NLO corrections to gauge-boson scattering at the LHC

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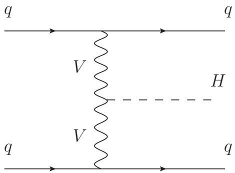
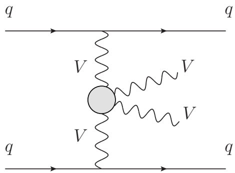
HEPTOOLS

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. My work
   - Why block structure?
   - Elements of calculation
5. Summary

SM Higgs Search



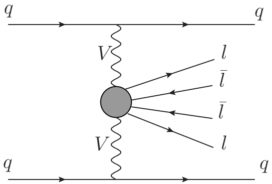


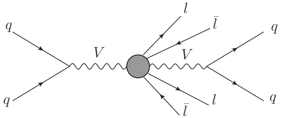
- vector boson fusion (qq → qqH)
  - possible discovery mode for a light SM Higgs boson
  - second largest cross-section for the light Higgs
  - no color exchange between initial quarks
    - background can be reduced thanks to forward jet tagging
    - relatively low luminosity needed for discovery
- 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?

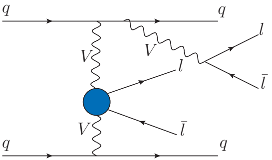
- new mechanism of EW symmetry breaking must be considered
- experiments impose constraints on the new strong dynamics (symmetry, mass scale, dynamics)
- reason to expect strong vector boson scattering
  - new effects preventing unitarity violation
- qq $\rightarrow$ qqWW
  - forward jet tagging and energy cuts reduce other background

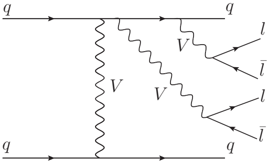
Diagrams - Tree Level

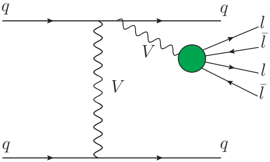




- following types of diagrams have to be included (to preserve gauge invariance)





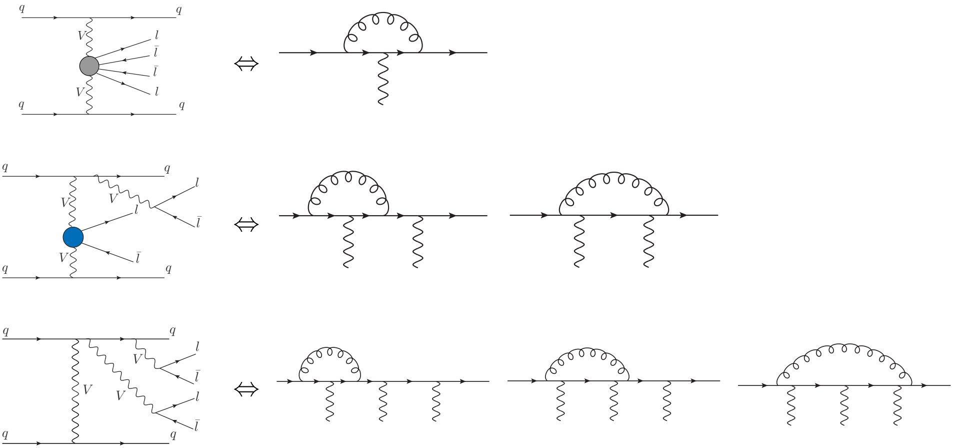


Tree-level studies

- 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)

Diagrams - NLO QCD Contributions

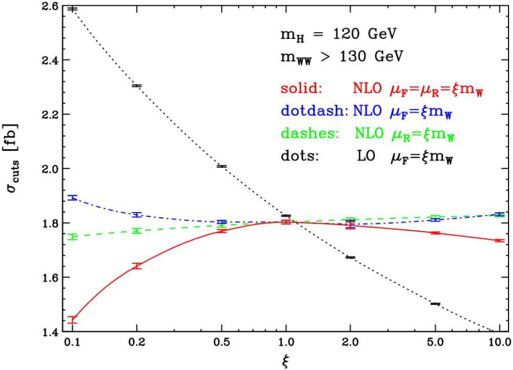
Virtual corrections

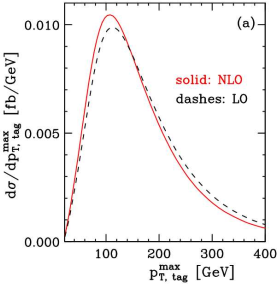


NLO QCD calculation

- full tree-level calculation and NLO QCD corrections (real and virtual contributions)
  - 2006 - Jäger, Oleari, Zeppenfeld: qq $\rightarrow$ jjWW $\rightarrow$ jjllll
  - 2006 - Jäger, Oleari, Zeppenfeld: qq $\rightarrow$ jjZZ $\rightarrow$ jjllll
  - 2007 - Bozzi, Jäger, Oleari, Zeppenfeld: qq $\rightarrow$ jjWZ $\rightarrow$ jjllll
- use of 'leptonic tensors'
  - faster code,
  - possibility to include new EW effects
- s-channel and interference neglected (due to VBF kinematics)
- analytical code in Maple, numerical in Fortran
- Monte Carlo program very fast thanks to modular structure

NLO QCD corrections - results for qq→qqWW

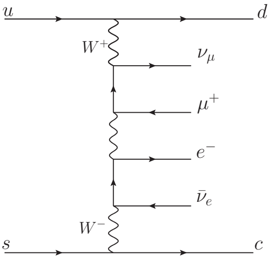




Jäger, Oleari, Zeppenfeld (2006)

Block structure

- EW parts are not affected by QCD corrections and only have to be evaluated once
- separating QCD and EW blocks
  - simplifies calculation
  - speeds up Monte Carlo simulations



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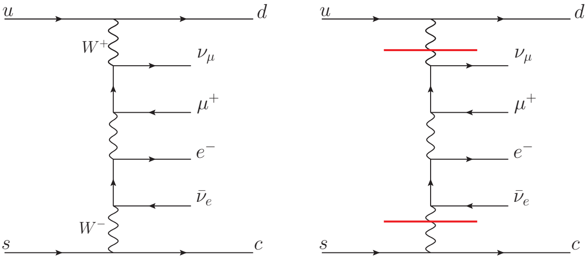

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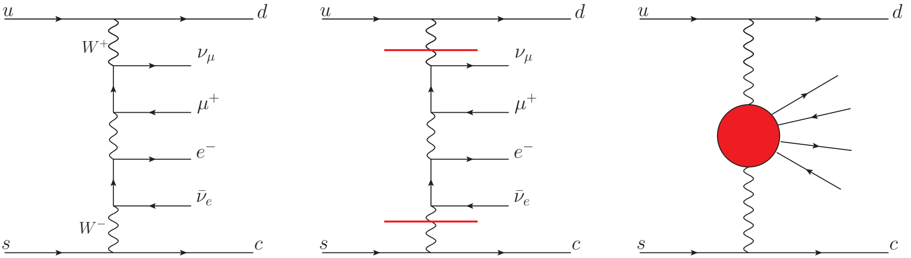
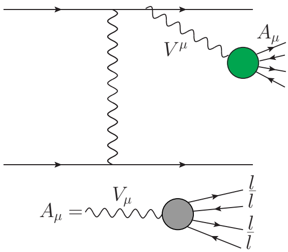


How it works

- example - $\mathcal{A}$-block:

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

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



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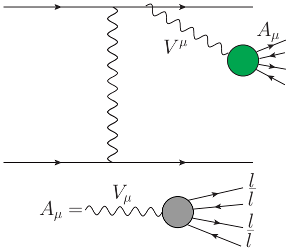

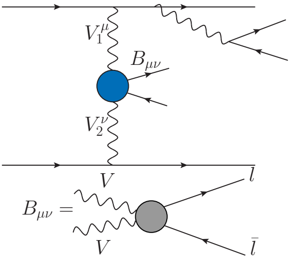

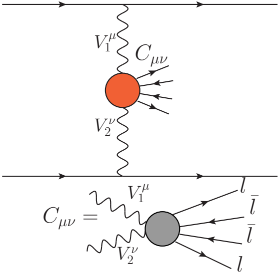

Elements of Calculation

- diagrams generated with FeynArts
  - EW and QCD blocks are generated independently, modified model used to accommodate the modular structure
- analytical expressions generated with FormCalc and modified within Mathematica
- Weyl-van-der-Waerden formalism - translates all kinematic objects into two-component WvdW spinors in chiral representation

$$\Psi = \begin{pmatrix} \phi_A \\ \psi^{\dot{A}} \end{pmatrix} \qquad \psi_A \phi^A = (\psi\phi) \quad \psi_{\dot{A}} \phi^{\dot{A}} = \langle \psi\phi \rangle$$

$$k_\mu \sigma^\mu_{\dot{A}B} = \sum_{i=1,2} \lambda_i n_{i\dot{A}} n_{iB} \qquad 2k_\mu p^\mu = (k\,p)\langle k\,p \rangle \qquad \varepsilon_{\mu+}(k)\sigma^\mu_{\dot{A}B} = \sqrt{2} n_{2,\dot{A}} n_{1,B}$$

1. introducing WvdW spinors

$$\bar{\Psi}(k_2)P_R\gamma^\mu\Psi(k_3) \mapsto k_2^a\sigma^\mu_{a\dot{b}}k_3^{\dot{b}}$$

2. open Lorentz indices contracted (polarization sum)

$$k_2^a\sigma^\mu_{a\dot{b}}k_3^{\dot{b}} \mapsto k_2^a\varepsilon_{\mu+}(k_1)\sigma^\mu_{a\dot{b}}k_3^{\dot{b}}$$

3. scalar products of individual spinors

$$k_2^a\varepsilon_{\mu+}(k_1)\sigma^\mu_{a\dot{b}}k_3^{\dot{b}} \mapsto 2\sqrt{2k_0(2)k_0(3)}\langle n_2(1)n_1(3)\rangle(n_1(1)n_1(2))$$

4. full forms of spinors are introduced

$$(n_1(1)n_1(2)) = (\sin\frac{\theta(1)}{2}, -e^{-\mathrm{i}\Phi(1)}\cos\frac{\theta(1)}{2}).\begin{pmatrix} e^{-\mathrm{i}\Phi(2)}\cos\frac{\theta(2)}{2} \\ \sin\frac{\theta(2)}{2}) \end{pmatrix}$$

5. introducing abbreviations reduces the size of expressions
6. a fully self-contained Fortran program is generated

- Fortran program
  - modular approach (using abbreviations)
  - produces numerical values for $\mathcal{M}^{\mu}_{QCD}\varepsilon_{i\mu}$ and $(\mathcal{A}.\varepsilon_i)$, $(\mathcal{B}.\varepsilon_i)$, $(\mathcal{C}.\varepsilon_i)$
  - independent EW and QCD blocks are "sewn" together
  - input - external momenta and helicities
- outlook
  - verification of the Fortran code by comparison with FormCalc and MadGraph results
  - full QCD NLO corrections with FormCalc - first independent check of the calculation by Zeppenfeld and his group
- development of Monte Carlo program in progress

Summary

- vector boson scattering is essential for
  - search for a light Higgs at the LHC
  - probing for new strong effects in case of no Higgs is found
- long and rich history of studies
- NLO corrections are fairly complicated
  - requires lot of computer power
  - new methods and strategies to cope with the large number of diagrams
- my work
  - constructed the building blocks in Mathematica + FormCalc
  - implemented modular structure in Fortran
  - verification of the code in progress
- future plan - EW corrections