GENERATION OF SPIN/CP STATES IN HIGGS PRODUCTION + 2 JETS
ANOMALOUS COUPLINGS IN VBFNLO

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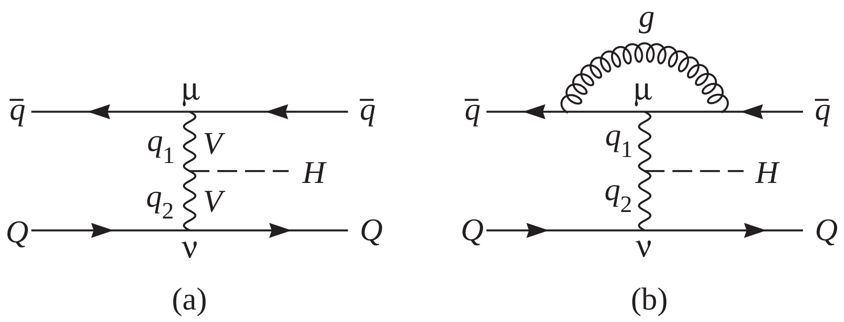
- Tensor structures
- Effective Lagrangians
- Implementation and reweighting
- Signal definition for heavy Higgs in VBF

Tensor structure of the HVV coupling

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



$$T^{\mu\nu} = a_1 \, g^{\mu\nu} + a_2 \, (q_1 \cdot q_2 \, g^{\mu\nu} - q_1^\nu q_2^\mu) + a_3 \, \varepsilon^{\mu\nu\rho\sigma} \, q_{1\rho} q_{2\sigma}$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\quad \mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

CP odd $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Implementation in VBFNLO

Start from effective Lagrangians

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}$$

or , alternatively,

$$\mathcal{L}_{\text{eff}} = \frac{f_{WW}}{\Lambda_6^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_{BB}}{\Lambda_6^2} \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi + \text{ CP-odd part} + \cdots$$

Implementation in VBFNLO

Start from effective Lagrangians (set PARAMETR1=.true. in anom_HVV.dat)

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}$$

or , alternatively, (set PARAMETR3=.true. in anom_HVV.dat)

$$\mathcal{L}_{\rm eff} = \frac{f_{WW}}{\Lambda_6^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_{BB}}{\Lambda_6^2} \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi + \text{ CP-odd part} + \cdots$$

see VBFNLO manual for details on how to set the anomalous coupling choices

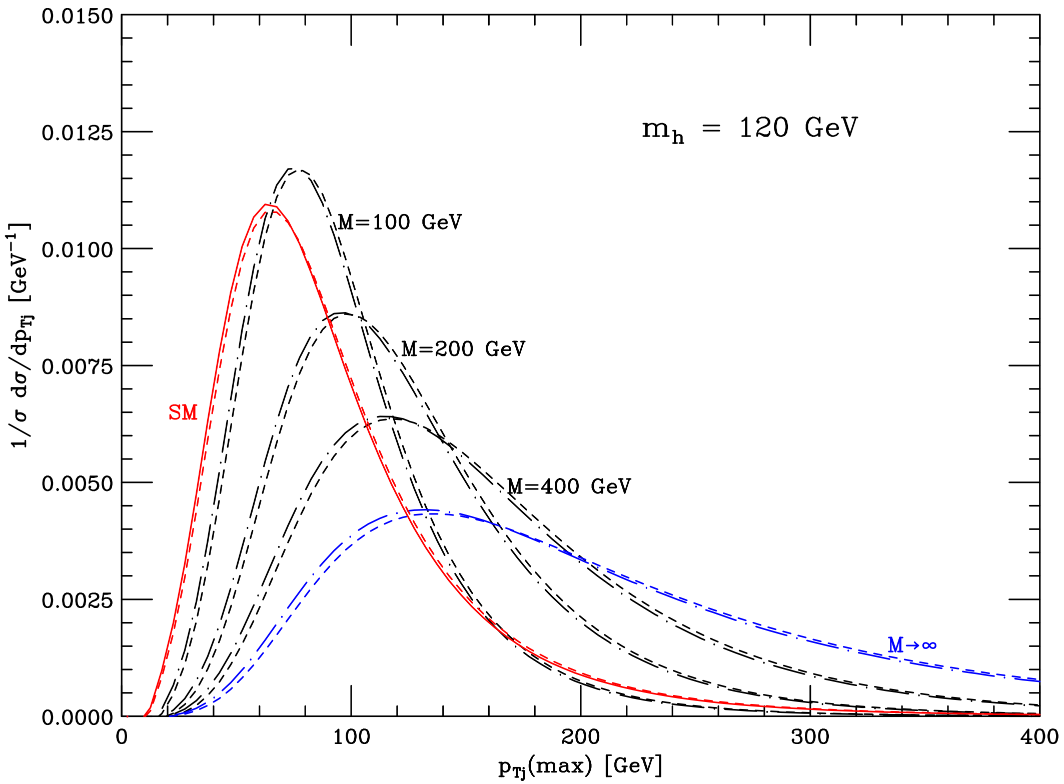
Remember to choose form factors in anom_HVV.dat

$$F_1 = \frac{M^2}{q_1^2 - M^2} \frac{M^2}{q_2^2 - M^2} \qquad \text{or} \qquad F_2 = -2\, M^2\, C_0\left(q_1^2, q_2^2, (q_1 + q_2)^2, M^2\right)$$

Jet transverse momentum

Form factors affect momentum transfer and thus jet transverse momenta

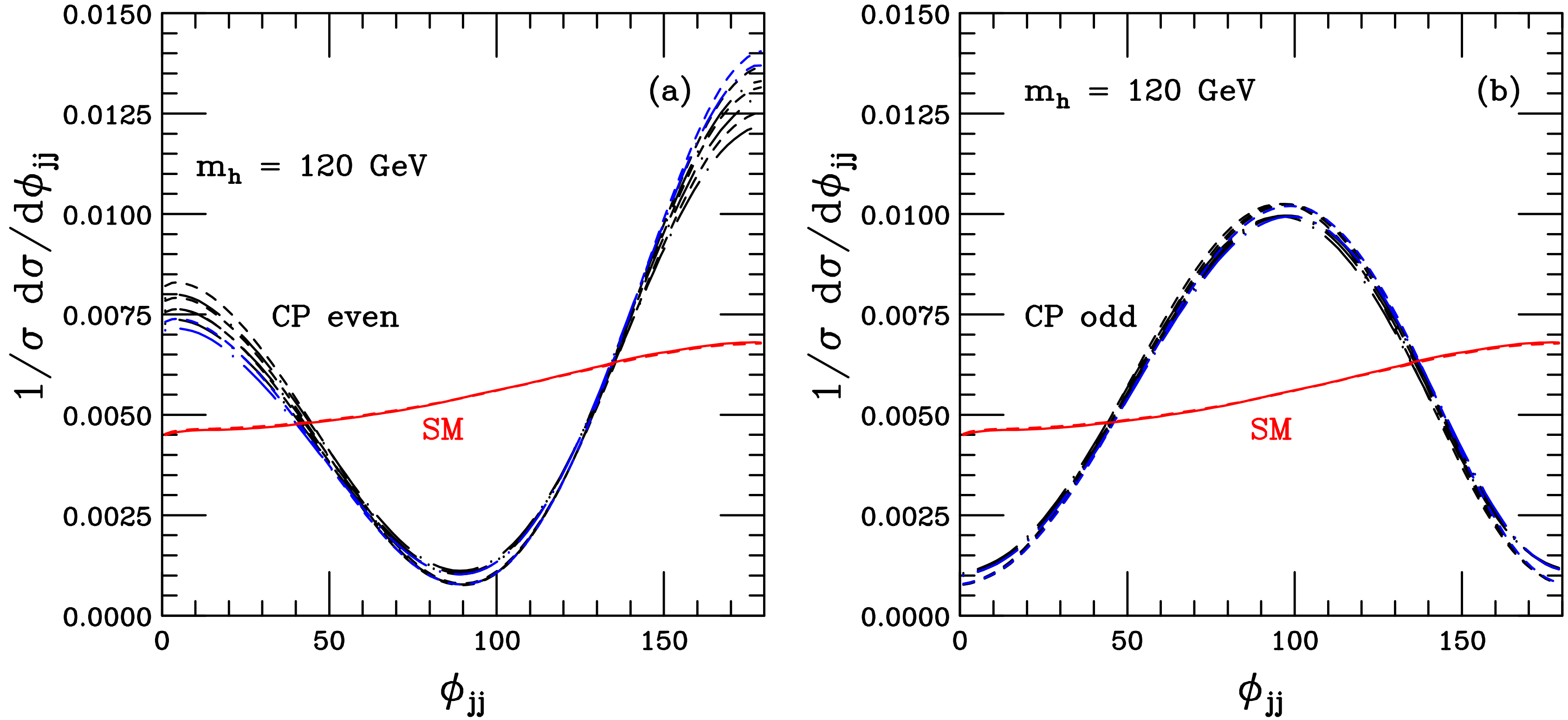
Figy, DZ hep-ph/0403297



- Change in tagging jet p_T distributions is sensitive indicator of anomalous couplings
- Can choose form-factor such as to approximate SM p_T distributions of the two tagging jets

Azimuthal angle correlations

Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of HVV vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

Reweighting factors?

- Replace VBFNLO phase space generator with reader for LHA events for H+2 and H+3 partons
- With some small changes (Franziska Schissler, in progress) VBFNLO can provide the matrix element squared for SM or anomalous coupling case for individual subprocesses. This includes the spin2 resonance case (talk last Friday by Jessica Frank)
- Because of initialization requirements, the SM and each anomalous coupling scenario are best done in individual runs.
- For Higgs production in VBF, NLO QCD virtual effects are vertex corrections only $\Longrightarrow$ constant factor multiplying Born amplitude $\Longrightarrow$ reweighting factors for LO and NLO H+2 parton contributions are identical
- Potential problem: Reweighting factors grow large at high tagging jet p_T for high form factor scales

Signal definition in VV scattering

Problem: heavy Higgs or technirho or .... interferes with continuum electroweak background
How do we take interference into account in our definition of the signal?

Notation:

$\mathcal{M}_X = \mathcal{M}_X(m_X) \sim \frac{s}{v^2}$ Signal amplitude for s-, t- and u-channel exchange of new particle X

$\mathcal{M}_B \sim \frac{-s}{v^2}$ continuum electroweak background amplitude

$\Longrightarrow B = \int d\Phi |\mathcal{M}_B|^2$ or $S = \int d\Phi \left[|\mathcal{M}_X|^2 + 2\mathrm{Re}\mathcal{M}_X\mathcal{M}_B^*\right]$ violate unitarity at large s

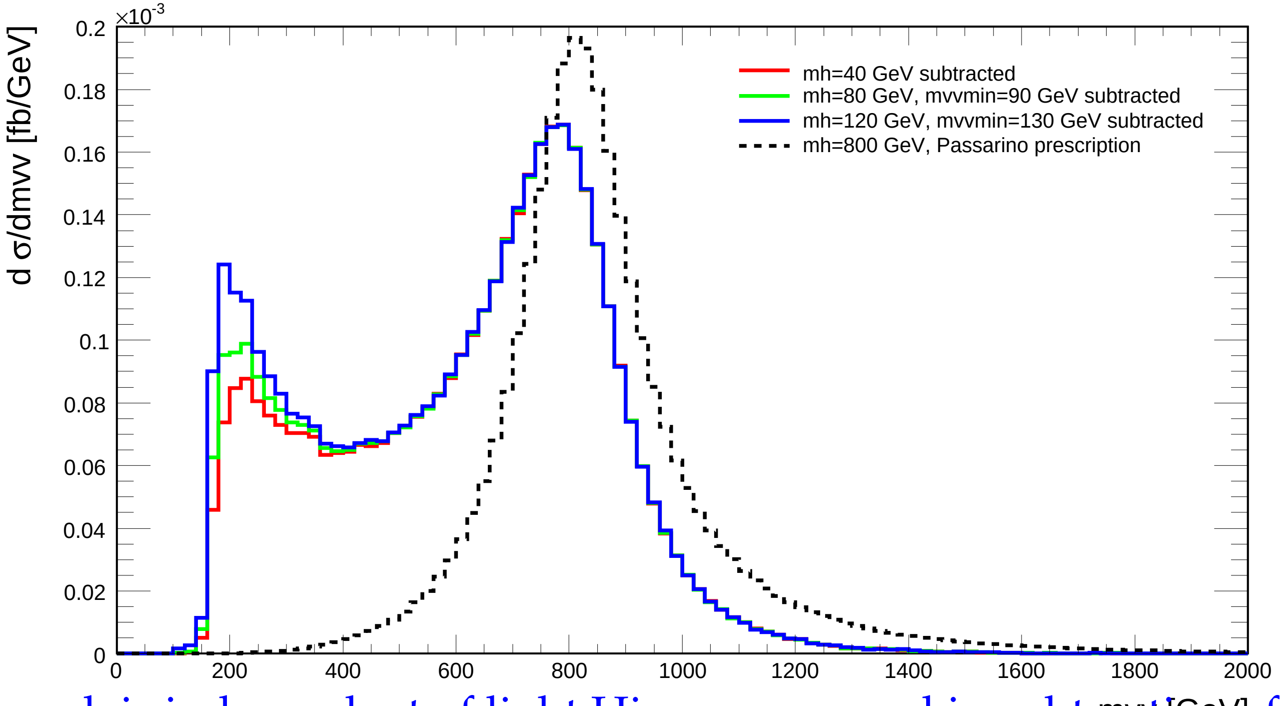
Compare to SM light Higgs scenario with $m_h = 125$ GeV or $m_h = 100$ GeV, i.e. define electroweak background: $B = \int d\Phi |\mathcal{M}_B + \mathcal{M}_h(m_h)|^2$ and
signal: $S = \int d\Phi |\mathcal{M}_B + \mathcal{M}_X(m_X)|^2 - B$
Integrate over suitable mass range $[m_X - \Gamma_1, m_X + \Gamma_2]$

Advantages:

- S and B are well defined and do not violate unitarity
- B is minimized since early onset of cancellations for light Higgs SM are taken into account
- Avoid potentially negative signal cross section due to dominance of (negative) interference terms

Resonance shape for heavy Higgs: LO $WWjj$ case

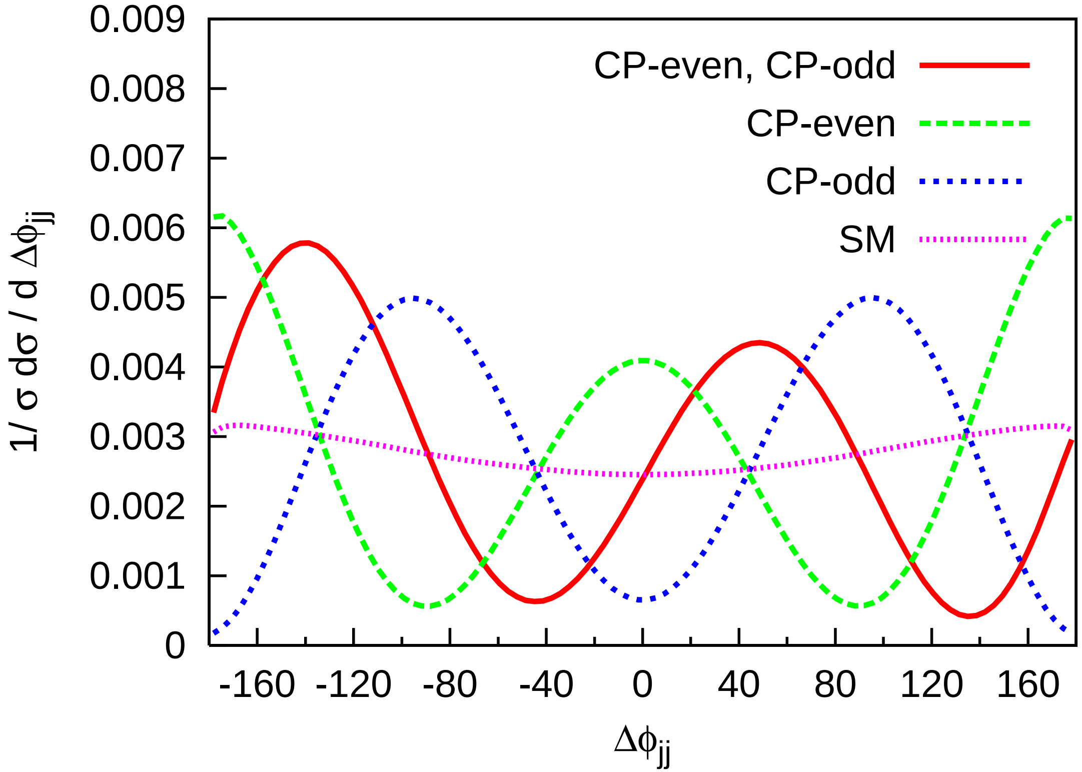
PRELIMINARY



- Resonance peak is independent of light Higgs mass used in subtraction of continuum background
- Some light Higgs mass dependence in threshold region around $m_{WW} = 200$ GeV $\Longrightarrow$ eliminate by cuts
- True resonance shape is not reproduced by modified Breit Wigner distribution

Backup

Signals for CP violation in the Higgs Sector



mixed CP case:
$a_2 = a_3, a_1 = 0$

pure CP-even case:
a_2 only

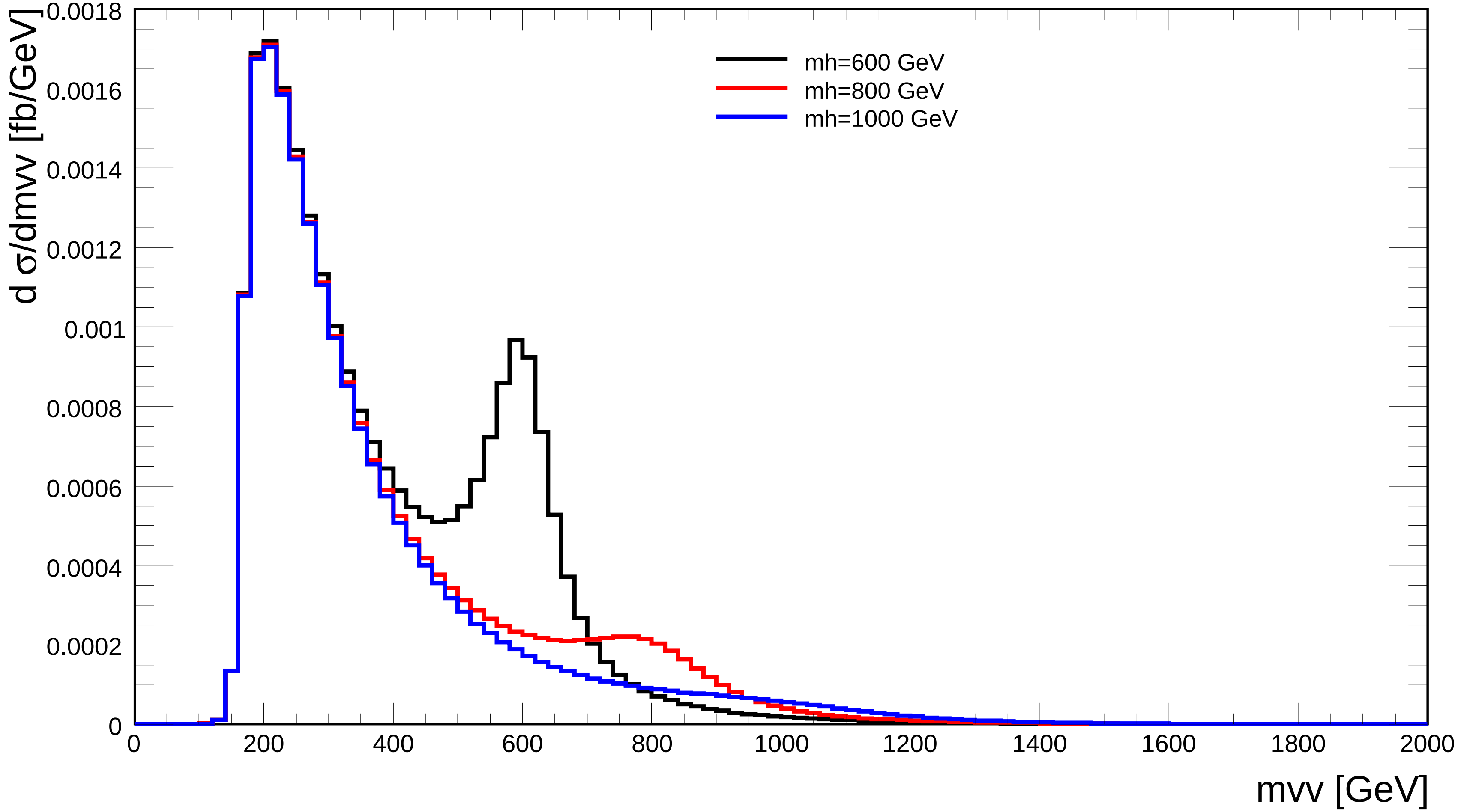
pure CP odd case:
a_3 only

Position of minimum of $\Delta\phi_{jj}$ distribution measures relative size of CP-even and CP-odd couplings. For

$$a_1 = 0, \qquad a_2 = d\ \cos\alpha, \qquad a_3 = d\ \sin\alpha,$$

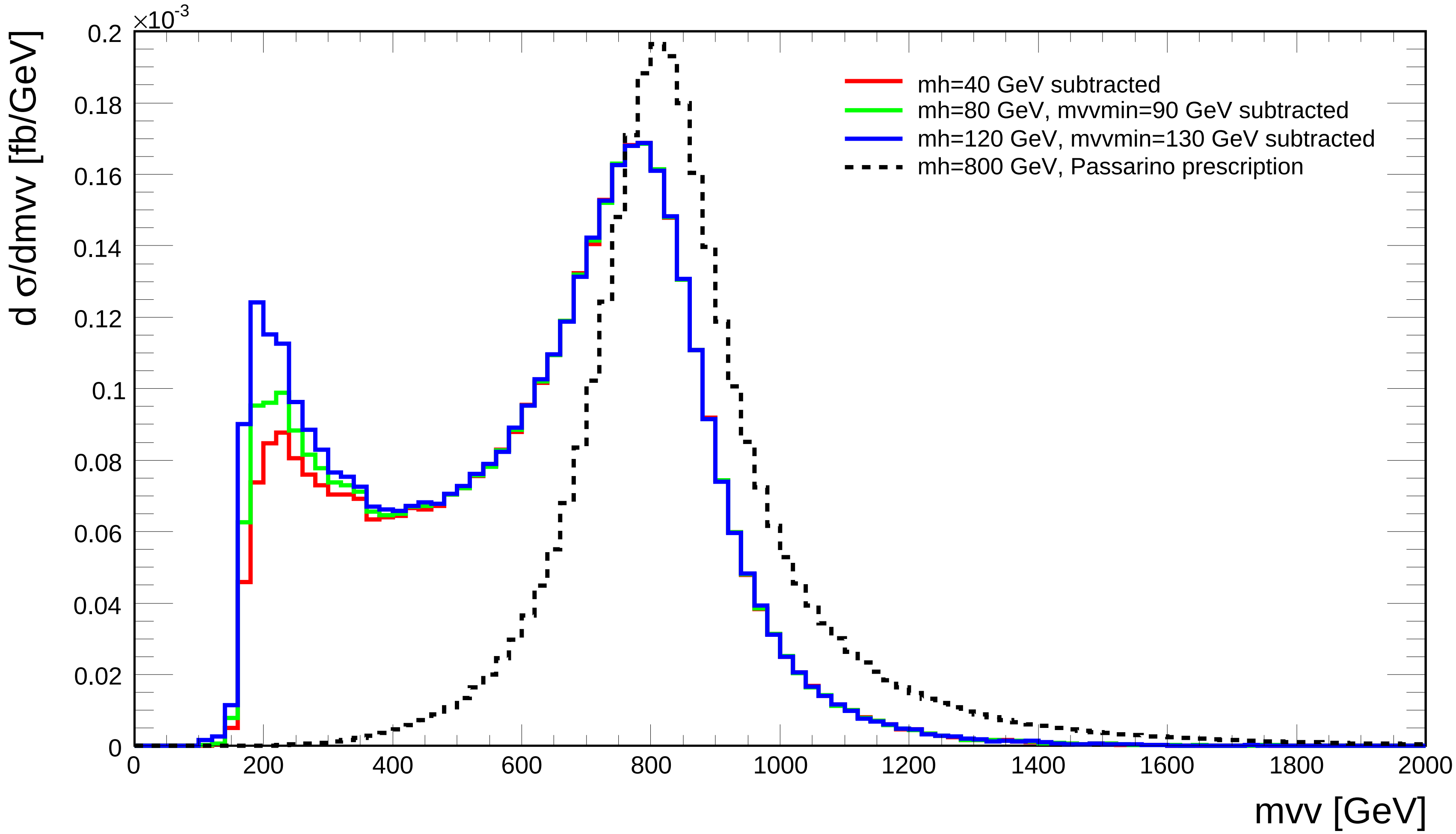
$\Longrightarrow$ Maxima at α and $\alpha \pm \pi$

WW invariant mass distribution: LO $WWjj$ case



Resonance shape for heavy Higgs: LO $WWjj$ case

PRELIMINARY



Resonance shape for heavy Higgs: NLO $WWjj$ case

PRELIMINARY