Karlsruher Institut für Technologie

Spin-2 Resonances in Vector Boson Fusion

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INSTITUT FÜR THEORETISCHE PHYSIK

Outline

Motivation

- Important Higgs detection channel at the LHC:
  Photon pair-production in Vector Boson Fusion
- Spin determination needed, spin-0 or spin-2 possible
- Effective model for the interaction of a spin-2 particle with electroweak bosons
- Implementation into Monte Carlo program VBFNLO
  at NLO QCD
- Goal: Distinguish between SM Higgs and spin-2
  in VBF photon pair-production
- Most powerful tool: Angular distributions

Effective Spin-2 model

- Effective model for the interaction of a spin-2 singlet particle T with electroweak bosons
- Starting from an effective ansatz $\mathcal{L}_{eff} = \sum_i \frac{f_i}{\Lambda} T_{\mu\nu} O_i^{\mu\nu}$ and constructing suitable operators $O_i^{\mu\nu}$ yields:

$$\mathcal{L}_{eff} = \frac{1}{\Lambda} T_{\mu\nu} \left(f_1\, B^{\alpha\nu} B^{\mu}{}_{\alpha} + f_2\, W_i^{\alpha\nu} W^{i\mu}{}_{\alpha} + 2 f_5 \, (D^\mu \Phi)^\dagger (D^\nu \Phi) \right)$$

$\Longrightarrow$ Relevant vertices: TW^+W^-, TZZ, $T\gamma\gamma$ and $T\gamma Z$

- Spin-2 triplet with T^0 and $T^\pm$ also analyzed, yields similar results for VBF photon pair-production
- Formfactor to preserve unitarity:

$$f(q_1^2, q_2^2, p_{sp2}^2) = \left(\frac{\Lambda_{ff}^2}{|q_1^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|q_2^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_{sp2}^2| + \Lambda_{ff}^2} \right)^{n_{ff}}$$

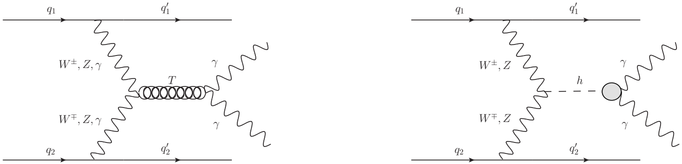
with q_1^2 and q_2^2: invariant masses of the initial electroweak bosons, p_{sp2}^2: invariant mass of a s-channel spin-2 particle

Implementation in VBFNLO (I)

- VBFNLO [Arnold et.al., 2011]
  - Parton-level Monte Carlo program
  - Simulates Vector-Boson-Fusion processes at hadron colliders at NLO QCD
  - Many other processes included, such as double and triple vector boson production
  - BSM physics: MSSM, Three-Site Higgsless model, anomalous couplings, ...
  - Spin-2 implementation will be public with the next release (also for VBF processes with 4 leptons in the final state)

Implementation in VBFNLO (II)

- Comparison of Higgs and spin-2 resonance,
  VBF processes $pp \to T\,jj \to \gamma\gamma jj$ and $pp \to h\,jj \to \gamma\gamma jj$
- Tree-level diagrams:



- Non-resonant Higgs and spin-2 graphs negligible
- SM background omitted
- NLO QCD corrections similar to SM case [Figy, Oleari, Zeppenfeld, 2003]

Input parameters and selection cuts

- pdfs: CTEQ6L1 at LO [Pumplin et.al, 2002], CT10 at NLO [Lai et.al, 2010]
- $\mu_F = \mu_R = Q = \sqrt{|q_{if}^2|}$ (q_{if}: 4-momentum transfer between initial and final-state quarks)
- $m_h = m_{\text{spin-2}} = 130$ GeV
- LHC $E_{cm} = 14$ TeV
- spin-2 parameters: couplings: $f_1 = f_2 = f_5 = 1,\ \Lambda = 20\,\text{TeV}$, formfactor: $\Lambda_{ff} = 400\,\text{GeV},\ n_{ff} = 3$
- cuts:
  - jets: $p_{T,j}^{\text{tag}} > 30\,\text{GeV}$, $|\eta_j| < 4.5$, $\Delta R_{jj} > 0.7$
  - VBF: $\Delta\eta_{jj} > 4$, $\eta_{j1}^{\text{tag}} \times \eta_{j2}^{\text{tag}} < 0$, $m_{jj} > 500\,\text{GeV}$
  - photons: $p_{T,\gamma} > 20\,\text{GeV}$, $|\eta_\gamma| < 2.5$, $\Delta R_{\gamma j} > 0.4$, $\Delta R_{\gamma\gamma} > 0.4$, $\eta_{j1}^{\text{tag}} < \eta_\gamma < \eta_{j2}^{\text{tag}}$

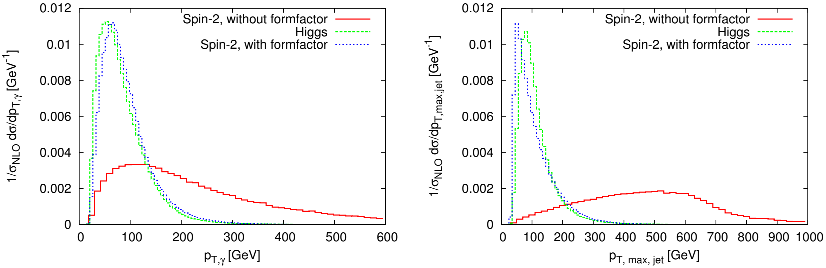
Results

- Total cross section

	LO cross section [fb]	NLO cross section [fb]	$K = \frac{\sigma_{NLO}}{\sigma_{LO}}$
SM Higgs	2.105	2.162	1.027
Spin-2	2.329	2.389	1.026

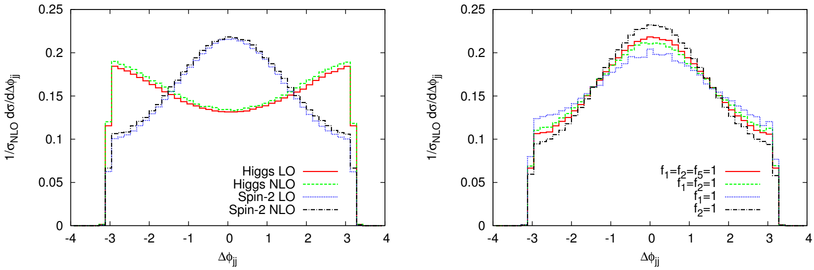
- Very narrow spin-2 resonance: $\Gamma_{\text{spin-2}} \approx 0.02$ MeV
  (Higgs: $\Gamma_h \approx 4$ MeV)
  - Introduction of a branching ratio parameter
    $\Longrightarrow$ quantifies additional, invisible branching modes of spin-2 particle
    $\Longrightarrow$ spin-2 width can be adjusted to the one of the Higgs

Transverse-momentum distributions



- Formfactor: $f(q_1^2, q_2^2, p_{sp2}^2) = \left(\frac{\Lambda_{ff}^2}{|q_1^2|+\Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|q_2^2|+\Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_{sp2}^2|+\Lambda_{ff}^2} \right)^{n_{ff}}$,
  $\Lambda_{ff} = 400\,\text{GeV},\ n_{ff} = 3$
- Spin-2 p_T distributions can be adjusted to those of the Higgs by tuning the formfactor parameters
  $\Longrightarrow p_T$ distributions not sufficient for spin determination

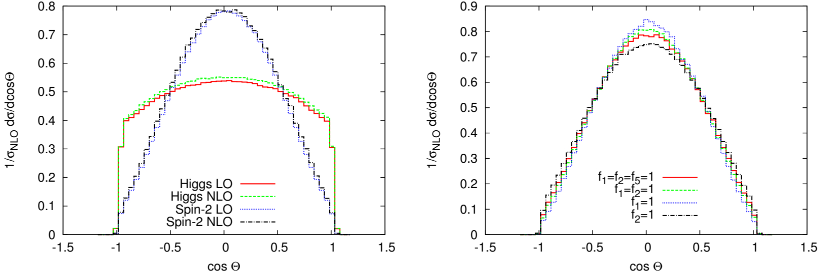
Angular distributions (I): Azimuthal angle difference of the two tagging jets



- Distinct shape for Higgs and spin-2
- Nearly independent of NLO corrections and spin-2 couplings (and formfactor parameters)

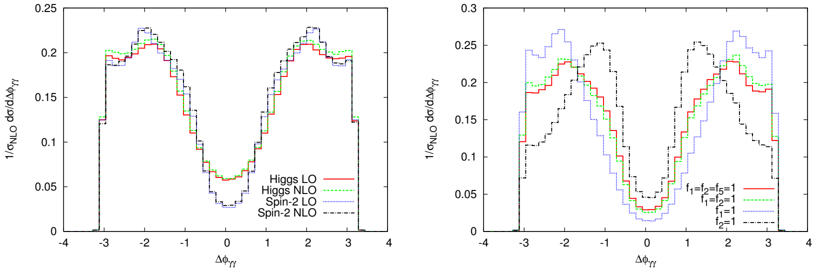
$\Longrightarrow$ Important distribution for spin determination

Angular distributions (II): cos Θ



- Θ: Angle between the momentum of an initial-state electroweak boson and an outgoing photon in the rest frame of the resonance
- Θ-dependence via Wigner *d*-functions $d^{j}_{m,m'}(\Theta)$ [Hagiwara, Li, Mawatari, 2009]
  $\Longrightarrow$ cos Θ distribution is an indicator of the spin
- Analogous distribution: Cosine of the angle between a final-state photon and the first or second tagging jet in the rest frame of the resonance

Angular distributions (III): Azimuthal angle difference of the final-state photons



- No clear difference between Higgs and spin-2
- Dependence on spin-2 couplings and formfactor parameters

$\Longrightarrow$ Additional information about a spin-2 resonance and its parameters

Summary

- Analysis of VBF photon pair-production via a SM Higgs or a spin-2 resonance
- Effective model for the interaction of a spin-2 particle with electroweak bosons
- Implementation into Monte Carlo program VBFNLO at NLO QCD
- Cross section, width and transverse-momentum distributions can be similar for Higgs and spin-2 depending on the spin-2 model parameters
- It is possible to distinguish between a Higgs and a spin-2 resonance via angular distributions:
    - Azimuthal angle difference of the two tagging jets
    - Cosine of the angle between the momentum of an initial electroweak boson and an outgoing photon in the rest frame of the resonance