NLO corrections to gauge-boson scattering at the LHC

Lucia Hošeková in collaboration with A. Denner and T. Motz

Paul Scherrer Institut

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HEPTOOLS

Tools and Precision Calculations for Physics Discoveries at Colliders

1. Motivation
   - Search for a light Higgs boson
   - Study of Electroweak Symmetry Breaking
2. What kinds of diagrams are involved?
3. What has been done so far?
   - Tree-level
   - NLO QCD corrections
4. Our project
   - Block Structure
   - Elements of calculation
   - Monte Carlo and cuts
5. Summary

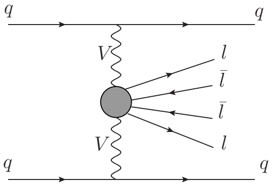
SM Higgs Search

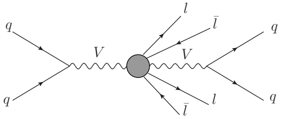
- vector boson fusion (qq → qqH)
    - possible discovery mode for a light SM Higgs boson
    - second largest cross-section for the light Higgs
    - background can be reduced thanks to forward jet tagging and surpressed QCD in the central region
    - relatively low luminosity needed for discovery
- vector boson scattering (qq → qqVV) - background to H → VV decay mode
- precise cross-section required to distinguish the Higgs signal

What if there is no light Higgs?

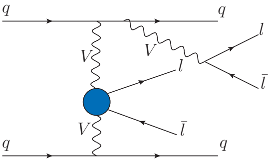
- the scattering of longitudinal W's grows with energy and violates unitarity
- Goldstone boson equivalence theorem - at large energies, longitudinal polarization states of massive bosons become equal to those of corresponding Goldstone bosons
- without Higgs, new mechanism of EW symmetry breaking must be considered
- new physics (composite Higgs, extra dimensions,...) predicts new resonances and modify VBF
- qq $\rightarrow$ qqWW
  - very sensitive channel for probing the new interaction
  - minimizes the background from transversely polarized WW
  - forward jet tagging and energy cuts reduce other background

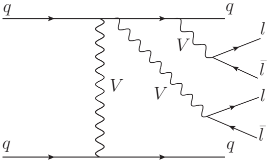
Diagrams - Tree Level

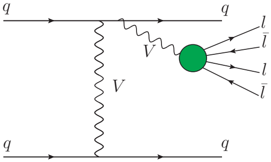




- following types of diagrams have to be included (to preserve gauge invariance)





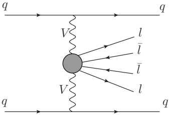


Tree-level studies

- first partial results Cahn, Dawson (1984)
- pp→qqWW in effective gauge boson approximation, only for longitudinal polarization Duncan, Kane, Repko (1986)
- exact calculation of pp→qqWW, all polarizations Dicus, Vega (1986)
- pp→qqZZ, effective gauge boson approximation Abbasabadi, Repko (1988)
- pp→qqZZ→qqllll, narrow width approximation Baur, Glover (1990)
- pp→(qqZW→qqZW)+X, effective gauge boson approximation, longitudinal polarization Dobado, Herrero, Terron (1991)
- pp→qqZW, full tree-level, leptonic decay correlations Barger, Cheung, Han, Stange, Zeppenfeld (1992)
- pp→qqWW - electroweak chiral lagrangian formalism, semileptonic decay Butterworth, Cox, Forshaw (2002)
- pp→qqllll - complete parton level analysis, SM and SILH Ballestrero, Accomando, Bevilacqua, Franzosi, Maina (2006-2010)
- multiple BSM studies for the LHC Han, Krohn, Wang, Zhu (2009), Cheung, Chiang, Yuan (2008)...

Diagrams - NLO QCD Contributions

Virtual corrections



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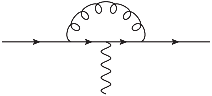

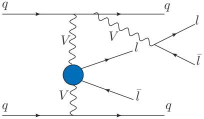

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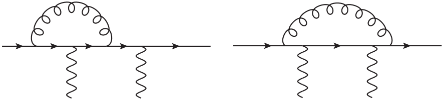

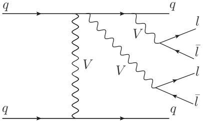

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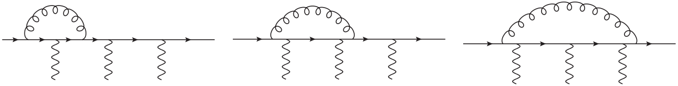
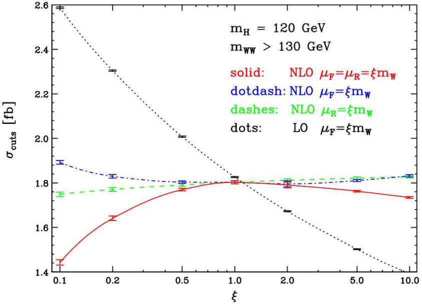
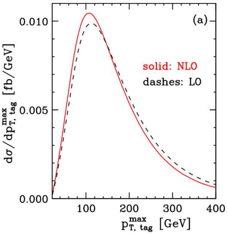


NLO QCD calculation

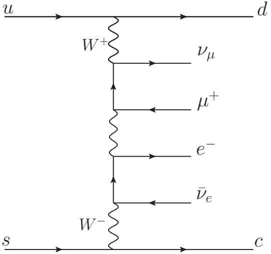
- full tree-level calculation and NLO QCD corrections (real and virtual contributions)
  - 2006 - Jäger, Oleari, Zeppenfeld: $qq \to jjW^+W^- \to jjllll$
  - 2006 - Jäger, Oleari, Zeppenfeld: $qq \to jjZZ \to jjllll$
  - 2007 - Bozzi, Jäger, Oleari, Zeppenfeld: $qq \to jjWZ \to jjllll$
  - 2009 - Jäger, Oleari, Zeppenfeld: $qq \to jjW^\pm W^\pm \to jjllll$





Block structure

- EW and QCD parts are completely independent and can be evaluated separately and reused
- introducing so called "leptonic tensors"
- separating QCD and EW blocks
  - simplifies calculation
  - speeds up Monte Carlo simulations



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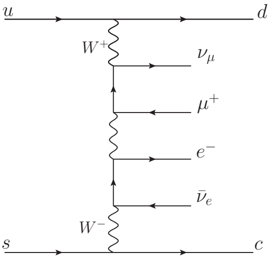

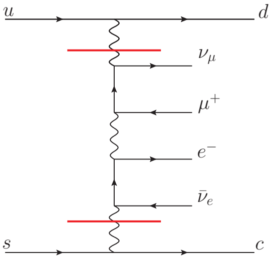

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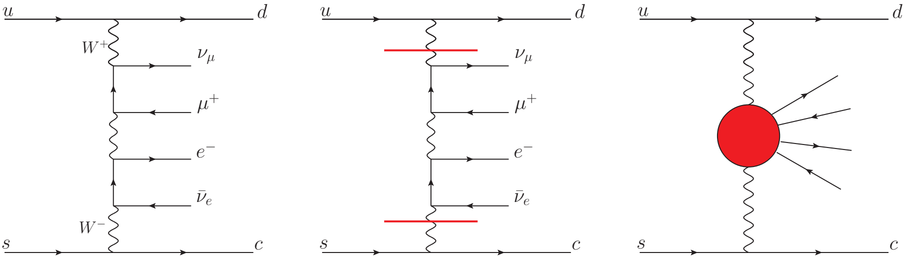
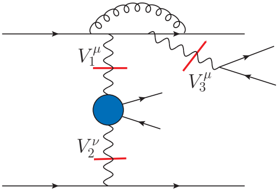


How it works - polarization sums

- relatively small number of building blocks required to construct large number of diagrams

$$\mathcal{M} = \mathcal{M}_{QCD\mu}\mathcal{A}^{\mu} = \mathcal{M}_{QCD\mu}g^{\mu\nu}\mathcal{A}_{\nu} \quad \text{and} \quad g_{\mu\nu} = -\sum_i \varepsilon(k)_{i\mu}\varepsilon(k)_{i\nu} + \frac{k_\mu k_\nu}{k^2}$$

$$\Rightarrow \quad \begin{aligned} \mathcal{M} &= -(\mathcal{M}_{QCD}\cdot\varepsilon_+)(\mathcal{A}\cdot\varepsilon_+) - (\mathcal{M}_{QCD}\cdot\varepsilon_-)(\mathcal{A}\cdot\varepsilon_-) \\ &\quad -(\mathcal{M}_{QCD}\cdot\varepsilon_0)(\mathcal{A}\cdot\varepsilon_0) + \tfrac{1}{k^2}(\mathcal{M}_{QCD}\cdot k)(\mathcal{A}\cdot k) \end{aligned}$$



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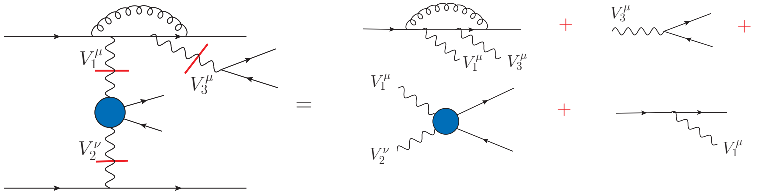

Elements of Calculation

- diagrams generated with FeynArts
  - EW and QCD blocks are generated independently
- analytical expressions generated with FormCalc and modified in Mathematica and exported to Fortran
- Weyl-van-der-Waerden formalism - translates all kinematic objects into two-component WvdW spinors in chiral representation

$$\Psi = \begin{pmatrix} \phi_A \\ \psi^{\dot{A}} \end{pmatrix} \qquad \psi_A \phi^A = (\psi\phi) \quad \psi_{\dot{A}} \phi^{\dot{A}} = \langle\psi\phi\rangle \qquad 2k_\mu p^\mu = (k\,p)\langle k\,p\rangle$$

- s- and u-channel obtained via crossing which amounts to sign reversal of certain spinors

Virtual and radiative corrections

- dipole subtraction

$$\sigma^{NLO} = \int_{m+1} d\sigma^R - \int_{m+1} d\sigma^A + \int_m \left(d\sigma^V + \int_1 d\sigma^A \right)$$

- NLO QCD corrections only needed for the QCD blocks
- external software (Coli) used to perform tensor reduction
- UV singularities are dealt with by generating counterterm blocks
- IR, soft and collinear singularities
  - regularized in dimensional regularization scheme
  - pole structure of the virtual blocks

$$\mathcal{M}_V = \mathcal{M}_B \frac{\alpha_s(\mu_R)}{3\pi} \left(\frac{\mu_R^2}{Q^2} \right)^{\varepsilon} \left(-\frac{2}{\varepsilon^2} - \frac{3}{\varepsilon} \right) + const. + o(\varepsilon)$$

Monte Carlo and cuts

- custom-made multi-channel Monte Carlo is being developed
- choosing proper cuts is essential for distinguishing VBF from the background
- 'typical' VBF cuts include
  - tagging jets - two hard reconstructed jets with $p_T \geq 20$ GeV and large rapidity separation $\triangle y_{jj} > 4$ and invariant mass $M_{jj} > 600$ GeV
  - parallel to the beam (within 1°) - $|\eta_j| < 4.9$
  - separation of jets and leptons $\triangle R_{ll} > 0.2$, $\triangle R_{jl} > 0.4$
  - jets in opposite hemispheres $y_{j1} \times y_{j2} < 0$
  - cuts on invariant masses of the leptons

Progress so far...

- leading order MEs ($qq \rightarrow jj4l$) incl. t-, s- and u-channel and their interferences - completed and compared with MadGraph and FormCalc results
- total LO cross section comparison with existing results (Zeppenfeld, Maina) and general-purpose integrators (MadEvent, SHERPA) in progress
- next-to-leading order - implemented virtual blocks and counterterms, testing pole structure and UV finiteness
- to be done - implementing real corrections MEs and comparison with results of Zeppenfeld et al.

Summary

- vector boson scattering might turn out to be principal for
  - search for a light Higgs at the LHC
  - probing for new strong effects in case of no Higgs is found
- full NLO corrections are fairly complicated (many legs, large number of diagrams) and require modular approach
- despite long history of studies NLO calculations started to emerge only recently (and only QCD corrections)
- our project - first independent verification of Zeppenfeld's calculation, incl. all channels and final states
- possibility of incorporating EW corrections and BSM physics in the future