Jet angular correlation in vector-boson fusion processes at hadron colliders

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based on the work with **Qiang Li** (Karlsruhe)
and **Kentarou Mawatari** (KIAS $\rightarrow$ Heidelberg)

KH, Qiang Li, Kentarou Mawatari,
arXiv:0810.xxxx [hep-ph]

Two recent works on massive graviton productions at hadron colliders:

- *Graviton production with 2 jets at the LHC in large extra dimensions*
  by KH, P.Konar, Q.Li, K.Mawatari, D.Zeppenfeld,
  JHEP 0804:019(2008)[arXiv:0801.1794[hep-ph]]

- *HELAS and MadGraph/MadEvent with spin-2 particles*
  by KH, J.Kanzaki, Q.Li, K.Mawatari,
  EPJC 56:435-447(2008)[arXiv:0805.2554[hep-ph]]

There were two motivations for the above works:

- jet physics as a probe of new physics

- tools for simulating new physics models

We found (confirmed the naive expectation) that

$\sigma(2jets)/\sigma(1jet)$ grows with the missing mass

when the missing p_T is common. This type of studies will be helpful in estimating the mass of a singly produced missing particle.

However, we failed to identify interesting angular correlations among two high p_T jets and the missing p_T direction, from which we hoped to obtain information about the spin of the produced particle.

This is in contrast to the observation made for $H + 2$ jets production, where the jet angular correlation can reveal its CP parity:

- *H + 2 jets via gluon fusion*
  by V.Del Duca, W.Kilgore, C.Oleari, C.Schmidt, D.Zeppenfeld,
  PRL 87:122001(2001)[arXiv:hep-ph/0105129]

- *Determining the structure of Higgs couplings at the LHC*
  by T.Plehn, D.L.Rainwater, D.Zeppenfeld,
  PRL 88:051801(2002)[arXiv:hep-ph/0105325]

- *Gluon fusion contributions to H + 2 jet production*
  by V.Del Duca, W.Kilgore, C.Oleari, C.Schmidt, D.Zeppenfeld,
  NPB 616:367(2001)[arXiv:hep-ph/0108030]

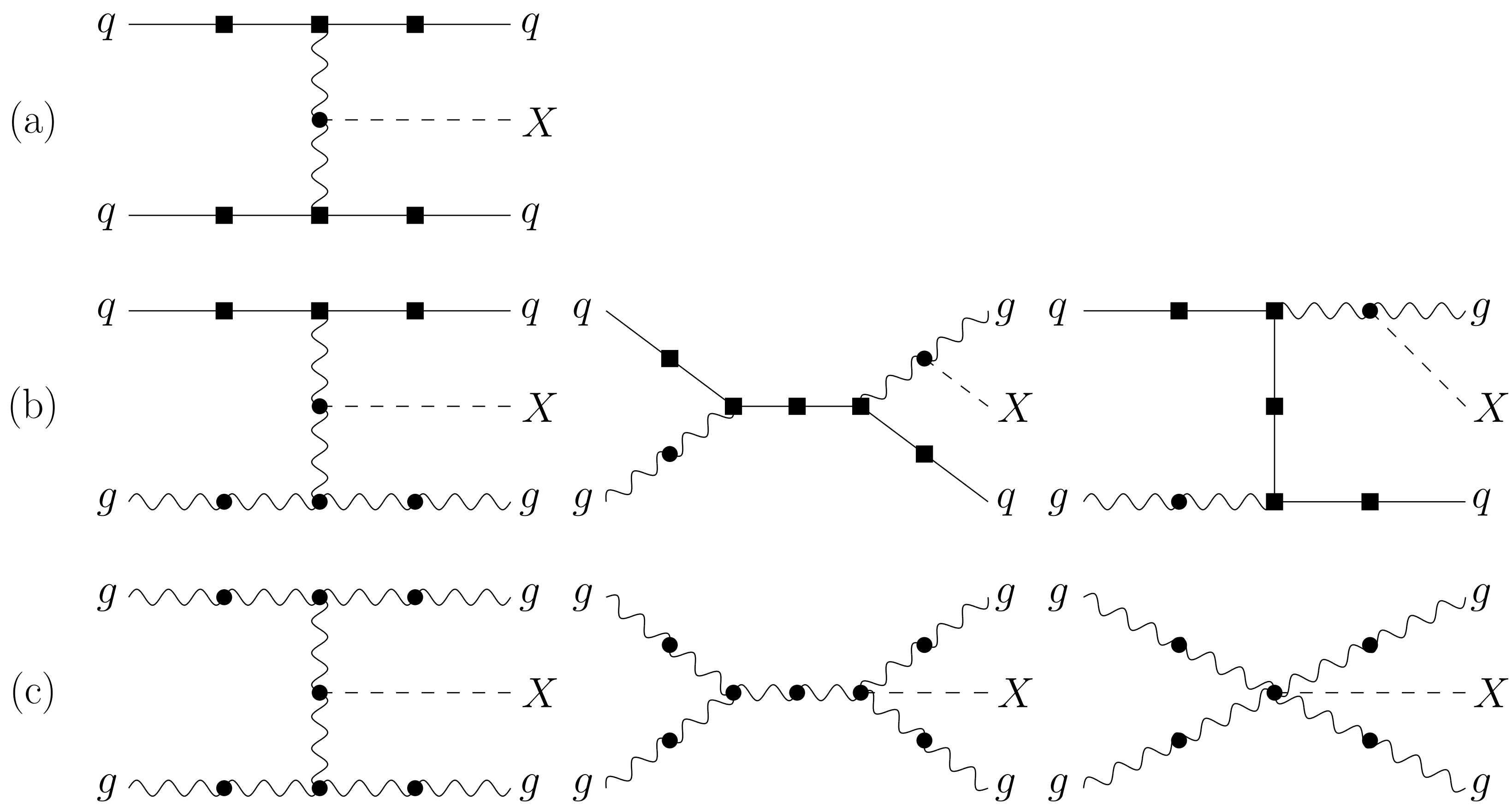
We try to understand the jet angular correlations associated with vector-boson (gluon, $W/Z/\gamma$) fusion production of a massive particle (X) with spin 0 and 2 ($J_X = 0$ or 2):

$$
\begin{aligned}
qq &\rightarrow qqX \quad \text{via} \quad g^*g^*, W^*W^*, Z^*Z^*, Z^*\gamma^*, \gamma^*\gamma^* \rightarrow X \\
qg &\rightarrow qgX \quad \text{via} \quad g^*g^* \rightarrow X \\
gg &\rightarrow ggX \quad \text{via} \quad g^*g^* \rightarrow X
\end{aligned}
$$

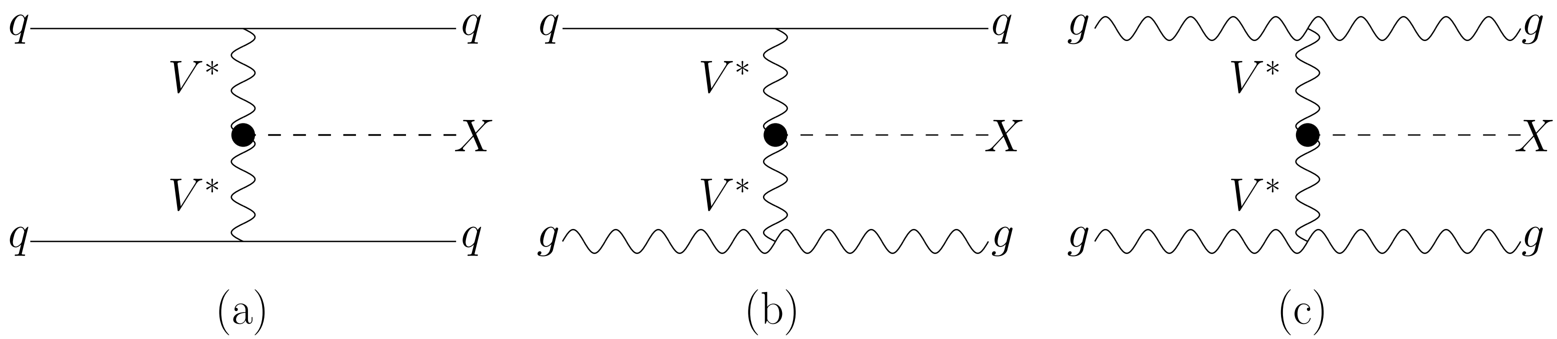
The results are then compared to the correlations in X decays into 4 jets (or 4 leptons):

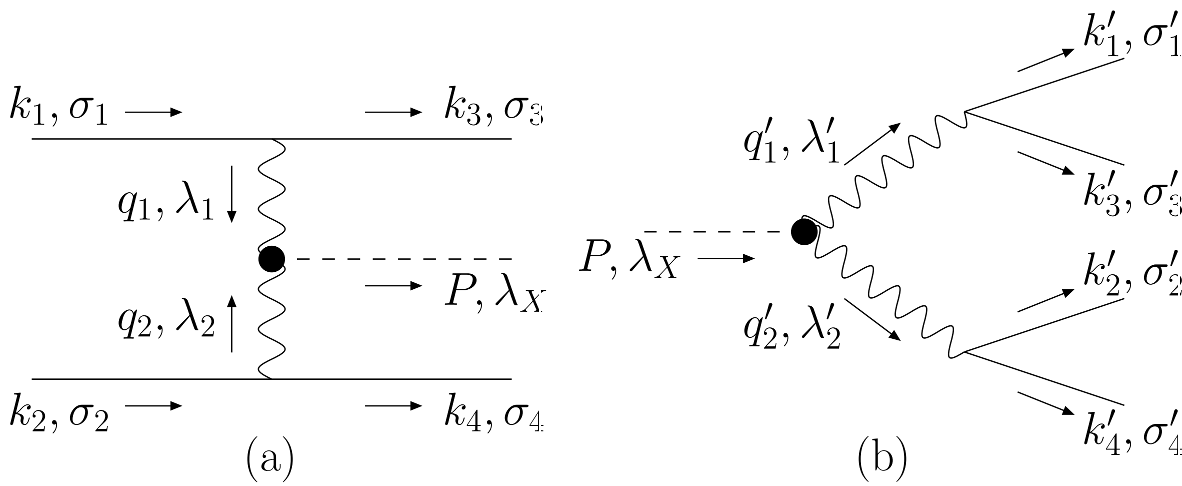
$$
\begin{aligned}
X &\rightarrow W^*W^*, Z^*Z^*, Z^*\gamma^*, \gamma^*\gamma^* \rightarrow f\bar{f}f\bar{f} \\
X &\rightarrow g^*g^* \rightarrow q\bar{q}q\bar{q} \\
X &\rightarrow g^*g^* \rightarrow q\bar{q}gg \\
X &\rightarrow g^*g^* \rightarrow gggg
\end{aligned}
$$

where $f\bar{f}$ can either be a quark-pair or a lepton-pair.



(a)
(b)
(c)
q
g
X


q
q
V*
V*
X
(a)
q
q
g
g
(b)
g
g
g
g
(c)


k1, σ1
k3, σ3
q1, λ1
q2, λ2
P, λX
k2, σ2
k4, σ4
(a)
P, λX
q′1, λ′1
q′2, λ′2
k′1, σ′1
k′3, σ′3
k′2, σ′2
k′4, σ′4
(b)

The helicity amplitudes for the VBF processes

$$\mathcal{M}^{\lambda_X}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = \sum_{V_1,V_2} J^{\mu_1'}_{V_1 a_1 a_3}(k_1,k_3;\sigma_1,\sigma_3)\, J^{\mu_2'}_{V_2 a_2 a_4}(k_2,k_4;\sigma_2,\sigma_4) \times D^{V_1}_{\mu_1'\mu_1}(q_1)\, D^{V_2}_{\mu_2'\mu_2}(q_2)\, \Gamma^{\mu_1\mu_2}_{XV_1V_2}(q_1,q_2;\lambda_X)^*$$

can be expressed by using

$$-g_{\mu'\mu} + \frac{q_{i\mu'} q_{i\mu}}{q_i^2} = \sum_{\lambda_i=\pm,0} (-1)^{\lambda_i+1}\, \epsilon_{\mu'}(q_i,\lambda_i)^*\, \epsilon_\mu(q_i,\lambda_i)$$

$$q_{i\mu} J^{\mu}_{V_i a_i a_{i+2}}(k_i,k_{i+2};\sigma_i,\sigma_{i+2}) = 0$$

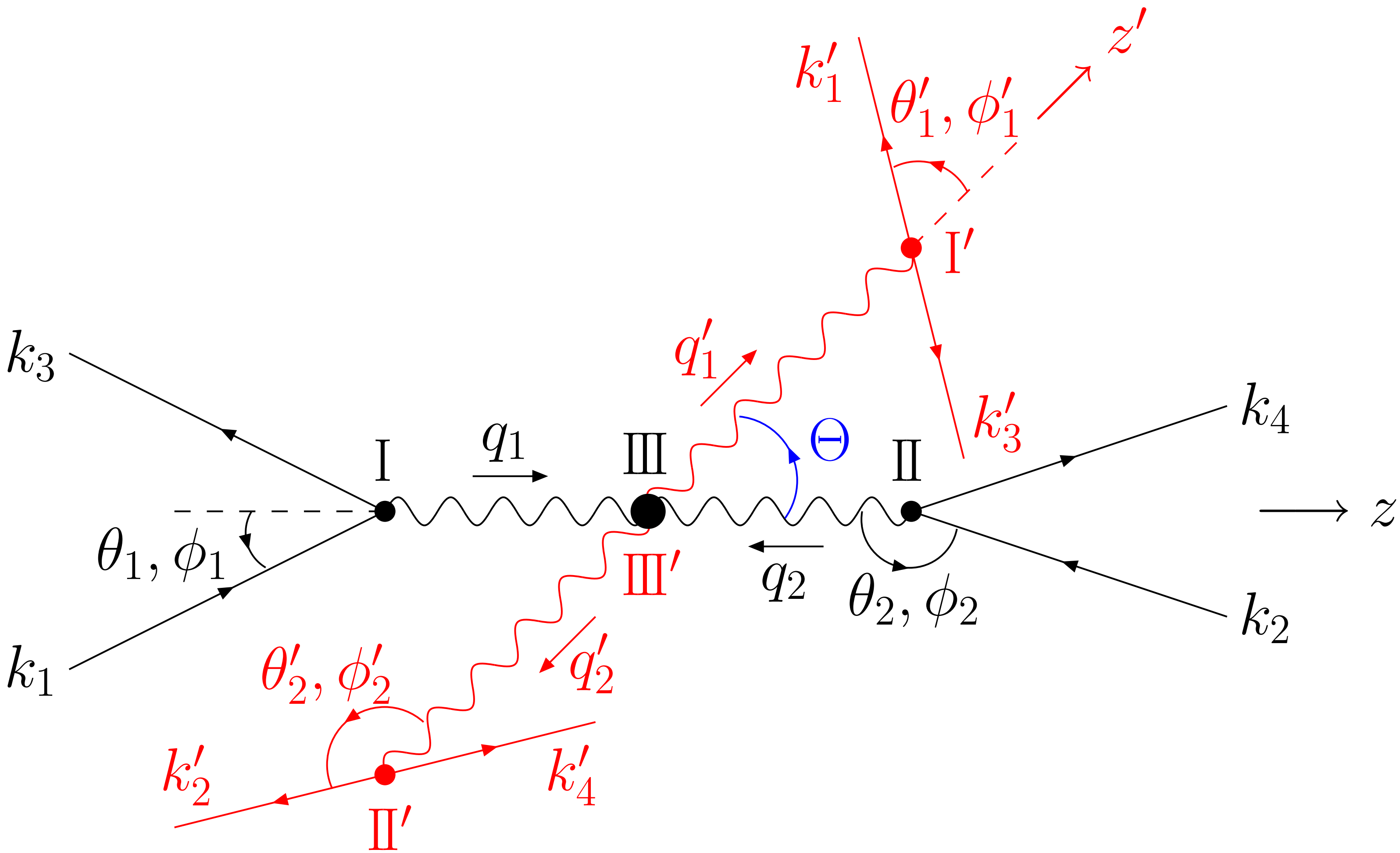
as follows:

$$\mathcal{M}^{\lambda_X}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = \sum_{V_1,V_2} \frac{1}{(q_1^2 - m_{V_1}^2)(q_2^2 - m_{V_2}^2)} \times \sum_{\lambda_{1,2}=\pm,0} \left(J^{V_1}_{a_1a_3}\right)^{\lambda_1}_{\sigma_1\sigma_3} \left(J^{V_2}_{a_2a_4}\right)^{\lambda_2}_{\sigma_2\sigma_4} \left(\mathcal{M}^{X}_{V_1V_2}\right)^{\lambda_X}_{\lambda_1\lambda_2}$$

where

$$\left(J^{V_i}_{a_ia_{i+2}}\right)^{\lambda_i}_{\sigma_i\sigma_{i+2}} = (-1)^{\lambda_i+1} J^{\mu}_{V_i a_i a_{i+2}}(k_i,k_{i+2};\sigma_i,\sigma_{i+2})\, \epsilon_\mu(q_i,\lambda_i)^*$$

$$\left(\mathcal{M}^{X}_{V_1V_2}\right)^{\lambda_X}_{\lambda_1\lambda_2} = \epsilon_{\mu_1}(q_1,\lambda_1)\, \epsilon_{\mu_2}(q_2,\lambda_2)\, \Gamma^{\mu_1\mu_2}_{XV_1V_2}(q_1,q_2;\lambda_X)^*$$



k_1'
z'
θ_1', ϕ_1'
I'
k_3
q_1'
k_3'
k_4
Θ
I
q_1
III
II
z
θ_1, ϕ_1
III'
q_2
θ_2, ϕ_2
k_2
k_1
q_2'
θ_2', ϕ_2'
k_2'
k_4'
II'

I) the q_1 Breit frame ($Q_1 = \sqrt{-q_1^2}$, $0 < \theta_1 < \pi/2$ and $0 < \phi_1 < 2\pi$):

$$q_1^\mu = k_1^\mu - k_3^\mu = (0,\, 0,\, 0,\, Q_1)$$
$$k_1^\mu = \tfrac{Q_1}{2\cos\theta_1}(1,\, \sin\theta_1\cos\phi_1,\, \sin\theta_1\sin\phi_1,\, \cos\theta_1)$$
$$k_3^\mu = \tfrac{Q_1}{2\cos\theta_1}(1,\, \sin\theta_1\cos\phi_1,\, \sin\theta_1\sin\phi_1,\, -\cos\theta_1)$$

II) the q_2 Breit frame ($Q_2 = \sqrt{-q_2^2}$, $\pi/2 < \theta_2 < \pi$ and $0 < \phi_2 < 2\pi$).

$$q_2^\mu = k_2^\mu - k_4^\mu = (0,\, 0,\, 0,\, -Q_2)$$
$$k_2^\mu = -\tfrac{Q_2}{2\cos\theta_2}(1,\, \sin\theta_2\cos\phi_2,\, \sin\theta_2\sin\phi_2,\, \cos\theta_2)$$
$$k_4^\mu = -\tfrac{Q_2}{2\cos\theta_2}(1,\, \sin\theta_2\cos\phi_2,\, \sin\theta_2\sin\phi_2,\, -\cos\theta_2)$$

III) the VBF frame

$$q_1^\mu + q_2^\mu = P^\mu = {q'_1}^\mu + {q'_2}^\mu = (M,\, 0,\, 0,\, 0)$$
$$q_1^\mu = \tfrac{M}{2}\big(1 - \tfrac{Q_1^2 - Q_2^2}{M^2},\, 0,\, 0,\, \beta\big)$$
$$q_2^\mu = \tfrac{M}{2}\big(1 - \tfrac{Q_2^2 - Q_1^2}{M^2},\, 0,\, 0,\, -\beta\big)$$
$${q'_1}^\mu = \tfrac{M}{2}\big(1 + \tfrac{{q'_1}^2 - {q'_2}^2}{M^2},\, \beta'\sin\Theta,\, 0,\, \beta'\cos\Theta\big)$$
$${q'_2}^\mu = \tfrac{M}{2}\big(1 + \tfrac{{q'_2}^2 - {q'_1}^2}{M^2},\, -\beta'\sin\Theta,\, 0,\, -\beta'\cos\Theta\big)$$

where $\beta = \bar{\beta}\big(-\frac{Q_1^2}{M^2}, -\frac{Q_2^2}{M^2}\big)$ and $\beta' = \bar{\beta}\big(\frac{{q'_1}^2}{M^2}, \frac{{q'_2}^2}{M^2}\big)$ with
$\bar{\beta}(a,b) \equiv (1 + a^2 + b^2 - 2a - 2b - 2ab)^{1/2}$.

$\hat{J}_1{}^{\lambda_1}_{\sigma_1\sigma_3}(f_{\sigma_1} \to f_{\sigma_3} V^*_{\lambda_1})$		$\left[\cos\theta_1 \to z_1/(2-z_1)\right]$
$\hat{J}_1{}^{+}_{++} = -\left(\hat{J}_1{}^{-}_{--}\right)^*$	$\dfrac{1}{2\cos\theta_1}(1+\cos\theta_1)\, e^{-i\phi_1}$	$\dfrac{1}{z_1}\, e^{-i\phi_1}$
$\hat{J}_1{}^{0}_{++} = \hat{J}_1{}^{0}_{--}$	$-\dfrac{1}{\sqrt{2}\cos\theta_1}\sin\theta_1$	$-\dfrac{\sqrt{2(1-z_1)}}{z_1}$
$\hat{J}_1{}^{-}_{++} = -\left(\hat{J}_1{}^{+}_{--}\right)^*$	$-\dfrac{1}{2\cos\theta_1}(1-\cos\theta_1)\, e^{i\phi_1}$	$-\dfrac{1-z_1}{z_1}\, e^{i\phi_1}$
$\hat{J}_1{}^{\lambda_1}_{+-} = \hat{J}_1{}^{\lambda_1}_{-+}$	0	0

$\hat{J}'_1{}^{\lambda'_1}_{\sigma'_1\sigma'_3}(V^*_{\lambda'_1} \to f_{\sigma'_1} \bar{f}_{\sigma'_3})$		$\left[\cos\theta'_1 \to 2z'_1 - 1\right]$
$\hat{J}'_1{}^{+}_{+-} = -\left(\hat{J}'_1{}^{-}_{-+}\right)^*$	$\dfrac{1}{2}(1+\cos\theta'_1)\, e^{i\phi'_1}$	$z'_1\, e^{i\phi'_1}$
$\hat{J}'_1{}^{0}_{+-} = \hat{J}'_1{}^{0}_{-+}$	$\dfrac{1}{\sqrt{2}}\sin\theta'_1$	$\sqrt{2z'_1(1-z'_1)}$
$\hat{J}'_1{}^{-}_{+-} = -\left(\hat{J}'_1{}^{+}_{-+}\right)^*$	$\dfrac{1}{2}(1-\cos\theta'_1)\, e^{-i\phi'_1}$	$(1-z'_1)\, e^{-i\phi'_1}$
$\hat{J}'_1{}^{\lambda'_1}_{++} = \hat{J}'_1{}^{\lambda'_1}_{--}$	0	0

$\widehat{J}_{1\,\sigma_1\sigma_3}^{\;\lambda_1}(g_{\sigma_1} \to g_{\sigma_3} V^*_{\lambda_1})$		$\left[\cos\theta_1 \to z_1/(2-z_1)\right]$
$\widehat{J}_{1\,++}^{\;+} = -\big(\widehat{J}_{1\,--}^{\;-}\big)^*$	$\dfrac{1}{2\sin\theta_1\cos\theta_1}(1+\cos\theta_1)^2\, e^{-i\phi_1}$	$\dfrac{1}{z_1\sqrt{1-z_1}}\, e^{-i\phi_1}$
$\widehat{J}_{1\,++}^{\;0} = \widehat{J}_{1\,--}^{\;0}$	$-\dfrac{1}{\sqrt{2}\cos\theta_1}$	$-\dfrac{2-z_1}{\sqrt{2}\, z_1}$
$\widehat{J}_{1\,++}^{\;-} = -\big(\widehat{J}_{1\,--}^{\;+}\big)^*$	$-\dfrac{1}{2\sin\theta_1\cos\theta_1}(1-\cos\theta_1)^2\, e^{i\phi_1}$	$-\dfrac{(1-z_1)^2}{z_1\sqrt{1-z_1}}\, e^{i\phi_1}$
$\widehat{J}_{1\,+-}^{\;+} = -\big(\widehat{J}_{1\,-+}^{\;-}\big)^*$	$-\dfrac{2}{\tan\theta_1}\, e^{i\phi_1}$	$-\dfrac{z_1}{\sqrt{1-z_1}}\, e^{i\phi_1}$
$\widehat{J}_{1\,+-}^{\;0/-} = \widehat{J}_{1\,-+}^{\;0/+}$	0	0

$\widehat{J}'^{\;\lambda'_1}_{1\,\sigma'_1\sigma'_3}(V^*_{\lambda'_1} \to g_{\sigma'_1} g_{\sigma'_3})$		$\left[\cos\theta'_1 \to 2z'_1 - 1\right]$
$\widehat{J}'^{\;+}_{1\,+-} = -\big(\widehat{J}'^{\;-}_{1\,-+}\big)^*$	$-\dfrac{1}{2\sin\theta'_1}(1+\cos\theta'_1)^2\, e^{i\phi'_1}$	$-\dfrac{{z'_1}^2}{\sqrt{z'_1(1-z'_1)}}\, e^{i\phi'_1}$
$\widehat{J}'^{\;0}_{1\,+-} = \widehat{J}'^{\;0}_{1\,-+}$	$-\dfrac{1}{\sqrt{2}}\cos\theta'_1$	$-\dfrac{2z'_1-1}{\sqrt{2}}$
$\widehat{J}'^{\;-}_{1\,+-} = -\big(\widehat{J}'^{\;+}_{1\,-+}\big)^*$	$\dfrac{1}{2\sin\theta'_1}(1-\cos\theta'_1)^2\, e^{-i\phi'_1}$	$\dfrac{(1-z'_1)^2}{\sqrt{z'_1(1-z'_1)}}\, e^{-i\phi'_1}$
$\widehat{J}'^{\;+}_{1\,++} = -\big(\widehat{J}'^{\;-}_{1\,--}\big)^*$	$\dfrac{2}{\sin\theta'_1}\, e^{-i\phi'_1}$	$\dfrac{1}{\sqrt{z'_1(1-z'_1)}}\, e^{-i\phi'_1}$
$\widehat{J}'^{\;0/-}_{1\,++} = \widehat{J}'^{\;0/+}_{1\,--}$	0	0

X	(λ_X)	V_i	$\Gamma^{\mu_1\mu_2}_{XV_1V_2}(q_1,q_2;\lambda_X)/g_{XV_1V_2}(q_1,q_2)$
H	(0)	W, Z	$g^{\mu_1\mu_2}$
H	(0)	$\gamma, Z/\gamma, g$	$q_1\cdot q_2\, g^{\mu_1\mu_2} - q_2^{\mu_1} q_1^{\mu_2}$
A	(0)	$\gamma, Z/\gamma, g$	$\epsilon^{\mu_1\mu_2\alpha\beta} q_{1\alpha} q_{2\beta}$
G	$(\pm 2, \pm 1, 0)$	W, Z, γ, g	$\epsilon_{\alpha\beta}(p_X,\lambda_X)\,\hat{\Gamma}^{\alpha\beta,\,\mu_1\mu_2}_{GVV}(q_1,q_2)$

λ_X	$(\lambda_1\lambda_2)$	CP-even H(WBF)	 H(loop-induced)	CP-odd A
0	$(\pm\pm)$	-1	$-\frac{1}{2}(M^2+Q_1^2+Q_2^2)$	$\mp\frac{i}{2}\sqrt{(M^2+Q_1^2+Q_2^2)^2-4Q_1^2Q_2^2}$
0	(00)	$\frac{(M^2+Q_1^2+Q_2^2)}{2Q_1Q_2}$	Q_1Q_2	0

λ_X	$(\lambda_1\lambda_2)$	G
± 2	$(\pm\mp)$	$-(M^2+Q_1^2+Q_2^2+2m_V^2)$
± 1	(± 0)	$\frac{1}{\sqrt{2}MQ_2}\left[Q_2^2(M^2-Q_1^2+Q_2^2)-m_V^2(M^2+Q_1^2-Q_2^2)\right]$
± 1	$(0\mp)$	$\frac{1}{\sqrt{2}MQ_1}\left[Q_1^2(M^2+Q_1^2-Q_2^2)-m_V^2(M^2-Q_1^2+Q_2^2)\right]$
0	$(\pm\pm)$	$\frac{1}{\sqrt{6}M^2}\left[(Q_1^2-Q_2^2)^2+M^2(Q_1^2+Q_2^2-2m_V^2)\right]$
0	(00)	$-\frac{1}{\sqrt{6}Q_1Q_2}\Big[4Q_1^2Q_2^2+2m_V^2(M^2+Q_1^2+Q_2^2)$ $-\frac{m_V^2}{M^2}\{(M^2+Q_1^2+Q_2^2)^2-4Q_1^2Q_2^2\}\Big]$

With the minimal cuts:

$$p_{T_j} > 20 \text{ GeV}, \quad |\eta_j| < 5, \quad R_{jj} = \sqrt{\Delta\eta_{jj}^2 + \Delta\phi_{jj}^2} > 0.6$$

plus the VBF cuts:

$$\eta_{j_1} > 0 > \eta_{j_2}, \quad \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2} > \Delta\eta_{jj\text{min}}$$

we find

$\sigma_{\text{VBF}}/\sigma_{\text{exact}}$	$\Delta\eta_{jj} > 3$	$\Delta\eta_{jj} > 4$	$\Delta\eta_{jj} > 5$
$qq \to qqH/A/G$	1.00/1.00/1.58	1.00/1.00/1.43	1.00/1.00/1.25
$qg \to qgH/A/G$	1.07/1.05/1.30	1.04/1.03/1.18	1.02/1.02/1.11
$gg \to ggH/A/G$	1.07/1.06/1.16	1.04/1.04/1.11	1.02/1.02/1.07

In addition, if we impose the p_{T_j} slicing cut:

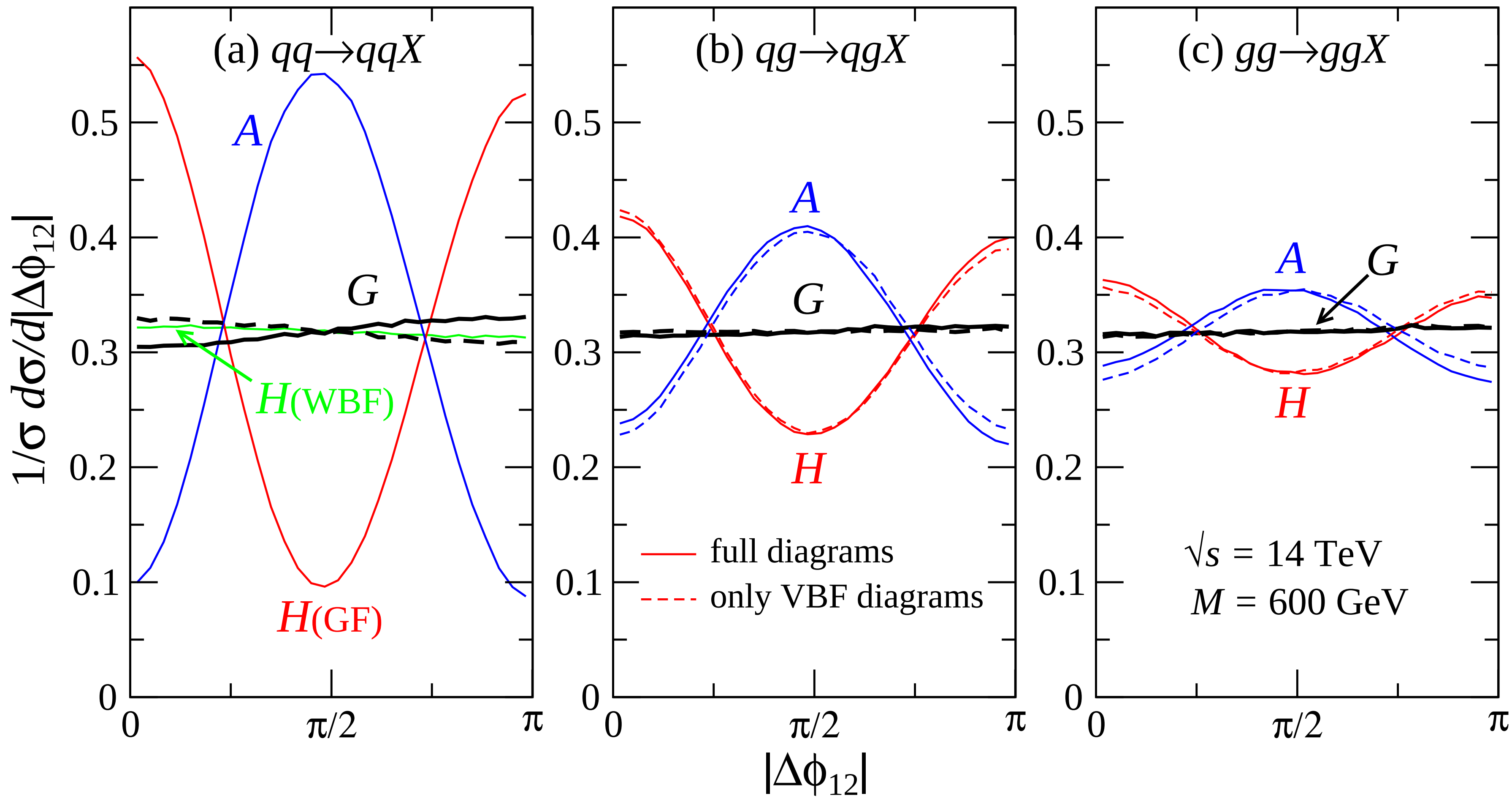
$$20 \text{ GeV} < p_{T_j} < 100 \text{ GeV}$$

we find

$\sigma_{\text{VBF}}/\sigma_{\text{exact}}$	$\Delta\eta_{jj} > 3$	$\Delta\eta_{jj} > 4$	$\Delta\eta_{jj} > 5$
$qq \to qqH/A/G$	1.00/1.00/1.02	1.00/1.00/1.02	1.00/1.00/1.02
$qg \to qgH/A/G$	1.04/1.04/1.07	1.03/1.03/1.06	1.02/1.02/1.04
$gg \to ggH/A/G$	1.05/1.05/1.09	1.04/1.04/1.07	1.02/1.02/1.05

$$\mathcal{M}^{\lambda_X=0}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = \sum_{V_1,V_2} \frac{1}{(q_1^2 - m_{V_1}^2)(q_2^2 - m_{V_2}^2)} \sum_{\lambda_{1,2}=\pm,0} \left(J^{V_1}_{a_1a_3}\right)^{\lambda_1}_{\sigma_1\sigma_3} \left(J^{V_2}_{a_2a_4}\right)^{\lambda_2}_{\sigma_2\sigma_4} \left(\mathcal{M}^X_{V_1V_2}\right)^0_{\lambda_1\lambda_2}$$
$$\sim \hat{J}_1{}^{+}_{\sigma_1\sigma_3} \hat{J}_2{}^{+}_{\sigma_2\sigma_4} \hat{\mathcal{M}}_X{}^{0}_{++} + \hat{J}_1{}^{0}_{\sigma_1\sigma_3} \hat{J}_2{}^{0}_{\sigma_2\sigma_4} \hat{\mathcal{M}}_X{}^{0}_{00} + \hat{J}_1{}^{-}_{\sigma_1\sigma_3} \hat{J}_2{}^{-}_{\sigma_2\sigma_4} \hat{\mathcal{M}}_X{}^{0}_{--}$$

$$\begin{aligned}\mathcal{M}^{\lambda_X=0}_{\sigma_1,\sigma_2} \sim & -\hat{J}_1{}^{+}_{\sigma_1}(\theta_1)\, \hat{J}_2{}^{+}_{\sigma_2}(\theta_2)\, \hat{\mathcal{M}}_X{}^{0}_{++} e^{-i\Delta\phi_{12}} \\ & - \hat{J}_1{}^{0}_{\sigma_1}(\theta_1)\, \hat{J}_2{}^{0}_{\sigma_2}(\theta_2)\, \hat{\mathcal{M}}_X{}^{0}_{00} \\ & - \hat{J}_1{}^{-}_{\sigma_1}(\theta_1)\, \hat{J}_2{}^{-}_{\sigma_2}(\theta_2)\, \hat{\mathcal{M}}_X{}^{0}_{--} e^{i\Delta\phi_{12}}\end{aligned}$$



(a) qq→qqX
(b) qg→qgX
(c) gg→ggX
1/σ dσ/d|Δφ12|
|Δφ12|
0
0.1
0.2
0.3
0.4
0.5
π/2
π
A
G
H(WBF)
H(GF)
H
full diagrams
only VBF diagrams
√s = 14 TeV
M = 600 GeV