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

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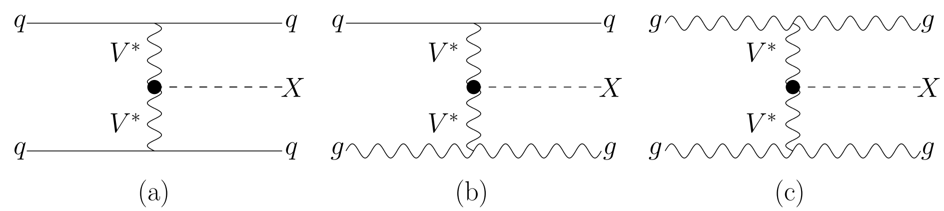

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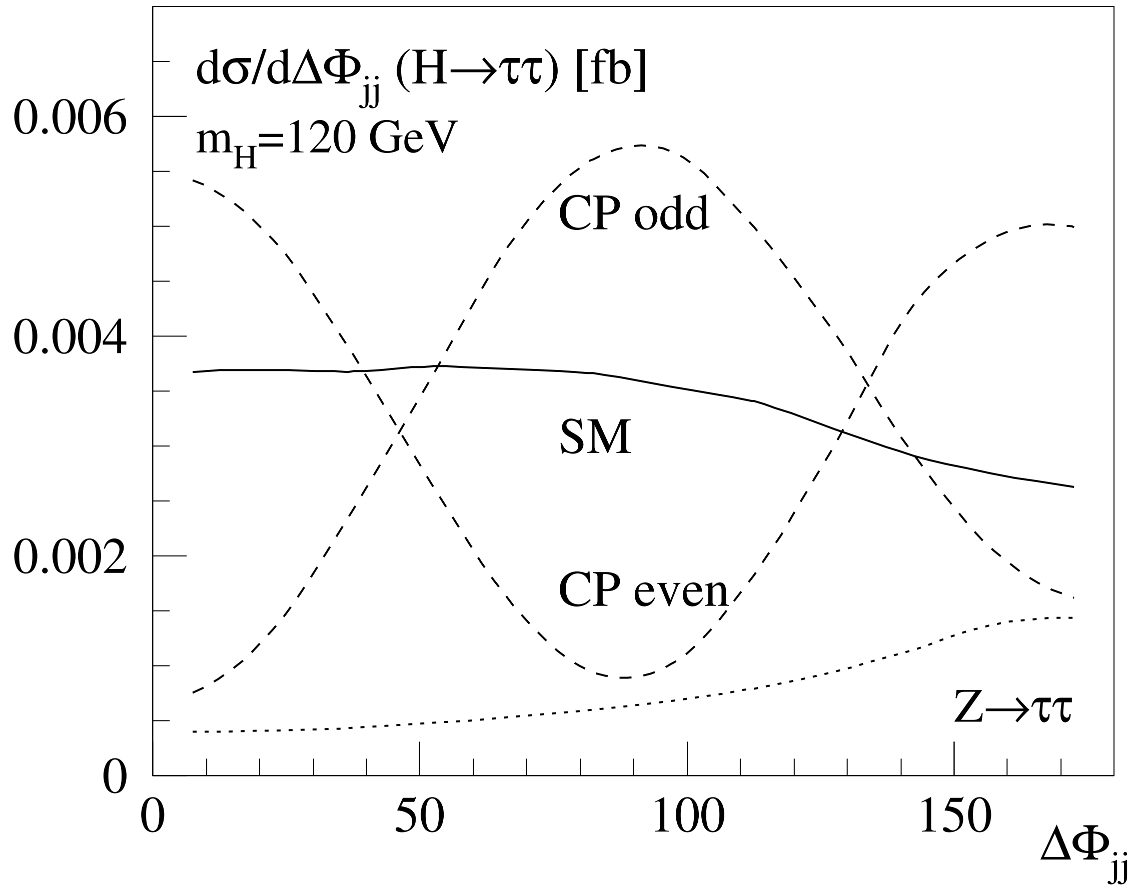
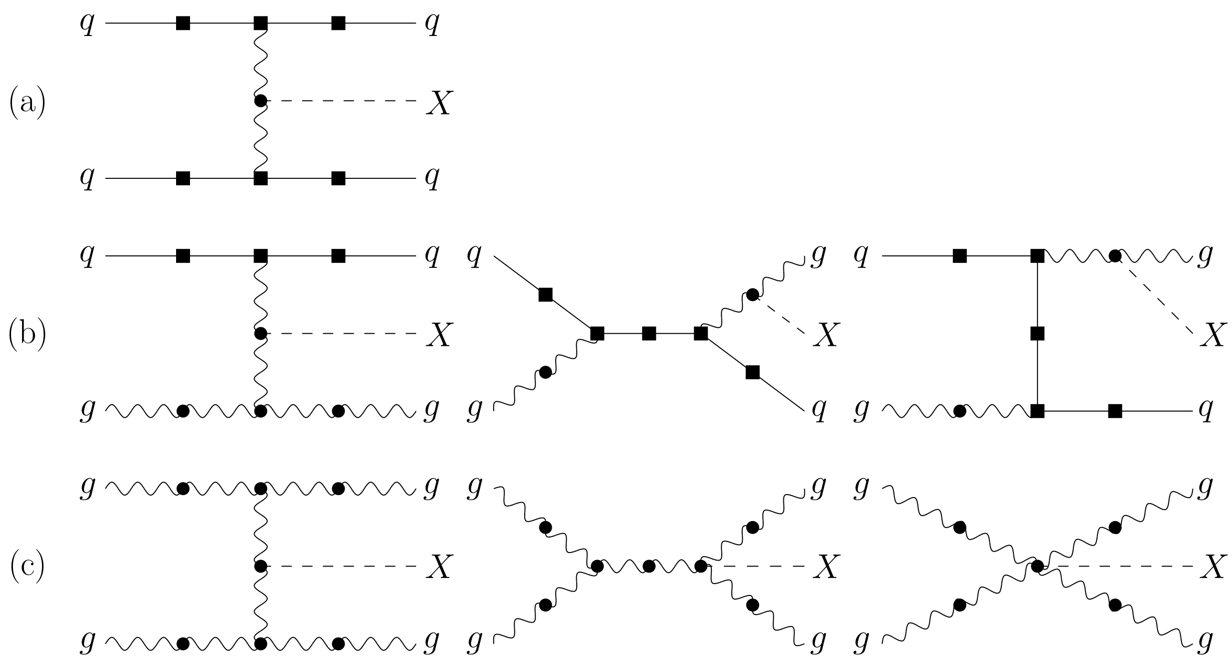
Azimuthal correlation between jets in Hjj events

T.Plehn, D.Rainwater, D.Zeppenfeld (2002)



- Azimuthal correlations reflect the tensor structures of the HVV coupling. Why does each tensor structure give such distributions?
- How about the correlation for spin-2 massive gravitons?

Subprocesses for $X + 2$ jet events



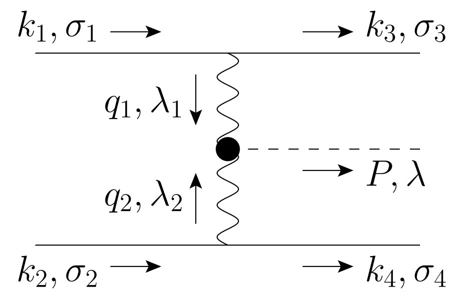
Higgs bosons: emitted from each of •

KK gravitons: emitted from each of • and □

Due to the t-channel propagators, the Xjj events via the VBF processes are dominantly produced when Q_i^2 are small, and hence the initial partons scatter to far forward and backward.

$\Longrightarrow$ The large rapidity separation cut, or the VBF cut, can select the VBF diagram among the full diagrams.

The VBF helicity amplitudes



The helicity amplitudes for VBF processes

$$\mathcal{M}^{\lambda}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = J^{\mu_1'}(k_1,k_3;\sigma_1,\sigma_3)\frac{-g_{\mu_1'\mu_1}+\frac{q_{1\mu_1'}q_{1\mu_1}}{m_V^2}}{q_1^2-m_V^2}J^{\mu_2'}(k_2,k_4;\sigma_2,\sigma_4)\frac{-g_{\mu_2'\mu_2}+\frac{q_{2\mu_2'}q_{2\mu_2}}{m_V^2}}{q_2^2-m_V^2}\Gamma^{\mu_1\mu_2}_{XVV}(q_1,q_2;\lambda)^*$$

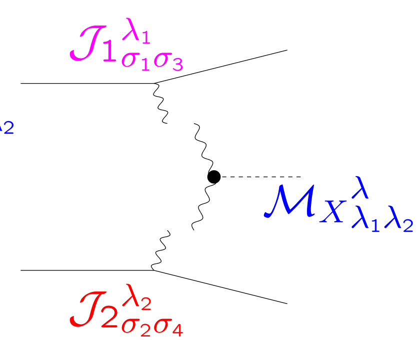
can be expressed by using

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

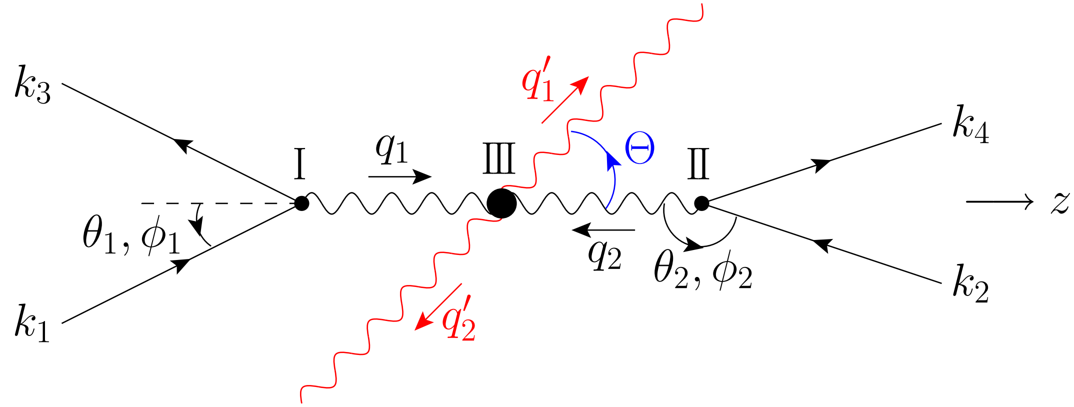
current conservation $$q_{i_\mu}J^{\mu}(k_i,k_{i+2};\sigma_i,\sigma_{i+2}) = 0$$

as the product of the three helicity amplitudes summed over the polarization of the intermediate vector-bosons:

$$\begin{aligned}\mathcal{M}^{\lambda}_{\sigma_1\sigma_3,\sigma_2\sigma_4} =& \frac{1}{q_1^2-m_V^2}J^{\mu_1'}(k_1,k_3;\sigma_1,\sigma_3)\sum_{\lambda_1=\pm,0}(-1)^{\lambda_1+1}\,\epsilon_{\mu_1'}(q_1,\lambda_1)^*\,\epsilon_{\mu_1}(q_1,\lambda_1)\\ &\times\frac{1}{q_2^2-m_V^2}J^{\mu_2'}(k_2,k_4;\sigma_2,\sigma_4)\sum_{\lambda_2=\pm,0}(-1)^{\lambda_2+1}\,\epsilon_{\mu_2'}(q_2,\lambda_2)^*\,\epsilon_{\mu_2}(q_2,\lambda_2)\\ &\times\Gamma^{\mu_1\mu_2}_{XVV}(q_1,q_2;\lambda)^*\\ =& \frac{1}{(q_1^2-m_V^2)(q_2^2-m_V^2)}\sum_{\lambda_1=\pm,0}\sum_{\lambda_2=\pm,0}\mathcal{J}1^{\lambda_1}_{\sigma_1\sigma_3}\,\mathcal{J}2^{\lambda_2}_{\sigma_2\sigma_4}\,\mathcal{M}X^{\lambda}_{\lambda_1\lambda_2}\end{aligned}$$



Kinematics



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

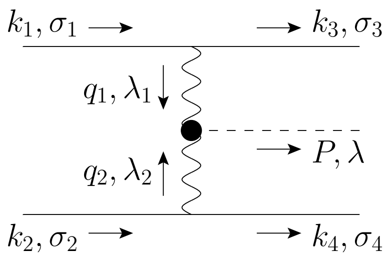
$$q_1^\mu = k_1^\mu - k_3^\mu = (0,\, 0,\, 0,\, Q_1)$$
$$k_1^\mu = \frac{Q_1}{2\cos\theta_1}(1,\, \sin\theta_1\cos\phi_1,\, \sin\theta_1\sin\phi_1,\, \cos\theta_1)$$
$$k_3^\mu = \frac{Q_1}{2\cos\theta_1}(1,\, \sin\theta_1\cos\phi_1,\, \sin\theta_1\sin\phi_1,\, -\cos\theta_1)$$

II) q_2 Breit frame ($Q_2 = \sqrt{-q_2^2}$, $\pi/2 < \theta_2 < \pi$):

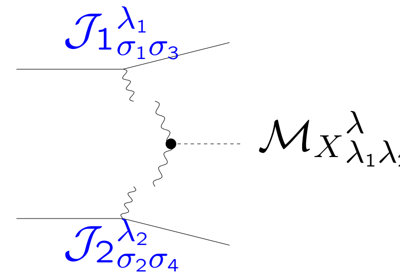
$$q_2^\mu = k_2^\mu - k_4^\mu = (0,\, 0,\, 0,\, -Q_2)$$
$$k_2^\mu = -\frac{Q_2}{2\cos\theta_2}(1,\, \sin\theta_2\cos\phi_2,\, \sin\theta_2\sin\phi_2,\, \cos\theta_2)$$
$$k_4^\mu = -\frac{Q_2}{2\cos\theta_2}(1,\, \sin\theta_2\cos\phi_2,\, \sin\theta_2\sin\phi_2,\, -\cos\theta_2)$$

III) VBF frame (X rest frame):

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



Current amplitudes



$$\mathcal{J}i^{\lambda_i}_{\sigma_i\sigma_{i+2}} = (-1)^{\lambda_i+1} J^\mu(k_i, k_{i+2}; \sigma_i, \sigma_{i+2})\, \epsilon_\mu(q_i, \lambda_i)^*$$

- Quark current vectors

$$J^\mu_{Vff'}(k_i, k_{i+2}; \sigma_i, \sigma_{i+2}) = g^{Vff'}_{\sigma_i}\, \bar{u}_{f'}(k_{i+2}, \sigma_{i+2})\, \gamma^\mu\, u_f(k_i, \sigma_i)$$

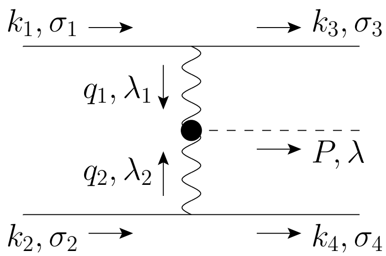
- Gluon current vectors

$$J^\mu_{ggg}(k_i, k_{i+2}; \sigma_i, \sigma_{i+2}) = g_s f^{abc}\, \epsilon^b_\alpha(k_i, \sigma_i)\, \epsilon^c_\beta(k_{i+2}, \sigma_{i+2})^* \times \Big[- g^{\alpha\beta}(k_i + k_{i+2})^\mu - g^{\beta\mu}(-k_{i+2} + q_i)^\alpha - g^{\mu\alpha}(-q_i - k_i)^\beta \Big]$$

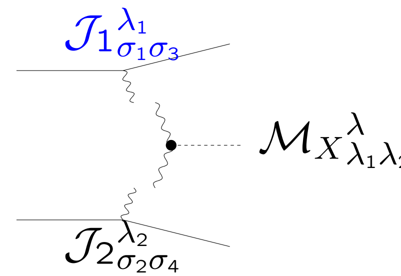
- Wavefunctions for the t-channel vector-bosons

$$\epsilon^\mu(q_1, \pm) = \frac{1}{\sqrt{2}}(0, \mp 1, -i, 0); \qquad \epsilon^\mu(q_2, \pm) = \frac{1}{\sqrt{2}}(0, \mp 1, i, 0)$$

$$\epsilon^\mu(q_1, 0) = (1, 0, 0, 0); \qquad \epsilon^\mu(q_2, 0) = (-1, 0, 0, 0)$$

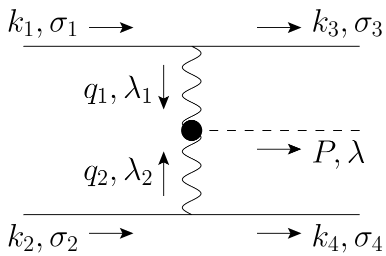


Current amplitudes

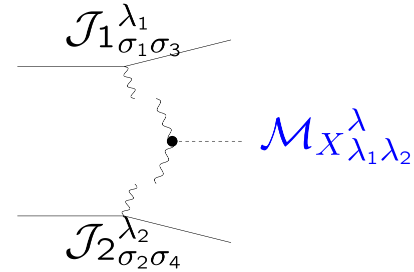


$\hat{\mathcal{J}}1^{\lambda_1}_{\sigma_1\sigma_3}$ (quark)	
$\hat{\mathcal{J}}1^{+}_{++} = -\left(\hat{\mathcal{J}}1^{-}_{--}\right)^*$	$\frac{1}{2\cos\theta_1}(1+\cos\theta_1)\, e^{-i\phi_1}$
$\hat{\mathcal{J}}1^{0}_{++} = \hat{\mathcal{J}}1^{0}_{--}$	$-\frac{1}{\sqrt{2}\cos\theta_1}\sin\theta_1$
$\hat{\mathcal{J}}1^{-}_{++} = -\left(\hat{\mathcal{J}}1^{+}_{--}\right)^*$	$-\frac{1}{2\cos\theta_1}(1-\cos\theta_1)\, e^{i\phi_1}$
$\hat{\mathcal{J}}1^{\lambda_1}_{+-} = \hat{\mathcal{J}}1^{\lambda_1}_{-+}$	0

$\hat{\mathcal{J}}1^{\lambda_1}_{\sigma_1\sigma_3}$ (gluon)	
$\hat{\mathcal{J}}1^{+}_{++} = -\left(\hat{\mathcal{J}}1^{-}_{--}\right)^*$	$\frac{1}{2\sin\theta_1\cos\theta_1}(1+\cos\theta_1)^2\, e^{-i\phi_1}$
$\hat{\mathcal{J}}1^{0}_{++} = \hat{\mathcal{J}}1^{0}_{--}$	$-\frac{1}{\sqrt{2}\cos\theta_1}$
$\hat{\mathcal{J}}1^{-}_{++} = -\left(\hat{\mathcal{J}}1^{+}_{--}\right)^*$	$-\frac{1}{2\sin\theta_1\cos\theta_1}(1-\cos\theta_1)^2\, e^{i\phi_1}$
$\hat{\mathcal{J}}1^{+}_{+-} = -\left(\hat{\mathcal{J}}1^{-}_{-+}\right)^*$	$-\frac{2}{\tan\theta_1}\, e^{i\phi_1}$
$\hat{\mathcal{J}}1^{0/-}_{+-} = \hat{\mathcal{J}}1^{0/+}_{-+}$	0



XVV vertex



- $VV \to X$ fusion amplitudes:

$$\mathcal{M}_X{}^{\lambda}_{\lambda_1\lambda_2} = \epsilon_\mu(q_1, \lambda_1)\, \epsilon_\nu(q_2, \lambda_2)\, \Gamma^{\mu\nu}_{XVV}(q_1, q_2; \lambda)^*$$

- Effective Lagrangian:

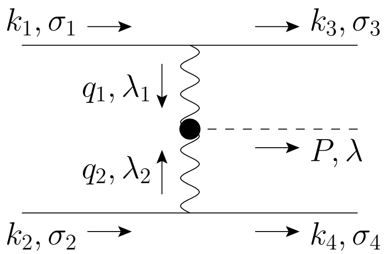
$$\mathcal{L}_{H,A} = -\frac{1}{4} g_{Hgg} H F^a_{\mu\nu} F^{a,\mu\nu} - \frac{1}{4} g_{Agg} A F^a_{\mu\nu} \tilde{F}^{a,\mu\nu}$$

$$\mathcal{L}_G = -\frac{1}{\Lambda} T^{\mu\nu} G_{\mu\nu}$$

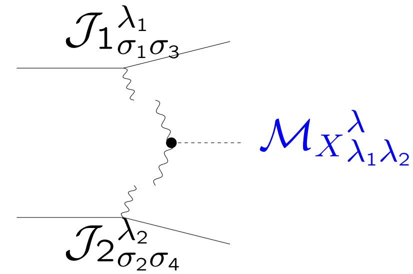
- XVV vertex:

X	(λ)	V	$\Gamma^{\mu\nu}_{XVV}/g_{XVV}$
H	(0)	W, Z	$g^{\mu\nu}$
H	(0)	$\gamma, Z/\gamma, g$	$q_1 \cdot q_2\, g^{\mu\nu} - q_2^\mu q_1^\nu$
A	(0)	$\gamma, Z/\gamma, g$	$\epsilon^{\mu\nu\alpha\beta} q_{1\alpha} q_{2\beta}$
G	$(\pm 2, \pm 1, 0)$	W, Z, γ, g	$\epsilon_{\alpha\beta}\, \hat{\Gamma}^{\alpha\beta\mu\nu}_{GVV}$

* $\epsilon^{\alpha\beta}(P, \lambda)$: *the polarization tensor;* $\hat{\Gamma}^{\alpha\beta\mu\nu}_{GVV}(q_1, q_2)$: *the GVV vertex*



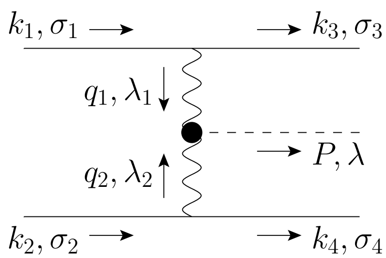
$V^*V^* \to H/A$ amplitudes



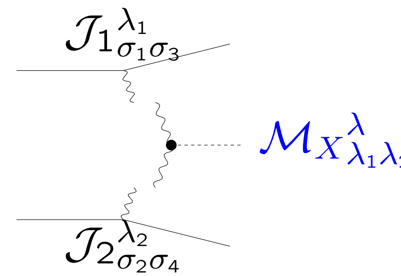
		CP-even		CP-odd
λ	$(\lambda_1\lambda_2)$	H(WBF)	H(loop-induced)	A
0	$(\pm\pm)$	-1	$-\frac{1}{2}(M^2+Q_1^2+Q_2^2)$	$\mp\frac{i}{2}\sqrt{(M^2+Q_1^2+Q_2^2)^2-4Q_1^2Q_2^2}$
0	(00)	$\frac{M^2+Q_1^2+Q_2^2}{2Q_1Q_2}$	Q_1Q_2	0

For $Q_1, Q_2 \ll M$, where the VBF contributions dominant,

- WBF H: produced by the longitudinally polarized vector-bosons.
- GF H/A: produced by the transversely polarized vector-bosons.



$g^* g^* \longrightarrow G$ amplitudes



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

For $Q_1, Q_2 \ll M$, the $\lambda = \pm 2$ states are dominantly produced through the collisions of the vector-bosons which have the opposite-sign transverse polarization.

Azimuthal correlations for Higgs bosons

The $J = 0$ VBF amplitudes are the sum of the three amplitudes:

$$\mathcal{M}^{\lambda=0}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = \frac{1}{(Q_1^2+m_V^2)(Q_2^2+m_V^2)} \sum_{\lambda_1=\pm,0} \sum_{\lambda_2=\pm,0} \mathcal{J}1^{\lambda_1}_{\sigma_1\sigma_3} \mathcal{J}2^{\lambda_2}_{\sigma_2\sigma_4} \mathcal{M}_X{}^{\lambda=0}_{\lambda_1\lambda_2}$$

$$\sim \quad \hat{\mathcal{J}}1^{+}_{\sigma_1\sigma_3} \hat{\mathcal{J}}2^{+}_{\sigma_2\sigma_4} \hat{\mathcal{M}}_X{}^{0}_{++} e^{-i(\phi_1-\phi_2)} + \hat{\mathcal{J}}1^{0}_{\sigma_1\sigma_3} \hat{\mathcal{J}}2^{0}_{\sigma_2\sigma_4} \hat{\mathcal{M}}_X{}^{0}_{00}$$
$$+ \hat{\mathcal{J}}1^{-}_{\sigma_1\sigma_3} \hat{\mathcal{J}}2^{-}_{\sigma_2\sigma_4} \hat{\mathcal{M}}_X{}^{0}_{--} e^{i(\phi_1-\phi_2)}$$

The squared amplitudes are

$$\sum_{\sigma_{1,\cdots,4}} \left|\mathcal{M}^{\lambda=0}_{\sigma_1\sigma_3,\sigma_2\sigma_4}\right|^2 = \Sigma_0 + \Sigma_1 \cos\Delta\phi + \Sigma_2 \cos 2\Delta\phi \quad (\Delta\phi \equiv \phi_1 - \phi_2)$$

The azimuthal correlation is manifestly expressed by the interference among different helicity states of the intermediate vector-bosons.

The different tensor structures of the XVV couplings give rise to the different azimuthal angle dependences:

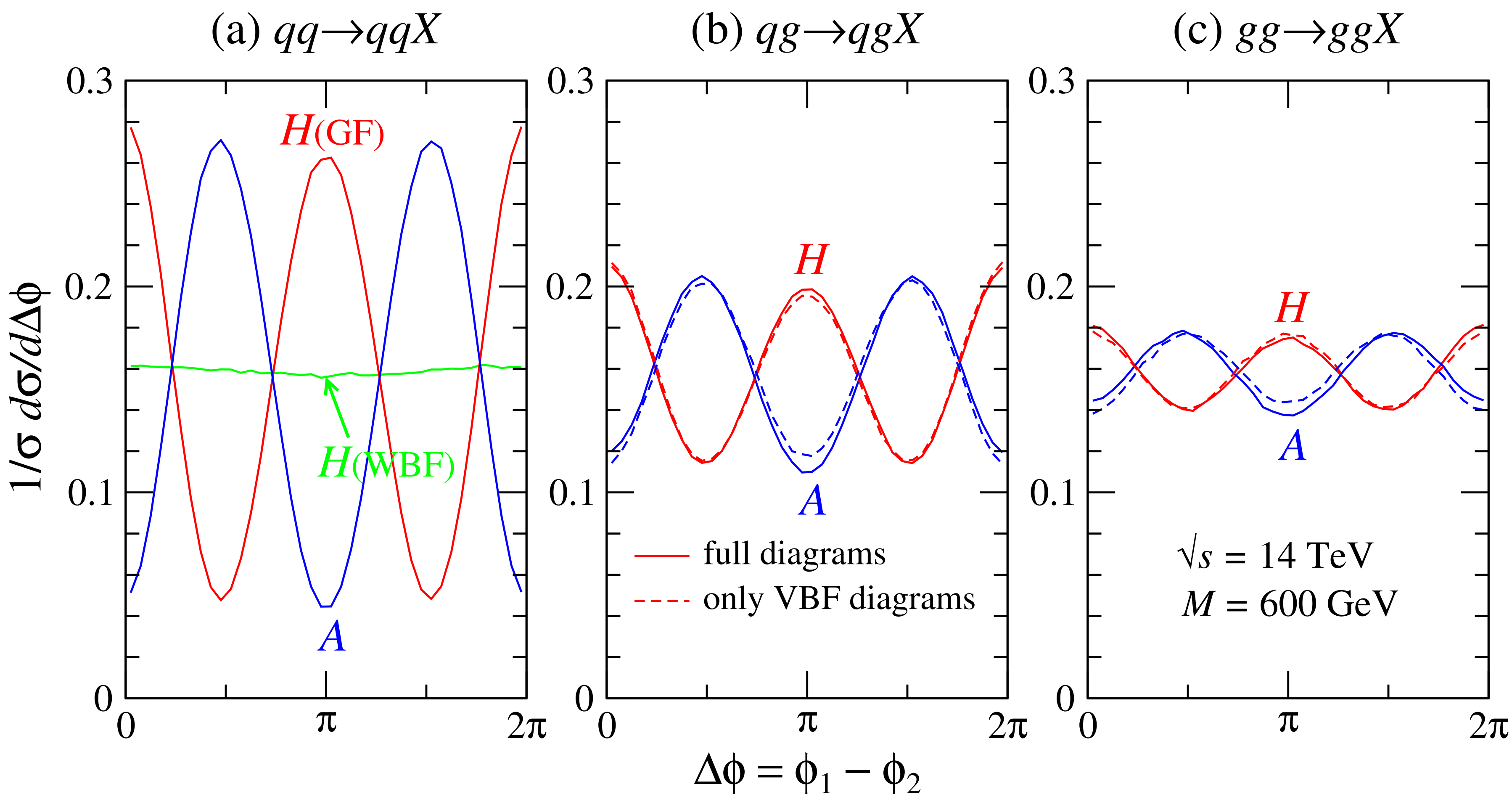
H(WBF) : $\mathcal{M}_{00} \gg \mathcal{M}_{++} = \mathcal{M}_{--}$ $\Rightarrow$ $d\hat{\sigma}/d\Delta\phi \sim$ constant

H(GF) : $\mathcal{M}_{00} \ll \mathcal{M}_{++} = \mathcal{M}_{--}$ $\Rightarrow$ $d\hat{\sigma}/d\Delta\phi \sim \Sigma_0 + |\Sigma_2| \cos 2\Delta\phi$

A : $\mathcal{M}_{00} = 0,\ \mathcal{M}_{++} = -\mathcal{M}_{--}$ $\Rightarrow$ $d\hat{\sigma}/d\Delta\phi \sim \Sigma_0 - |\Sigma_2| \cos 2\Delta\phi$

$\Delta\phi$ distributions for Higgs bosons

The VBF cuts: $\eta_{j_1} > 0 > \eta_{j_2}$, $\Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2} > 4$



$\Longrightarrow$ The VBF contributions can reproduce the distributions with the exact matrix elements very well even for the GF processes.

Azimuthal correlations for gravitons

The VBF G production plus its 2-body decay amplitudes are

$$\mathcal{M}_{\sigma_{1,\cdots,4};\sigma_{5,6}} = \frac{1}{Q_1^2 Q_2^2} \sum_{\lambda_1} \sum_{\lambda_2} \mathcal{J}1^{\lambda_1}_{\sigma_1\sigma_3} \mathcal{J}2^{\lambda_2}_{\sigma_2\sigma_4} \mathcal{M}G^{\lambda=\lambda_1-\lambda_2}_{\lambda_1\lambda_2} \frac{d^2_{\lambda,\lambda'}(\Theta)}{P^2 - M^2 + iM\Gamma} \mathcal{M}'^{\lambda'=\sigma_5-\sigma_6}_{G\sigma_5\sigma_6}$$

$$\sim \quad \hat{\mathcal{J}}1^{+}_{\sigma_1\sigma_3} \hat{\mathcal{J}}2^{-}_{\sigma_2\sigma_4} \hat{\mathcal{M}}G^{+2}_{+-} e^{-i(\phi_1+\phi_2)} d^2_{+2,\lambda'}(\Theta)$$

$$+ \hat{\mathcal{J}}1^{-}_{\sigma_1\sigma_3} \hat{\mathcal{J}}2^{+}_{\sigma_2\sigma_4} \hat{\mathcal{M}}G^{-2}_{-+} e^{i(\phi_1+\phi_2)} d^2_{-2,\lambda'}(\Theta)$$

The squared amplitudes are

$$\sum_{\sigma_{1,\cdots,4}} \left|\mathcal{M}_{\sigma_{1,\cdots,4};\sigma_{5,6}}\right|^2 = \Sigma_0 + \Sigma_1 \cos 2\Phi \quad (\Phi \equiv \phi_1 + \phi_2)$$

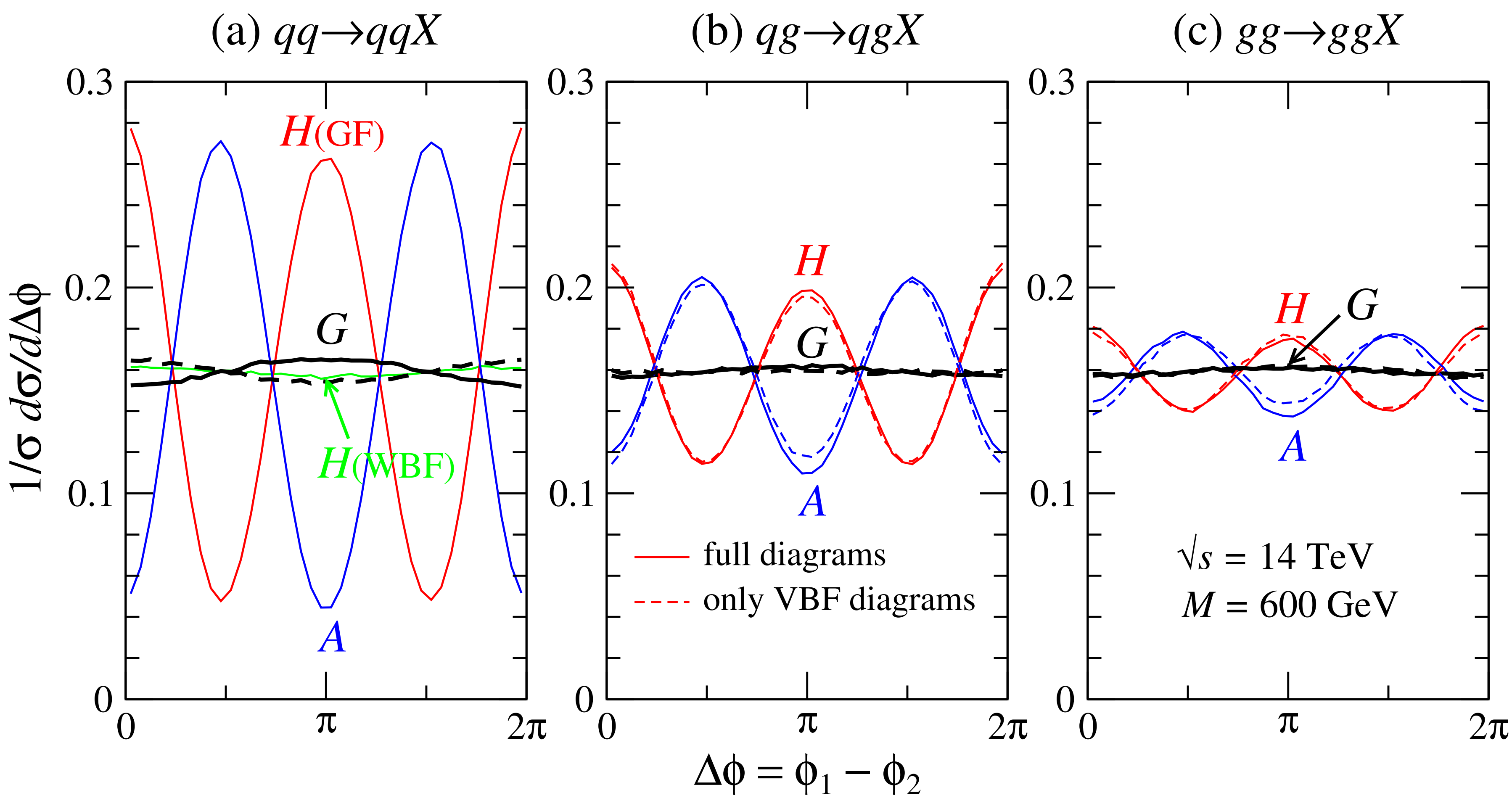
where

$$\Sigma_0 \propto \left(d^2_{+2,\lambda'}(\Theta)\right)^2 + \left(d^2_{-2,\lambda'}(\Theta)\right)^2 = \begin{cases} \frac{1}{8}(1 + 6\cos^2\Theta + \cos^4\Theta) & \text{for } \lambda' = \pm 2 \\ \frac{1}{2}(1 - \cos^4\Theta) & \text{for } \lambda' = \pm 1 \\ \frac{3}{4}\sin^4\Theta & \text{for } \lambda' = 0 \end{cases}$$

$$\Sigma_1 \propto 2\, d^2_{+2,\lambda'}(\Theta)\, d^2_{-2,\lambda'}(\Theta) = \begin{cases} +\frac{1}{8}\sin^4\Theta & \text{for } \lambda' = \pm 2 \\ -\frac{1}{2}\sin^4\Theta & \text{for } \lambda' = \pm 1 \\ +\frac{3}{4}\sin^4\Theta & \text{for } \lambda' = 0 \end{cases}$$

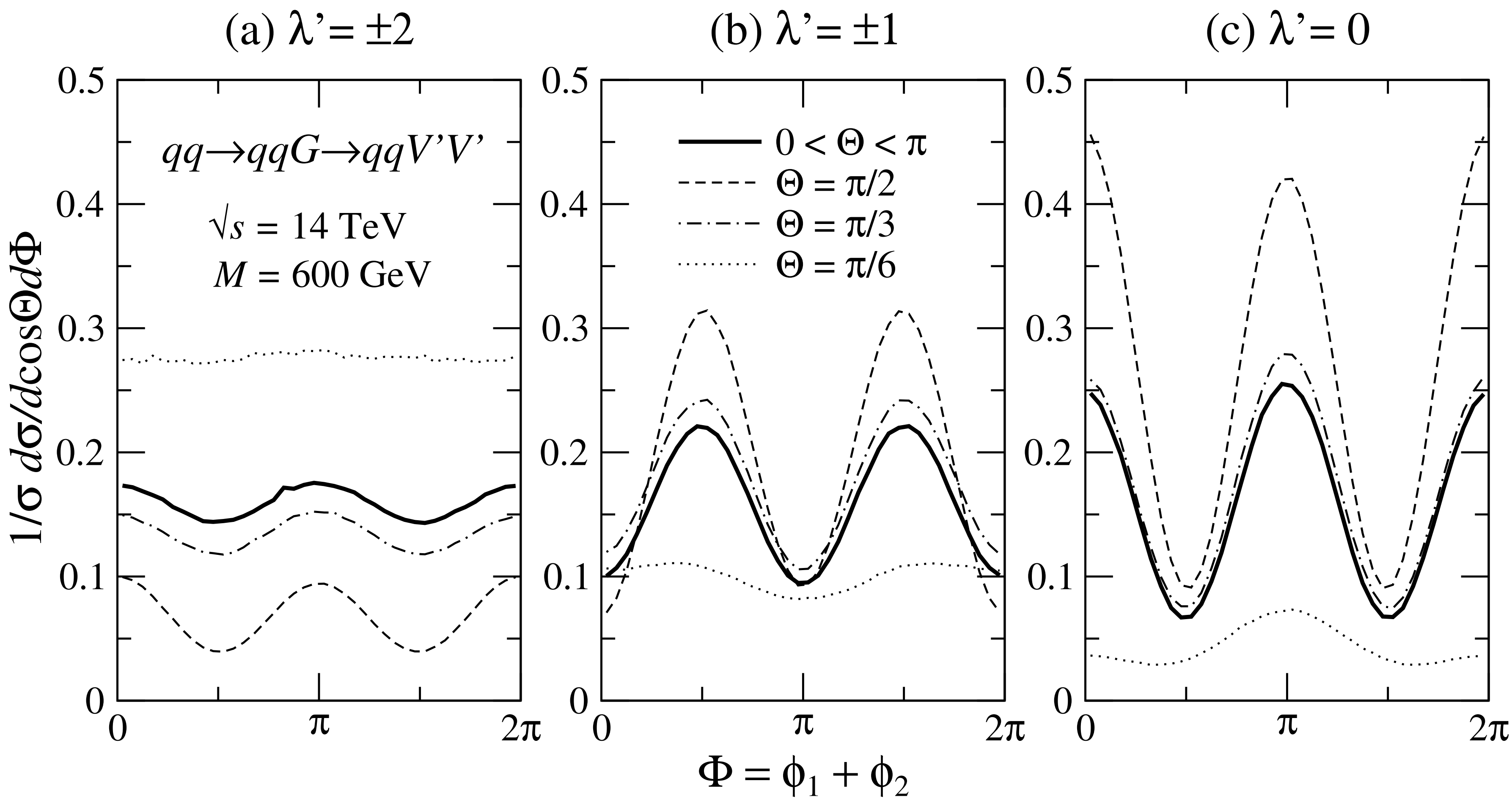
$\Longrightarrow$ The azimuthal Φ correlations depend on Θ and λ'.

$(\phi_1 - \phi_2)$ distributions for gravitons



"HELAS and MadGraph/MadEvent with spin-2 particles"
K.Hagiwara, J.Kanzaki, Q.Li, KM, EPJC(2008)
(The code is available at *http://madgraph.kek.jp/KEK/*.)

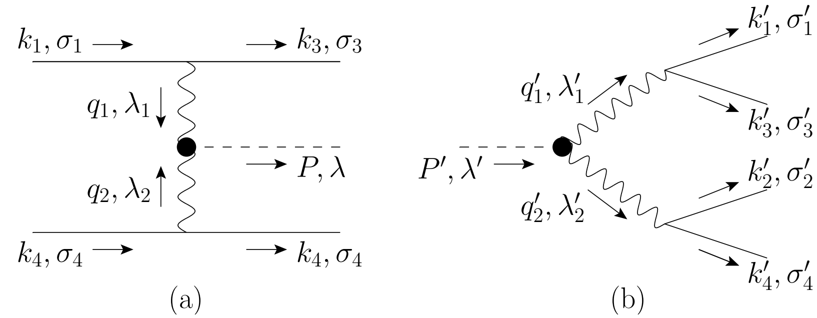
$(\phi_1 + \phi_2)$ distributions for gravitons



$$\sum_{\sigma_{1,\cdots,4}} \left| \mathcal{M}_{\sigma_{1,\cdots,4};\sigma_{5,6}} \right|^2 = \Sigma_0 + \Sigma_1 \cos 2\Phi; \quad \Sigma_1 \propto \begin{cases} +\frac{1}{8}\sin^4\Theta & \text{for } \lambda' = \pm 2 \\ -\frac{1}{2}\sin^4\Theta & \text{for } \lambda' = \pm 1 \\ +\frac{3}{4}\sin^4\Theta & \text{for } \lambda' = 0 \end{cases}$$

The Θ and λ' dependent azimuthal Φ correlations !

Summary



- We have studied
  - heavy particle (H/A and G) productions in association with two jets via VBF (=WBF+GF) processes at the LHC.
  - (their decays into 4 leptons/jets via a vector-boson pair.)
- We showed
  - the helicity amplitudes explicitly for the VBF subprocesses.
  - the VBF amplitudes can reproduce the exact matrix elements by imposing the selection (large rapidity separation) cuts.
  - non-trivial azimuthal correlations of the jets are manifestly expressed as the quantum interference among different helicity states of the intermediate vector-bosons.
- These correlations reflect the spin and CP nature of the produced heavy particles.