Karlsruher Institut für Technologie

NLO QCD corrections to *VVj* and *VVV* production & Higgs + 2*j* via gluon fusion

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INSTITUTE FOR THEORETICAL PHYSICS

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Motivation: *VVV* + *VVj* Production at LHC

- Standard Model background for SUSY processes with multi-lepton + $\not{p}_T$ signature
- Possibility to obtain information about triple and quartic electroweak couplings
- QCD corrections to $pp \to VVj + X, \;\; pp \to VVV + X$ on experimentalist's wishlist: [The QCD,EW,and Higgs Working group: hep-ph/0604120]

Process ($V \in \{Z, W, \gamma\}$	Relevant for
1. $pp \to VV +$ jet	$t\bar{t}H$, new physics
2. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$
3. $pp \to t\bar{t} +$ 2 jet	$t\bar{t}H$
4. $pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$,new physics
5. $pp \to VV +$ 2 jets	VBF $\to H \to VV$
6. $pp \to V +$ 3 jets	various new physics signatures
7. $pp \to VVV$	SUSY trilepton

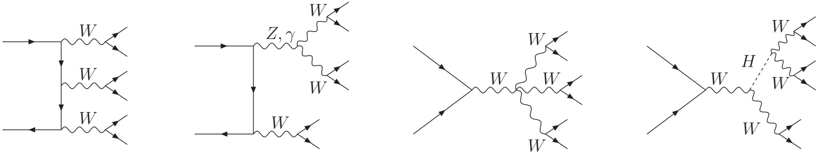
Status of NLO QCD corrections *VVV*

- ZZZ without Higgs-contributions and leptonic decays [Lazopoulos,Menikov,Petriello;hep-ph/0703273]
- $ZZZ, W^+W^-Z, W^+W^+W^-$ and W^+ZZ without Higgs-contributions and leptonic decays [Binoth,Ossola,Papadopoulos,Pittau; arXiv:0804.0350]

In VBFNLO with leptonic decays:

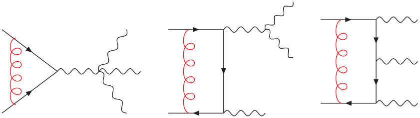
- W^+W^-Z, $W^\pm W^\mp W^\pm$ and $ZZW^\pm$ and Higgs graphs [Hankele,Zeppen -feld;arXiv:0712.3544; FC,Hankele,Oleari,Prestel,Zeppenfeld;arXiv:0809.0790]
- $W^+W^-\gamma$ and $ZZ\gamma$ [Bozzi,FC,Hankele,Zeppenfeld:arXiv:0911.0438]
- $W^\pm Z\gamma$ [Bozzi,FC,Rauch,Rzehak,Zeppenfeld:arXiv:1011.2206]
- $W^\pm\gamma\gamma$ without [Baur, Wackeroth,Weber;arXiv:1001.2688] with leptonic decays [Bozzi,FC,Rauch: In preparation]
- $Z\gamma\gamma(\gamma\gamma\gamma)$ [Bozzi,FC,Rauch: In preparation]

Example: $W^{\pm}W^{\pm}W^{\mp}$ Production



- All resonant and non-resonant matrix elements as well as spin correlations of final state leptons and Higgs contributions included
- Interference terms due to indentical particles in the final state have been neglected (0.1% effect)
- All fermion mass effects neglected($H\tau\tau$-coupling=0): 1% effect

Virtual and Real Corrections

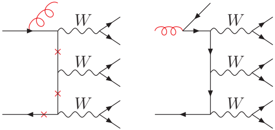


I II III

I Vertex Corrections propor -tional to Born amplitude

II 4-point functions

III Up to 5-point functions (Pentagons)



- Final and initial state gluons
- Hundred of Feynman-graphs
- Soft and collinear singularities subtracted with Catani-Seymour prescription

Loop Integrals: Software in Mathematica to compute up to Hexagons

Input for LHC phenomenology

- PDFs: CTEQ6L1 at LO and CTEQ6M, $\alpha_s(m_z)$ at NLO
- Cuts and Masses:

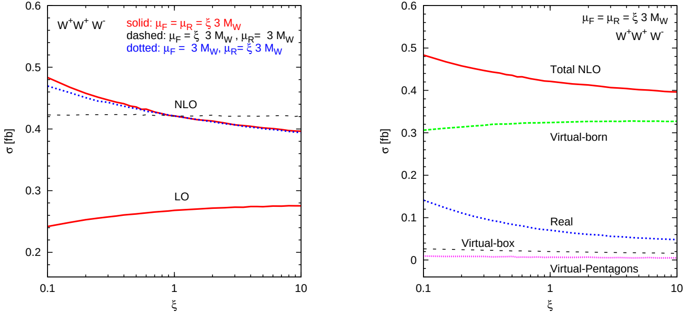
$$p_{T_{l(\gamma)}} > 20(20)\ \mathrm{GeV} \qquad |y_{l(\gamma)}| < 2.5 \qquad R_{l\gamma(j)} > 0.4 \qquad R_{j\gamma} > 0.7$$

$$m_H = 120GeV, \qquad M_W = 80.398GeV, \qquad M_Z = 91.1876GeV$$

$$\sin\theta_W = 0.22264, \qquad \alpha^{-1} = 1/132.3407$$

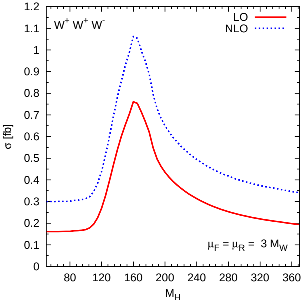
$$G_F = 1.16637 \cdot 10^{-5} GeV^{-2}$$

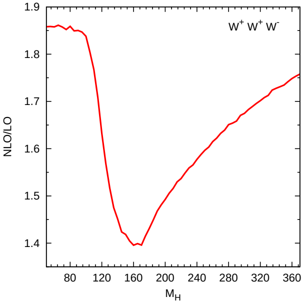
$W^+W^+W^-$ Production



- At LO small μ_F-dependence, no $\alpha_s(\mu_R)$
- At NLO scale dependence is dominated by $\alpha_s(\mu_R)$
- Real emission contribution drives overall scale dependence at NLO (Real + finite collinear + substracted dipole terms)

Higgs Mass dependence

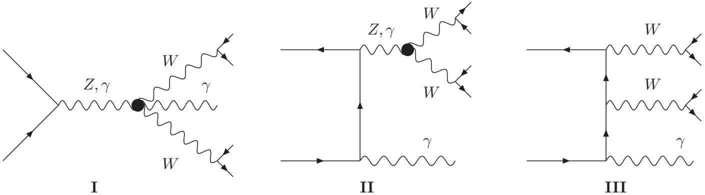




- Cross section reflects behavior of BR($H \rightarrow WW$)
- K-factor is reduced by the H contributions

  $\rightarrow$ K-factor=1.3 for Higgs contributions.

$W^+W^-\gamma$, $ZZ\gamma$ and $W^\pm Z\gamma$ Production



- Different infrared divergences structure of individual loop integrals but same final virtual expression.
- Photon isolation from jets for real emission contributions: use Frixione isolation

$$\Sigma_i E_{T_i}\,\theta(\delta - R_{i\gamma}) \leq p_{T_\gamma}\,\frac{1-\cos\delta}{1-\cos\delta_0} \qquad (\text{for all} \quad \delta \leq \delta_0)$$

- Final state radiation becomes important: adapt phase space

$W^+W^-\gamma$ Production

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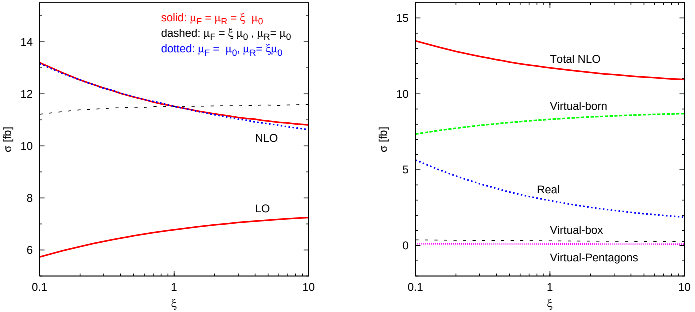
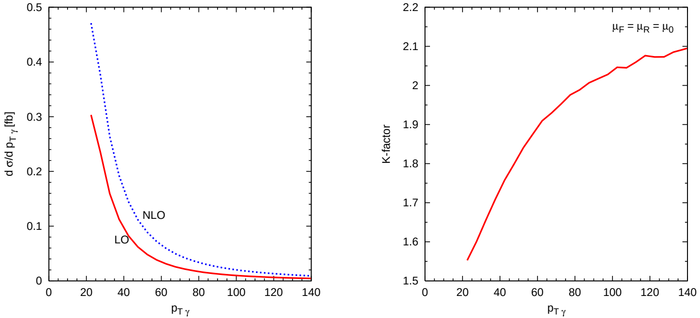
Variation of μ_F, μ_R about $\mu_0 = m_{WW\gamma}$



- LO scale variation smaller that NLO corrections
- NLO scale uncertainty due to real emission contributions

$W^+W^-\gamma$ Production

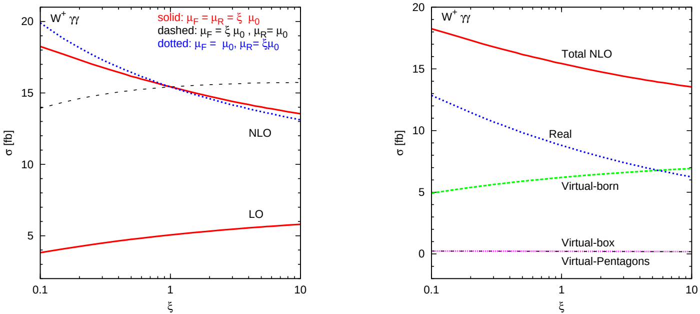


- Strong phase space dependence of K-factor
- No cte factor can be applied to correct the distributions
  - $\longrightarrow$ Devoted MC programs with flexible cut and distributions

VBFNLO at http://www-itp.particle.uni-karlsruhe.de/vbfnlo/

$W^{\pm}\gamma\gamma$ Production

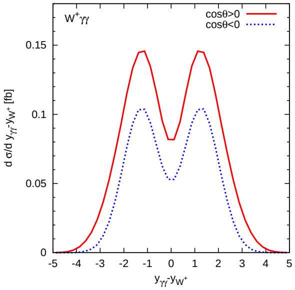
Background to new physics (LSP gravitino). Quartic Couplings

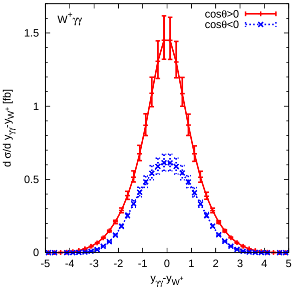


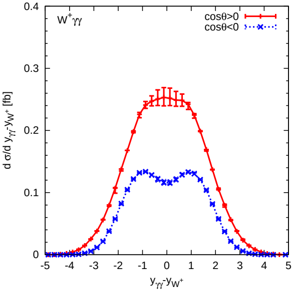
- Large K factor around 3.3!
- Real corrections dominate overall scale uncertainty

$W^{\pm}\gamma\gamma$ Production

LO suppressed by Radiation Zero



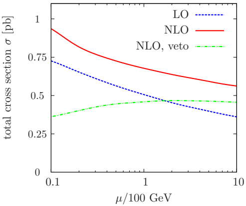


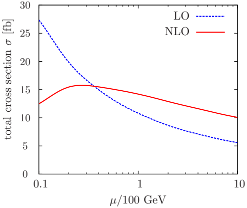


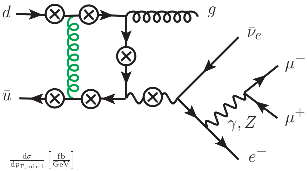
- K-factor in central region around 18
- Additional veto might help to detect Radiation Zero

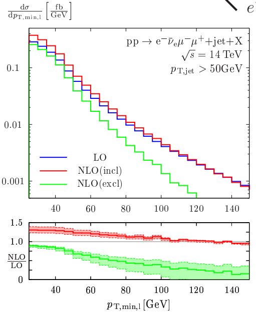
NLO QCD $W\gamma j$ and $W^{\pm}Zj$

- $W^{\pm}\gamma j$ and $W^{\pm}Zj$ affect measurement of triple couplings and are backgrounds to new physics searches.





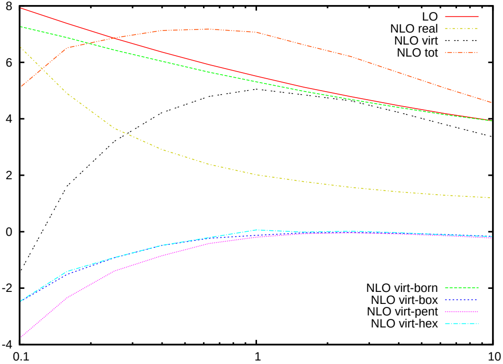




- Tevatron low energy simulates jet veto sample at LHC
- Reduce scale uncertainty of total vetoed sample accidental.

$W^{\pm}\gamma\gamma + j$ Production

Scale uncertainty of LO $W^{\pm}\gamma\gamma j$ dominates in NLO $W^{\pm}\gamma\gamma$



Scale uncertainty slightly improved $\rightarrow$ Improve NLO $W^{\pm}\gamma\gamma$ vetoed samples

Hexagons small but, drives overall statistical uncertainty(3 days of CPU time per point).

First NLO QCD calculation of VVVJ production: [FC,C.Englert,M.Rauch]

Status of $VV + j$ production

- WWj: Dittmaier,Kallweit,Uwer, Phys. Rev. Lett. **100** (2008) 062003, Nucl. Phys. B **826** (2010) 18;
- ZZj: Binoth,Gleisberg,Karg,Kauer,Sanguinetti, Phys. Lett. B **683** (2010) 154;

In VBFNLO with leptonic decays:

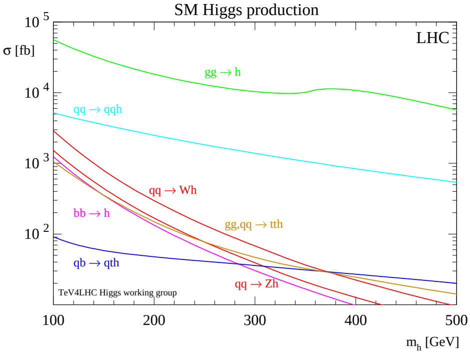
- $W^{\pm}\gamma j$: F.C,Englert,Spannowsky,Zeppenfeld,Europhys. Lett. **88** (2009) 11001;
- $W^{\pm}Zj$:FC,Englert,Kallweit,Spannowsky,Zeppenfeld, JHEP **1007** (2010) 076.
- $Z\gamma j$:F.C,Englert,Spannowsky (In preparation)

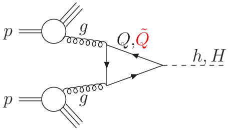
Anomalous dimension at NLO QCD:

- $W^{\pm}Zj$: F.C,Englert,Spannowsky, Phys. Rev. **D82** (2010) 054015.
- $W^{\pm}\gamma j$:F.C,Englert,Spannowsky [arXiv:1010.1291 [hep-ph]].

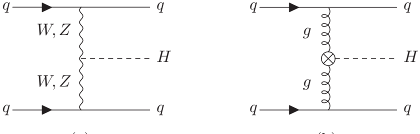
First results for VVVj soon:FC,Englert,Rauch

Gluon Fusion: *H* + 2J





- Measurement of the Htt and effective Hgg couplings

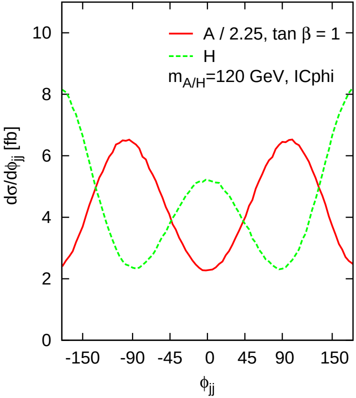


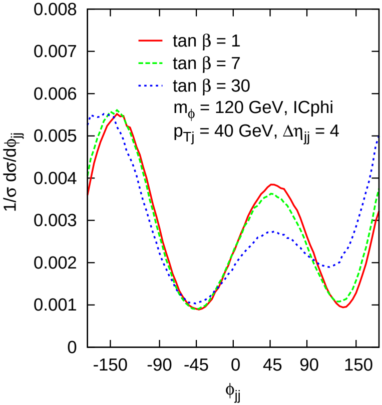
(a) (b)

- Hjj GF background to Hjj WBF
- $gg \rightarrow ggH$, $qq \rightarrow qqH$, $qg \rightarrow qgH$
- As signal: Distinguish between CP-even and CP-odd Higgs

Gluon Fusion: H/A + 2j vs ϕ + 2j

$$\mathcal{L}_{SM} = y_f H\bar{\Psi}\Psi, \quad \mathcal{L}_{=} i\bar{y}_f A\bar{\Psi}\gamma_5\Psi, \quad \mathcal{L} = \tilde{y}_f \Phi\bar{\Psi}(1 + i\gamma_5)\gamma_5\Psi$$





Conclusions

- NLO QCD corrections are large: $30 - 40\%$ for VVj, $40 - 70\%$ for VVV, for $V\gamma\gamma$ 300%
- Scale dependence uncertainty is significantly improved
- Strong phase space dependence

$\rightarrow$ Devoted and flexible MonteCarlo program: VBFNLO

- $W^{\pm}Zj$ production dilutes sensitivity to anomalous couplings in $W^{\pm}Z$ production
- H+jj is a promising channel to investigate the CP properties of the Higgs
  - Next release of VBFNLO: spring 2011 with all VVj, VVV processes and more WBF. Also ϕ jj via gluon fusion with full mass dependence and bottom contributions

http://www-itp.particle.uni-karlsruhe.de/vbfnlo/