Four Polarizations of the W at High Energies

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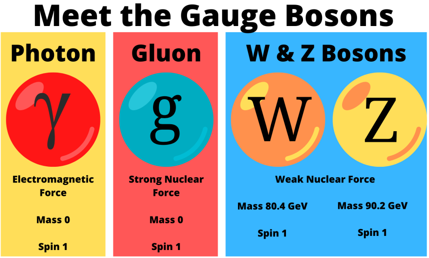
[1]in collaboration with **Richard Ruiz**, arXiv id: 2512.10015 (submitted to JHEP)

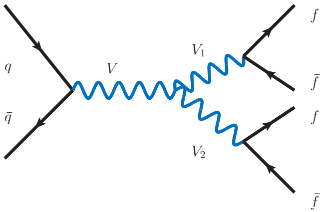
Gauge Bosons: Mediators of the fundamental forces

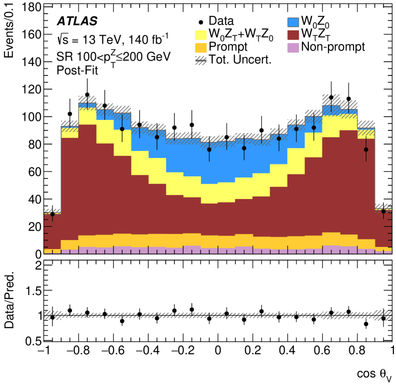


- Spin-1 particles, three spin states: $s_z = -1, 0, +1$ (3 dof)
- In high-energy scattering, described by a Lorentz 4-vector: $A^\mu \equiv (A^0, A^1, A^2, A^3)$ (4 dof)
- Gauge condition is added to the Lagrangian to remove the unphysical dof in calculations
- Massive gauge boson (3 dof): 2 transverse and 1 longitudinal states (helicity, $\lambda = \pm 1, 0$)
- Massless gauge boson (2 dof): 2 transverse states (Helicity, $\lambda = \pm 1$)

Motivation

- Studying weak boson polarization is a probe of gauge theory and EWSB



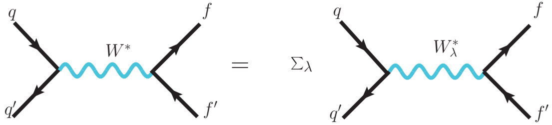


Source: ATLAS Collaboration, arXiv:2402.16365

- Extraction of gauge boson helicities is difficult but affects the kinematics of their decay products

Motivation (continued)

- When gauge bosons interact, their polarization states interfere



- Unpolarized amplitude = sum over amplitudes of polarized weak bosons

$$\mathcal{M}_{\text{unpol}} = \sum_{\lambda=0,\pm1,S} \mathcal{M}_\lambda = \sum_{\lambda=0,\pm1,S} J^\mu_{\text{in}}\, \Pi_\lambda J^\nu_{\text{out}} \tag{1}$$

$$|\mathcal{M}_{\text{unpol}}|^2 = \sum_{\lambda=0,\pm1,S} \underbrace{|\mathcal{M}_\lambda|^2}_{\text{incoherent terms}} + \underbrace{\sum_{\lambda\neq\lambda'} \mathcal{M}_\lambda \mathcal{M}'_\lambda}_{\text{interference terms}} \tag{2}$$

- Predictions assume that interference between different helicity states is negligible
- In general, interference is not guaranteed to be negligible
- Ensuring gauge invariance requires keeping track of scalar polarization ($\lambda = S$)

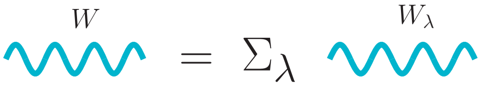
Goal and Outline

- **Main Goal:**
  1. To investigate the interference effects
  2. To explore the condition when it is negligible

- **Outline:**
  1. Introduce the relevant tools/expressions
  2. Construct the analytical structure of the interference
  3. Perform power counting of interference terms
  4. Find the conditions under which the interference is minimized
  5. Numerical case studies of interference at the matrix-element and cross section levels

Propagators

- Unpolarized propagator = the sum over propagators for each polarization state



- Unpolarized propagator: [2]

$$\begin{aligned}
\Pi_{\mu\nu} &= \frac{-i}{D_W(q^2)}\left[g_{\mu\nu} - \left(\frac{1-\xi}{D_W(q^2,\xi)}\right) q_\mu q_\nu\right] \\
&= \frac{i}{D_W(q^2)} \sum_{\lambda=0,\pm1,S} \eta_\lambda \epsilon_\mu(\lambda)\epsilon^*_\nu(\lambda) \\
&= \sum_{\lambda=0,\pm1,S} \Pi^\lambda_{\mu\nu} \qquad (3)
\end{aligned}$$

where, $D_W(q^2) = q^2 - \tilde{M}_W^2,\ D_W(q^2,\xi) = q^2 - \xi\tilde{M}_W^2,\ \tilde{M}_W^2 = M_W^2 - i\Gamma_W M_W$

[2] $\eta_0 = \eta_{\pm1} = 1, \eta_s = -1$

Propagators for W boson in unitary gauge $(\xi \to \infty)$

- Unpolarized propagator:

$$\Pi_{\mu\nu} = \frac{-i}{D_W(q^2)} \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{\tilde{M}_W^2} \right) \tag{4}$$

- Transverse propagator sum $(\lambda = \pm 1)$:

$$\Pi^T_{\mu\nu} = \frac{i}{D_W(q^2)} \sum_{\lambda=\pm 1} \eta_\lambda \epsilon_\mu(\lambda) \epsilon^*_\nu(\lambda) = \frac{i}{D_W(q^2)} (-g_{\mu\nu} - \Theta_{\mu\nu}) \tag{5}$$

- Longitudinal propagator $(\lambda = 0)$:

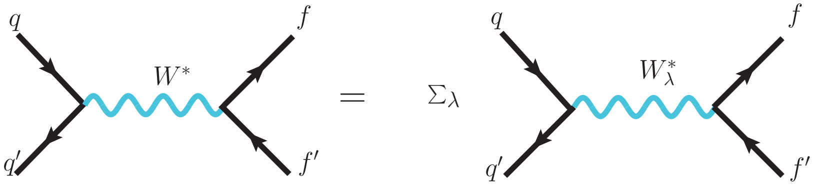
$$\Pi^0_{\mu\nu} = \frac{i}{D_W(q^2)} \left(\Theta_{\mu\nu} + \frac{q_\mu q_\nu}{q_W^2} \right) \tag{6}$$

- Scalar propagator$(\lambda = S)$:

$$\Pi^S_{\mu\nu} = \frac{i}{D_W(q^2)} \left(\frac{q_\mu q_\nu}{q_W^2} - \frac{q_\mu q_\nu}{\tilde{M}_W^2} \right) \tag{7}$$

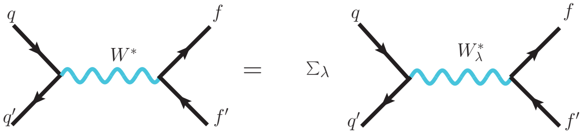
Matrix elements

- polarized matrix elements have special "polarized" propagators
- polarized matrix elements can otherwise be built from usual Feynman rules



$$\mathcal{M} = \sum_{\lambda=0,\pm1,S} \mathcal{M}_\lambda = \sum_{\lambda=0,\pm1,S} J^\mu_{\rm in}\ \Pi^\lambda_{\mu\nu}\ J^\nu_{\rm out} \tag{8}$$

Matrix elements (continued)



- Matrix elements for polarized propagators:

$$\mathcal{M}_{\text{unpol}} = -i\left(\mathcal{G} - \frac{\mathcal{Q}}{\tilde{M}_W^2}\right) \;; \qquad \mathcal{M}_{\lambda=T} = -i(\mathcal{G} + \vartheta) \;;$$

$$\mathcal{M}_{\lambda=0} = i\left(\vartheta + \frac{\mathcal{Q}}{q^2}\right) \;; \qquad \mathcal{M}_{\lambda=S} = i\left(\frac{\mathcal{Q}}{q^2} - \frac{\mathcal{Q}}{\tilde{M}_W^2}\right) \;;$$

where, $\mathcal{G} = \frac{1}{D_W(q^2)} \; J^\mu_{\text{in}} \; \boldsymbol{g}_{\boldsymbol{\mu\nu}} J^\nu_{\text{out}};\;\; \vartheta = \frac{1}{D_W(q^2)} \; J^\mu_{\text{in}} \; \boldsymbol{\Theta}_{\boldsymbol{\mu\nu}} J^\nu_{\text{out}};\;\; \mathcal{Q} = \frac{1}{D_W(q^2)} \; J^\mu_{\text{in}} \boldsymbol{q}_{\boldsymbol{\mu}} \boldsymbol{q}_{\boldsymbol{\nu}} J^\nu_{\text{out}}$

Interference

- Interference in unitary gauge:

$$
\begin{aligned}
\mathcal{I} = |\mathcal{M}_{\mathrm{unpol}}|^2 - \sum_{\lambda=T,0,S} |\mathcal{M}_\lambda|^2 &= \sum_{\lambda\neq\lambda',\ \lambda=T,0,S} \mathcal{M}^*_\lambda \mathcal{M}_{\lambda'} \\
&= -2|\vartheta|^2 - 2\mathrm{Re}(\mathcal{G}^*\vartheta) - \frac{2}{\tilde{M}_W^2}\mathrm{Re}(\mathcal{G}^*\mathcal{Q}) - \frac{2}{q^2}\mathrm{Re}(\mathcal{Q}^*\vartheta) \\
&\quad + \frac{2M_W^2(q^2 - M_W^2 - \Gamma_V^2)}{q^4|\tilde{M}_W^2|^2}|\mathcal{Q}|^2
\end{aligned}
\tag{9}
$$

- Partial cancellations occur at squared matrix element level

- Even in the on-shell limit, the interference remains non-zero

Some nice analytical expressions

- For W momentum, $q^\mu = (E_V, |\vec{q}|\sin\theta_V\cos\phi_V, |\vec{q}|\sin\theta_V\sin\phi_V, |\vec{q}|\cos\theta_V)$, $\Theta_{\mu\nu}(\theta_V,\phi_V)$ is given by:

$$\Theta_{\mu\nu} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & \cos^2\phi_V\ \sin^2\theta_V & \cos\phi_V\ \sin^2\theta_V\ \sin\phi_V & \cos\theta_V\ \cos\phi_V\ \sin\theta_V \\ 0 & \cos\phi_V\ \sin^2\theta_V\ \sin\phi_V & \sin^2\theta_V\ \sin^2\phi_V & \cos\theta_V\ \sin\phi_V\ \sin\theta_V \\ 0 & \cos\theta_V\ \cos\phi_V\ \sin\theta_V & \cos\theta_V\ \sin\phi_V\ \sin\theta_V & \cos^2\theta_V \end{bmatrix} \tag{10}$$

- Also we can decompose $\Theta_{\mu\nu}$ in a nice way:

$$\Theta_{\mu\nu} = \frac{(n\cdot q)}{(n\cdot q)^2 - q^2 n^2}\left[-n_\mu q_\nu - q_\mu n_\nu + \frac{q^2}{(n\cdot q)} n_\mu n_\nu + \frac{n^2}{(n\cdot q)} q_\mu q_\nu\right] \tag{11}$$

- The choices of n_μ are frame dependent: $n_\mu = \underbrace{(1,\vec{0})}_{\mathrm{time-like}}$ or $\underbrace{(0,-\hat{q})}_{\mathrm{space-like}}$ or $\underbrace{(1,-\hat{q})}_{\mathrm{light-like}}$

- Contractions of n_μ and q_μ with J^ν_{in} and J^ν_{out} generate the structures $\Theta_{\mu\nu}$ and $\mathcal{Q}$

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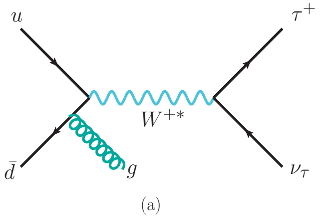
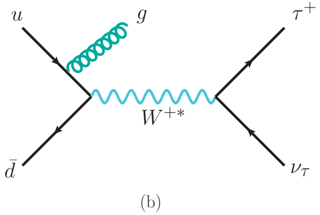
Case studies: $u\bar{d} \to W^{*}g \to \tau\nu_{\tau}g$



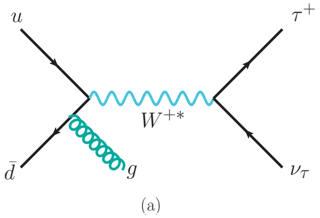


- Incoming current: $J^{\mu}_{\rm in} = D^{\mu}_{in} + U^{\mu}_{in}$

$$D^{\mu}_{in} = \bar{v}_R(p_d) \underbrace{\left(-ig\gamma^{\rho} T^{a}_{ij}\right)}_{\text{Quark-gluon vertex}} \epsilon^{*}_{\rho}(k) \underbrace{\left(\frac{-i\not{p}_b}{p_b^2}\right)}_{\text{Fermion propagator}} \underbrace{\left(-\frac{ig}{\sqrt{2}}\gamma^{\mu} P_L\right)}_{\text{W-u-d vertex}} u_L(p_u), \qquad (12)$$

$$U^{\mu}_{\rm in} = \bar{v}_R(p_d) \left(-\frac{ig}{\sqrt{2}}\gamma^{\mu} P_L\right) \left(\frac{i\not{p}_a}{p_a^2}\right) \left(-ig\gamma^{\rho} T^{a}_{ij}\right) \epsilon^{*}_{\rho}(k)\, u_L(p_u) \qquad (13)$$

Case studies: $u\bar{d} \to W^* g \to \tau \nu_\tau g$ (continued)

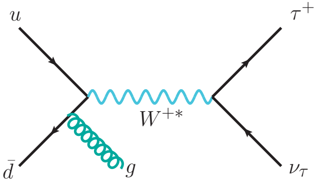


- Outgoing currents:

$$J^{\nu}_{\text{out}}(\tau_R^+ \nu_L) = \bar{u}_L(p_\nu) \left(-\frac{ig}{\sqrt{2}} \gamma^\nu P_L \right) v_R(p_\tau) \quad (14)$$

$$J^{\nu}_{\text{out}}(\tau_L^+ \nu_L) = \bar{u}_L(p_\nu) \left(-\frac{ig}{\sqrt{2}} \gamma^\nu P_L \right) v_L(p_\tau) \quad (15)$$

Case studies: $u\bar{d} \to W^* g \to \tau \nu_\tau g$ (continued)



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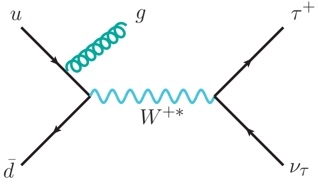


(b)

- Matrix elements:

$$\mathcal{M}_{\rm unpol} = -i(\mathcal{G} - \mathcal{Q}); \quad \mathcal{M}_{\lambda=T} = -i(\mathcal{G} + \vartheta) \; ; \tag{16}$$

$$\mathcal{M}_{\lambda=0} = i\left(\vartheta + \frac{\mathcal{Q}}{q^2}\right) \; ; \quad \mathcal{M}_{\lambda=S} = i\left(\frac{\mathcal{Q}}{q^2} - \frac{\mathcal{Q}}{\tilde{M}_W^2}\right) \tag{17}$$

Case studies: $u\bar{d} \to W^* g \to \tau \nu_\tau g$ (continued)

- Total incoming current is orthogonal to the W momenta for $m_u,\ m_d = 0$:

$$J^{\mu}_{in} q_\mu = (D^{\mu}_{in} + U^{\mu}_{in}) q_\mu = 0$$

- $\mathcal{Q}$ term:

$$\mathcal{Q} = \mathcal{Q}_U + \mathcal{Q}_D = (D^{\mu}_{in} + U^{\mu}_{in}) q_\mu \ q_\beta J^{\beta}_{\mathrm{out}} = 0$$

- Theta term:

$$\vartheta \propto J^{\mu}_{\mathrm{in}} \ \Theta_{\mu\nu} \ J^{\nu}_{\mathrm{out}}$$

$$\propto \left[-J^{\mu}_{\mathrm{in}} n_\mu q_\nu J^{\nu}_{\mathrm{out}} - J^{\mu}_{\mathrm{in}} q_\mu \ n_\nu J^{\nu}_{\mathrm{out}} + \frac{q^2}{(n \cdot q)} J^{\mu}_{\mathrm{in}} n_\mu n_\nu J^{\nu}_{\mathrm{out}} + \frac{n^2}{(n \cdot q)} J^{\mu}_{\mathrm{in}} q_\mu \ q_\nu J^{\nu}_{\mathrm{out}} \right] \neq 0$$

- Matrix elements reduce to:

$$\mathcal{M}_{\mathrm{unpol}} = -i\mathcal{G} \ ; \ \mathcal{M}_{\lambda=T} = -i(\mathcal{G} + \vartheta) \ ; \ \mathcal{M}_{\lambda=0} = i\vartheta \ ; \ \mathcal{M}_{\lambda=S} = 0$$

- Interference reduces to:

$$\mathcal{I}^{W+1g} = -2|\vartheta|^2 - 2 \ \mathrm{Re}(\mathcal{G}^* \vartheta) = -2 \ \mathrm{Re}[(\mathcal{G} + \vartheta)^* \vartheta] \neq 0 \qquad (18)$$

Power counting of Interference

- Naive scaling with hard scattering energy in partonic frame

- Assuming that W^* and g are produced at wide angles and at high p_T scale:

$$E_g, E_W \sim E_u, E_d = \sqrt{\hat{s}}/2$$

- Energy scale dependence:

$$\begin{aligned} u_L(p_u) &\sim \sqrt{E_u} \\ p_{a/b} &\sim \sqrt{E_{u/d}\ E_g} \\ \gamma^\mu, P_{L/R} &\sim E^0 \\ T^a_{ij}, \epsilon(k) &\sim E^0 \end{aligned}$$

Power counting of Interference(continued)

$$\mathcal{M}_{\rm unpol}(\nu_L \tau_R^+) \;\propto\; \frac{\sqrt{E_\nu}\sqrt{E_\tau}}{D_W(q^2)}\;, \quad \mathcal{M}_{\rm unpol}(\nu_L \tau_L^+) \propto \frac{\sqrt{E_\nu}\sqrt{E_\tau}}{D_W(q^2)}\;\frac{m_\tau}{E_\tau} \tag{19}$$

$$\mathcal{M}_{\lambda=T}(\nu_L \tau_R^+) \;\propto\; \frac{\sqrt{E_\nu}\sqrt{E_\tau}}{D_W(q^2)}\;\frac{E_W^2}{E_W^2-q^2}\left(1+\frac{m_\tau^2}{E_W E_\tau}\right) \tag{20}$$

$$\mathcal{M}_{\lambda=T}(\nu_L \tau_L^+) \;\propto\; \frac{\sqrt{E_\nu}\sqrt{E_\tau}}{D_W(q^2)}\;\frac{E_W^2}{E_W^2-q^2}\,\frac{m_\tau}{E_\tau}\left(1+\frac{E_\tau}{E_W}\right) \tag{21}$$

$$\mathcal{M}_{\lambda=0}(\nu_L \tau_R^+) \;\propto\; \frac{\sqrt{E_\nu}\sqrt{E_\tau}}{D_W(q^2)}\;\frac{E_W^2}{E_W^2-q^2}\left(\frac{m_\tau^2}{E_W E_\tau}+\frac{q^2}{E_W^2}\right) \tag{22}$$

$$\mathcal{M}_{\lambda=0}(\nu_L \tau_L^+) \;\propto\; \frac{\sqrt{E_\nu}\sqrt{E_\tau}}{D_W(q^2)}\;\frac{E_W^2}{E_W^2-q^2}\left(\frac{m_\tau}{E_W}+\frac{m_\tau}{E_\tau}\,\frac{q^2}{E_W^2}\right) \tag{23}$$

Power counting of Interference(continued)

- In high energy limit ($m_\tau = 0$), helicity configuration for $\nu_L \tau_L^+$ is suppressed

$$\mathcal{M}_{\lambda=T}(\nu_L \tau_L^+),\ \mathcal{M}_{\lambda=0}(\nu_L \tau_L^+),\ \mathcal{I}_{\rm pol}^{W+1g}(\nu_L \tau_L^+) \overset{m_\tau \to 0}{\sim} 0$$

- Energy dependence of matrix elements and interference for helicity state $\nu_L \tau_R^+$:

$$\mathcal{M}_{\lambda=T}(\nu_L \tau_R^+) \overset{m_\tau \to 0}{\sim} \frac{\sqrt{E_\nu}\sqrt{E_\tau}}{D_W(q^2)} \frac{E_W^2}{E_W^2 - q^2} \tag{24}$$

$$\mathcal{M}_{\lambda=0}(\nu_L \tau_R^+) \overset{m_\tau \to 0}{\sim} \frac{\sqrt{E_\nu}\sqrt{E_\tau}}{D_W(q^2)} \frac{E_W^2}{E_W^2 - q^2} \frac{q^2}{E_W^2} \tag{25}$$

$$\mathcal{M}_{\rm unpol}(\nu_L \tau_R^+) \overset{m_\tau \to 0}{\sim} \frac{\sqrt{E_\nu}\sqrt{E_\tau}}{D_W(q^2)} \tag{26}$$

- Contribution of longitudinal state decreases with increase of W energy

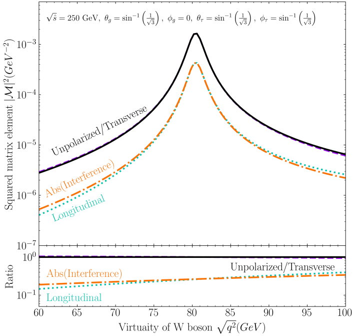
Power counting of Interference(continued)

- Energy scale dependence of ratio:

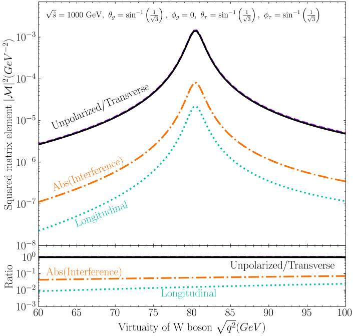
$$
\begin{aligned}
\mathcal{R}^{W+1g}_{\text{pol int}} &\equiv \frac{\mathcal{I}^{W+1g}_{\text{pol}}(\nu_L \tau_R^+) + \mathcal{I}^{W+1g}_{\text{pol}}(\nu_L \tau_L^+)}{|\mathcal{M}_{\text{unpol}}(\nu_L \tau_R^+)|^2 + |\mathcal{M}_{\text{unpol}}(\nu_L \tau_L^+)|^2} \\
&\overset{m_\tau \to 0}{\sim} \frac{E_W^4}{(E_W^2 - q^2)^2} \left(\frac{q^2}{E_W^2}\right) \\
&\sim \frac{q^2}{E_W^2} \left[1 + \mathcal{O}\left(\frac{q^2}{E_W^2}\right)\right]^2
\end{aligned} \tag{27}
$$

- In high energy limit ($m_\tau \to 0$), interference is suppressed with increasing E_W

Numerical analysis of Interference: $|\mathcal{M}|^2$ vs $\sqrt{q^2}$ plots



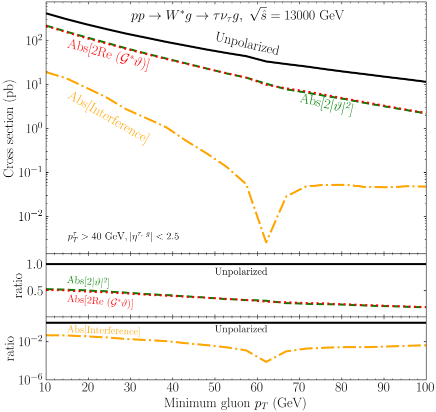
(a)



(b)

- Peak is around $m_W \approx 80$ GeV: $|\mathcal{M}|^2 \sim \frac{1}{|D_W(q^2)|^2} \sim \frac{1}{(q^2 - m_W^2)^2 + (\Gamma_W m_W)^2}$
- $\sqrt{s}$: $250\ \mathrm{GeV} \rightarrow 1000\ \mathrm{GeV}$; $\quad \mathcal{I} : O(10\%) \rightarrow O(5\%)$

Numerical analysis of Interference: Cross section plot



- Results after integration over whole phase space: $\sigma_\lambda = \frac{1}{N} \int d\Phi\ |\mathcal{M}_\lambda|^2$
- Interference:

$$\mathcal{I}^{W+1g} = \underbrace{-2|\vartheta|^2}_{\text{term1}} - \underbrace{2\ \mathrm{Re}(\mathcal{G}^*\vartheta)}_{\text{term2}}$$

$$= -2\ \mathrm{Re}[\mathcal{M}^*_{\lambda=T}\mathcal{M}_{\lambda=0}]$$

- For low value of $p_{T\min}$, Abs[term 1] $>$ Abs[term 2]
- For high value of $p_{T\min} \implies$ large $E_W \implies$ Interference is small

Conclusion

- Study of helicity polarized vector boson is an important probe to understand the gauge theory and EWSB
- We introduce some tools (Θ-decomposition) that simplifies interference structures and can be useful for other multiboson processes
- In practice, for LHC experiments, the center-of-mass energy is high enough that fermions can be treated as massless, which leads to the dominance of particular helicity processes and makes interference negligible

Thank You

Back up slides

Back up slides

- Field decomposition:

$$A^{\mu}(x) = \int \frac{d^3k}{(2\pi)^3 2E_k} \sum_{\lambda=0}^{4} \left[\varepsilon^{\mu}(k,\lambda) a(k,\lambda) e^{ik\cdot x} + \varepsilon^{*\mu}(k,\lambda) a^{\dagger}(k,\lambda) e^{-ik\cdot x} \right] \ . \quad (28)$$

Recap of Gauge Symmetry

- Lagrangian of photon field:

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} \quad \text{where} \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \tag{29}$$

- Gauge transformation:

$$A_\mu \to A'_\mu = A_\mu + \partial_\mu \alpha(x) \tag{30}$$

- Gauge symmetry:

$$F'_{\mu\nu} = \partial_\mu(A_\nu + \partial_\nu \alpha) - \partial_\nu(A_\mu + \partial_\mu \alpha) = F_{\mu\nu} \tag{31}$$

  Lagrangian is invariant under this transformation for different choices of α

- Gauge invariance: Redundancy of the system
  $\implies$ each choice of $\alpha \longleftrightarrow$ same physical state

Gauge Fixing

- Gauge invariance: several field configurations describe the same physical state
- Gauge fixing: Selects one suitable field configuration, making the theory consistent and the propagator well defined
- It is implemented by adding an extra unphysical term to the Lagrangian:

$$\mathcal{L}_{GF} = -\frac{1}{2\xi}(\partial_\mu A^\mu)^2 \tag{32}$$

- Gauge parameter ξ is a unphysical parameter, physical observables are independent of ξ
- For massive gauge bosons, gauge fixing introduces unphysical particles like Goldstone boson: Goldston (ξ) + Scalar (ξ) $\rightarrow$ Physical observable

$$|\mathcal{M}_{\rm unpol}|^2 = |\mathcal{G}|^2 + \frac{1}{|\tilde{M}_W^2|^2}|\mathcal{Q}|^2 - 2{\rm Re}(\mathcal{G}^*\mathcal{Q}) \tag{33}$$

$$|\mathcal{M}_{\lambda=T}|^2 = |\mathcal{G}|^2 + |\vartheta|^2 + 2{\rm Re}(\mathcal{G}^*\vartheta) \tag{34}$$

$$|\mathcal{M}_{\lambda=0}|^2 = |\vartheta|^2 + \frac{1}{q^4}|\mathcal{Q}|^2 + 2{\rm Re}(\vartheta^*\mathcal{Q}) \tag{35}$$

$$|\mathcal{M}_{\lambda=S}|^2 = \left(\frac{1}{q^4} + \frac{1}{|\tilde{M}_W^2|^2} - \frac{2}{q^2\tilde{M}_W^2}\right)|\mathcal{Q}|^2 \tag{36}$$

where,

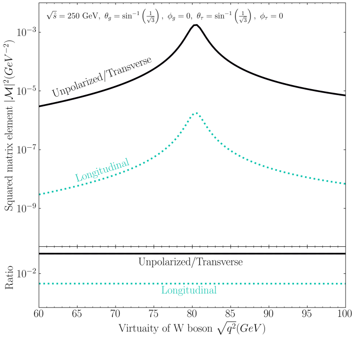
$$\mathcal{G} = \mathcal{G}_U + \mathcal{G}_D,\ \vartheta = \vartheta_U + \vartheta_D,\ \mathcal{Q} = \mathcal{Q}_U + \mathcal{Q}_D \tag{37}$$

$$\mathcal{G}_U = \frac{i}{D_W(q^2)}\left(U_{in}^{\alpha}\ g_{\alpha\beta}\ J_{\rm out}^{\beta}\right), \quad \mathcal{G}_D = \frac{i}{D_W(q^2)}\left(D_{in}^{\alpha}\ g_{\alpha\beta}\ J_{\rm out}^{\beta}\right) \tag{38}$$

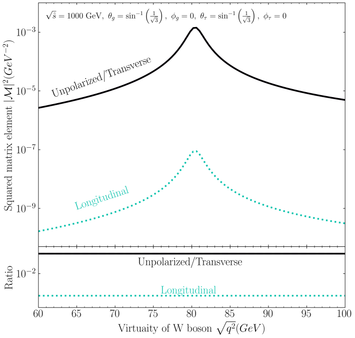
Energy scale dependence of interference:

$$\mathcal{I}_{\rm pol}^{W+1g}(\nu_L\tau_R^+) \overset{m_\tau\to 0}{\sim} \frac{E_\tau E_\nu}{|D_W(q^2)|^2}\frac{q^2\ E_W^2}{(E_W^2-q^2)^2} \tag{39}$$

Numerical analysis of Interference: $|\mathcal{M}|^2$ vs $\sqrt{q^2}$ plots(continued)



(a)



(b)

- A special kinematic configuration where $J^0_{\text{out}} = 0$ which makes $J^\beta_{\text{out}} n_\beta = 0 \implies \vartheta = 0,\ \mathcal{I} = 0$
- Interference effect varies with phase space points
- Interference is non zero even in on-shell limit