Azimuthal angle correlation in vector-boson fusion processes at hadron colliders

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Contents

Introduction

Azimuthal angle correlations in WBF

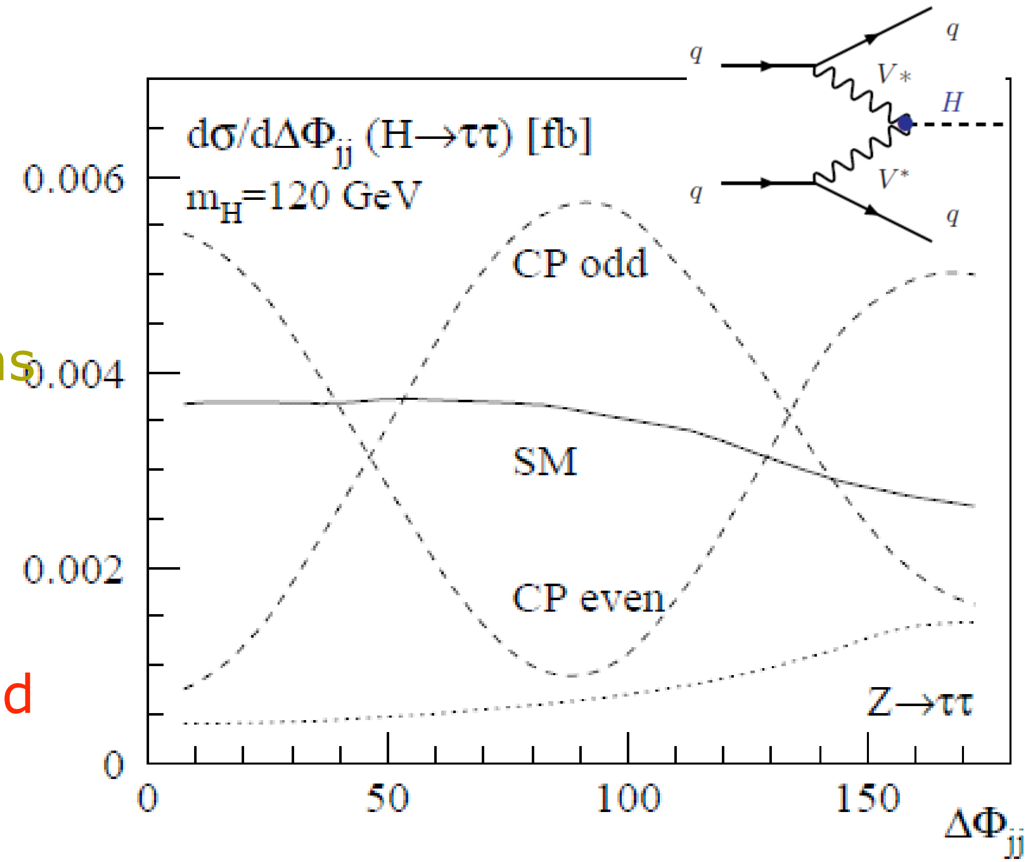
- The anomalous HWW coupling

$$\mathcal{L}_5 = \frac{1}{\Lambda_{e,5}} H\, W^+_{\mu\nu} W^{-\mu\nu} + \frac{1}{\Lambda_{o,5}} H\, \widetilde{W}^+_{\mu\nu} W^{-\mu\nu}$$

- The azimuthal correlations reflects the tensor structure of the Higgs couplings.

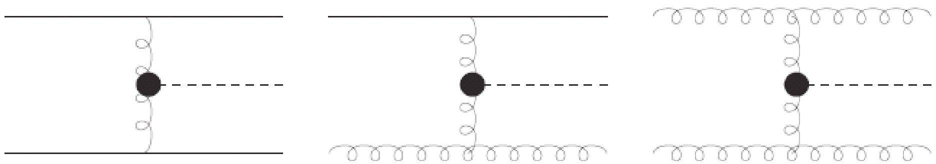
➢ Why is SM flat ? Why is CP-even (odd) suppressed at phi=90 (0 and 180) ?

T.Plehn, D.Rainwater, D.Zeppenfeld
PRL88(2002)051801



GF contribution

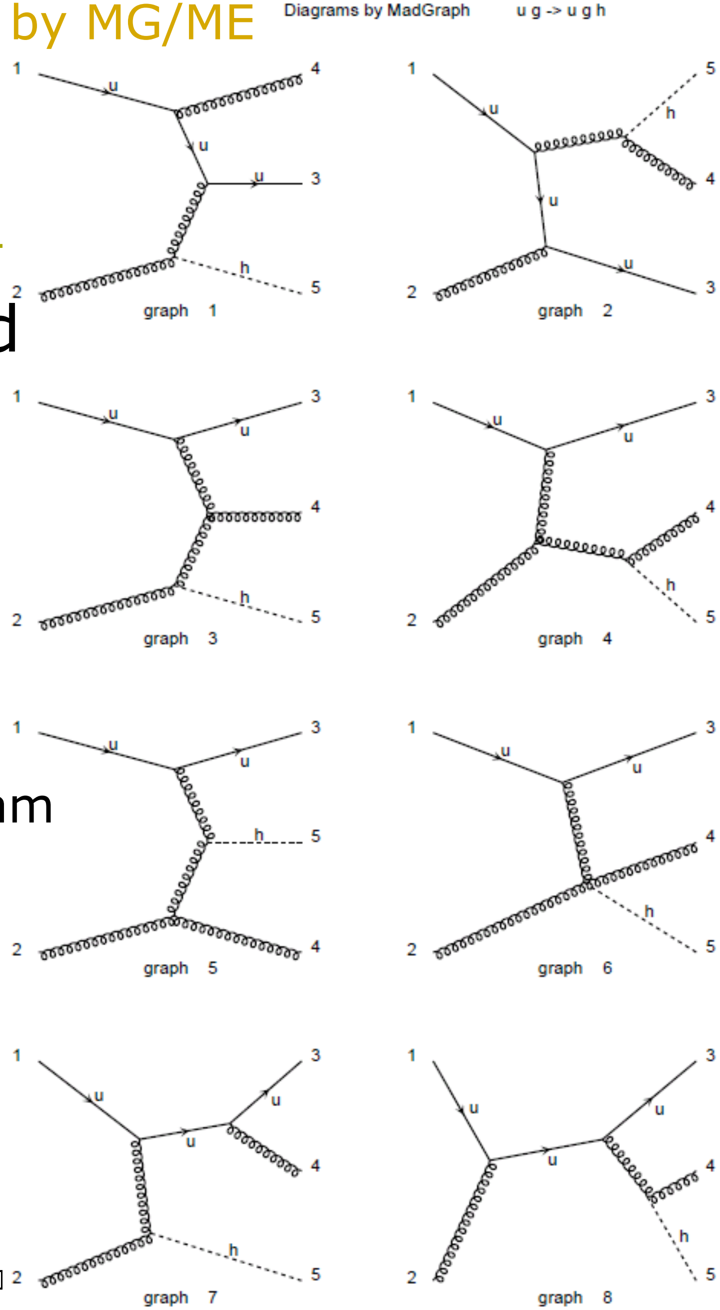
- H+2jet events are produced also via gluon fusion (GF).
- The subprocesses



  - qq'->qq'H (V=W,Z,g)
    - only one t-channel VBF diagram
  - qg->qgH (V=g)
    - 8 diagrams
  - gg->ggH (V=g)
    - 26 diagrams

(in the Higgs effective field theory)

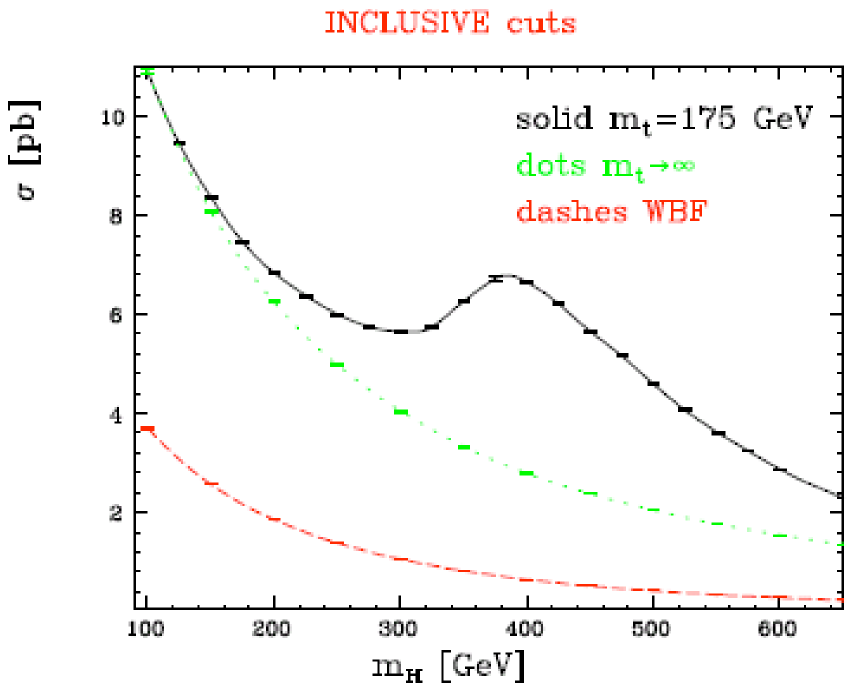
by MG/ME



WBF vs. GF

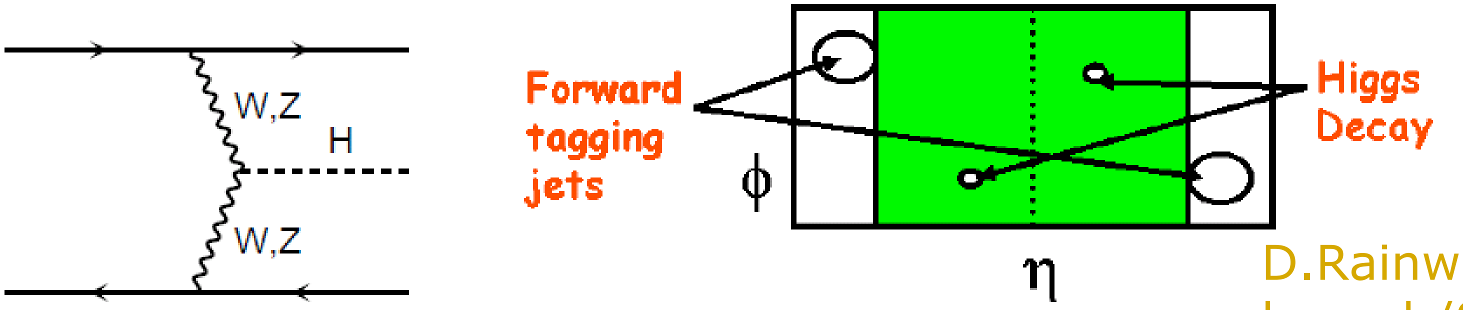
V. Del Duca et al.
NPB616(2001)367
hep-ph/0312184

$p_{T_j} > 20$ GeV, $|\eta_j| < 5$, $R_{jj} > 0.6$



The GF contribution dominates over the whole Higgs mass spectrum.

The distinctive kinematics of WBF

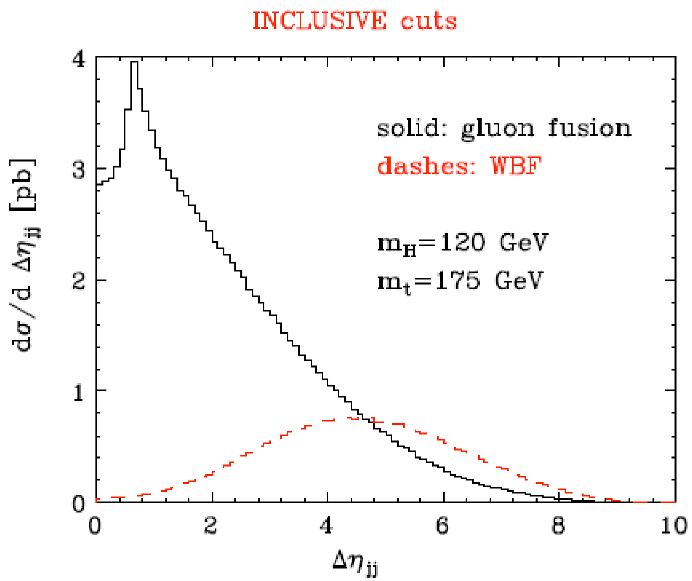


D.Rainwater
hep-ph/0702124

FIG. 20: WBF Higgs production Feynman diagram and lego plot schematic of a typical event.

- Far forward and backward jets.
- The Higgs boson is produced centrally.

↑ the t-channel weak-boson propagator

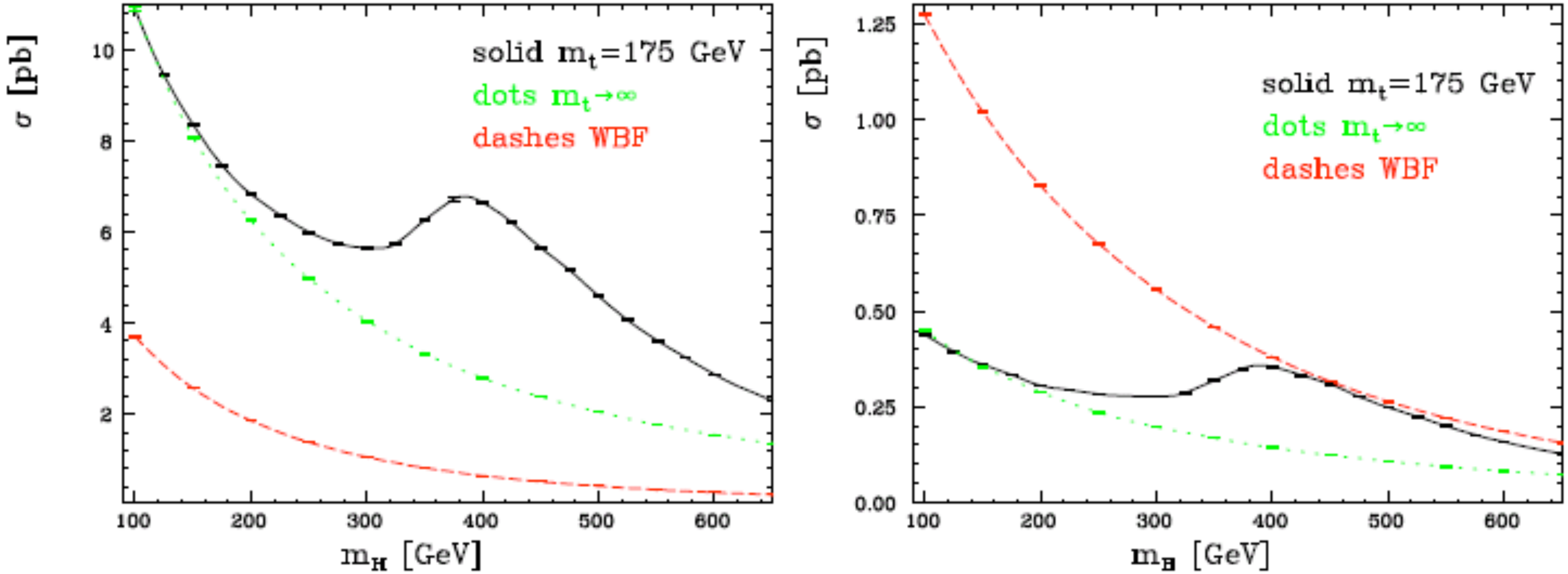


WBF vs. GF with VBF cuts

V. Del Duca et al.
NPB616(2001)367
hep-ph/0312184

VBF cuts

$p_{T_j} > 20$ GeV, $|\eta_j| < 5$, $R_{jj} > 0.6$ $|\Delta\eta_{jj}| > 4.2$, $\eta_{j_1} \cdot \eta_{j_2} < 0$, $m_{jj} > 600$ GeV

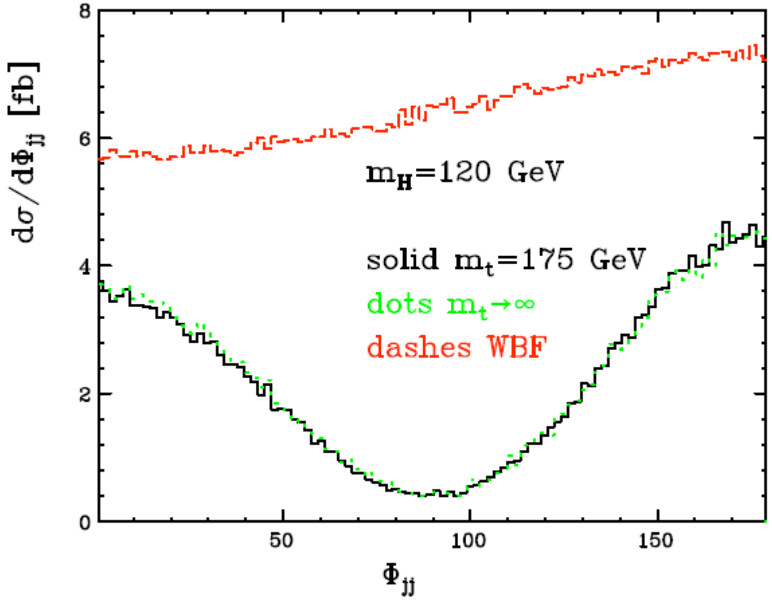


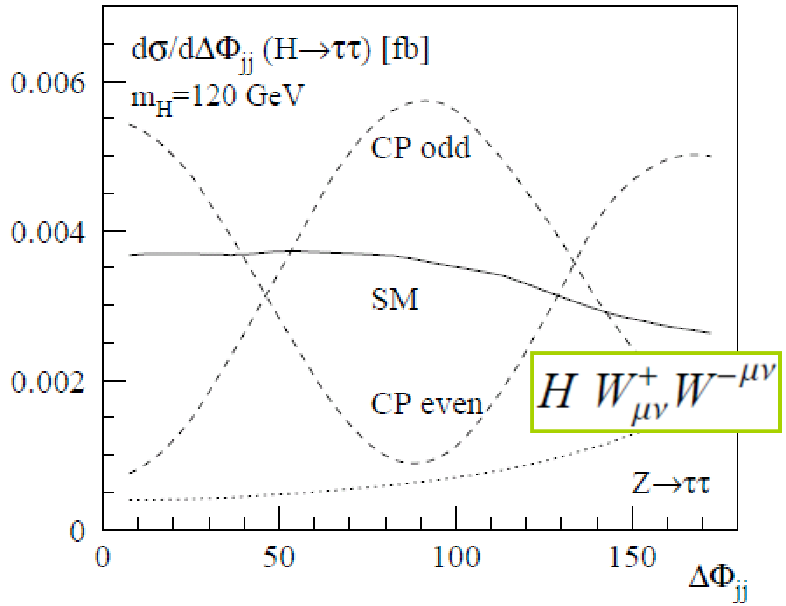
By the VBF cuts, the WBF contribution dominates over GF.

WBF vs. GF in the az dis.

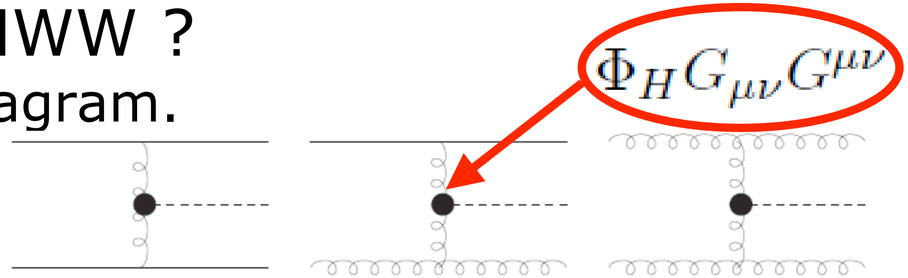
V. Del Duca et al.
NPB616(2001)367
hep-ph/0312184

w/ VBF cuts





- Why GF ~ D5 CP-even HWW ?
  - VBF cuts select the VBF diagram.
  - Effective Hgg coupling



Dijet rapidity separation

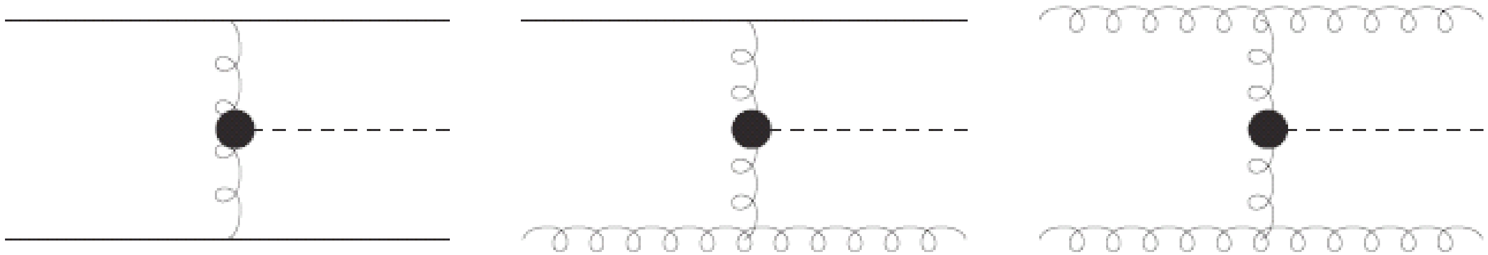
$\sigma_{\rm VBF}/\sigma_{\rm full}$	$\Delta\eta_{jj} > 3$	$\Delta\eta_{jj} > 4$	$\Delta\eta_{jj} > 4.2$	$\Delta\eta_{jj} > 4.5$
$qq' \to qq'H$	1.000	1.000	1.000	1.000
$qg \to qgH$	0.782	0.904	0.925	0.947
$gg \to ggH$	0.730	0.877	0.902	0.933

Table 6: Ratio of the VBF cross section to the full cross section for the different dijet rapidity separation.

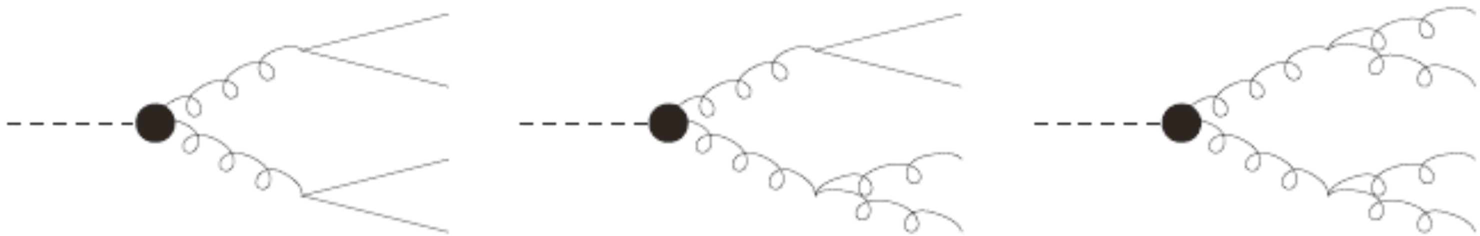
- By the dijet large rapidity separation cut, the VBF diagram dominates over other diagrams.
  - We consider only one VBF diagram.

Production vs. Decay

- H + 2 jet production via VBF



- H decay to 4 jets via a vector-boson pair

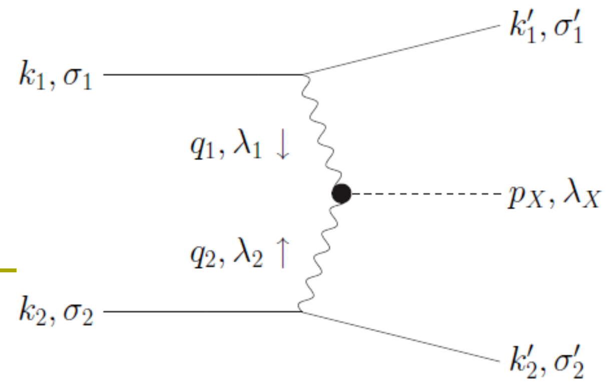


Both have identical topology.

➢ It may be useful to compare the production correlations with the decay correlations.

Formalism and Kinematics

Helicity formalism



- For the VBF process

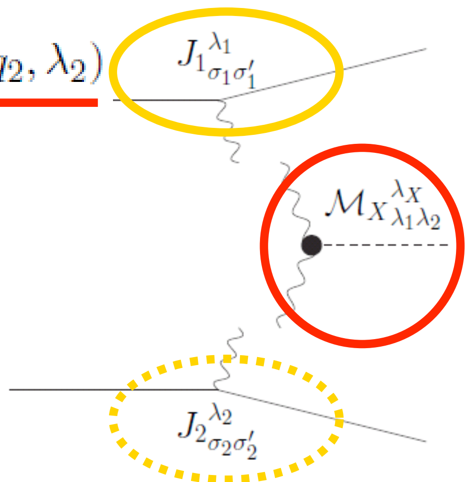
$$\mathcal{M}^{\lambda_X}_{\sigma_1\sigma'_1\sigma_2\sigma'_2} = J^{\mu'_1}_{f_1}(q_1;\sigma_1,\sigma'_1)\frac{-g_{\mu'_1\mu_1}+\frac{q_{1\mu'_1}q_{1\mu_1}}{m_V^2}}{q_1^2-m_V^2}J^{\mu'_2}_{f_2}(q_2;\sigma_2,\sigma'_2)\frac{-g_{\mu'_2\mu_2}+\frac{q_{2\mu'_2}q_{2\mu_2}}{m_V^2}}{q_2^2-m_V^2}\Gamma^{\mu_1\mu_2}_X(q_1,q_2;\lambda_X)$$

  - the completeness relation for space-like vector-boson

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

  - the conserved current $q_{i\mu}J^\mu_{f_i}(q_i;\sigma_i,\sigma'_i)=0$

$$\begin{aligned}\mathcal{M}^{\lambda_X}_{\sigma_1\sigma'_1\sigma_2\sigma'_2} &= \frac{1}{q_1^2-m_V^2}J^{\mu'_1}_{f_1}(q_1;\sigma_1,\sigma'_1)\sum_{\lambda_1=\pm,0}(-1)^{\lambda_1+1}\,\varepsilon^*_{\mu'_1}(q_1,\lambda_1)\,\varepsilon_{\mu_1}(q_1,\lambda_1)\\ &\times\frac{1}{q_2^2-m_V^2}J^{\mu'_2}_{f_2}(q_2;\sigma_2,\sigma'_2)\sum_{\lambda_2=\pm,0}(-1)^{\lambda_2+1}\,\varepsilon^*_{\mu'_2}(q_2,\lambda_2)\,\varepsilon_{\mu_2}(q_2,\lambda_2)\\ &\times\Gamma^{\mu_1\mu_2}_X(q_1,q_2;\lambda_X)\\ &=\frac{1}{(q_1^2-m_V^2)(q_2^2-m_V^2)}\sum_{\lambda_1,\lambda_2}J_1{}^{\lambda_1}_{\sigma_1\sigma'_1}J_2{}^{\lambda_2}_{\sigma_2\sigma'_2}\mathcal{M}_X{}^{\lambda_X}_{\lambda_1\lambda_2}\end{aligned}$$



Kinematics

I) the q_1 Breit frame

$$q_1^\mu = k_1^\mu - k_1'^\mu = \left(0,\ 0,\ 0,\ \sqrt{Q_1^2}\right)$$

$$k_1^\mu = \frac{\sqrt{Q_1^2}}{2\cos\theta_1}(1,\ \sin\theta_1\cos\phi_1,\ \sin\theta_1\sin\phi_1,\ \cos\theta_1)$$

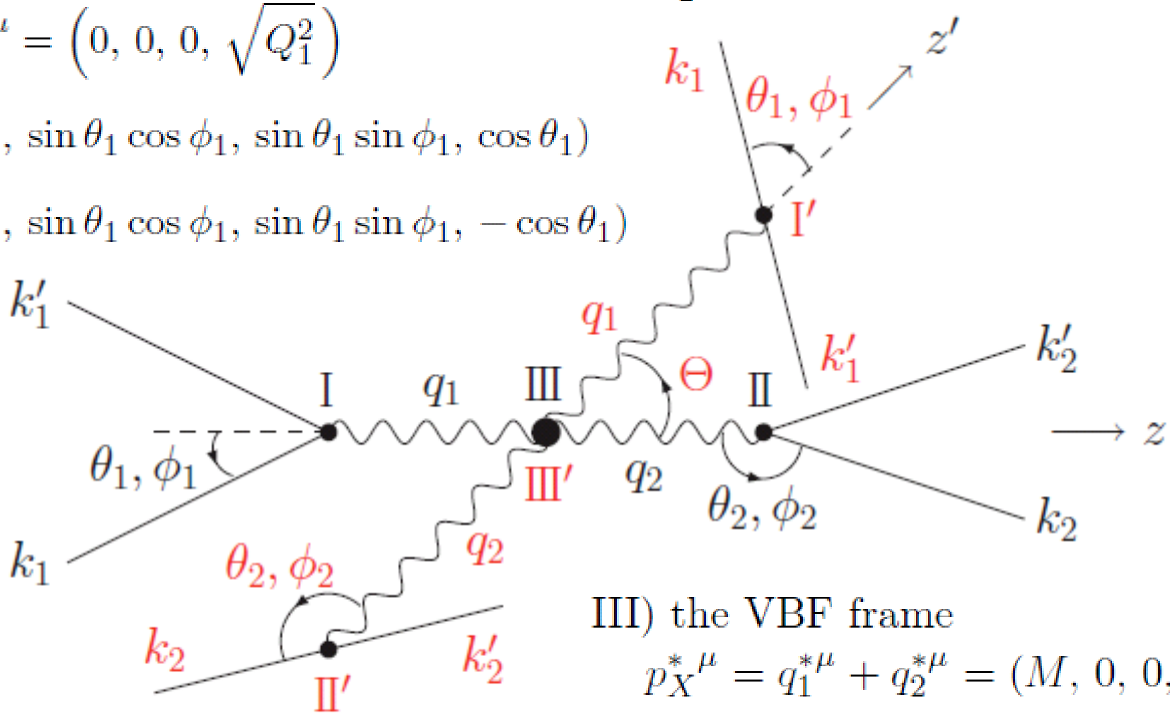
$$k_1'^\mu = \frac{\sqrt{Q_1^2}}{2\cos\theta_1}(1,\ \sin\theta_1\cos\phi_1,\ \sin\theta_1\sin\phi_1,\ -\cos\theta_1)$$

I$'$) the q_1 rest frame

$$q_1^\mu = k_1^\mu + k_1'^\mu = \left(\sqrt{q_1^2},\ 0,\ 0,\ 0\right)$$

$$k_1^\mu = \frac{\sqrt{q_1^2}}{2}(1,\ \sin\theta_1\cos\phi_1,\ \sin\theta_1\sin\phi_1,\ \cos\theta_1)$$

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



III) the VBF frame

$$p_X^{*\mu} = q_1^{*\mu} + q_2^{*\mu} = (M,\ 0,\ 0,\ 0)$$

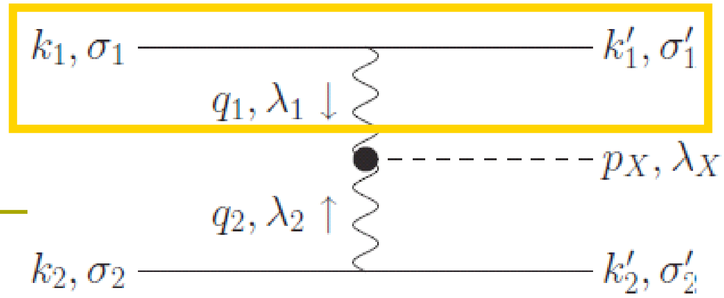
$$q_1^{*\mu} = \frac{M}{2}\left(1 - \frac{Q_1^2 - Q_2^2}{M^2},\ 0,\ 0,\ \beta^*\right)$$

$$q_2^{*\mu} = \frac{M}{2}\left(1 - \frac{Q_2^2 - Q_1^2}{M^2},\ 0,\ 0,\ -\beta^*\right)$$

Helicity amplitudes for the VBF process

- Quark current amplituds
- Qluon current amplitudes
- XVV production amplitudes

Current amplitudes

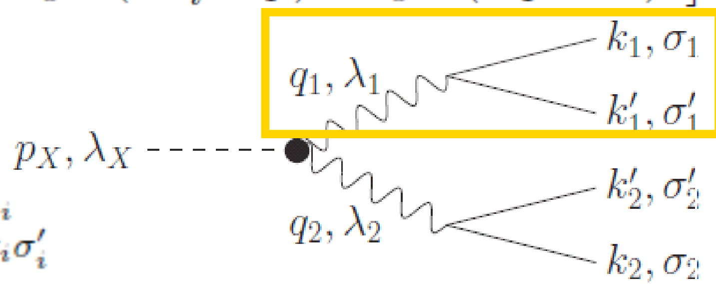


- For the production

$$J^{\lambda_i}_{i\,\sigma_i\sigma_i'} = (-1)^{\lambda_i+1} J^\mu_{f_i}(q_i;\sigma_i,\sigma_i')\,\varepsilon^*_\mu(q_i,\lambda_i) \;\equiv g_i\sqrt{2Q_i^2}\,\tilde{J}^{\lambda_i}_{i\,\sigma_i\sigma_i'}$$

  - quark: $J^\mu_q(q_i;\sigma_i,\sigma_i') = g_i\,\bar{u}(k_i',\sigma_i')\,\gamma^\mu\,u(k_i,\sigma_i)$
  - gluon: $J^\mu_g(q_i;\sigma_i,\sigma_i') = g_i\,\varepsilon_\alpha(k_i,\sigma_i)\varepsilon^*_\beta(k_i',\sigma_i')$

$$\times\left[-g^{\alpha\beta}(k_i+k_i')^\mu - g^{\beta\mu}(-k_i'+q_i)^\alpha - g^{\mu\alpha}(-q_i-k_i)^\beta\right]$$



- For the decay

$$J^{\lambda_i}_{i\,\sigma_i\sigma_i'} = \varepsilon_\mu(q_i,\lambda_i)\,J^\mu_{f_i}(q_i;\sigma_i,\sigma_i') \;\equiv g_i\sqrt{2q_i^2}\,\tilde{J}^{\lambda_i}_{i\,\sigma_i\sigma_i'}$$

  - quark: $J^\mu_q(q_i;\sigma_i,\sigma_i') = g_i\,\bar{u}(k_i,\sigma_i)\,\gamma^\mu\,v(k_i',\sigma_i')$
  - gluon: $J^\mu_g(q_i;\sigma_i,\sigma_i') = g_i\,\varepsilon^*_\alpha(k_i,\sigma_i)\varepsilon^*_\beta(k_i',\sigma_i')$

$$\times\left[-g^{\alpha\beta}(-k_i+k_i')^\mu - g^{\beta\mu}(-k_i'-q_i)^\alpha - g^{\mu\alpha}(q_i+k_i)^\beta\right]$$

Quark current amplitudes

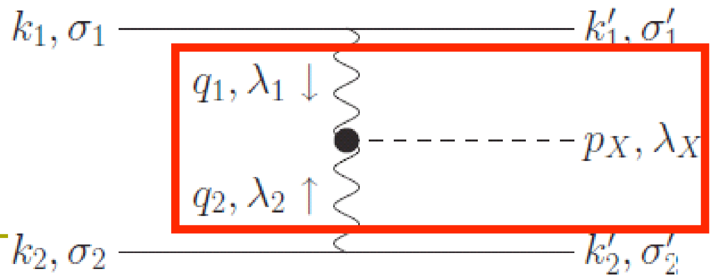
$\tilde{J}^{\lambda_1}_{1\,\sigma_1\sigma_1'}(q_{\sigma_1} \to q_{\sigma_1'} V^*_{\lambda_1})$		$[\cos\theta_1 \xrightarrow{\beta_1=1} z_1/(2-z_1)]$
$\tilde{J}^{\,+}_{1\,++} = -(\tilde{J}^{\,-}_{1\,--})^*$	$\frac{1}{2\cos\theta_1}(1+\cos\theta_1)\, e^{-i\phi_1}$	$\frac{1}{z_1}\, e^{-i\phi_1}$
$\tilde{J}^{\,0}_{1\,++} = \tilde{J}^{\,0}_{1\,--}$	$-\frac{1}{\sqrt{2}\cos\theta_1}\sin\theta_1$	$-\frac{\sqrt{2(1-z_1)}}{z_1}$
$\tilde{J}^{\,-}_{1\,++} = -(\tilde{J}^{\,+}_{1\,--})^*$	$-\frac{1}{2\cos\theta_1}(1-\cos\theta_1)\, e^{i\phi_1}$	$-\frac{1-z_1}{z_1}\, e^{i\phi_1}$
$\tilde{J}^{\,\lambda_1}_{1\,+-} = \tilde{J}^{\,\lambda_1}_{1\,-+}$	0	0
$\tilde{J}^{\lambda_1}_{1\,\sigma_1\sigma_1'}(V^*_{\lambda_1} \to q_{\sigma_1} \bar{q}_{\sigma_1'})$		$[\cos\theta_1 \xrightarrow{\beta_1=1} 2z_1 - 1]$
$\tilde{J}^{\,+}_{1\,+-} = -(\tilde{J}^{\,-}_{1\,-+})^*$	$\frac{1}{2}(1+\cos\theta_1)\, e^{i\phi_1}$	$z_1\, e^{i\phi_1}$
$\tilde{J}^{\,0}_{1\,+-} = \tilde{J}^{\,0}_{1\,-+}$	$\frac{1}{\sqrt{2}}\sin\theta_1$	$\sqrt{2z_1(1-z_1)}$
$\tilde{J}^{\,-}_{1\,+-} = -(\tilde{J}^{\,+}_{1\,-+})^*$	$\frac{1}{2}(1-\cos\theta_1)\, e^{-i\phi_1}$	$(1-z_1)\, e^{-i\phi_1}$
$\tilde{J}^{\,\lambda_1}_{1\,++} = \tilde{J}^{\,\lambda_1}_{1\,--}$	0	0

Table 1: The reduced helicity amplitudes $\tilde{J}^{\lambda_1}_{1\,\sigma_1\sigma_1'}$ for the incoming quark current $q \to qV^*$ in the VBF frame (top) and for the outgoing quark current $V^* \to q\bar{q}$ in the X rest frame (bottom). The kinematical variables are defined in the Breit frame for $q \to qV^*$ and in the vector-boson rest frame for $V^* \to q\bar{q}$. In the third column the splitting amplitudes are also shown in the $\beta_1 = 1$ limit, where z_1 is the energy fraction of the initial particle and β_1 is the boost factor.

Gluon current amplitudes

$\tilde J^{\lambda_1}_{1\,\sigma_1\sigma'_1}(g_{\sigma_1}\to g_{\sigma'_1} g^*_{\lambda_1})$		$[\cos\theta_1 \xrightarrow{\beta_1=1} z_1/(2-z_1)]$
$\tilde J^{\,+}_{1++} = -(\tilde J^{\,-}_{1--})^*$	$\frac{1}{2}\tan\theta_1(1+\cos\theta_1)^2 e^{-i\phi_1}\cdot\frac{1}{1-\beta_1^2\cos^2\theta_1}$	$\frac{1}{z_1\sqrt{1-z_1}}e^{-i\phi_1}$
$\tilde J^{\,0}_{1++}=\tilde J^{\,0}_{1--}$	$-\frac{1}{\sqrt{2}}\tan\theta_1\sin\theta_1\cdot\frac{1}{1-\beta_1^2\cos^2\theta_1}$	$-\frac{2-z_1}{\sqrt{2}\,z_1}$
$\tilde J^{\,-}_{1++}=-(\tilde J^{\,+}_{1--})^*$	$-\frac{1}{2}\tan\theta_1(1-\cos\theta_1)^2 e^{i\phi_1}\cdot\frac{1}{1-\beta_1^2\cos^2\theta_1}$	$-\frac{(1-z_1)^2}{z_1\sqrt{1-z_1}}e^{i\phi_1}$
$\tilde J^{\,+}_{1+-}=-(\tilde J^{\,-}_{1-+})^*$	$-\frac{1}{2}\tan\theta_1\cos^2\theta_1 e^{-i\phi_1}\cdot\frac{(1+\beta_1)^2}{1-\beta_1^2\cos^2\theta_1}$	$-\frac{z_1}{\sqrt{1-z_1}}e^{-i\phi_1}$
$\tilde J^{\,0}_{1+-}=\tilde J^{\,0}_{1-+}$	$-\frac{1}{\sqrt{2}}\cos\theta_1\cdot\frac{1-\beta_1^2}{1-\beta_1^2\cos^2\theta_1}$	0
$\tilde J^{\,-}_{1+-}=-(\tilde J^{\,+}_{1-+})^*$	$\frac{1}{2}\tan\theta_1\cos^2\theta_1 e^{i\phi_1}\cdot\frac{(1-\beta_1)^2}{1-\beta_1^2\cos^2\theta_1}$	0
$\tilde J^{\lambda_1}_{1\,\sigma_1\sigma'_1}(g^*_{\lambda_1}\to g_{\sigma_1} g_{\sigma'_1})$		$[\cos\theta_1 \xrightarrow{\beta_1=1} 2z_1-1]$
$\tilde J^{\,+}_{1+-}=-(\tilde J^{\,-}_{1-+})^*$	$-\frac{1}{2}\sin\theta_1(1+\cos\theta_1)^2 e^{i\phi_1}\cdot\frac{\beta_1^2}{1-\beta_1^2\cos^2\theta_1}$	$-\frac{z_1^2}{\sqrt{z_1(1-z_1)}}e^{i\phi_1}$
$\tilde J^{\,0}_{1+-}=\tilde J^{\,0}_{1-+}$	$-\frac{1}{\sqrt{2}}\sin^2\theta_1\cos\theta_1\cdot\frac{\beta_1^2}{1-\beta_1^2\cos^2\theta_1}$	$-\frac{2z_1-1}{\sqrt{2}}$
$\tilde J^{\,-}_{1+-}=-(\tilde J^{\,+}_{1-+})^*$	$\frac{1}{2}\sin\theta_1(1-\cos\theta_1)^2 e^{-i\phi_1}\cdot\frac{\beta_1^2}{1-\beta_1^2\cos^2\theta_1}$	$\frac{(1-z_1)^2}{\sqrt{z_1(1-z_1)}}e^{-i\phi_1}$
$\tilde J^{\,+}_{1++}=-(\tilde J^{\,-}_{1--})^*$	$-\frac{1}{2}\sin\theta_1 e^{i\phi_1}\cdot\frac{(1+\beta_1)^2}{1-\beta_1^2\cos^2\theta_1}$	$-\frac{1}{\sqrt{z_1(1-z_1)}}e^{i\phi_1}$
$\tilde J^{\,0}_{1++}=\tilde J^{\,0}_{1--}$	$-\frac{1}{\sqrt{2}}\cos\theta_1\cdot\frac{1-\beta_1^2}{1-\beta_1^2\cos^2\theta_1}$	0
$\tilde J^{\,-}_{1++}=-(\tilde J^{\,+}_{1--})^*$	$\frac{1}{2}\sin\theta_1 e^{-i\phi_1}\cdot\frac{(1-\beta_1)^2}{1-\beta_1^2\cos^2\theta_1}$	0

XVV vertex



- $\mathcal{M}_X{}^{\lambda_X}_{\lambda_1\lambda_2} = \varepsilon_{\mu_1}(q_1,\lambda_1)\varepsilon_{\mu_2}(q_2,\lambda_2)\,\Gamma_X^{\mu_1\mu_2}(q_1,q_2;\lambda_X)$
- The XVV vertex

X	(λ_X)	V	$\Gamma_X^{\mu_1\mu_2}(q_1,q_2;\lambda_X)/g_{XVV}$
H	(0)	W,Z	$g^{\mu_1\mu_2}$
H	(0)	$g,(\gamma)$	$(q_1\cdot q_2)\,g^{\mu_1\mu_2} - q_2^{\mu_1}q_1^{\mu_2}$
A	(0)	$g,(\gamma)$	$\varepsilon^{\mu_1\mu_2\alpha\beta}q_{1\alpha}q_{2\beta}$
G	$(\pm2,\pm1,0)$	$W,Z,g,(\gamma)$	$\tilde{\Gamma}_G^{\alpha\beta,\,\mu_1\mu_2}(q_1,q_2)\,\varepsilon_{\alpha\beta}(p_X,\lambda_X)$

- The polarization tensor and the GXX vertex

$$\varepsilon^{\mu\nu}(p,\pm2) = \varepsilon^{\mu}(p,\pm)\,\varepsilon^{\nu}(p,\pm)$$

$$\varepsilon^{\mu\nu}(p,\pm1) = \frac{1}{\sqrt{2}}\left[\varepsilon^{\mu}(p,\pm)\,\varepsilon^{\nu}(p,0) + \varepsilon^{\mu}(p,0)\,\varepsilon^{\nu}(p,\pm)\right]$$

$$\varepsilon^{\mu\nu}(p,0) = \frac{1}{\sqrt{6}}\left[\varepsilon^{\mu}(p,+)\,\varepsilon^{\nu}(p,-) + \varepsilon^{\mu}(p,-)\,\varepsilon^{\nu}(p,+) + 2\,\varepsilon^{\mu}(p,0)\,\varepsilon^{\nu}(p,0)\right]$$

$$\tilde{\Gamma}_G^{\mu\nu,\,\rho\sigma}(q_1,q_2) = (m_V^2 + q_1\cdot q_2)\,C^{\mu\nu,\,\rho\sigma} + D^{\mu\nu,\,\rho\sigma}(q_1,q_2)$$

$$C_{\mu\nu,\,\rho\sigma} = g^{\mu\rho}g^{\nu\sigma} + g^{\mu\sigma}g^{\nu\rho} - g^{\mu\nu}g^{\rho\sigma}$$

$$D_{\mu\nu,\,\rho\sigma}(q_1,q_2) = g^{\mu\nu}q_1^{\sigma}q_2^{\rho} - \left[g^{\mu\sigma}q_1^{\nu}q_2^{\rho} + g^{\mu\rho}q_1^{\sigma}q_2^{\nu} - g^{\rho\sigma}q_1^{\mu}q_2^{\nu} + (\mu\leftrightarrow\nu)\right]$$

XVV amplitudes

for $Q_1^2, Q_2^2 \ll M^2$

λ_X	$(\lambda_1\lambda_2)$	HWW/HZZ	Hgg	Agg
0	$(\pm\pm)$	1	$\frac{1}{2}(M^2+Q_1^2+Q_2^2)$	$\mp\frac{1}{2}\sqrt{(M^2+Q_1^2+Q_2^2)^2-4Q_1^2Q_2^2}$
0	(00)	$\frac{(M^2+Q_1^2+Q_2^2)}{2\sqrt{Q_1^2Q_2^2}}$	$\sqrt{Q_1^2Q_2^2}$	0

Table 4: The helicity amplitudes $\mathcal{M}_X{}^{\lambda_X}_{\lambda_1\lambda_2}$ for the Higgs production $V^*_{\lambda_1}V^*_{\lambda_2} \to (H,A)_{\lambda_X}$ in the VBF frame, where M is the Higgs boson mass and Q_1^2 and Q_2^2 are off-shell values of the vector-bosons. The coupling constants g_{XVV} are set to unity.

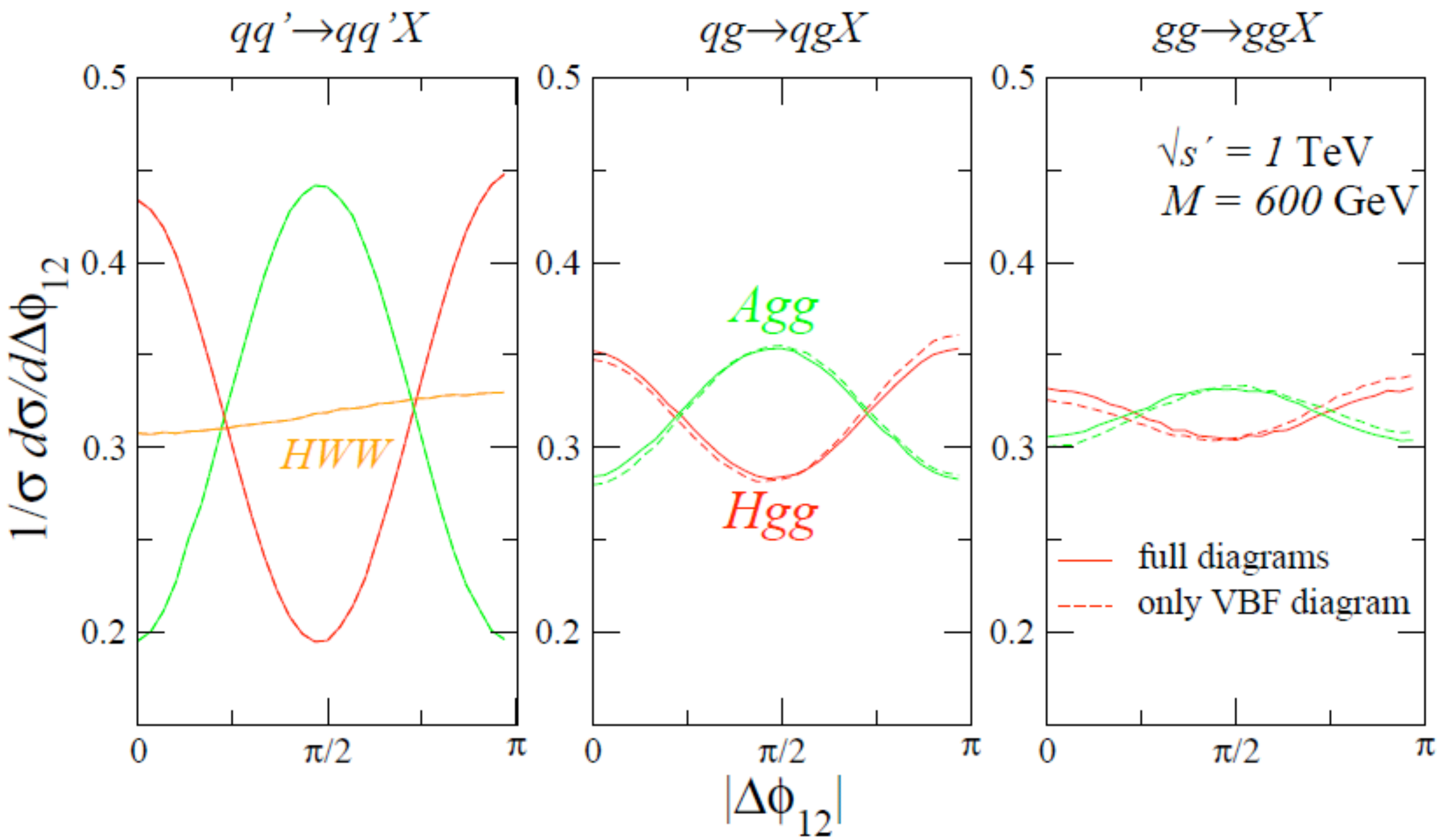
λ_X	$(\lambda_1\lambda_2)$	GVV
± 2	$(\pm\mp)$	$M^2+Q_1^2+Q_2^2$
± 1	$(\pm 0)/(0\mp)$	$\sqrt{\frac{Q_2^2}{2M^2}}(M^2-Q_1^2+Q_2^2) \Big/ -\sqrt{\frac{Q_1^2}{2M^2}}(M^2+Q_1^2-Q_2^2)$
0	$(\pm\pm)/(00)$	$-\frac{1}{\sqrt{6}M^2}[(Q_1^2-Q_2^2)^2+M^2(Q_1^2+Q_2^2)] \Big/ -\frac{4}{\sqrt{6}}\sqrt{Q_1^2Q_2^2}$

Table 5: The same as Table 4, but for the massive-graviton produciton $V^*_{\lambda_1}V^*_{\lambda_2} \to G_{\lambda_X}$.

Azimuthal angle correlations

- Higgs bosons
- Massive-gravitons

For Higgs bosons



Quantum interference between the different helicity states

- The full helicity amplitude for the Higgs boson

$$\mathcal{M}^0_{\sigma_1\sigma_1'\sigma_2\sigma_2'} = \frac{1}{(q_1^2 - m_V^2)(q_2^2 - m_V^2)} \sum_{\lambda_1,\lambda_2} J1^{\lambda_1}_{\sigma_1\sigma_1'} J2^{\lambda_2}_{\sigma_2\sigma_2'} \mathcal{M}X^0_{\lambda_1\lambda_2}$$

$$\sim J1^+_{\sigma_1\sigma_1'} J2^+_{\sigma_2\sigma_2'} \mathcal{M}X^0_{++} + J1^0_{\sigma_1\sigma_1'} J2^0_{\sigma_2\sigma_2'} \mathcal{M}X^0_{00} + J1^-_{\sigma_1\sigma_1'} J2^-_{\sigma_2\sigma_2'} \mathcal{M}X^0_{--}$$

- For, e.g., $\sigma_1 = \sigma_1' = \sigma_2 = \sigma_2' = +$

$$\begin{aligned}\mathcal{M}^0 \sim & +J_1{}^+(\theta_1,\beta_1)J_2{}^+(\theta_2,\beta_2)\mathcal{M}X^0_{++}e^{-i(\phi_1-\phi_2)} \\ & - J_1{}^0(\theta_1,\beta_1)J_2{}^0(\theta_2,\beta_2)\mathcal{M}X^0_{00} \\ & + J_1{}^-(\theta_1,\beta_2)J_2{}^-(\theta_2,\beta_2)\mathcal{M}X^0_{--}e^{i(\phi_1-\phi_2)} \\ \equiv & +J_{12}^{++}\mathcal{M}X^0_{++}e^{-i\Delta\phi_{12}} - J_{12}^{00}\mathcal{M}X^0_{00} + J_{12}^{--}\mathcal{M}X^0_{--}e^{i\Delta\phi_{12}}\end{aligned}$$

  - H(WBF): $\mathcal{M}_{00} \gg \mathcal{M}_{++}, \mathcal{M}_{--} \Longrightarrow$ flat
  - H: $\mathcal{M}_{00} \ll \mathcal{M}_{++}, \mathcal{M}_{--} \Longrightarrow \sim +\cos 2\Delta\phi_{12}$
  - A: $\mathcal{M}_{00} = 0,\ \mathcal{M}_{++} = -\mathcal{M}_{--} \Longrightarrow \sim -\cos 2\Delta\phi_{12}$

Spin-2 massive-graviton

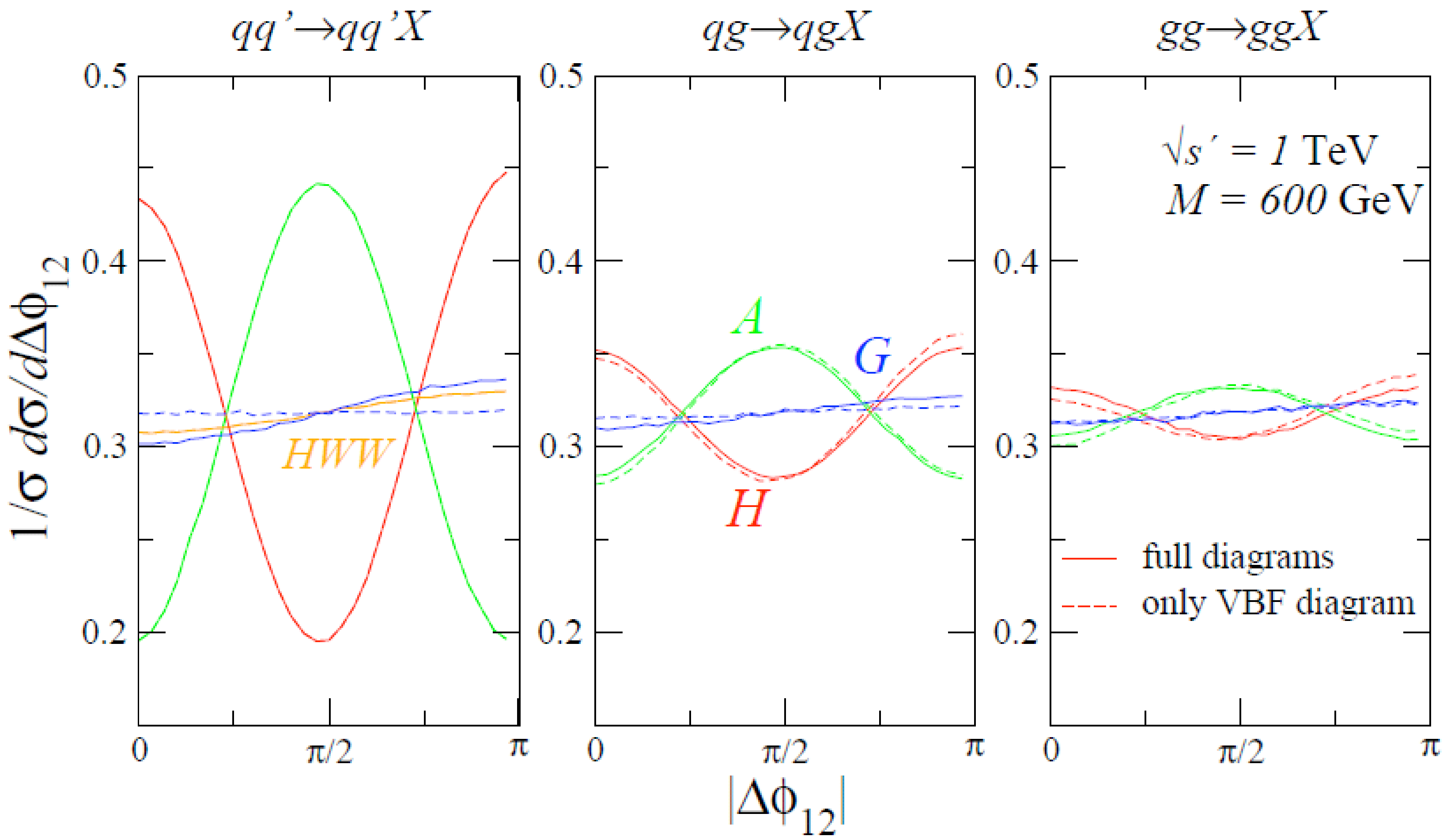
- The full helicity amplitude for the massive-graviton
  - The $\lambda_X = \pm 2$ caes is dominant.

$$\mathcal{M}^{\pm 2}_{\sigma_1\sigma_1'\sigma_2\sigma_2'} = \frac{1}{(q_1^2 - m_V^2)(q_2^2 - m_V^2)} \sum_{\lambda_1,\lambda_2} J_1{}^{\lambda_1}_{\sigma_1\sigma_1'} J_2{}^{\lambda_2}_{\sigma_2\sigma_2'} \mathcal{M}_X{}^{\pm 2}_{\lambda_1\lambda_2}$$

$$\sim J_1{}^{\pm}_{\sigma_1\sigma_1'} J_2{}^{\mp}_{\sigma_2\sigma_2'} \mathcal{M}_X{}^{\pm 2}_{\pm\mp}$$

  - There is no interference term.
    - No azimuthal dependence.

For massive-gravitons



Summary

- We studied Higgs boson and massive-graviton productions in association with two jets via VBF (=WBF+GF) and their decays at hadron colliders.
- We showed
  - the helicity amp explicitly for the VBF subprocesses.
  - the VBF amp reproduces the exact matrix elements by taking into account the dijet large rapidity separation.
  - quantum interference between different helicity states of the intermediate vector-bosons leads to a non-trivial azimuthal angle correlation of the jets in the production and in the decay.
- These correlations reflect the spin and CP nature of the Higgs bosons and the massive-gravitons.