\nu}{q^2-\xi M_V^2+i\xi\Gamma_V M_V}\right)$$

summing recovers unpolarized propagator

$$\sum_{\lambda\in\{0,\pm1,S\}} \eta_\lambda \ \varepsilon_\mu(q,\lambda) \ \varepsilon^*_\nu(q,\lambda) \ = \ g_{\mu\nu} + \frac{(\xi-1)\ q_\mu q_\nu}{(q^2-\xi M_V^2+i\xi M_V\Gamma_V)}$$

$\Theta_{\mu\nu}$ captures forward and backward motion

$$\Theta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & \hat{q}_x^2 & \hat{q}_x\ \hat{q}_y & \hat{q}_x\ \hat{q}_z \\ 0 & \hat{q}_x\ \hat{q}_y & \hat{q}_y^2 & \hat{q}_y\ \hat{q}_z \\ 0 & \hat{q}_x\ \hat{q}_z & \hat{q}_y\ \hat{q}_z & \hat{q}_z^2 \end{pmatrix}$$

$$= \frac{(n\cdot q)}{(n\cdot q)^2 - q^2 n^2}\left[-n_\mu q_\nu - q_\mu n_\nu + \frac{q_\mu q_\nu n^2}{(n\cdot q)} + \frac{n_\nu n_\mu q^2}{(n\cdot q)}\right]$$

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$$\Theta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & \hat{q}_x^2 & \hat{q}_x\,\hat{q}_y & \hat{q}_x\,\hat{q}_z \\ 0 & \hat{q}_x\,\hat{q}_y & \hat{q}_y^2 & \hat{q}_y\,\hat{q}_z \\ 0 & \hat{q}_x\,\hat{q}_z & \hat{q}_y\,\hat{q}_z & \hat{q}_z^2 \end{pmatrix}$$

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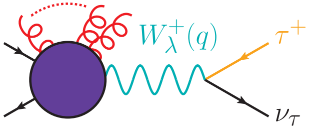
n^μ is an unphysical book keeping device, e.g.,

$$n^\mu = (1, -\hat{q}), \text{ with } n^2 = 0 \text{ (light-like)}$$
$$n^\mu = (1,\ \vec{0}), \text{ with } n^2 = +1 \text{ (time-like)}$$
$$n^\mu = (0, -\hat{q}), \text{ with } n^2 = -1 \text{ (space-like)}$$

this is a covariant gauge (R_ξ, Unitary), not an axial gauge!

earlier examples in ACOT-II ('94); Beenakker, et al ('94); also Hagiwara, Mawatari, et al [2003.03003], Dittmaier [2507.06568]

Step 4: chug & plug



$$\mathcal{M}_\lambda = G^\nu_{in} \cdot \Pi^V_{\nu\mu}(q,\lambda) \cdot J^\mu_{out}$$

✓ G^ν_{in} has some restrictions

✓ $J^\mu_{out} = \overline{u}(p,\lambda)\ \gamma^\mu(g_L P_L + g_R P_R) v(p',\lambda')$

✓ a little $\hat{z}$ boosting, a little $\hat{y}$ rotating

unintegrated pol. interference with θ_f, ϕ_f defined in $(\bar{f}f')$ rest frame

$$\mathcal{I} \propto \Re\left[\mathcal{M}^*_{\lambda=0}\mathcal{M}_{\lambda=T}\right] = \Re\left[\sum I^k_{\lambda,\lambda'}\right]$$

- $I^1_{LR} \sim -|g_L|^2 \sin\theta_f\,(\cos\theta_f\cos\phi_f - i\sin\phi_f)$
- $I^1_{RL} \sim -|g_R|^2 \sin\theta_f\,(\cos\theta_f\cos\phi_f + i\sin\phi_f)$
- $I^2_{LR} \sim -|g_L|^2 \sin\theta_f\,(\cos\theta_f\sin\phi_f + i\cos\phi_f)$
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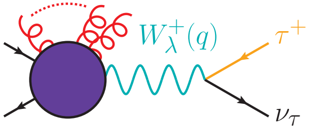

$$\mathcal{M}_\lambda \ = \ G^\nu_{in} \cdot \Pi^V_{\nu\mu}(q,\lambda) \cdot J^\mu_{out}$$

- ✓ G^ν_{in} has some restrictions
- ✓ $J^\mu_{out} = \overline{u}(p,\lambda)\ \gamma^\mu(g_L P_L + g_R P_R) v(p',\lambda')$
- ✓ a little $\hat{z}$ boosting, a little $\hat{y}$ rotating

unintegrated pol. interference with θ_f, ϕ_f defined in $(f\bar{f}')$ rest frame

$$\mathcal{I} \propto \ \Re\left[\mathcal{M}^*_{\lambda=0}\mathcal{M}_{\lambda=T}\right] \ = \Re\left[\Sigma\ I^k_{\lambda,\lambda'}\right]$$

- $I^1_{LR} \ \sim \ -|g_L|^2 \ \sin\theta_f \left(\cos\theta_f \cos\phi_f - i\sin\phi_f\right)$
- $I^1_{RL} \ \sim \ -|g_R|^2 \ \sin\theta_f \left(\cos\theta_f \cos\phi_f + i\sin\phi_f\right)$
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- $I^2_{RL} \ \sim \ -|g_R|^2 \ \sin\theta_f \left(\cos\theta_f \sin\phi_f - i\cos\phi_f\right)$

integrated pol. interference

- $\int_0^{2\pi} \ d\phi_f\ I^k_{\lambda\lambda'} \ = \ 0 \leftarrow$ rotation symm about decay axis
- $\int_{-1}^{+1} \ d\cos\theta_f \left(I^k_{LR} + I^k_{RL}\right) \ \sim \ \left(|g_L|^2 - |g_R|^2\right) \leftarrow$ fwd-bkd (a)symmetry

summary and conclusion

gauge qfts are weird but neat and work ☺

deep dive into polarization interference for intermediate weak bosons in high-energy scattering
w/ Basu [2512.10015, 2605.xxxxx]

- **identified analytical structures** that make evaluation and power counting of polarized amplitues more manifest
- **showed small pol. interference** is tied to properties/$V - A$ structure of conserved currents, $q \cdot J = 0$
- **proposed scheme** for combining polarizations, Goldstones, and F.P. ghosts that improves robustness against gauge choice

thank you for your attention!

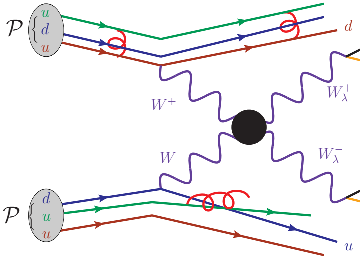
backup

polarization in `MadGraph5_aMC@NLO`

Polarization in MadGraph:

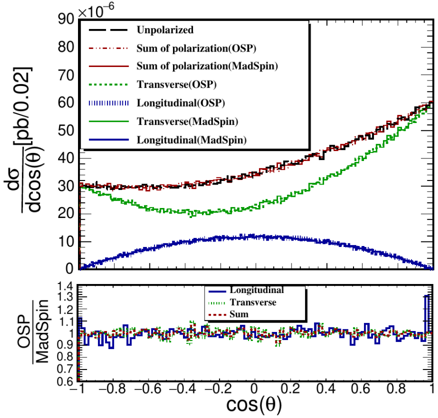
– diagram selection
– BW pole + truncated prop
– restrict $\sqrt{q^2}$ integral to $M_V \pm 10\Gamma_V$

Buarque-Franzosi, OM, RR, Shil (JHEP'20) [1912.01725]



```
> set group_subprocesses false
> generate p p > w+ w-{0} j j
        QED=4 QCD=0, w- > e- ve
```

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



counting polarizations

Unpolarized propagator in R_ξ gauge

$$\Pi^V_{\mu\nu}(q,\xi) = \frac{-i}{q^2 - M_V^2 + iM_V\Gamma_V}\left(g_{\mu\nu} - \frac{(1-\xi)q_\mu q_\nu}{q^2 - \xi M_V^2 + \xi M_V \Gamma_V}\right) = \sum_\lambda \Pi^V_{\mu\nu}(q,\lambda,\xi)$$

- Unitary gauge: 4 polarizations, $\lambda = \pm 1, 0, S$
- General covariant gauges (R_ξ): 4 + Goldstone
- Axial gauges: 3 polarizations (no $\lambda = S$) +Goldstone

key: roles and poles of $\lambda = 0, S, G, c$ migrate across different gauges

't Hooft ('71), BRS('74,'75), T('75)

$$\frac{-i\ \varepsilon_\mu(q,\lambda)\ \varepsilon^*_\nu(q,\lambda)}{q^2 - M_V^2} =$$

$V_\lambda(q)$

Observation: since **sum over all** polarized amplitudes $\mathcal{M}_\lambda$ is gauge invariant, **sum of non-transverse states** in difference gauges are related

w/ Basu [2512.10015]

$$\sum_{\lambda=0,S,G} \Pi^V_{\mu\nu}(q,\lambda,\xi)\ \Big|_{R_\xi} \overset{\text{Ward}}{=} \sum_{\lambda=0,S} \Pi^V_{\mu\nu}(q,\lambda)\ \Big|_{Unitary}$$

$$= \frac{i}{q^2 - M_V^2 + iM_V\Gamma_V}\left(\Theta_{\mu\nu} - \frac{q_\mu q_\nu}{M_V^2 - M_V\Gamma_V}\right)$$

Idea: 2 Polarization (2P) Scheme for covariant gauges **(R_ξ,Unitary)**

- transverse pol. $(\lambda = T)$ sums over $\lambda = \pm 1$
- long-scalar pol. $(\lambda = 0')$ sums over $\lambda = 0, S, G$

minor conceptual change when interpreting LHC results

ghost mechanics (for non-specialists)

The Original Sin(s) of Gauge QFT

- **QM**: spin-1 states have 2 **(massless and on-shell)** or 3 **(massive or off-shell)** dof

- **Manifest Lorentz invariance** is useful $\implies$ A^μ carries extra dof(s)

  spurious/extra divergence at $q^2 = 0$ in propagator for intermediate vector boson with $\lambda = 0$

- **gauge fixing**: modify **(not remove!)** "scalar/aux." polarization to fix A^μ

  add $\partial_\mu A^\mu$ terms to theory. these project/collect $\lambda = S$ in helicity basis

- **SSB**: Goldstones offset gauge charges of Higgs, mixes with $\partial_\mu A^\mu$

- **non-Abelian:** Faddeev-Popov ghosts offset charges in **gauge fixing**

- **'t Hooft+BRST:** everything. is. a. mess. but an ***unphysical mess***
  $\implies$ possible to swap $\partial_\mu A^\mu$, G, $c, \bar{c}$ $\implies$ things work. masses related

  gauge fixing $\iff$ assigning roles to unphysical fields