NLO corrections to vector-boson scattering at the LHC

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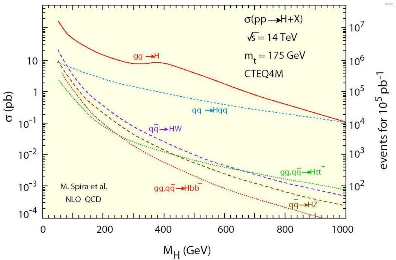
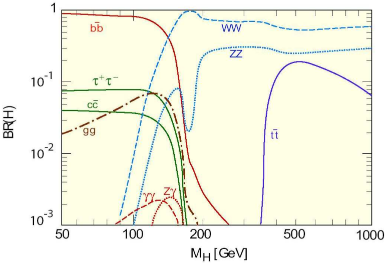
HEPTOOLS

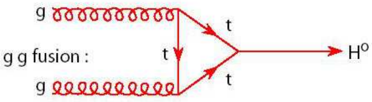
Tools and Precision Calculations for Physics Discoveries at Colliders

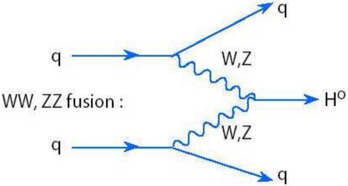
1. Motivation
   - Search for a light Higgs boson
   - Study of Electroweak Symmetry Breaking
2. What kinds of diagrams are involved?
3. What has been done so far?
   - Tree-level
   - NLO QCD corrections
4. Our project
   - Many subprocesses, many diagrams
   - Block Structure
   - Elements of calculation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

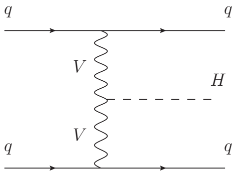
SM Higgs Search

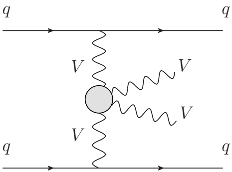








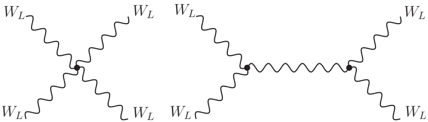




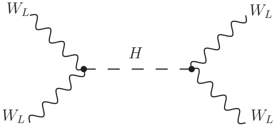
- vector boson fusion (qq $\rightarrow$ qqH)
  - possible discovery mode for a light SM Higgs boson
  - second largest cross-section for the light Higgs
  - statistically significant thanks to forward jet tagging and surpressed QCD in the central region
  - relatively low luminosity needed for discovery
- vector boson scattering (qq $\rightarrow$ qqVV) - background to H $\rightarrow$ VV decay mode via VBF
- VBF can be used to determine Higgs properties and constraint its couplings to gauge bosons

What if there is no light Higgs?

- the scattering of longitudinal W's grows with energy and violates unitarity



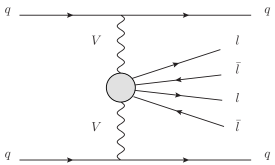
$$\propto g_W^2 \frac{E^2}{M_W^2}$$

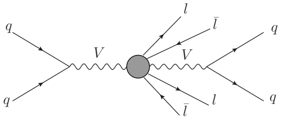


$$\propto -g_W^2 \frac{E^2}{M_W^2}$$

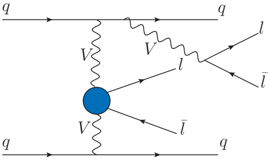
- without Higgs, new mechanism of EW symmetry breaking must be considered
- new physics (composite Higgs, extra dimensions,...) predicts new resonances and modify VBF
- qq $\rightarrow$ qqWW very sensitive channel to new interaction
- minimizes the background from transversely polarized WW

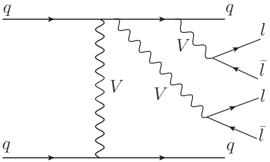
Diagrams - Leading Order

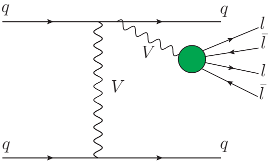




- following types of diagrams have to be included (to preserve gauge invariance)





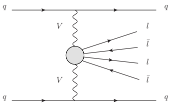


Tree-level studies

- 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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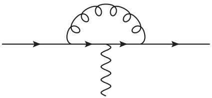

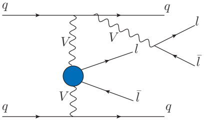

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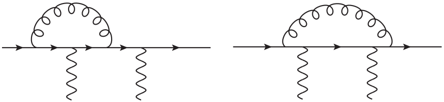

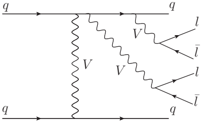

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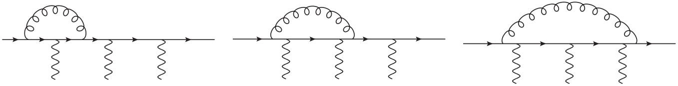
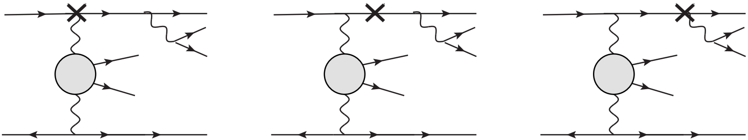


Counterterms



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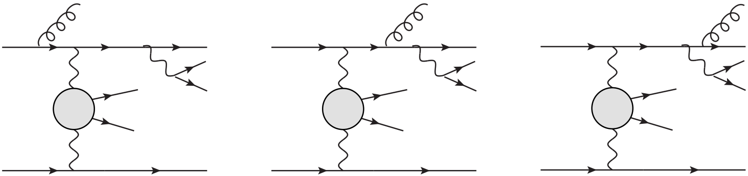
Real corrections



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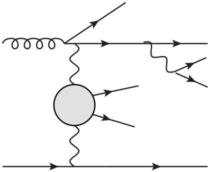
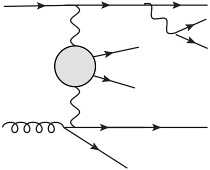
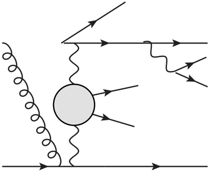
Initial state gluon

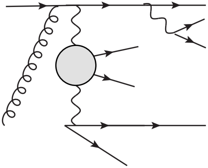
- spacelike gauge bosons





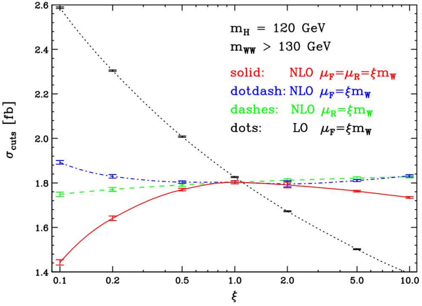
- timelike gauge bosons

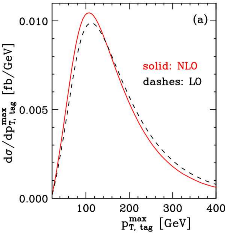




NLO QCD calculation

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





Organizing the Subprocesses

$qq \to qq\ W^+W^+$	$uc \to ds\ e^+\nu_e\mu^+\nu_\mu$	$qq \to qq\ ZZ$	$ds \to ds\ e^+e^-\mu^+\mu^-$
$qq \to qq\ W^-W^-$	$us \to dc\ e^-\bar{\nu}_e\mu^-\bar{\nu}_\mu$		$uc \to uc\ e^+e^-\mu^+\mu^-$
$qq \to qq\ W^+Z$	$uc \to dc\ e^+\nu_e\mu^+\mu^-$		$us \to dc\ e^+e^-\mu^+\mu^-$
	$us \to ds\ e^+\nu_e\mu^+\mu^-$		$us \to us\ e^+e^-\mu^+\mu^-$
$qq \to qq\ W^+W^-$	$ds \to ds\ e^+\nu_e\mu^-\bar{\nu}_\mu$		$ds \to ds\ e^+e^-\nu_\mu\bar{\nu}_\mu$
	$uc \to uc\ e^+\nu_e\mu^-\bar{\nu}_\mu$		$uc \to uc\ e^+e^-\nu_\mu\bar{\nu}_\mu$
	$us \to dc\ e^+\nu_e\mu^-\bar{\nu}_\mu$		$us \to dc\ e^+e^-\nu_\mu\bar{\nu}_\mu$
	$us \to us\ e^+\nu_e\mu^-\bar{\nu}_\mu$		$us \to us\ e^+e^-\nu_\mu\bar{\nu}_\mu$

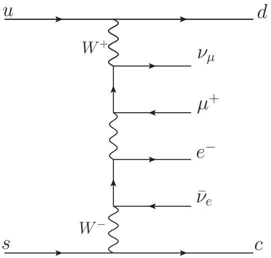
- one subprocess involves between 300 and 2000 Feynman diagrams
- u-channel and s-channel obtained via crossing
- interferences between channels at LO

Example - $uc \to ds\, W^+W^+ \;\to\; ds\, e^+\nu_e\mu^+\nu_\mu$

$QQ \to QQe^\pm\nu_e\mu^\pm\nu_\mu$		$\bar{Q}Q \to \bar{Q}Qe^\pm\nu_e\mu^\pm\nu_\mu$	
$uc \to dse^+\nu_e\mu^+\nu_\mu$	t	$\bar{d}c \to \bar{u}se^+\nu_e\mu^+\nu_\mu$	t
$cu \to dse^+\nu_e\mu^+\nu_\mu$	u	$c\bar{d} \to \bar{u}se^+\nu_e\mu^+\nu_\mu$	u
$uu \to dde^+\nu_e\mu^+\nu_\mu$	$\frac{t+u}{2}$	$\bar{s}u \to \bar{c}de^+\nu_e\mu^+\nu_\mu$	t
$cs \to sse^+\nu_e\mu^+\nu_\mu$	$\frac{t+u}{2}$	$u\bar{s} \to \bar{c}de^+\nu_e\mu^+\nu_\mu$	u
$\bar{Q}\bar{Q} \to \bar{Q}\bar{Q}e^\pm\nu_e\mu^\pm\nu_\mu$		$\bar{d}u \to \bar{u}de^+\nu_e\mu^+\nu_\mu$	$t+s$
$\bar{d}\bar{s} \to \bar{u}\bar{c}e^+\nu_e\mu^+\nu_\mu$	t	$u\bar{d} \to \bar{u}de^+\nu_e\mu^+\nu_\mu$	$t+s$
$\bar{s}\bar{d} \to \bar{u}\bar{c}e^+\nu_e\mu^+\nu_\mu$	u	$\bar{s}c \to \bar{c}se^+\nu_e\mu^+\nu_\mu$	$t+s$
$\bar{d}\bar{d} \to \bar{u}\bar{u}e^+\nu_e\mu^+\nu_\mu$	$\frac{t+u}{2}$	$c\bar{s} \to \bar{c}se^+\nu_e\mu^+\nu_\mu$	$t+s$
$\bar{c}\bar{c} \to \bar{s}\bar{s}e^+\nu_e\mu^+\nu_\mu$	$\frac{t+u}{2}$	$\bar{d}u \to \bar{c}se^+\nu_e\mu^+\nu_\mu$	s
		$u\bar{d} \to \bar{c}se^+\nu_e\mu^+\nu_\mu$	s

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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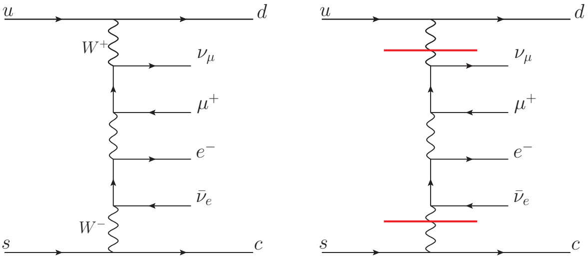

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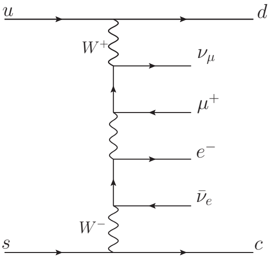
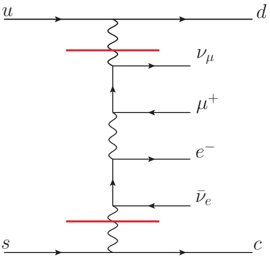
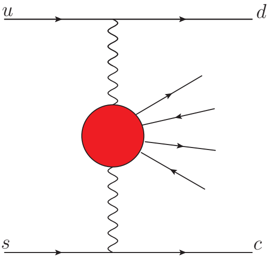




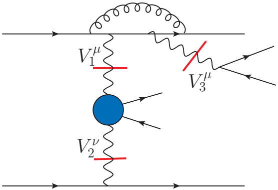


How it works - polarization sums

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

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

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



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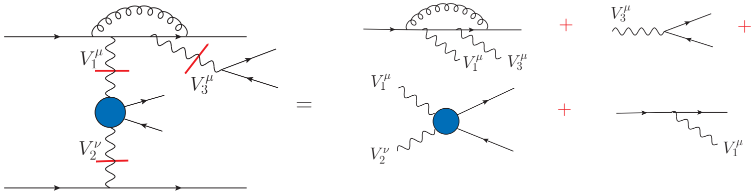

Elements of Calculation

- 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

Dipole subtraction method

$$\sigma = \int_m d\sigma^B + \int_{m+1} d\sigma^R + \int_m d\sigma^V$$

- $d\sigma^B$: Born cross-section - no singularities
- $d\sigma^R$: real cross-section - collinear and soft singularities
- $d\sigma^V$: virtual cross-section - IR singularities
- KLN-theorem: singularities in σ^R and σ^V cancel each other
- analytical integration not possible
- dipole subtraction

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

- $d\sigma^A$: subtraction term containing all IR singularities and analytically integrable over 1-particle phase-space causing collinear and soft singularities

$$\int_{m+1} d\sigma^A = \sum_{dipoles} \int_m d\sigma^{B'} \otimes \int_1 dV_{dipole}$$

- $d\sigma^{B'}$: colour correlated Born matrix elements
- dV_{dipole}: process independent dipole terms implemented in the MC program
- $d\sigma^B$, $d\sigma^R$, $d\sigma^V$, $d\sigma^{B'}$ calculated using helicity formalism
- external software (Coli, LoopTools) used to perform tensor reduction
- UV singularities are dealt with by generating counterterm blocks
- IR, soft and collinear singularities
  - regularized in dimensional regularization (LoopTools, Coli) or mass regularization scheme (Coli)
  - 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, Ballestrero) with different sets of cuts
- LO analysis with and without approximations (s-channel, interferences, mass scheme) in progress
- next-to-leading order - implemented, interfacing with MC and comparison with existing results (Zeppenfeld) in progress
- to be done - gluon exchange at LO

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
- possibility of incorporating EW corrections and BSM physics in the future