NLO QCD corrections for the LHC and Higgs physics

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- Introduction
- NLO QCD corrections within VBFNLO
- Anomalous couplings and effective Lagrangians in Higgs physics and beyond

Introduction/Motivation

- LHC can measure many signal and background processes with many leptons, photons and/or jets with unprecedented precision.
- Matching this precision on the theoretical side requires NLO corrections.
- Many background determinations are made with *data driven techniques*. Background is measured in signal poor region (sideband) and measurement provides correct normalization for calculated cross section. Theory is still needed for extrapolation to signal rich region.
- We have calculated NLO QCD corrections for a variety of cross sections with vector bosons in the final state. Calculations are publicly available within the VBFNLO program package.
  Code can be downloaded from http://www.itp.kit.edu/∼vbfnloweb/

QCD corrections to VBF processes

Precise predictions require QCD corrections

$qq \to qqH$ Han, Valencia, Willenbrock (1992); Figy, Oleari, DZ: hep-ph/0306109; Campbell, Ellis, Berger (2004)

- Higgs coupling measurements

$qq \to qqZ$ and $qq \to qqW$ Oleari, DZ: hep-ph/0310156, Schissler, DZ arXiv:1302.2884

- $Z \to \tau\tau$ as background for $H \to \tau\tau$
- measure central jet veto acceptance at LHC

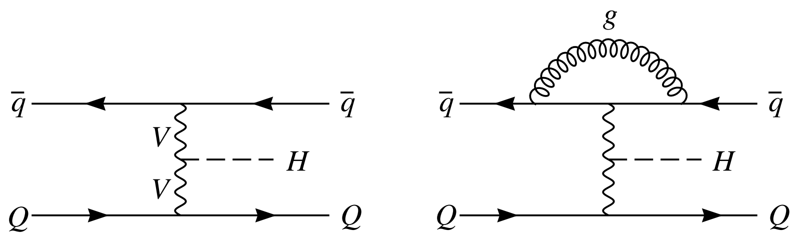
$qq \to qqWW$, $qq \to qqZZ$, $qq \to qqWZ$ Jäger, Oleari, Bozzi, DZ: hep-ph/0603177, hep-ph/0604200, hep-ph/0701105

- $qqWW$ is background to $H \to WW$ in VBF
- underlying process is weak boson scattering:
  $WW \to WW$, $WW \to ZZ$, $WZ \to WZ$ etc.
  $\Longrightarrow$ measure weak boson scattering

Generic features of QCD corrections to VBF

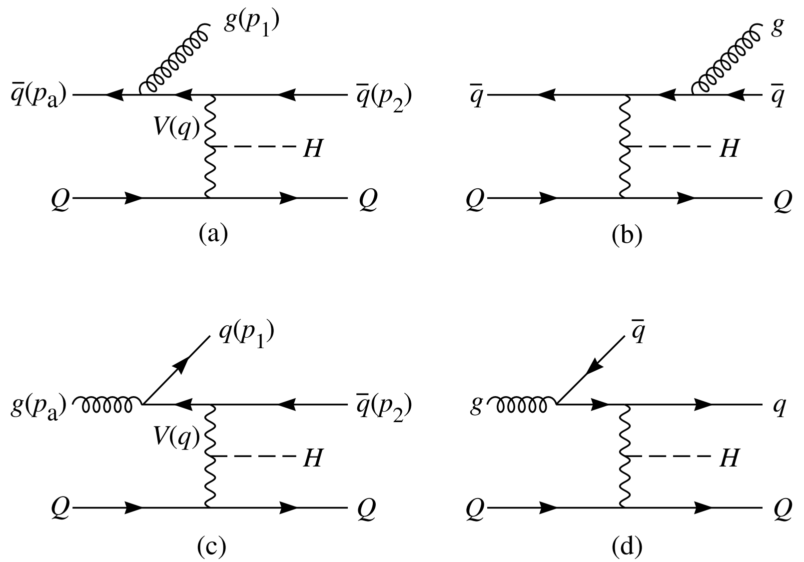
t-channel color singlet exchange $\Longrightarrow$ QCD corrections to different quark lines are independent

Born and vertex corrections to upper line



No *t*-channel gluon exchange at NLO

real emission contributions: upper line



Features are generic for all VBF processes

Real emission

Calculation is done using Catani-Seymour subtraction method

Consider $q(p_a)Q \to g(p_1)q(p_2)QH$. Subtracted real emission term

$$|\mathcal{M}_{\rm emit}|^2 - 8\pi\alpha_s \frac{C_F}{Q^2}\frac{x^2+z^2}{(1-x)(1-z)}|\mathcal{M}_{\rm Born}|^2 \qquad \text{with } 1-x = \frac{p_1\cdot p_2}{(p_1+p_2)\cdot p_a},\quad 1-z = \frac{p_1\cdot p_a}{(p_1+p_2)\cdot p_a}$$

is integrable $\Longrightarrow$ do by Monte Carlo

Integral of subtracted term over $d^{3-2\varepsilon}\mathbf{p}_1$ can be done analytically and gives

$$\frac{\alpha_s}{2\pi}C_F\left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon}\Gamma(1+\epsilon)|\mathcal{M}_{\rm Born}|^2\left[\frac{2}{\epsilon^2}+\frac{3}{\epsilon}+9-\frac{4}{3}\pi^2\right]\delta(1-x)$$

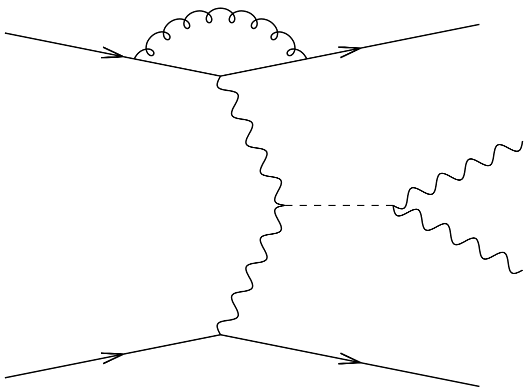
after factorization of splitting function terms (yielding additional "finite collinear terms")

The divergence must be canceled by virtual corrections for all VBF processes

only variation: meaning of Born amplitude $\mathcal{M}_{\rm Born}$

Higgs production

Most trivial case: Higgs production
Virtual correction is vertex correction only



virtual amplitude proportional to Born

$$\mathcal{M}_V = \mathcal{M}_{\text{Born}} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7\right] + \mathcal{O}(\epsilon)$$

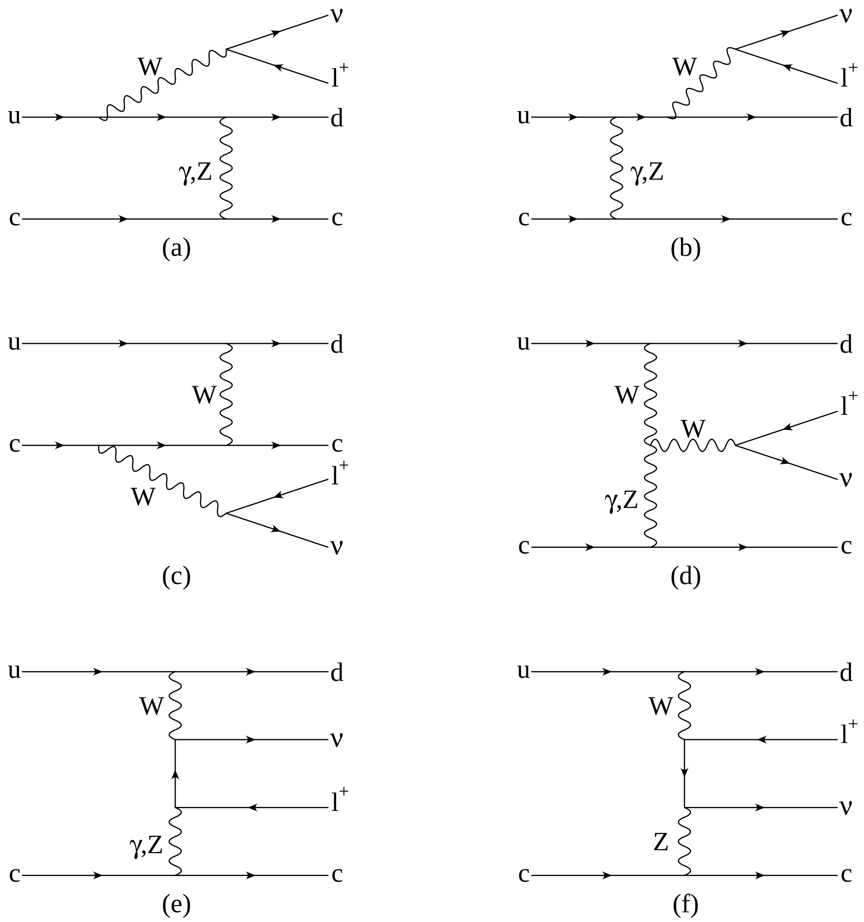
- Divergent piece canceled via Catani Seymour algorithm

Remaining virtual corrections are accounted for by trivial factor multiplying Born cross section

$$|\mathcal{M}_{\text{Born}}|^2 \left(1 + 2\alpha_s \frac{C_F}{2\pi} c_{\text{virt}}\right)$$

- Factor 2 for corrections to upper and lower quark line
- Same factor to Born cross section absorbs most of the virtual corrections for other VBF processes

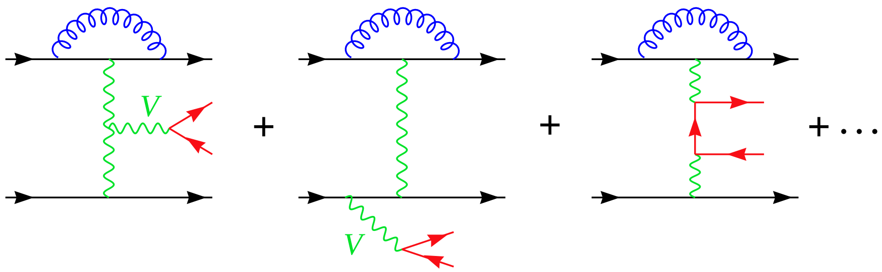
W and Z production



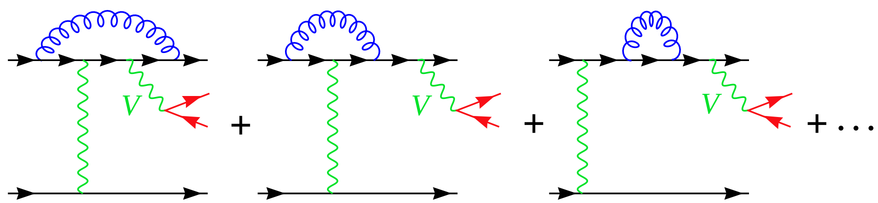
- $10 \cdots 24$ Feynman graphs
- ⇒ use amplitude techniques, i.e. numerical evaluation of helicity amplitudes
- However: numerical evaluation works in d=4 dimensions only

Virtual contributions

Vertex corrections: same as for Higgs case



New: Box type graphs (plus gauge related diagrams)



For each individual pure vertex graph $\mathcal{M}^{(i)}$ the vertex correction is proportional to the corresponding Born graph

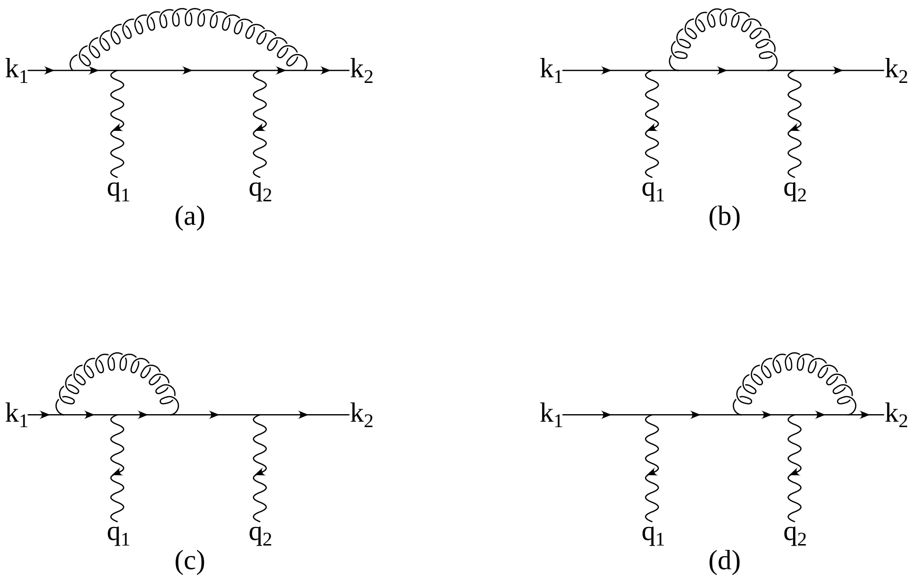
$$\mathcal{M}_V^{(i)} = \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^\epsilon \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7\right]$$

Vector boson propagators plus attached quark currents are effective polarization vectors

build a program to calculate the finite part of the sum of the graphs

Boxline corrections

Virtual corrections for quark line with 2 EW gauge bosons



The external vector bosons correspond to $V \to l_1 \bar{l}_2$ decay currents or quark currents

Divergent terms in 4 Feynman graphs combine to multiple of corresponding Born graph

$$\mathcal{M}^{(i)}_{\text{boxline}} = \mathcal{M}^{(i)}_{B} F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7 \right]$$

$$+ \frac{\alpha_s(\mu_R)}{4\pi} C_F \widetilde{\mathcal{M}}_\tau(q_1, q_2)(-e^2) g_\tau^{V_1 f_1} g_\tau^{V_2 f_2}$$

$$+ \mathcal{O}(\epsilon)$$

with $F(Q) = \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^\epsilon \Gamma(1+\epsilon)$

$\widetilde{\mathcal{M}}_\tau(q_1, q_2) = \widetilde{\mathcal{M}}_{\mu\nu} \epsilon_1^\mu \epsilon_2^\nu$ is universal virtual $qqVV$ amplitude: use like HELAS calls in MadGraph

Handling of IR and collinear divergences

Use tensor decomposition a la Passarino-Veltman

Split $B_0 \quad \cdots \quad D_{ij}$ functions into divergent and finite parts

With $s = (q_1 + q_2)^2$, $t = (k_2 + q_2)^2 = (k_1 - q_1)^2$ we get, for example,

$$
\begin{aligned}
B_0(q^2) &= \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left[\frac{1}{\epsilon} + 2 - \ln\frac{q^2 + i0^+}{s} + \mathcal{O}(\epsilon)\right] \\
&= \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left[\frac{1}{\epsilon} + \widetilde{B}_0(q^2) + \mathcal{O}(\epsilon)\right] \\
D_0(k_2, q_2, q_1) &= \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left[\frac{1}{st}\left(\frac{1}{\epsilon^2} + \frac{1}{\epsilon}\ln\frac{q_1^2 q_2^2}{t^2}\right) + \widetilde{D}_0(k_2, q_2, q_1) + \mathcal{O}(\epsilon)\right] \\
D^{\mu\nu}(k_2, q_2, q_1) &= \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left(\frac{1}{\epsilon}\left(k_1^\mu k_1^\nu d_2(q_1^2, t) + k_2^\mu k_2^\nu d_2(q_2^2, t)\right) + \widetilde{D}^{\mu\nu}(k_2, q_2, q_1) + \mathcal{O}(\epsilon)\right)
\end{aligned}
$$

with $d_2(q^2, t) = 1/(s(q^2 - t)^2)\ [t \ln(q^2/t) - (q^2 - t)]$

Finite $\widetilde{D}_{ij}$ have standard PV recursion relations $\Longrightarrow$ determine them numerically

Virtual corrections

Born sub-amplitude is multiplied by same factor as found for pure vertex corrections
$\Rightarrow$ when summing all Feynman graphs the divergent terms multiply the complete $\mathcal{M}_B$

Complete virtual corrections

$$\mathcal{M}_V \quad = \quad \mathcal{M}_B \;\; F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{4\pi^2}{3} - 8 \right] + \widetilde{\mathcal{M}}_V$$

where $\widetilde{\mathcal{M}}_V$ is finite, and is calculated with amplitude techniques.
The interference contribution in the cross-section calculation is then given by

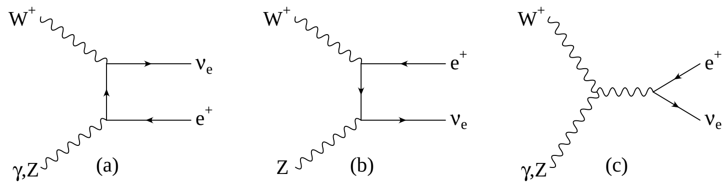
$$2\,\mathrm{Re}\,[\mathcal{M}_V \mathcal{M}_B^*] = |\mathcal{M}_B|^2 F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{4\pi^2}{3} - 8 \right] \; + 2\,\mathrm{Re}\left[\widetilde{\mathcal{M}}_V \mathcal{M}_B^* \right]$$

The divergent term, proportional to $|\mathcal{M}_B|^2$, cancels against the subtraction terms
just like in the Higgs case.

3 weak bosons on a quark line: $qq \to qqWW$, $qqZZ$, $qqWZ$ at NLO

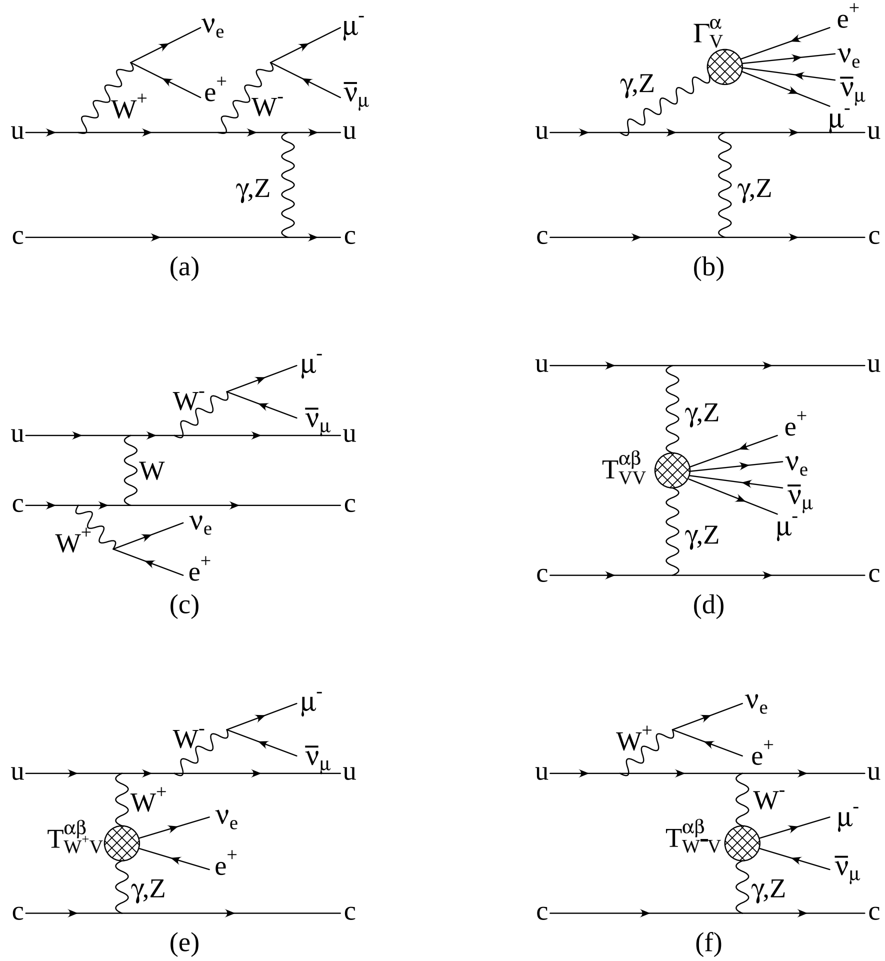
- example: WW production via VBF with leptonic decays: $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\Longrightarrow$ 181 Feynman diagrams at LO
- CC $\Longrightarrow$ 92 Feynman diagrams at LO

Use modular structure, e.g. leptonic tensor



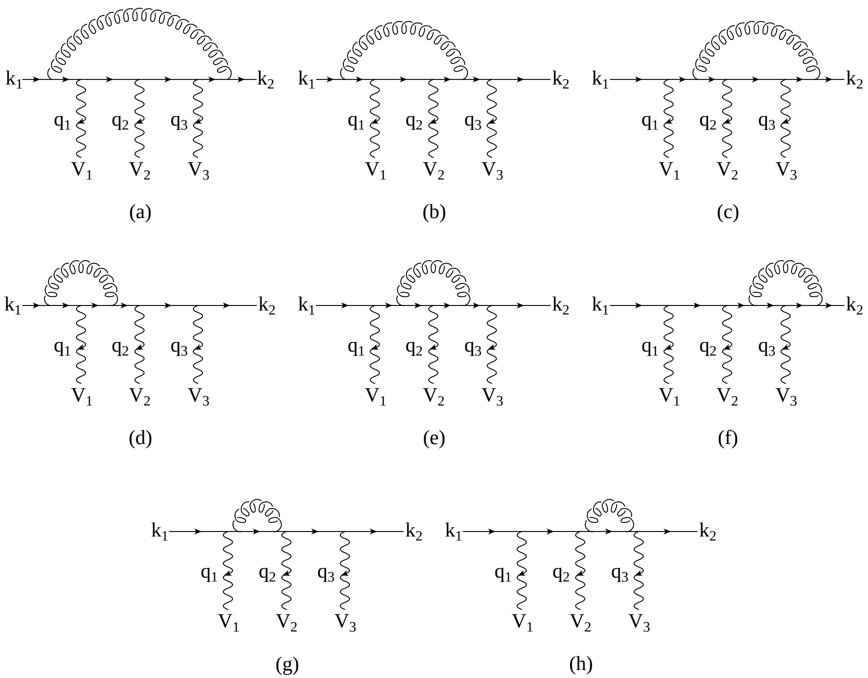
Calculate once, reuse in different processes

Speedup factor ≈ 70 compared to 2005 version of MadGraph for real emission corrections



New for virtual: penline corrections

Virtual corrections involve up to pentagons



The external vector bosons correspond to $V \to l_1 \bar{l}_2$ decay currents or quark currents

The sum of all QCD corrections to a single quark line is simple

$$\mathcal{M}_V^{(i)} = \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\text{virt}}\right] + \widetilde{\mathcal{M}}_{V_1V_2V_3,\tau}^{(i)}(q_1,q_2,q_3) + \mathcal{O}(\epsilon)$$

- Divergent pieces sum to Born amplitude: canceled via Catani Seymour algorithm
- Use amplitude techniques to calculate finite remainder of virtual amplitudes

Pentagon tensor reduction with Denner-Dittmaier is stable at 0.1% level

Gauge invariance tests

Numerical problems flagged by gauge invariance test: use Ward identities for penline and boxline contributions

$$q_2^{\mu_2}\widetilde{\mathcal{E}}_{\mu_1\mu_2\mu_3}(k_1,q_1,q_2,q_3) = \widetilde{\mathcal{D}}_{\mu_1\mu_3}(k_1,q_1,q_2+q_3) - \widetilde{\mathcal{D}}_{\mu_1\mu_3}(k_1,q_1+q_2,q_3)$$

With Denner-Dittmaier recursion relations for E_{ij} functions the ratios of the two expressions agree with unity (to 10% or better) at more than 99.8% of all phase space points.

Ward identities reduce importance of computationally slow pentagon contributions when contracting with $W^{\pm}$ polarization vectors

$$J_{\pm}^{\mu} = x_{\pm}\, q_{\pm}^{\mu} + r_{\pm}^{\mu}$$

choose $x_{\pm}$ such as to minimize pentagon contribution from remainders $r_{\pm}$ in all terms like

$$J_{+}^{\mu_1} J_{-}^{\mu_2}\widetilde{\mathcal{E}}_{\mu_1\mu_2\mu_3}(k_1,q_+,q_-,q_0) = r_{+}^{\mu_1}\, r_{-}^{\mu_2}\,\widetilde{\mathcal{E}}_{\mu_1\mu_2\mu_3}(k_1,q_+,q_-,q_0) + \text{box contributions}$$

Resulting true pentagon piece contributes to the cross section at permille level $\Longrightarrow$ totally negligible for phenomenology

Phenomenology

Study LHC cross sections within typical VBF cuts

- Identify two or more jets with k_T-algorithm ($D = 0.8$)

$$p_{Tj} \geq 20 \text{ GeV}, \qquad |y_j| \leq 4.5$$

- Identify two highest p_T jets as tagging jets with wide rapidity separation and large dijet invariant mass

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4, \qquad M_{jj} > 600 \text{ GeV}$$

- Charged decay leptons ($\ell = e,\ \mu$) of W and/or Z must satisfy

$$p_{T\ell} \geq 20 \text{ GeV}, \qquad |\eta_\ell| \leq 2.5, \qquad \triangle R_{j\ell} \geq 0.4,$$
$$m_{\ell\ell} \geq 15 \text{ GeV}, \qquad \triangle R_{\ell\ell} \geq 0.2$$

and leptons must lie between the tagging jets

$$y_{j,min} < \eta_\ell < y_{j,max}$$

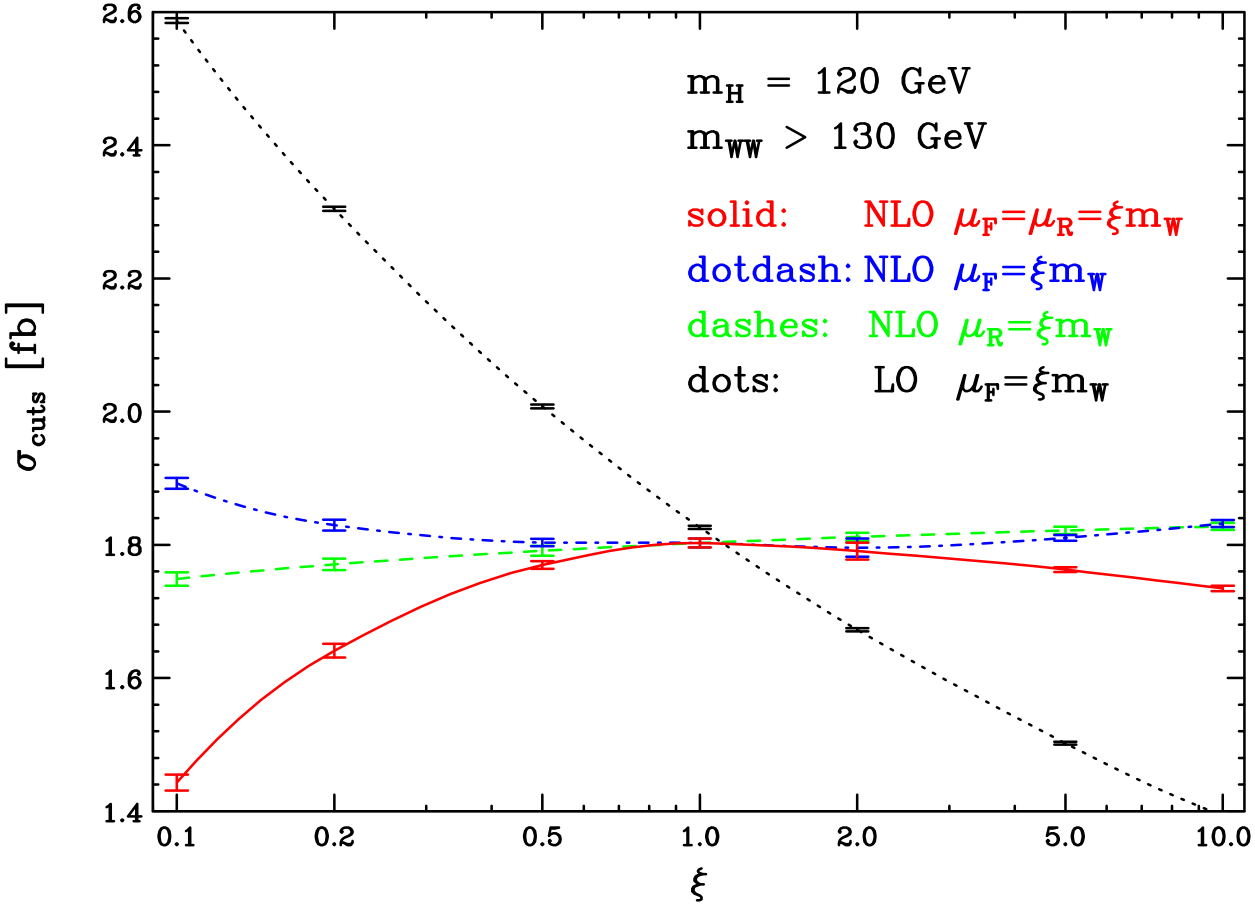
For scale dependence studies we have considered

$\mu = \xi\ m_V$ fixed scale $\qquad$ $\mu = \xi\ Q_i$ weak boson virtuality : $Q_i^2 = 2k_{q_1} \cdot k_{q_2}$

WW production: $pp \to jje^+\nu_e\mu^-\bar{\nu}_\mu X$ @ LHC

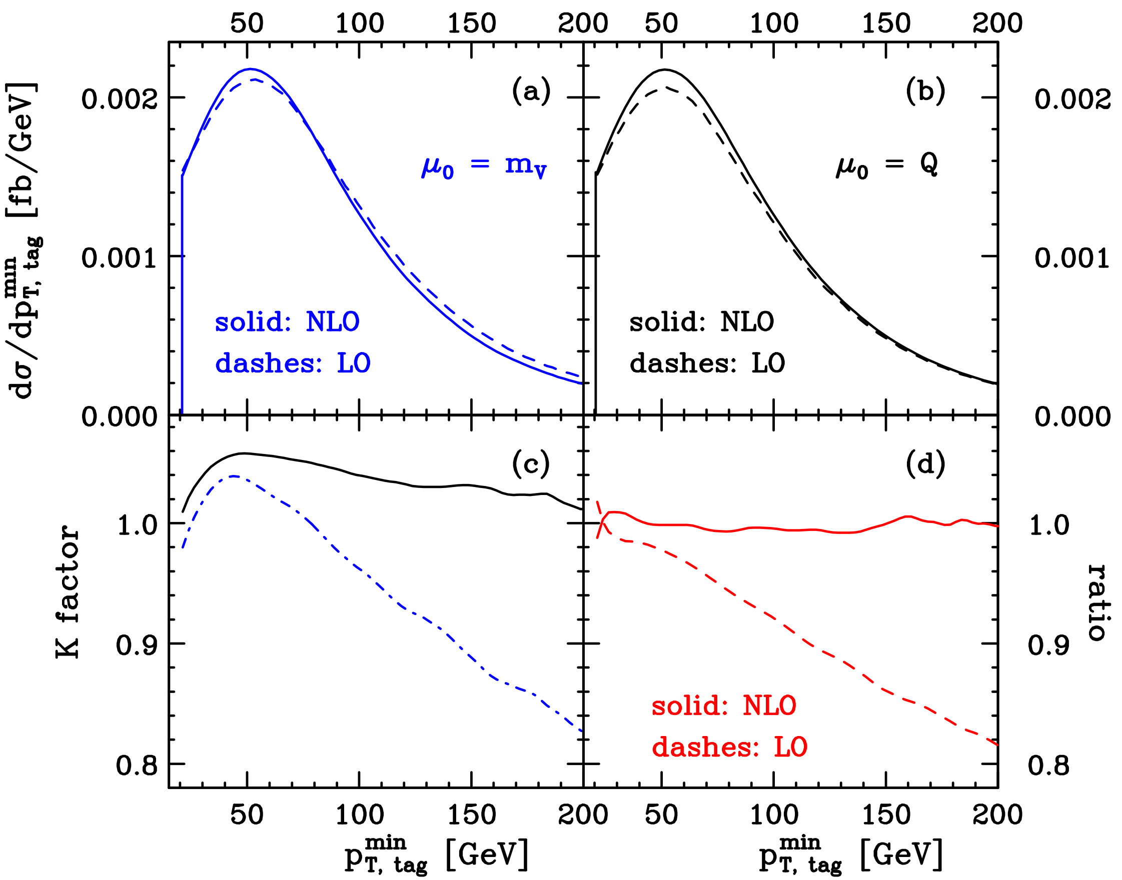
Stabilization of scale dependence at NLO

Jäger, Oleari, DZ hep-ph/0603177



WZ production in VBF, $WZ \to e^+ \nu_e \mu^+ \mu^-$

Transverse momentum distribution of the softer tagging jet

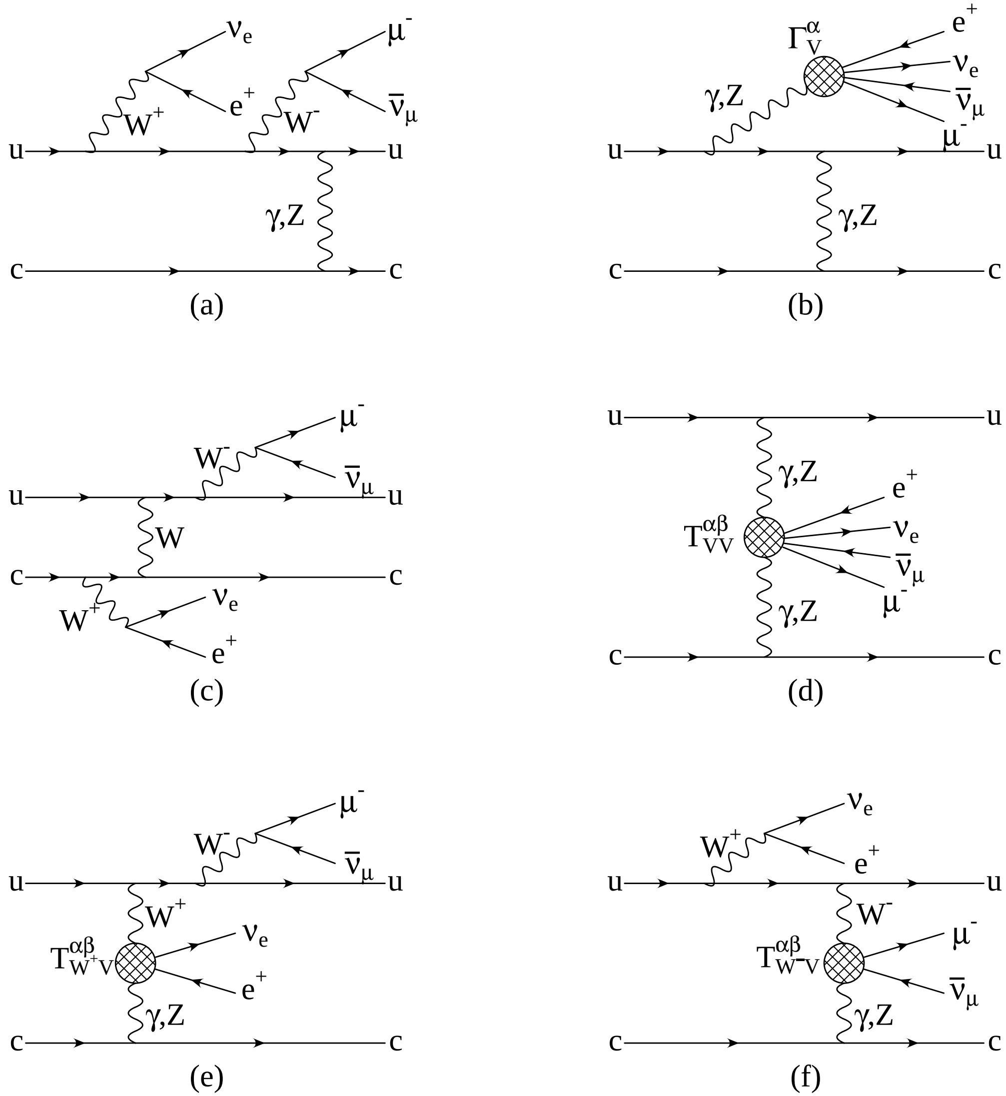


- Shape comparison LO vs. NLO depends on scale
- Scale choice $\mu = Q$ produces approximately constant K-factor
- Ratio of NLO curves for different scales is unity to better than 2%: scale choice matters very little at NLO

Use $\mu_F = Q$ at LO to best approximate the NLO results

$qq \to qqVV$: 3 weak bosons on a quark line

- NLO corrections to $qq \to qqVV$ contain all loops with a virtual gluon attached to a quark line with one, two or three weak bosons
- Crossing and replacing one quark line by a lepton line yields $q\bar{q} \to VVV$ production processes with leptonic decays of the weak bosons
- Recycle virtual contributions from NLO corrections to VBF
- Decompose calculation into modules which can be used in different NLO calculations



Extending VBFNLO: VVV and VVj Production at NLO QCD

Additional processes implemented in 2008 release of VBFNLO:

- Triple weak boson production: $VVV = W^\pm W^\mp W^\pm$, W^+W^-Z and $W^\pm ZZ$ with leptonic decay of the weak bosons and full $H \to WW$ and $H \to ZZ$ contributions
  Work in collaboration with V. Hankele, S. Prestel, C. Oleari and F. Campanario

New processes which were made available in 2011 release:

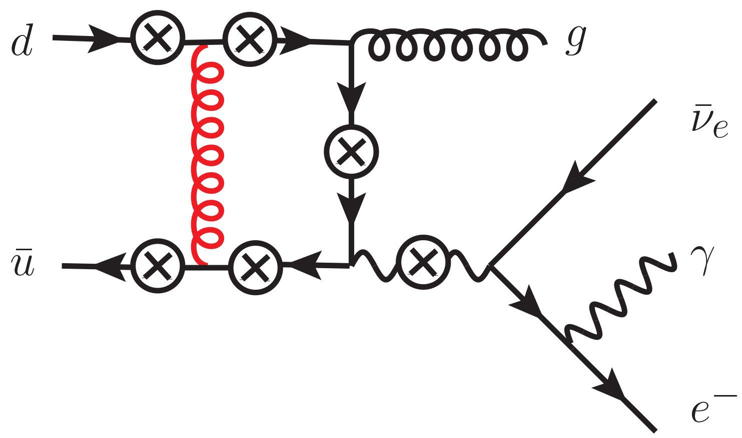
- $W^+W^-\gamma$, $ZZ\gamma$ $WZ\gamma$, $W\gamma\gamma$ production with leptonic decay of weak bosons
  Work in collaboration with G. Bozzi, F. Campanario, M. Rauch, H. Rzehak
- $W^\pm\gamma j$ and WZj production (with W, Z leptonic decay and final state photon radiation)
  Work with C.Englert, F. Campanario, S. Kallweit, M. Spannowsky
- $H\gamma jj$ production in VBF
  Work in collaboration with K. Arnold, B. Jäger, T. Figy
- BSM effects like anomalous couplings and heavy vector resonances

NLO QCD Corrections to $W\gamma j$ Production

- Provide NLO QCD corrections including leptonic W decay, e.g.

$$pp \to e^+ \nu_e \gamma j\,, \qquad pp \to e^- \bar{\nu}_e \gamma j$$

- Sizable cross section at LHC (1.2 pb) and Tevatron (15 fb) for $p_{Tj}, p_{T\gamma} > 50$ GeV and separation cuts (later)
- Measurement of anomalous $WW\gamma$ coupling: veto on jets in $W\gamma$ events requires good knowledge of cross section and distributions: want NLO
- Photon isolation à la Frixione probed at NLO level



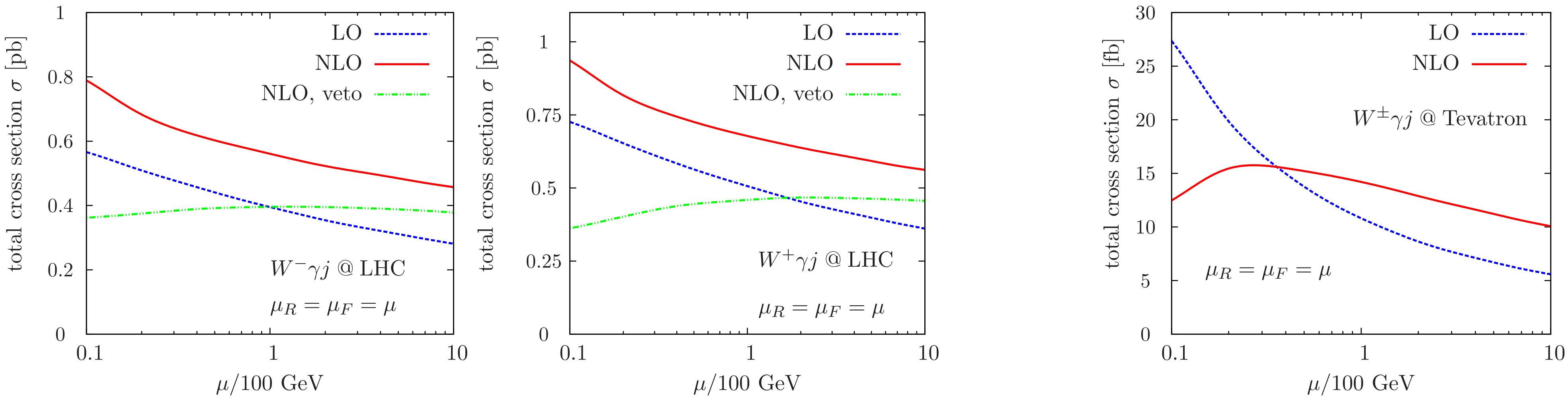
- Initial and final state photon radiation. Final radiation from lepton is important
- Virtual corrections up to pentagons
- External gluon already at tree level $\Longrightarrow$ *nonabelian* boxes with three gluon vertex
- Larger number of subtraction terms

Scale dependence: LHC and Tevatron

Identify lepton, photon and one or more jets with k_T-algorithm ($D = 0.7$)

$p_{Tj,\gamma} \geq 50\,\text{GeV}\,, \quad |y_j| \leq 4.5\,, |\eta_\gamma| \leq 2.5, \qquad p_{Tl} \geq 20\,\text{GeV}\,, \quad |\eta_l| \leq 2.5 \qquad R_{l,\gamma}, R_{l,j} > 0.2$

Frixione isolation of photons with $\delta_0 = 1$ Cross sections are for $W \to e\nu_e$ only



Scale variation at LHC for $\mu_F = \mu_R = 2^{\pm 1} \cdot 100$ GeV: $\pm 11\%$ at LO reduced to $\pm 7\%$ at NLO
Almost flat behaviour for veto of additional jets of $p_T > 50$ GeV should be taken as accidental and not as a measure of NLO uncertainties

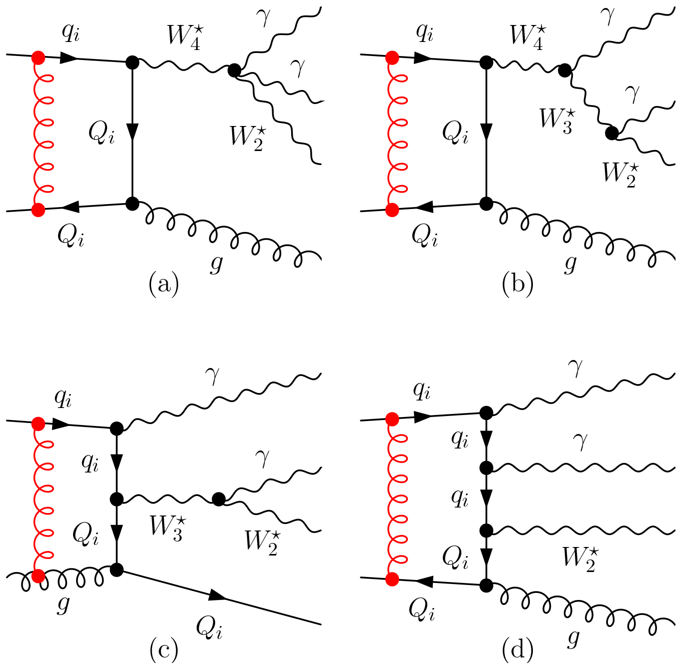
NLO QCD Corrections to $W\gamma\gamma j$ Production

Campanario, Englert, Rauch, DZ arXiv:1106.4009

- Provide NLO QCD corrections including leptonic W decay, e.g.

$$pp \to e^+ \nu_e \gamma\gamma j\,, \qquad pp \to e^- \bar{\nu}_e \gamma\gamma j$$

- LHC14 cross section is about 25 fb for p_{Tj}, $p_{T\gamma}$, $p_{Tl} > 20$ GeV and separation cuts (later)
- Measurement of anomalous $WW\gamma\gamma$ coupling: veto on jets in $W\gamma$ events requires good knowledge of cross section and distributions: want NLO



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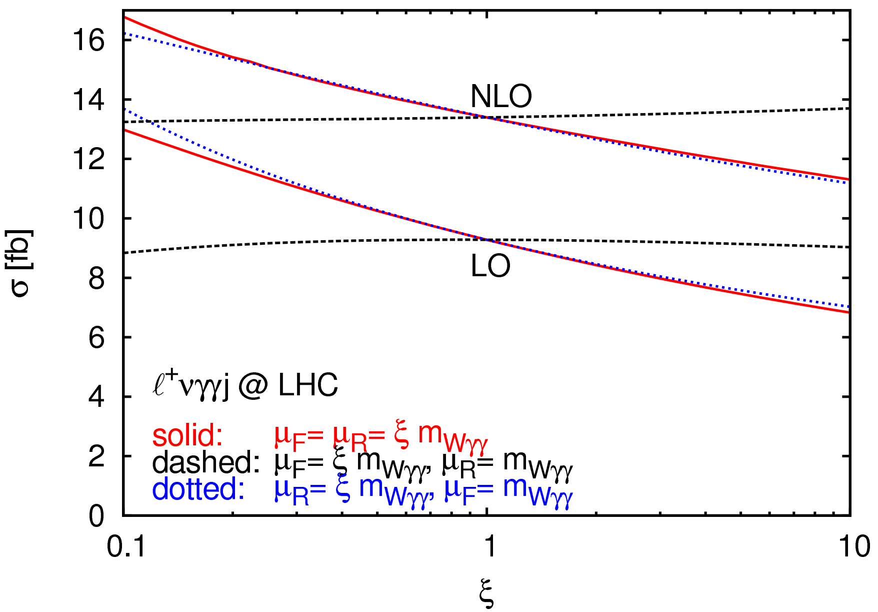
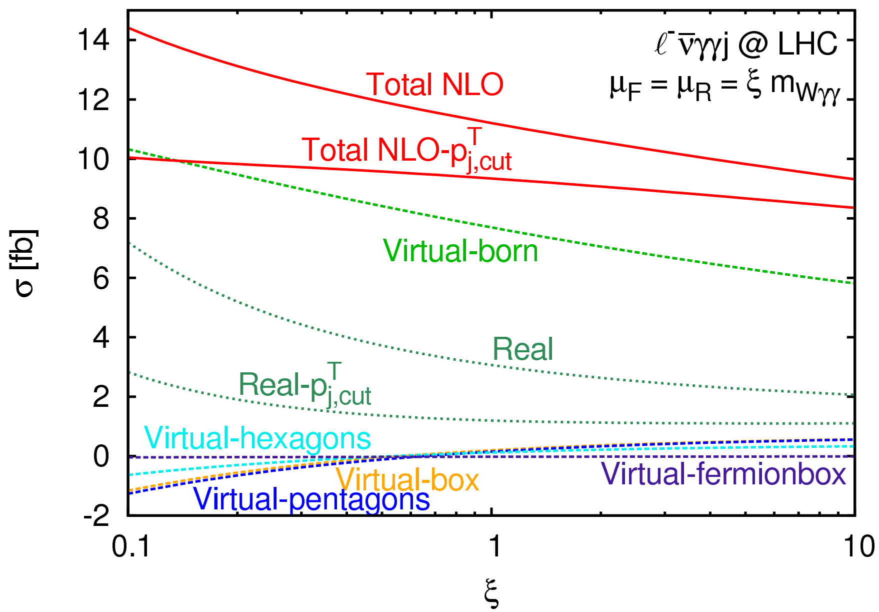
Frixione isolation of photons with $\delta_0 = 0.7$

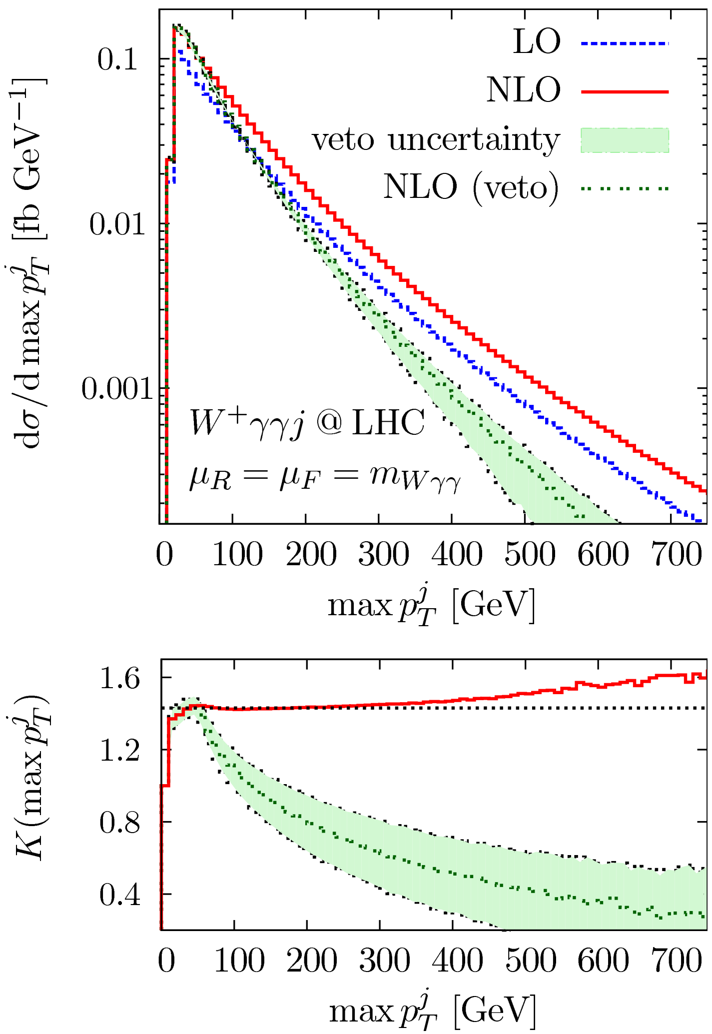




Scale variation at LHC for $\mu_F = \mu_R = 2^{\pm 1} \cdot m_{W\gamma\gamma}$ $\pm 11\%$ at NLO (not much reduced from LO)

Almost flat behaviour for veto of additional jets of $p_T > 50$ GeV

Scale variation with jet veto



Consider p_T of hardest jet

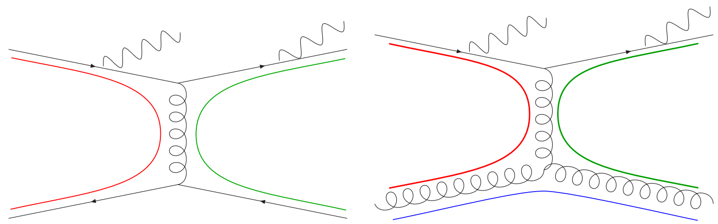
- Jet veto introduces very large scale variations at high p_T
- Small scale dependence in integrated cross section due to accidental cancellation between different phase space regions

Extensions in 2012 update of VBFNLO

Additional NLO QCD corrected processes implemented in 2012 release of VBFNLO:

- $W\gamma\gamma j$ production as first true 2→4 process
- Triple weak boson production is now complete: all $V_1V_2V_3$ production processes for any $V_i = W^{\pm}, Z, \gamma$
- Same sign WW scattering in VBF: W^+W^+jj final states
- Diboson production processes (WZ, $W\gamma$, ZZ, $Z\gamma$ and $\gamma\gamma$) now included. WZ and $W\gamma$ production are provided with anomalous WWV couplings
- Anomalous couplings implemented in the VBF production of Vjj final states
- Spin 2 resonance implemented in VBF: test if Higgs has spin 0 or spin 2

Next 2→4 process at NLO: QCD $WZjj$ production



- 4 flavour scheme
- Cuts:

  $p_{Tj} > 20$ GeV, $|\eta_j| < 4.5$,

  $p_{Tl} > 20$ GeV, $|\eta_l| < 2.5$,

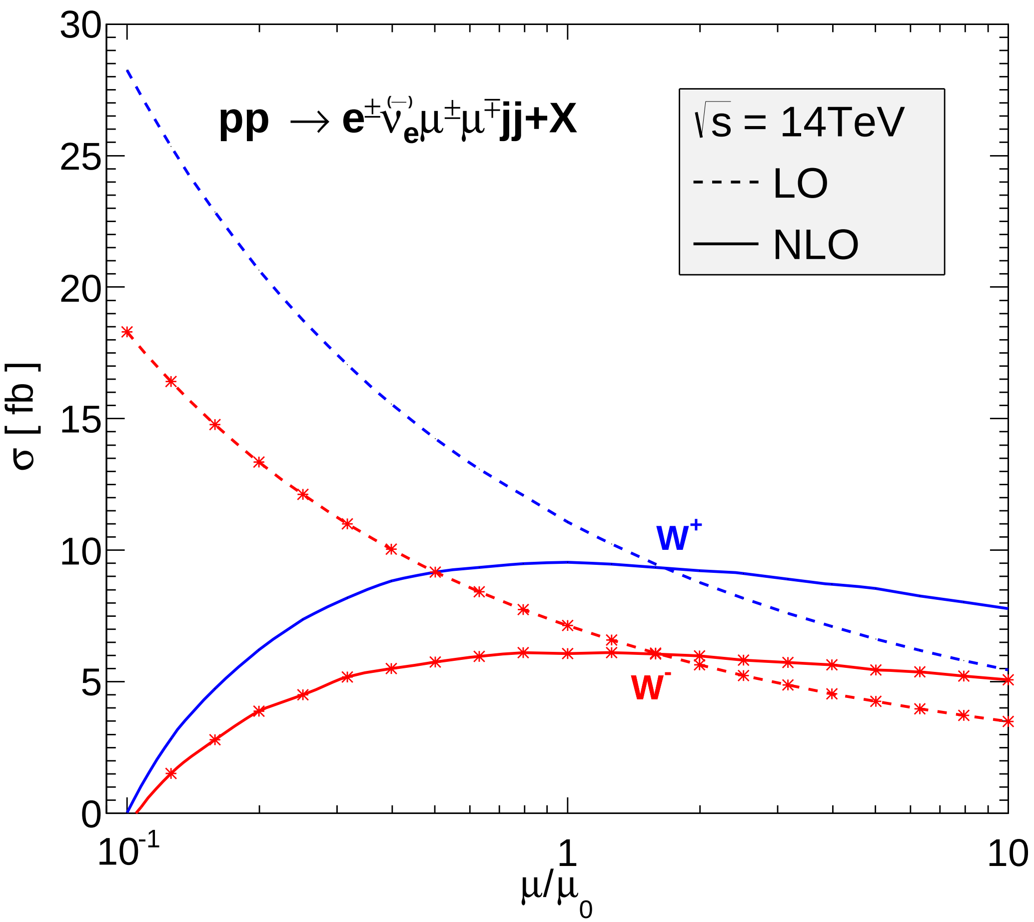
  $R_{jj} > 0.4$, $R_{ll} > 0.3$, $R_{jl} > 0.4$,

  $m_{\mu^+\mu^-} > 15$ GeV, $\not{p}_T > 30$ GeV
- PDF:

  LO: CTEQ6l1

  NLO: CT10, $NF = 4$

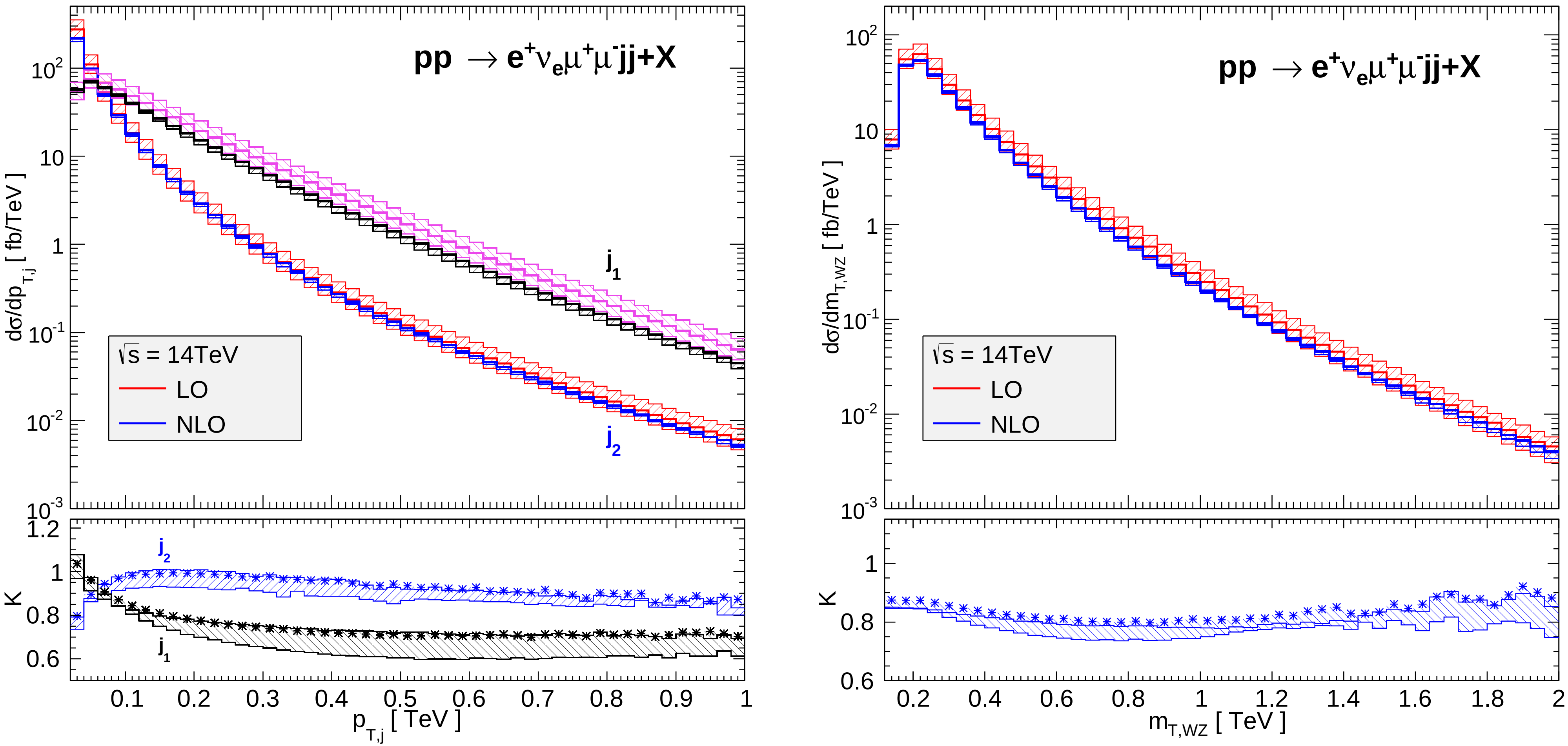
scale dependence: $\mu_0 = \left(\sum p_{T,\text{jet}} + E_{T,W} + E_{T,Z}\right)/2$



Work with Matthias Kerner, Paco Campanario, Ninh Duc Le: arXiv:1305.1623

Distributions for QCD $WZjj$ production

jet transverse momenta (p_T-ordered) transverse mass of WZ system



Comments on $WZjj$ cross sections and distributions

- Strong phase space dependence of K-factors
- VBFNLO code is extremely fast:
  1% statistical error for full NLO QCD corrected "$WZjj$" cross section reached with a single core in 2.5 hours
- Special care is taken to produce numerically stable code:
  gauge invariance tests flag phase space points with numerical instabilities
  virtual corrections are recalculated with quadruple precision when needed
- W^+W^+jj and W^-W^-jj production at NLO QCD has been implememted also and agrees with earlier calculations of Melia, Melnikov, Rontsch and Zanderighi

Latest QCD $VVjj$ process at NLO: $W\gamma jj$ production

- Cuts:

  $p_{T(j,l)} > 20$ GeV, $|y_j| < 4.5$,

  $p_{T\gamma} > 30$ GeV, $|y_{(l,\gamma)}| < 2.5$,

  $R_{l,(j\gamma)} > 0.4$, $R_{j\gamma} > 0.7$, $\not{p}_T > 30$ GeV

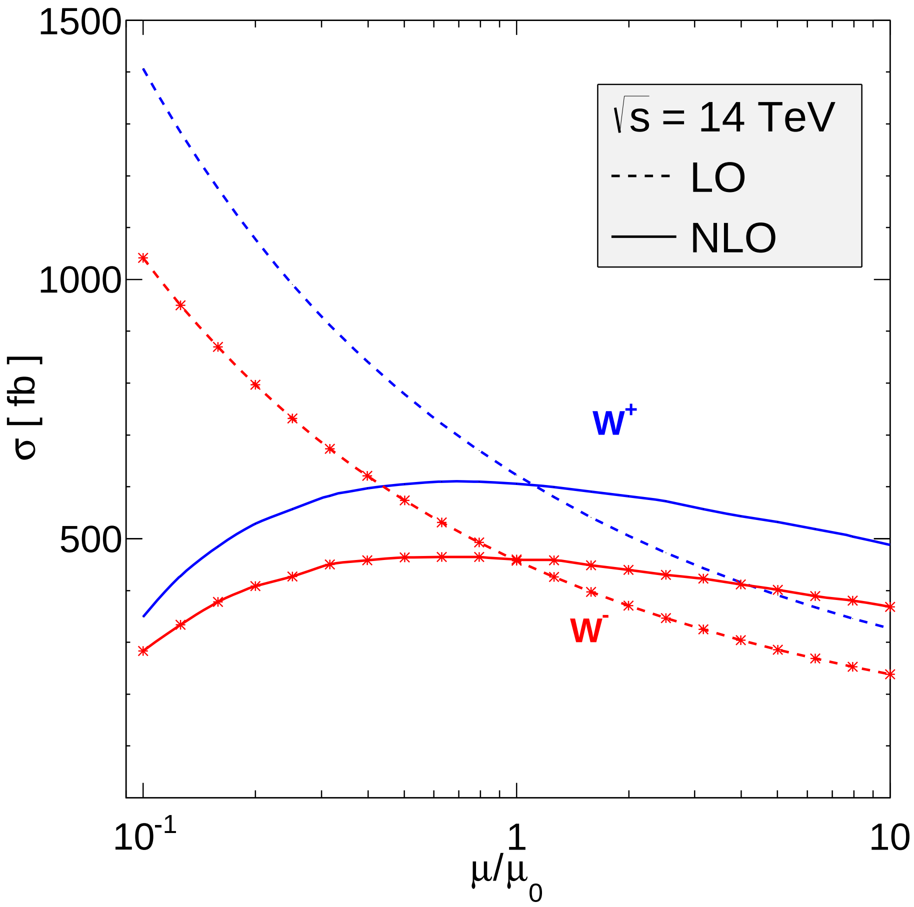
  anti-k_T with $R = 0.4$

  photon isolation $\delta_0 = 0.7$ (Frixione)

- PDF: MSTW2008
- Scale:

  $$\mu_F = \mu_R = \mu_0$$
  $$= \frac{1}{2}\left(\sum_{\text{jet } i} p_{T,i} \cdot e^{b|y_i - y_{12}|} + E_{T,W} + p_{T,\gamma}\right)$$

  with $E_{T,W} = \sqrt{p_{T,W}^2 + m_W^2}$, $y_{12} = \frac{y_1+y_2}{2}$

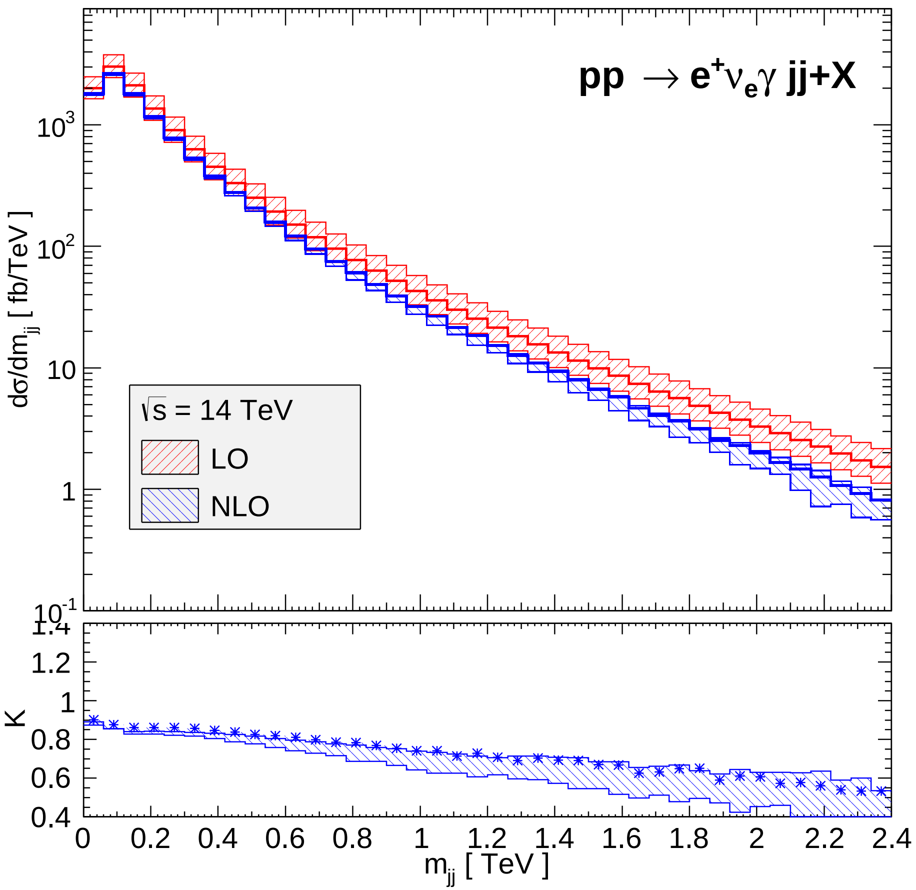


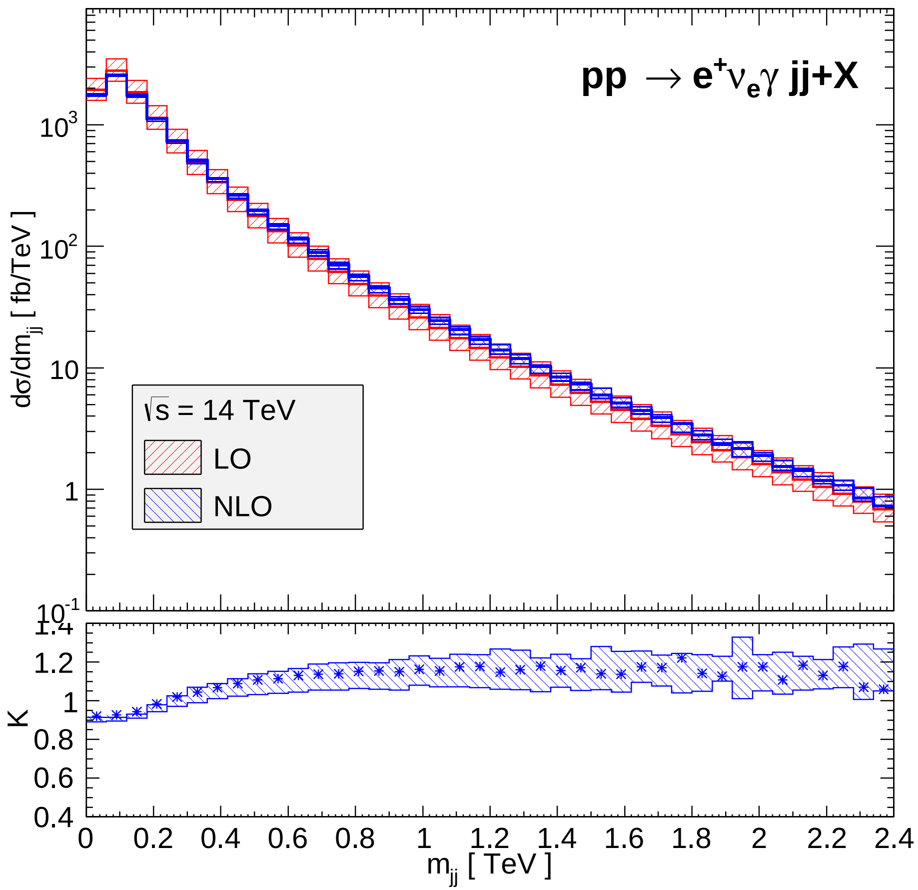
→ Scale dependence reduced

Work with Matthias Kerner, Paco Campanario, Ninh Duc Le: arXiv:1402.0505

$W\gamma jj$ distributions: dijet invariant mass

μ_1 (without $e^{\Delta y/2}$) μ_2 (with $e^{\Delta y/2}$)



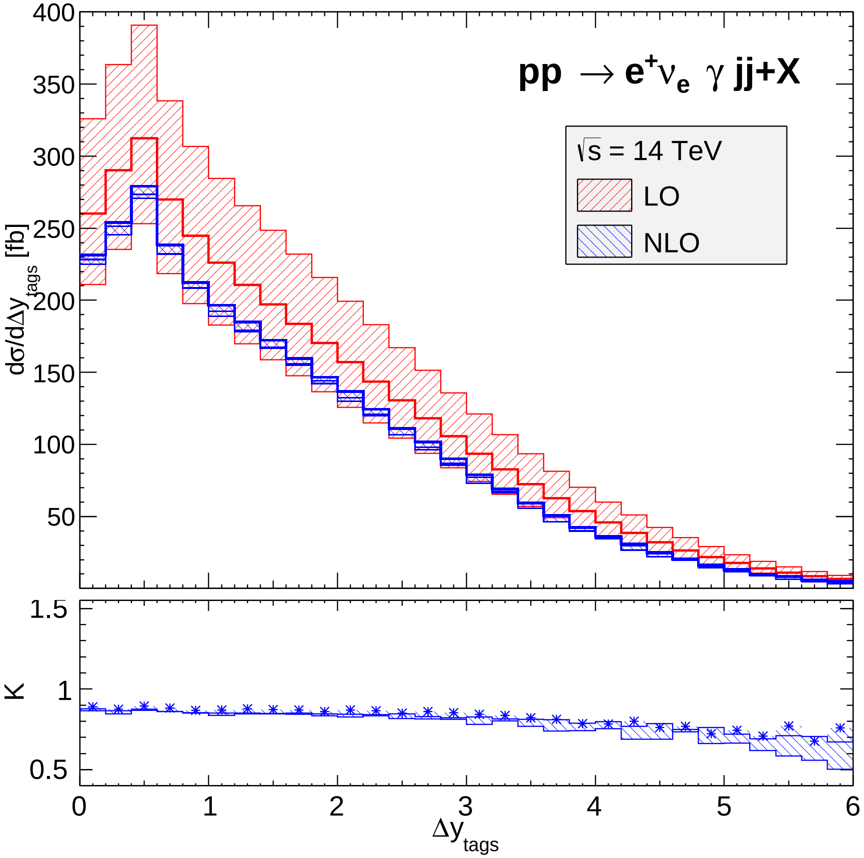


Results for both scales agree (within $2^{\pm 1}$-scale variation)

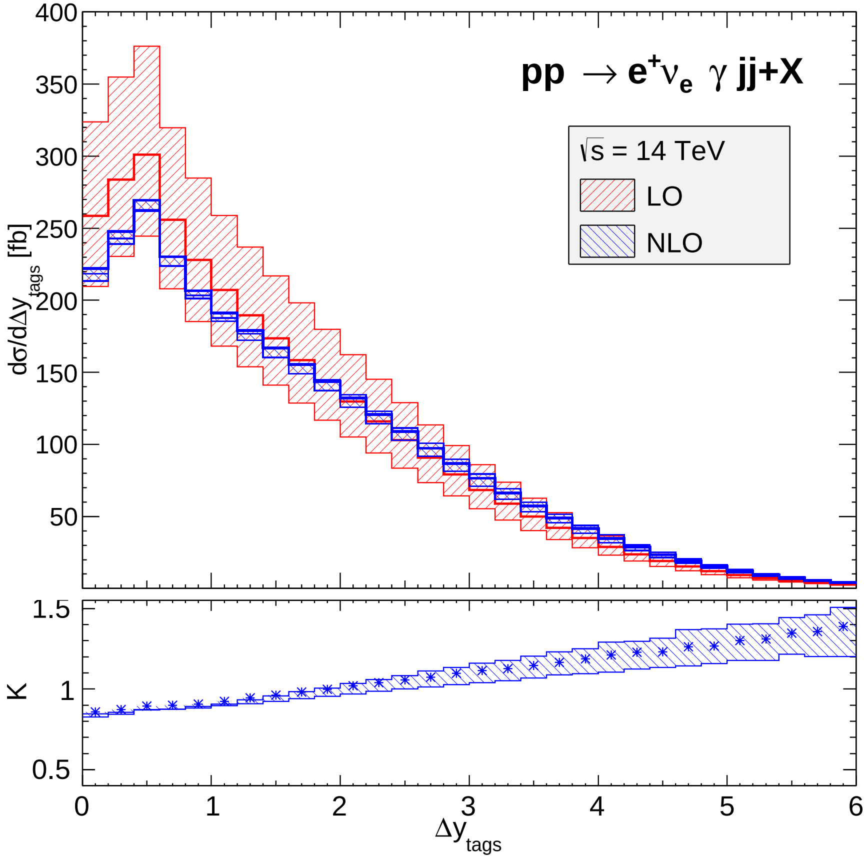
different K-factors due to $\alpha_s(\mu)$ dependence of LO

Dijet rapidity separation

μ_1 (without $e^{\Delta y/2}$)



μ_2 (with $e^{\Delta y/2}$)



$$m_{jj}^2 = 2 p_{T1} p_{T2} \left(\cosh \Delta y - \cos \Delta\phi\right)$$

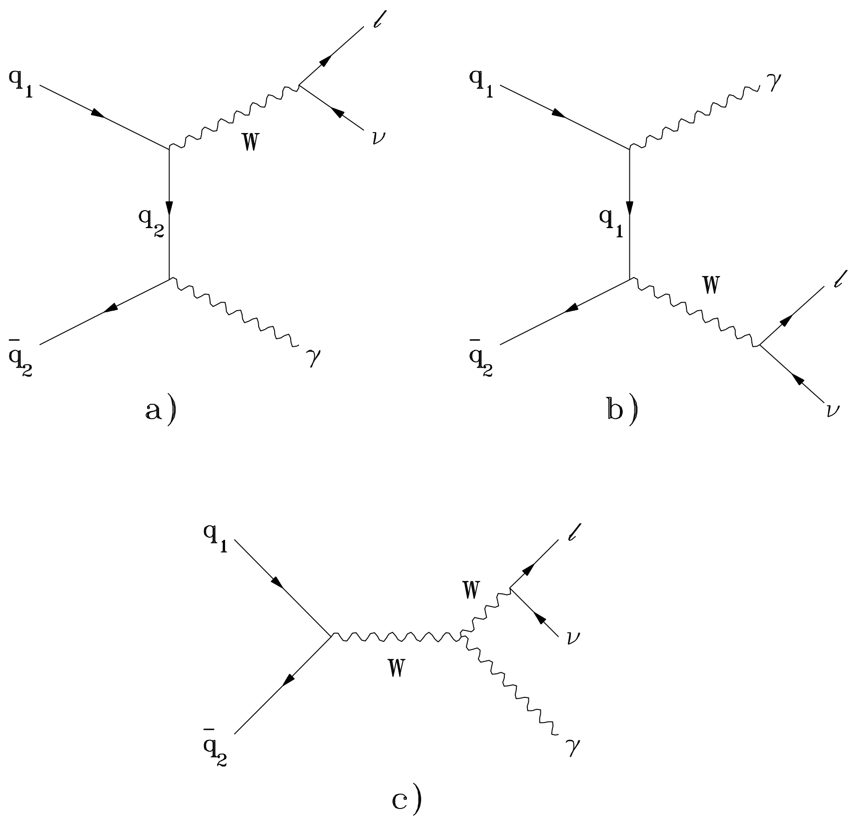
large Δy: $\quad m_{jj} \approx \sqrt{p_{T1} p_{T2}}\, e^{\Delta y/2} \quad < \quad \mu_2 \approx \frac{p_{T1}+p_{T2}}{2}\, e^{\Delta y/2}$

Extensions in 2014 update of VBFNLO

Additional NLO QCD corrected processes implemented in upcoming 2014 release:

- QCD $WZjj$ production at order $\alpha^2\alpha_s^3$
- $W\gamma jj$ production from VBF and order $\alpha^2\alpha_s^3$ QCD sources
- Same sign QCD $WWjj$ production
- WH and WHj associated production (with anomalous couplings)
- Higgs pair production in VBF
- Inclusion of hadronic decay of one W or Z for all VVV triple vector boson production and $VVjj$ vector boson scattering processes
  Hadronic decay simulated at LO only, but K factor is $1 + \alpha_s/\pi \approx 1.04$
  Code is stable when one jet only is produced from Z, γ^* decay
- Anomalous couplings for $VV \rightarrow VV$ scattering processes.

EW boson pair production: $q\bar{q} \to W^+W^-$, $W\gamma$ etc.



- Test non-abelian structure of SM
- Repeat studies of $e^+e^- \to W^+W^-$ and $q\bar{q} \to V_1 V_2$ of LEP and Tevatron

Parameterize WWV couplings by effective Lagrangian

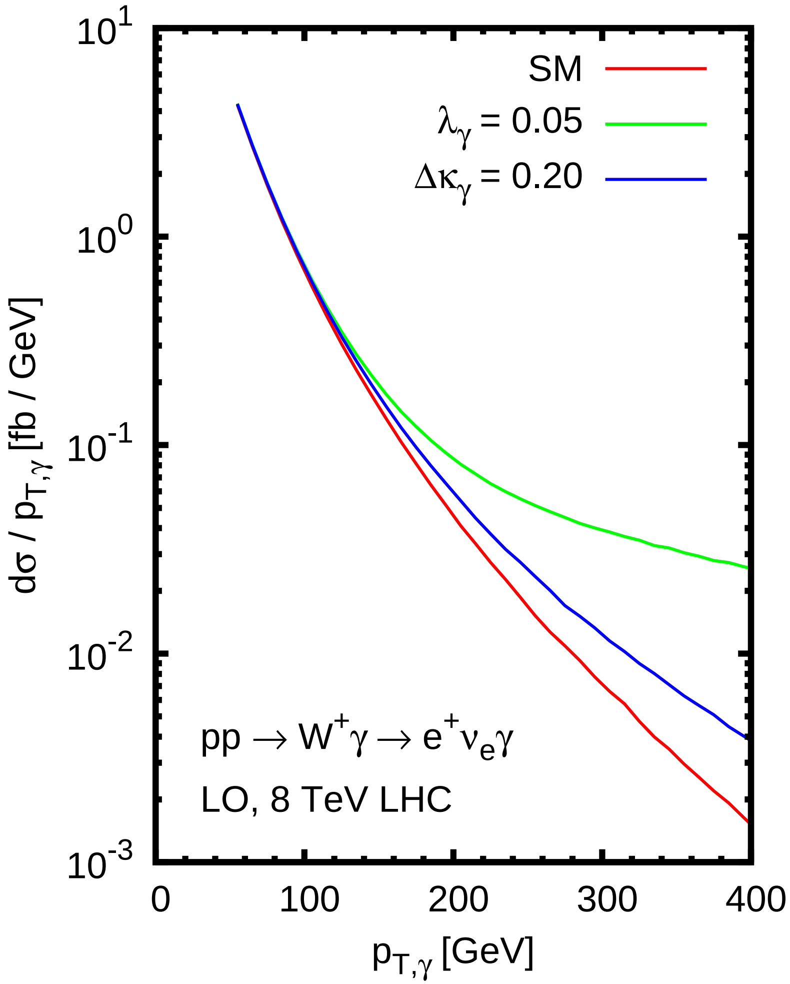
$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu} \right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$

Deviations from SM values (anomalous triple gauge couplings, aTGC)

$$\Delta g_1^V = g_1^V - 1\,, \quad \Delta\kappa_V = g_1^V - 1\,, \quad \lambda_V$$

must be form factors to preserve unitarity at high energy, $\sqrt{\hat{s}}$

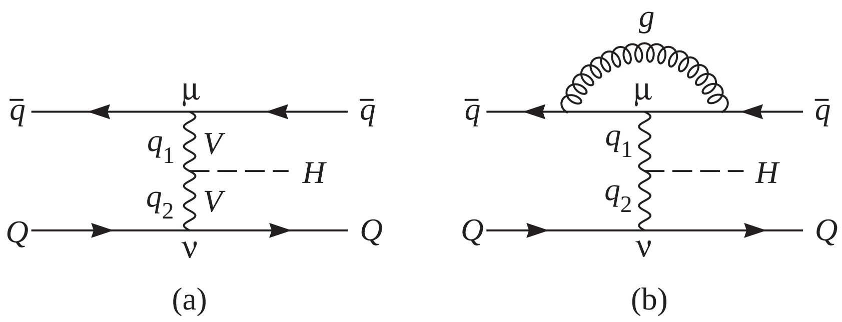
Effects of anomalous couplings



- Anomalous couplings lead to enhanced production of hard events with $J = 1$
  $\Longrightarrow$ mostly central events
- Anomalous couplings are produced by loop-effects of heavy particles with new interactions
  $\Longrightarrow$ form-factor effects
- $\sqrt{\hat{s}}$-dependence of form factors unknown
  $\Longrightarrow$ shape of $\sqrt{\hat{s}}$- or p_T-distributions is ambiguous
- loop effects typically produce small to modest deviations
  $\Longrightarrow$ form-factor effects expected to strongly reduce enhancements at high p_T

Tensor structure of the HVV coupling

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



$$T^{\mu\nu} = a_1\, g^{\mu\nu} + a_2\, \left(q_1 \cdot q_2\, g^{\mu\nu} - q_1^{\nu} q_2^{\mu}\right) + a_3\, \varepsilon^{\mu\nu\rho\sigma}\, q_{1\rho} q_{2\sigma}$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\quad \mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

CP odd $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Implementation in VBFNLO

Start from effective Lagrangians

$$
\begin{aligned}
\mathcal{L} \quad = \quad & \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W_-^{\mu\nu} + \\
& \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}
\end{aligned}
$$

or , alternatively,

$$
\mathcal{L}_{\text{eff}} \quad = \quad \frac{f_{WW}}{\Lambda_6^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_{BB}}{\Lambda_6^2} \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi + \text{ CP-odd part} + \cdots
$$

Implementation in VBFNLO

Start from effective Lagrangians (set PARAMETR1=.true. in anom_HVV.dat)

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W_-^{\mu\nu} +$$
$$\frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}$$

or , alternatively, (set PARAMETR3=.true. in anom_HVV.dat)

$$\mathcal{L}_{\text{eff}} = \frac{f_{WW}}{\Lambda_6^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_{BB}}{\Lambda_6^2} \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi + \text{ CP-odd part} + \cdots$$

see VBFNLO manual for details on how to set the anomalous coupling choices

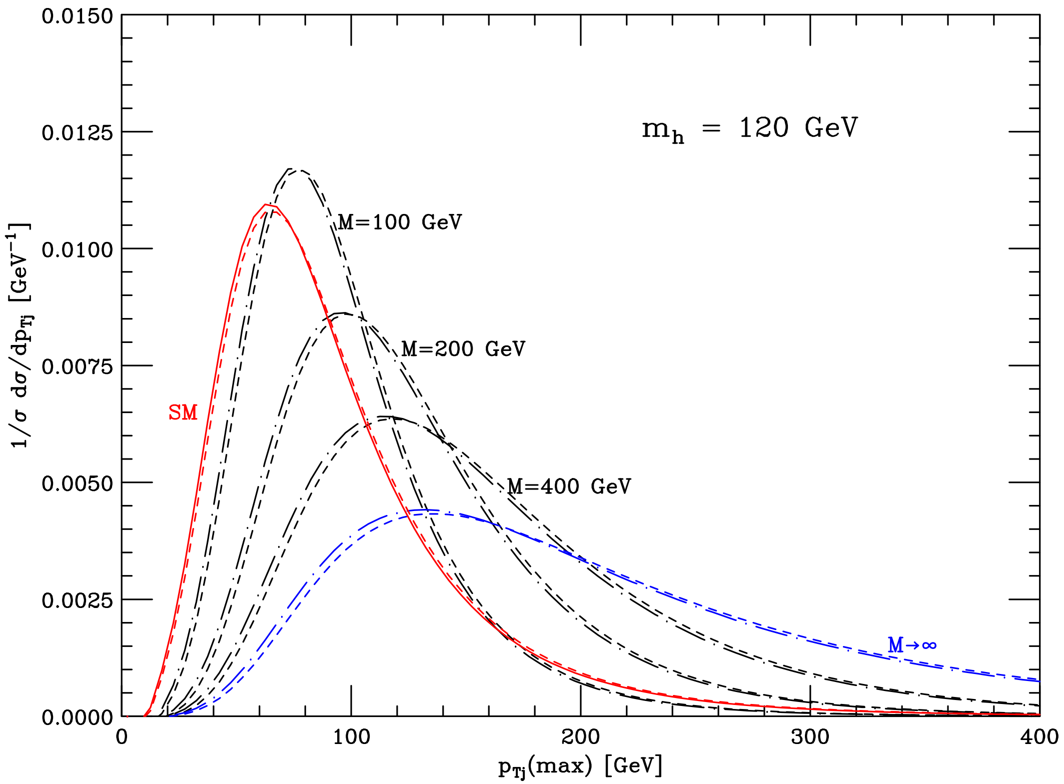
Remember to choose form factors in anom_HVV.dat

$$F_1 = \frac{M^2}{q_1^2 - M^2} \frac{M^2}{q_2^2 - M^2} \qquad \text{or} \qquad F_2 = -2\, M^2\, C_0\left(q_1^2, q_2^2, (q_1 + q_2)^2, M^2\right)$$

Jet transverse momentum

Form factors affect momentum transfer and thus jet transverse momenta

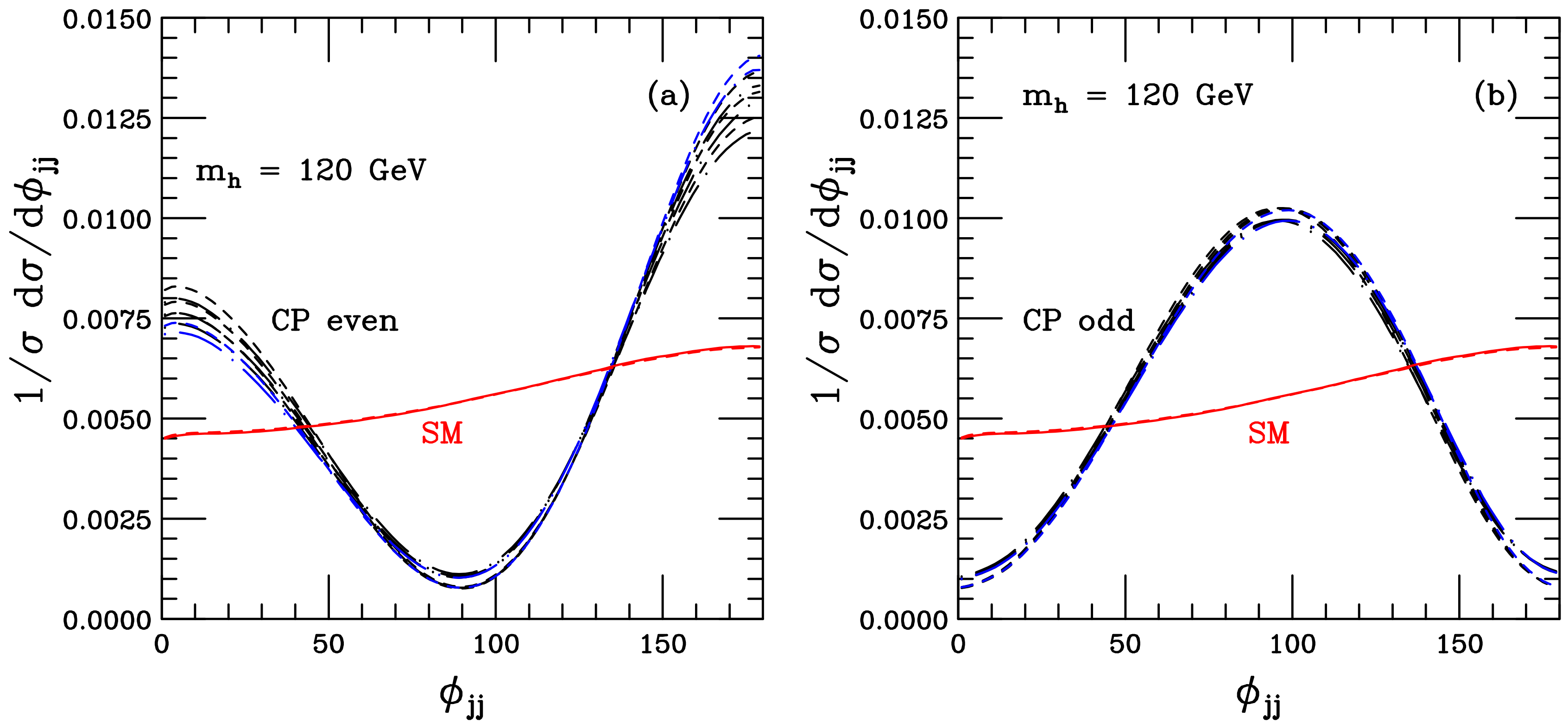
Figy, DZ hep-ph/0403297



- Change in tagging jet p_T distributions is sensitive indicator of anomalous couplings
- Can choose form-factor such as to approximate SM p_T distributions of the two tagging jets

Azimuthal angle correlations

Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of HVV vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

Signal definition in VV scattering

Problem: heavy Higgs or technirho or .... interferes with continuum electroweak background
How do we take interference into account in our definition of the signal?

Notation:

$\mathcal{M}_X = \mathcal{M}_X(m_X) \sim \frac{s}{v^2}$ Signal amplitude for s-, t- and u-channel exchange of new particle X

$\mathcal{M}_B \sim \frac{-s}{v^2}$ continuum electroweak background amplitude

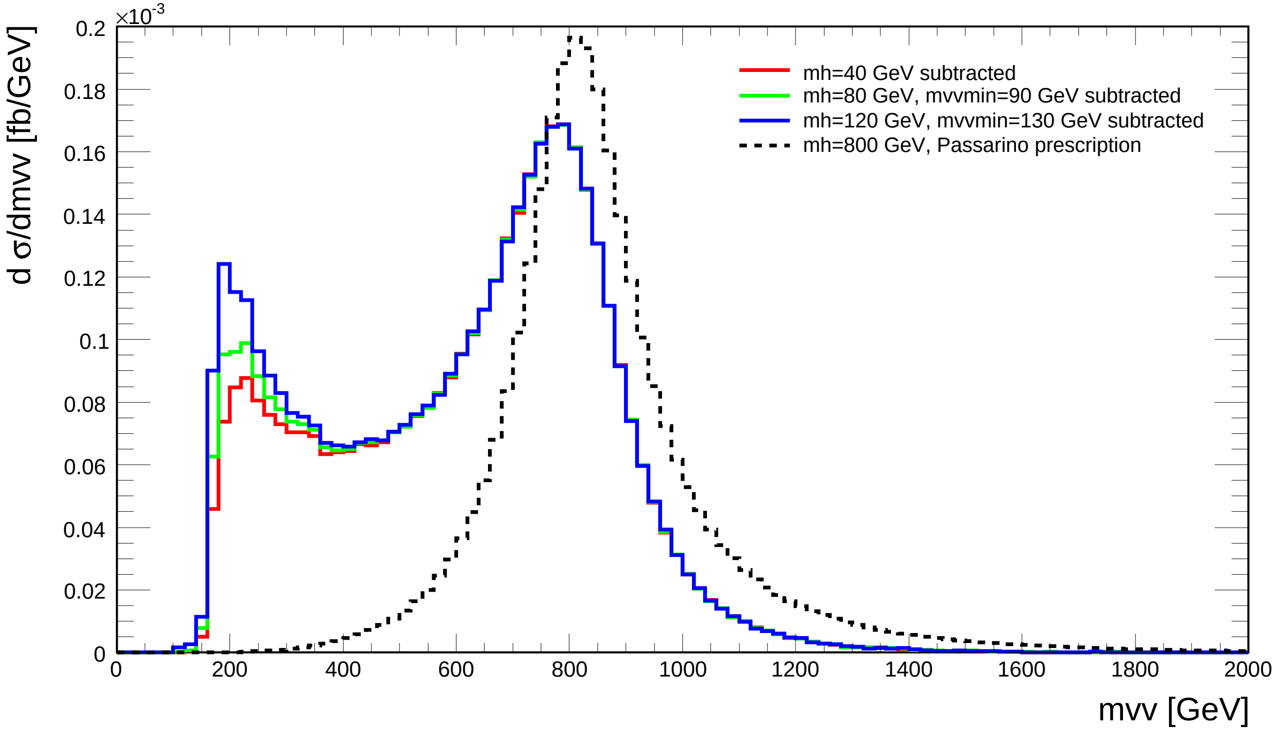
$\Longrightarrow B = \int d\Phi |\mathcal{M}_B|^2$ or $S = \int d\Phi \left[|\mathcal{M}_X|^2 + 2\text{Re}\mathcal{M}_X\mathcal{M}_B^*\right]$ violate unitarity at large s

Compare to SM light Higgs scenario with $m_h = 125$ GeV or $m_h = 100$ GeV, i.e. define electroweak background: $B = \int d\Phi |\mathcal{M}_B + \mathcal{M}_h(m_h)|^2$ and
signal: $S = \int d\Phi |\mathcal{M}_B + \mathcal{M}_X(m_X)|^2 - B$
Integrate over suitable mass range $[m_X - \Gamma_1, m_X + \Gamma_2]$

Advantages:

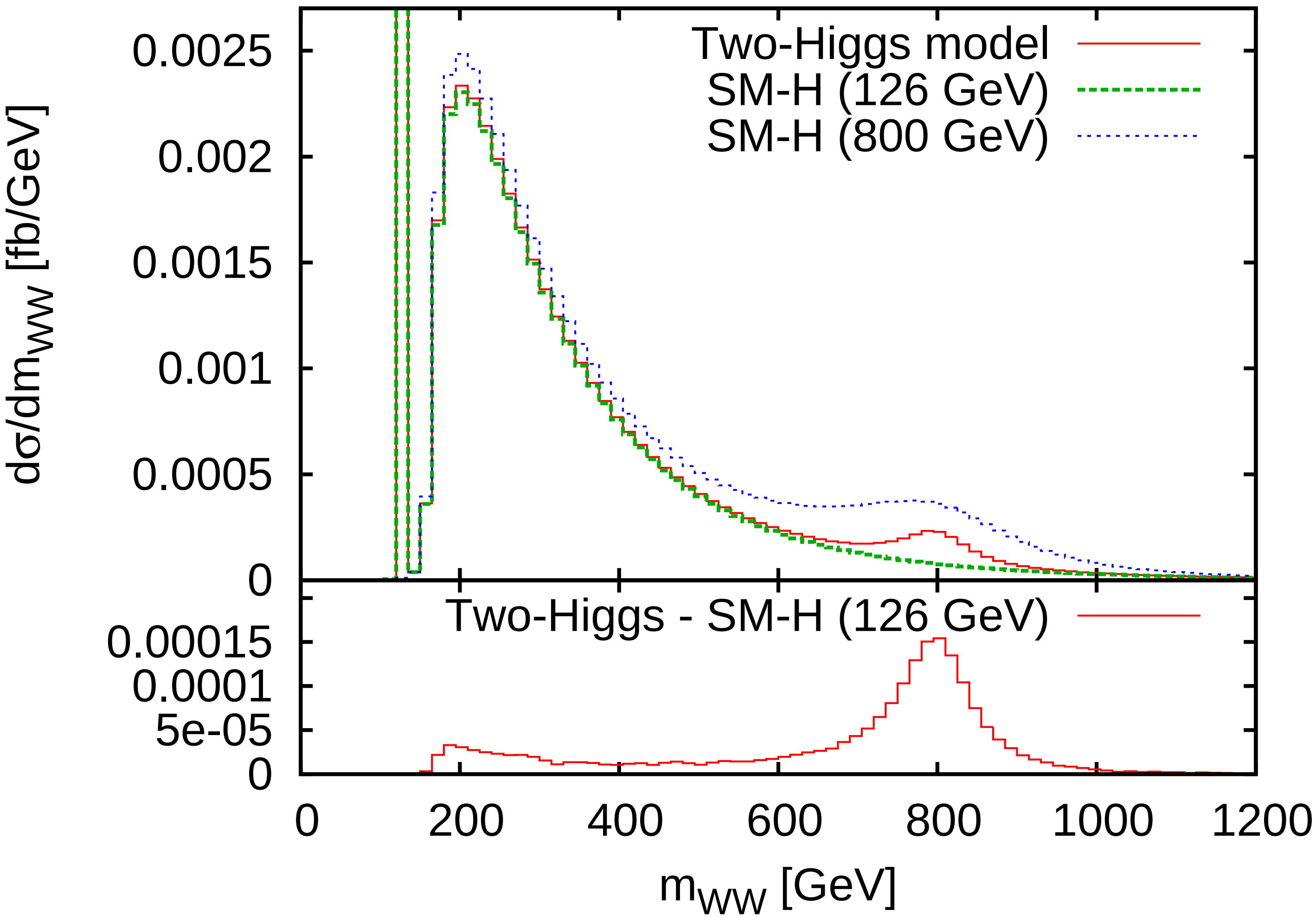
- S and B are well defined and do not violate unitarity
- B is minimized since early onset of cancellations for light SM Higgs are taken into account
- Avoid potentially negative signal cross section due to dominance of (negative) interference terms

Resonance shape for heavy Higgs: LO $WWjj$ case



- Resonance peak is independent of light Higgs mass used in subtraction of continuum background
- Some light Higgs mass dependence in threshold region around $m_{WW} = 200$ GeV $\Longrightarrow$ eliminate by cuts
- True resonance shape is not reproduced by modified Breit Wigner distribution

More realistic: additional heavy Higgs



- Light Higgs at 126 GeV with reduced coupling (here $g^2_{hWW} = 0.7\times$ SM value)
- Heavy Higgs is narrower than SM case due to reduction of $g^2_{HWW} = 0.3\times$ SM value

Conclusions

- VBFNLO provides NLO QCD corrections to a host of processes, in particular vector boson fusion, VVV production and $VVj(j)$ production
- All off-shell diagrams as well as the Higgs-contributions have been considered.
- 2014 update will include various $VVjj$ QCD processes as well as new anomalous coupling contributions

  Code is available at
  http://www.itp.kit.edu/∼vbfnloweb

- VBFNLO is collaborative effort! Thanks to
  V. Hankele, B. Jäger, M. Worek, S. Palmer, F. Campanario, M. Rauch, C. Oleari, K. Arnold, J. Bellm, G. Bozzi, C. Englert, B. Feigl, T. Figy, J. Frank, M. Kerner, G. Klämke, M. Kubocz, S. Plätzer, S. Prestel, H. Rzehak, F. Schissler, M. Spannowsky, Ninh Duc Le, R. Roth, N. Kaiser, O. Schlimpert