VBFNLO: VECTOR BOSON FUSION AND MORE

Dieter Zeppenfeld
Karlsruhe Institute of Technology

SFB TR9 Computational Theoretical Particle Physics KA AC B

Bundesministerium
für Bildung
und Forschung

Dresden, 5. Jan. 2012

- Introduction
- Vector Boson Fusion
- NLO QCD corrections to VV scattering
- Other NLO QCD processes in VBFNLO
- Conclusions

Electroweak symmetry breaking: Higgs (and more?)

Higgs Search = search for dynamics of $SU(2) \times U(1)$ breaking

- Discover the Higgs boson
- Measure its couplings and probe
  mass generation for gauge bosons and fermions

SM: Fermion masses arise from Yukawa couplings via $\quad \Phi^\dagger \rightarrow (0, \frac{v+H}{\sqrt{2}})$

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= -\Gamma_d^{ij}\bar{Q}_L'^{\,i}\Phi d_R'^{\,j} - \Gamma_d^{ij*}\bar{d}_R'^{\,i}\Phi^\dagger Q_L'^{v\,j} + \dots \qquad = -\Gamma_d^{ij}\,\frac{v+H}{\sqrt{2}}\,\bar{d}_L'^{\,i}\,d_R'^{\,j} + \dots \\ &= -\sum_f m_f\,\bar{f}f\left(1+\frac{H}{v}\right)\end{aligned}$$

- Test SM prediction: $\bar{f}fH$ Higgs coupling strength $= m_f/v$
- Observation of $Hf\bar{f}$ Yukawa coupling is no proof that v.e.v exists

Higgs coupling to gauge bosons

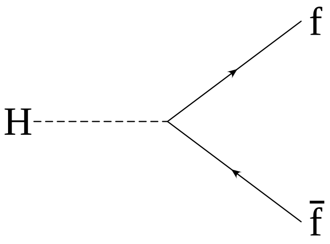
Kinetic energy term of Higgs doublet field:

$$\left(D^\mu\Phi\right)^\dagger\left(D_\mu\Phi\right)=\frac{1}{2}\partial^\mu H\partial_\mu H+\left[\left(\frac{gv}{2}\right)^2 W^{\mu+}W^-_\mu+\frac{1}{2}\frac{\left(g^2+g'^2\right)v^2}{4}Z^\mu Z_\mu\right]\left(1+\frac{H}{v}\right)^2$$

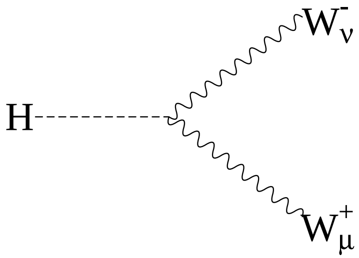
- W, Z mass generation: $m_W^2=\left(\frac{gv}{2}\right)^2,\ m_Z^2=\frac{\left(g^2+g'^2\right)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples proportional to mass: coupling strength $=2\,m_V^2/v\sim g^2v$ within SM

Measurement of WWH and ZZH couplings is essential for identification of H as agent of symmetry breaking: Without a v.e.v. such a trilinear coupling is impossible at tree level

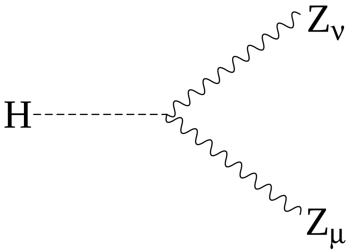
Feynman rules for SM Higgs couplings



$$-i\frac{m_f}{v}1$$



$$ig\, m_W\, g_{\mu\nu}$$

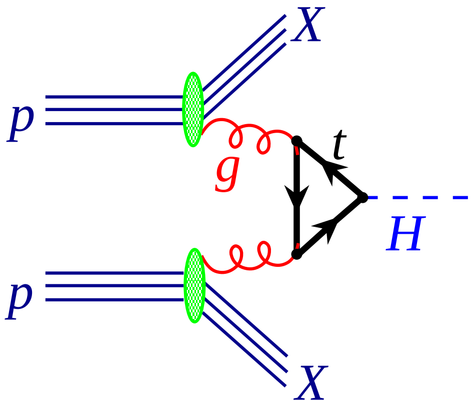


$$i\,g\,\frac{1}{\cos\theta_W}\,m_Z\,g_{\mu\nu}$$

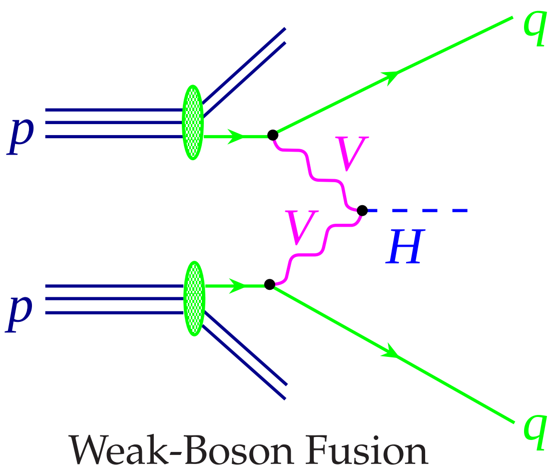
Verify tensor structure of HVV couplings. Loop induced couplings lead to $HV_{\mu\nu}V^{\mu\nu}$ effective coupling and different tensor structure: $g_{\mu\nu} \quad \rightarrow \quad q_1 \cdot q_2\, g_{\mu\nu} - q_{1\nu}q_{2\mu}$

Distinguish scalar from pseudoscalar Higgs couplings to fermions.

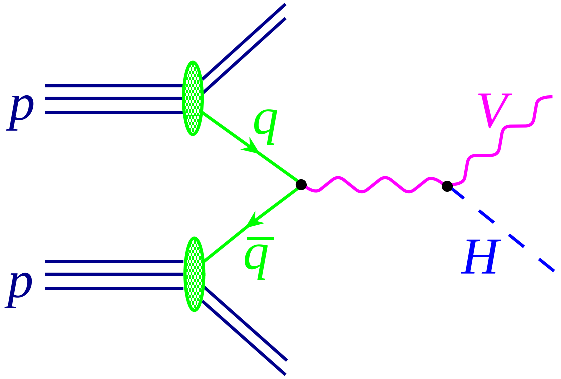
Higgs Production Channels at the LHC



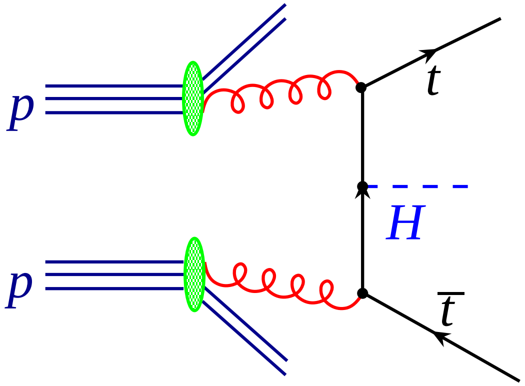
Gluon fusion



Weak-Boson Fusion



Higgs Strahlung



$t\bar{t}H$

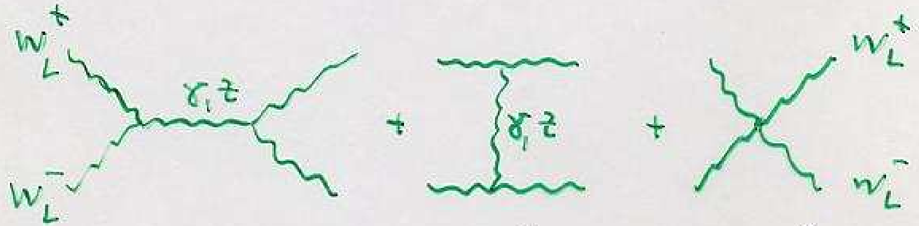
WW scattering and unitarity

Consider longitudinal W's

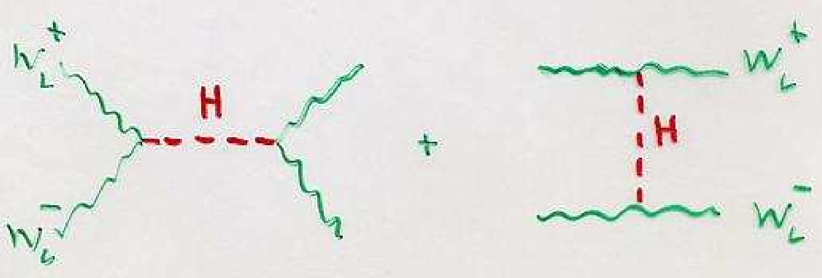
$$W_L^+ W_L^- \rightarrow W_L^+ W_L^-$$

Polarisation vector

$$\varepsilon_L^\mu = \frac{p^\mu}{m_W} + \mathcal{O}\left(\frac{m_W}{E}\right) \sim \frac{\sqrt{s}}{m_W}$$



$$\mathcal{M} \sim \underbrace{\frac{s^2}{m_W^4} \qquad \frac{s^2}{m_W^4} \qquad \frac{s^2}{m_W^4}}_{s/m_W^2}$$



$$\frac{s}{m_W^2} \qquad \frac{s}{m_W^2}$$

sum $\sim s^0$ for $s \gg m_H^2$

Unitarity of WW scattering

Partial wave amplitudes are bounded by a constant

$\Longrightarrow \quad \mathcal{M} \sim \frac{s}{m_W^2}$ violates unitarity at sufficiently high energy

Without the Higgs contribution, the $J = 0$ partial wave violates unitarity for $\sqrt{s} > 1.2$ TeV

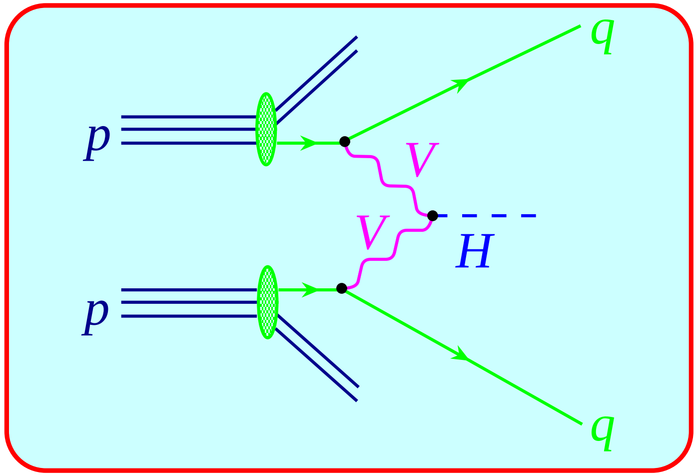
Destructive interference between Higgs exchange amplitudes and gauge boson scattering amplitudes works for $s > m_H^2$ only

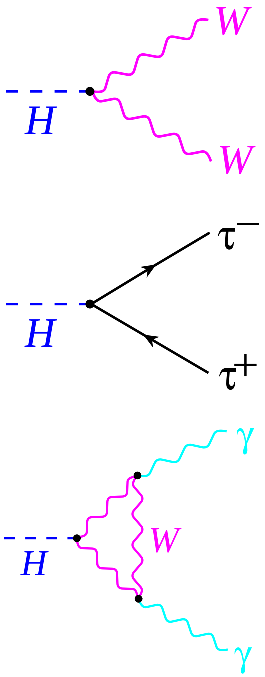
$$\Longrightarrow \quad m_H \lesssim 1\ \text{TeV}$$

or new physics at the TeV scale

or both

Vector Boson Fusion





$m_H > 120$ GeV

$m_H < 140$ GeV

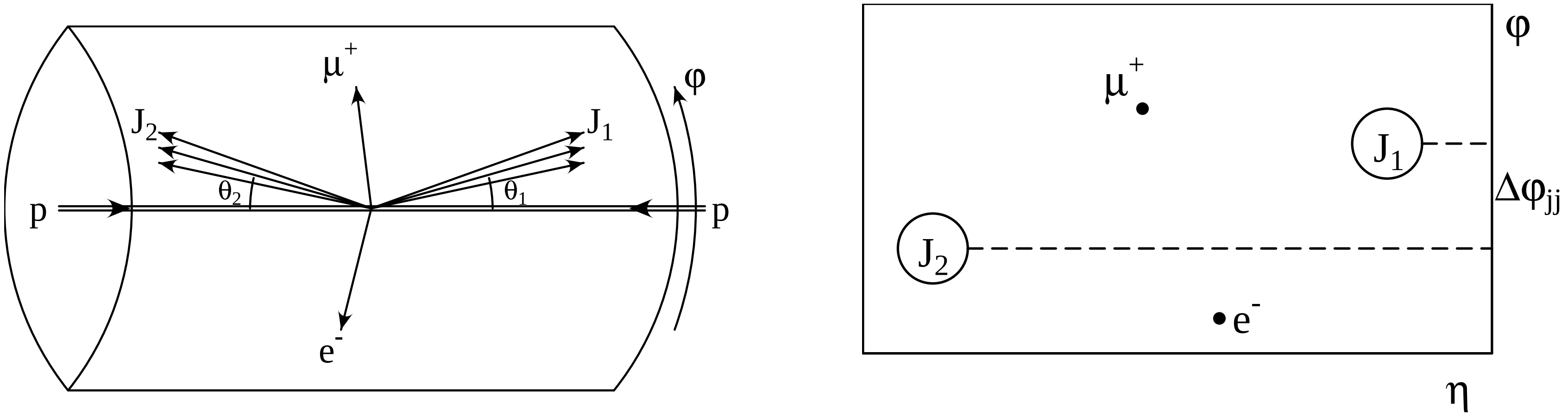
$m_H < 150$ GeV

[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .]

Most measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \times$ BR, of order 10%.

Would like theory errors below 5% $\Longrightarrow$ Need NLO corrections

VBF signature



Characteristics:

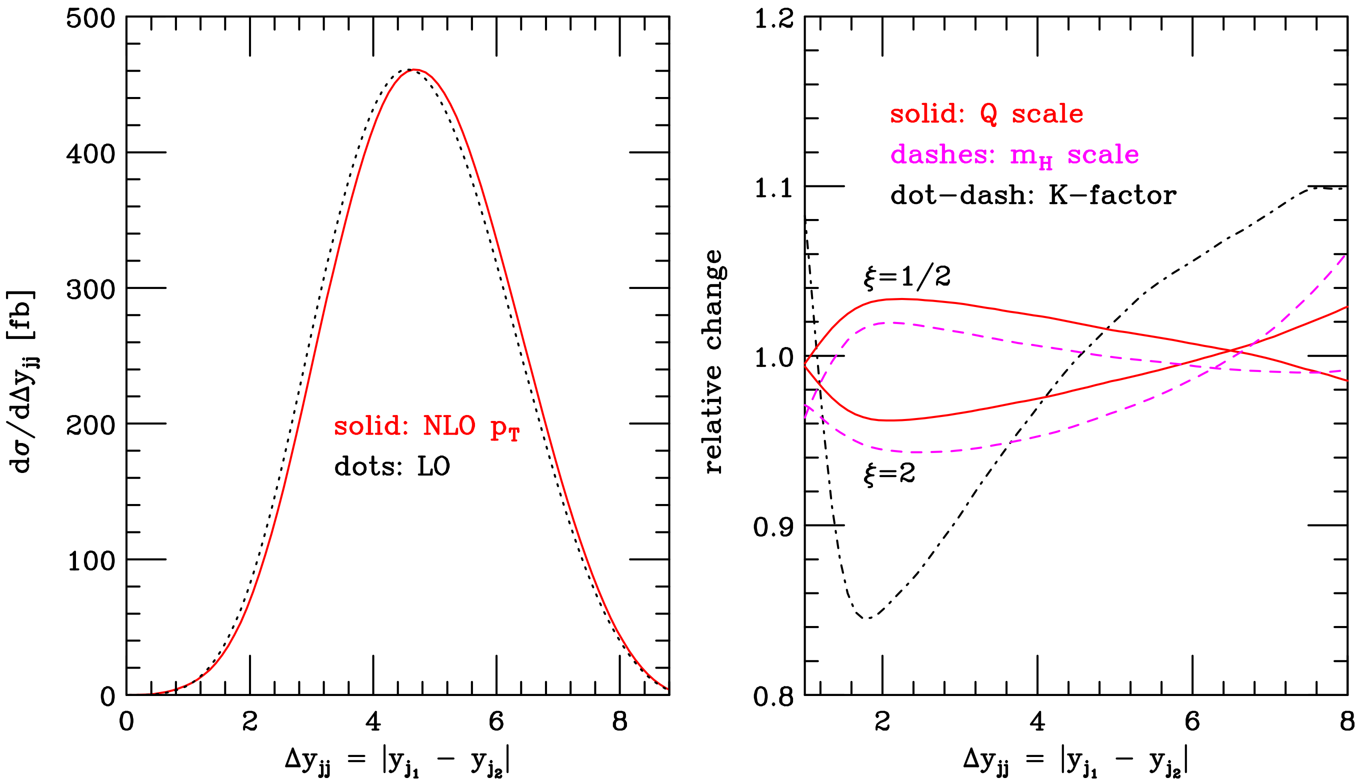
- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- large rapidity separation and large invariant mass of the two tagging jets
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange (central jet veto: no extra jets between tagging jets)

NLO QCD corrections to VBF

- Small QCD corrections of order 10%
- Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- K-factor is phase space dependent
- QCD corrections under excellent control
- ✗ Need electroweak corrections for 5% uncertainty

  Ciccolini, Denner, Dittmaier, 0710.4749

  Figy, Palmer, Weiglein arXiv:1012.4789



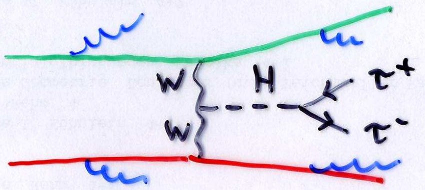
$m_H = 120$ GeV, typical VBF cuts

Central jet veto

- $t\bar{t}$ + jets background for $qq \to qqH$, $H \to W^+W^-$

  $\Rightarrow$ veto b-jets from $t \to bW$

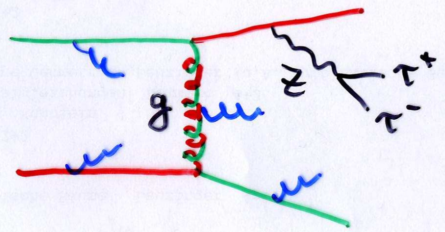
- t-channel color singlet exchange



"synchrotron" radiation between initial and final quark direction

$\Rightarrow$ central jets suppressed

- Major QCD backgrounds: t-channel color octet exch.

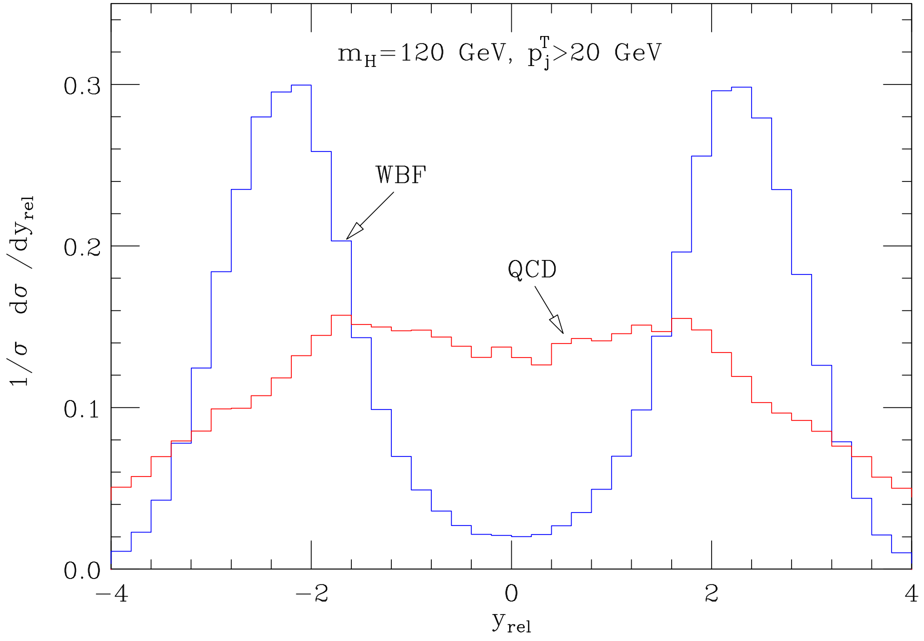


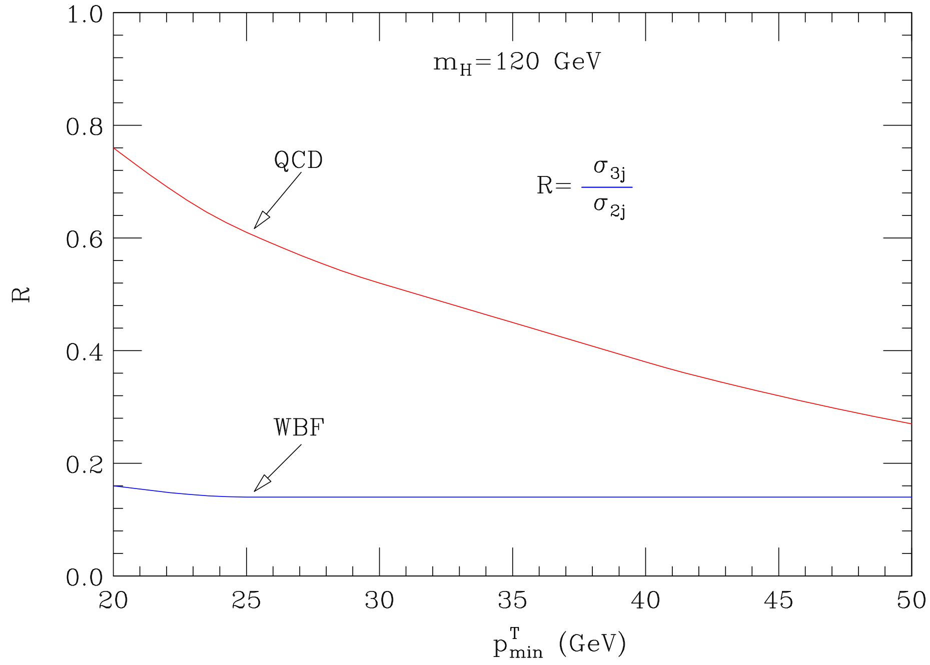
deflection of color charge by ~180° $\Rightarrow$ strong color acceleration

$\Rightarrow$ enhanced central gluon emis.

$\Rightarrow$ central jet veto suppresses QCD backgrounds to weak boson fusion

Central Jet Veto: $Hjjj$ from VBF vs. gluon fusion

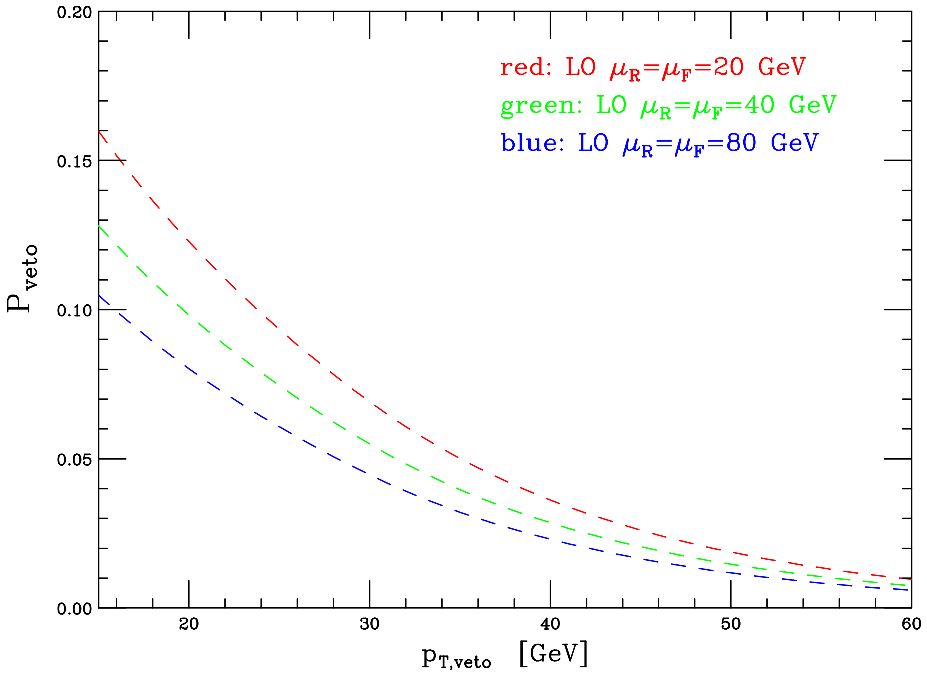




[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- Angular distribution of third (softest) jet follows classically expected radiation pattern
- QCD events have higher effective scale and thus produce harder radiation than VBF (larger three jet to two jet ratio for QCD events)
- Central jet veto can be used to distinguish Higgs production via GF from VBF

VBF Higgs signal and CJV



$$p_{Tj}^{veto} > p_{T,veto}, \quad \eta_j^{veto} \in (\eta_j^{\text{tag } 1}, \eta_j^{\text{tag } 2})$$

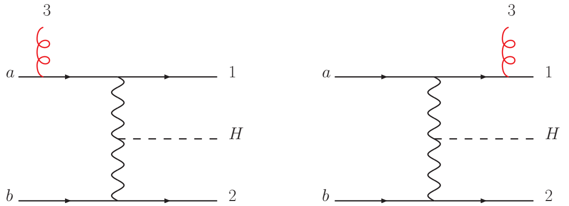
$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3^{LO}}{dp_{Tj}^{veto}}$$

- Scale variation at LO for σ_{3j}: $+33\%$ to -17% for $p_{T,veto} = 15$ GeV
- The uncertainty in P_{veto} feeds into the uncertainty of coupling measurements at the LHC
- In order to constrain couplings more precisely, the NLO QCD corrections to $Hjjj$ are needed: T. Figy, V. Hankele, and DZ, arXiv:0710.5621 (JHEP)

Ingredients of the NLO Calculation

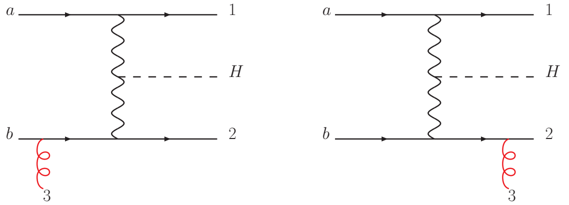
- Born: 3 final state partons + Higgs via VBF

$$\mathcal{M}_B = \delta_{i_2 i_b} t^{a_3}_{i_1 i_a} \Big[\mathcal{M}_{B,1a} :$$



$$\Big]$$

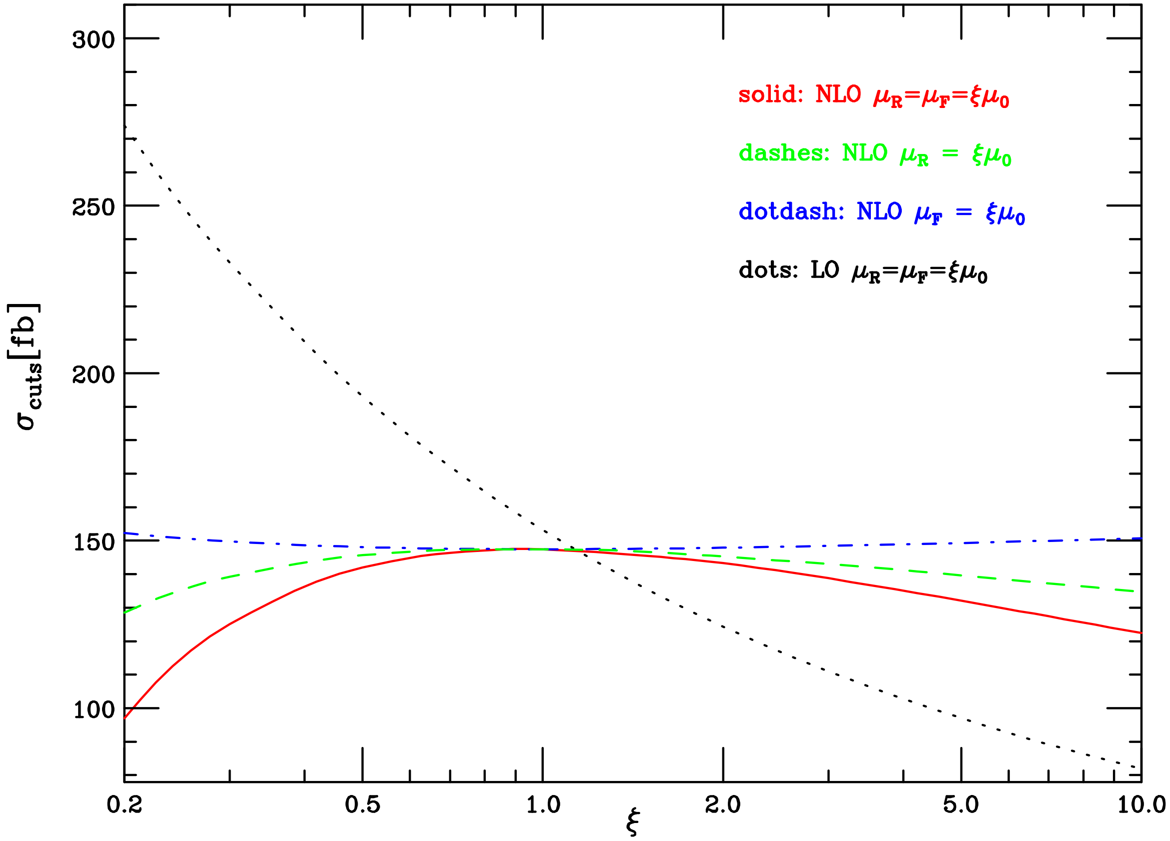
$$+ \; \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \Big[\mathcal{M}_{B,2b} :$$



$$\Big]$$

- Catani, Seymour subtraction method
- Real: 4 final state partons + Higgs via VBF
- Virtual: Two classes of gauge invariant subsets
  - Box + Vertex + Propagator
  - Pentagon + Hexagon are small and can be neglected

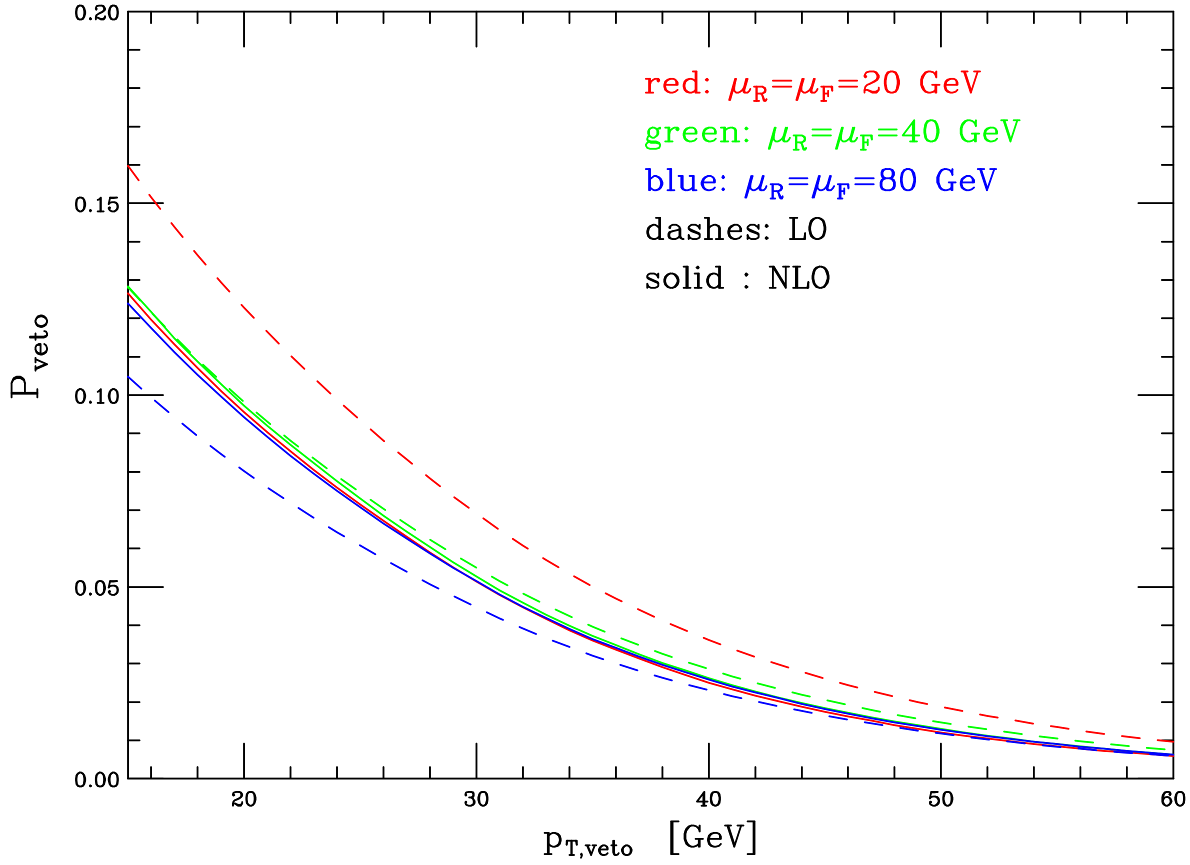
Total $Hjjj$ Cross Section at the LHC: NLO vs LO



$\mu_0 = 40$ GeV
$\xi = 2^{\mp 1}$ scale variations:

- LO: +26% to −19%
- NLO: less than 5%

Veto Probability for the VBF Signal



$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3}{dp_{Tj}^{veto}}$$

Scale variations, $p_{T,veto} = 15$ GeV:

- LO: +33% to −17%
- NLO: −1.4% to −3.4%

Reliable prediction for perturbative part of veto probability at NLO

NLO corrections available in VBFNLO

Parton level Monte Carlo programs for various NLO calculations, including

- QCD corrections for Higgs production via VBF

  Figy, Oleari, DZ

  Now includes electroweak and SUSY corrections to VBF Higgs production

  Figy,Palmer,Weiglein

- QCD corrections to Higgs plus 3 jet production in VBF

  Figy,Hankele, DZ

- QCD corrections to VBF W and Z production ($qq \to qqV$)

  Oleari, DZ

- QCD corrections to weak boson scattering processes ($qq \to qqVV$)

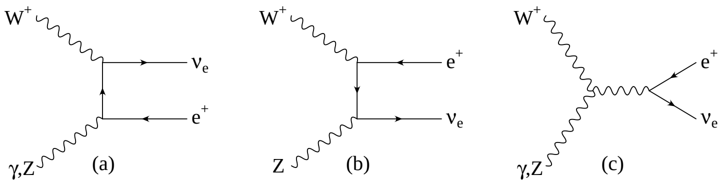
  Jäger, Oleari, DZ

Code is available at http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb/

Weak boson scattering: $qq\to qqWW$, $qqZZ$, $qqWZ$ at NLO

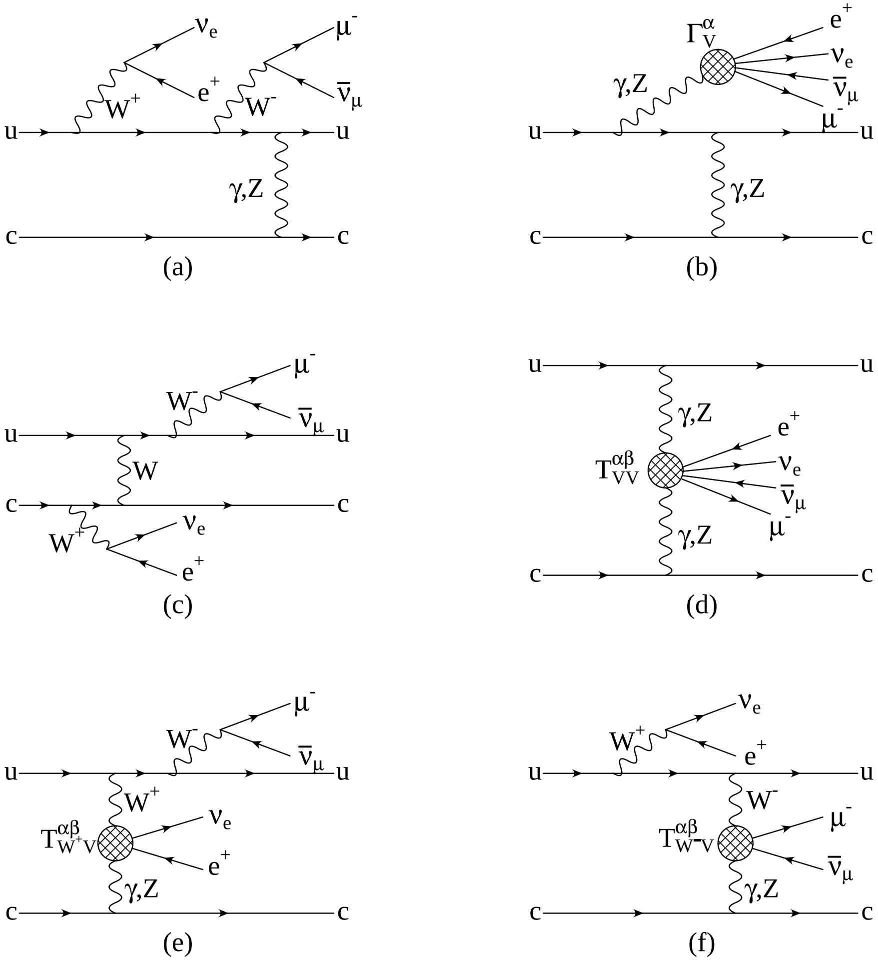
- example: WW production via VBF with leptonic decays: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\Longrightarrow$ 181 Feynman diagrams at LO
- CC $\Longrightarrow$ 92 Feynman diagrams at LO

Use modular structure, e.g. leptonic tensor



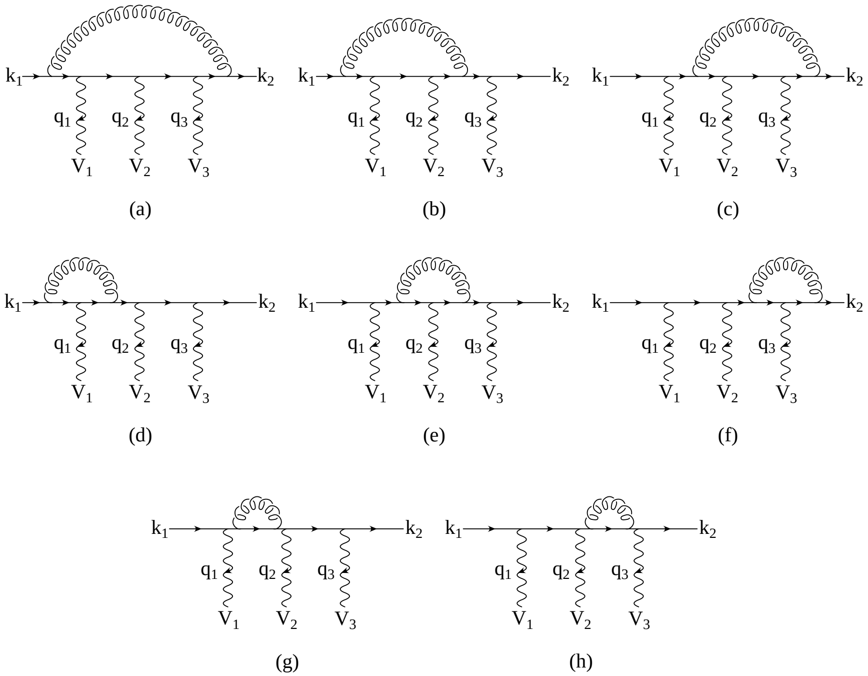
Calculate once, reuse in different processes

Speedup factor ≈ 70 compared to MadGraph for real emission corrections



Most challenging for virtual: pentagon 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

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

- 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

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

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

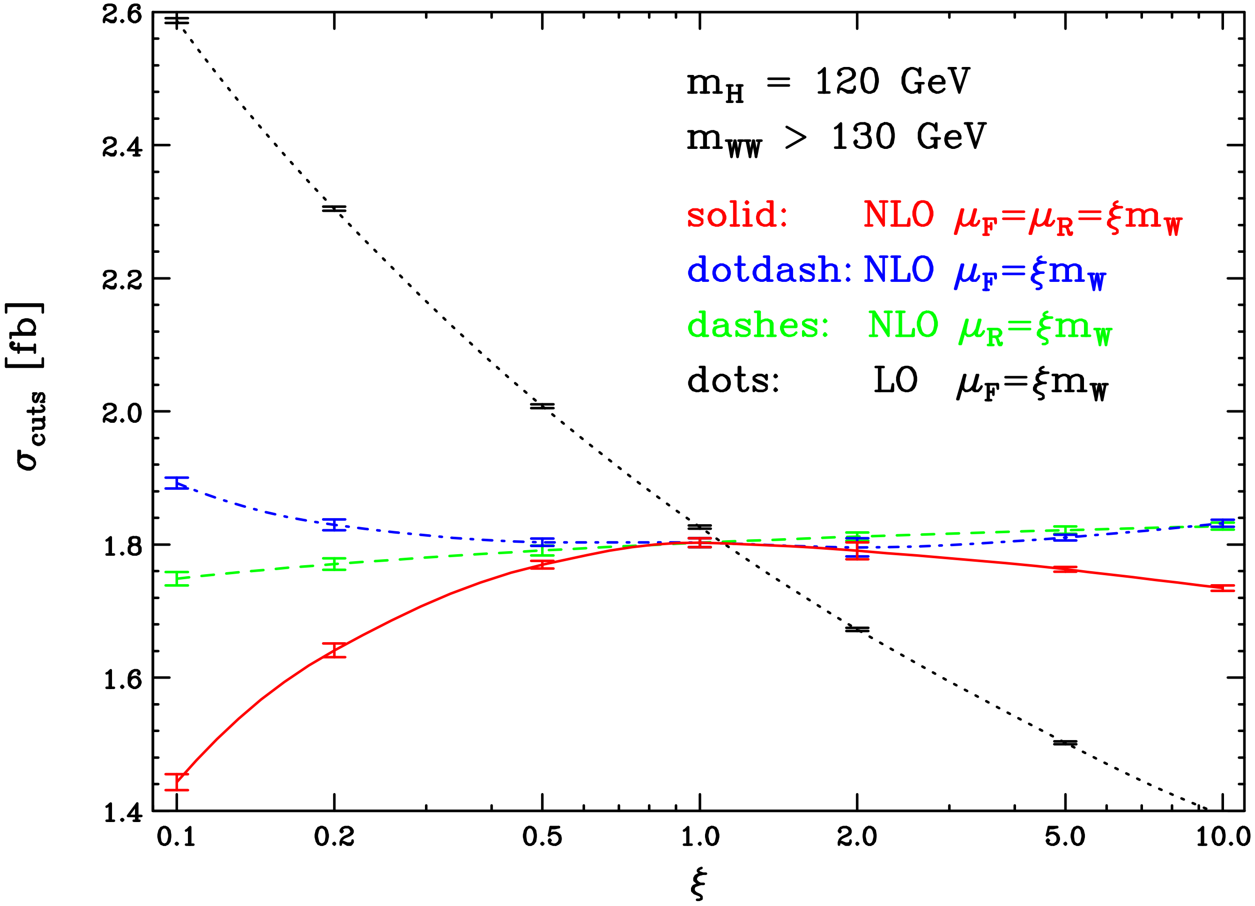
For scale dependence studies we have considered

$\mu = \xi\ m_V$ 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

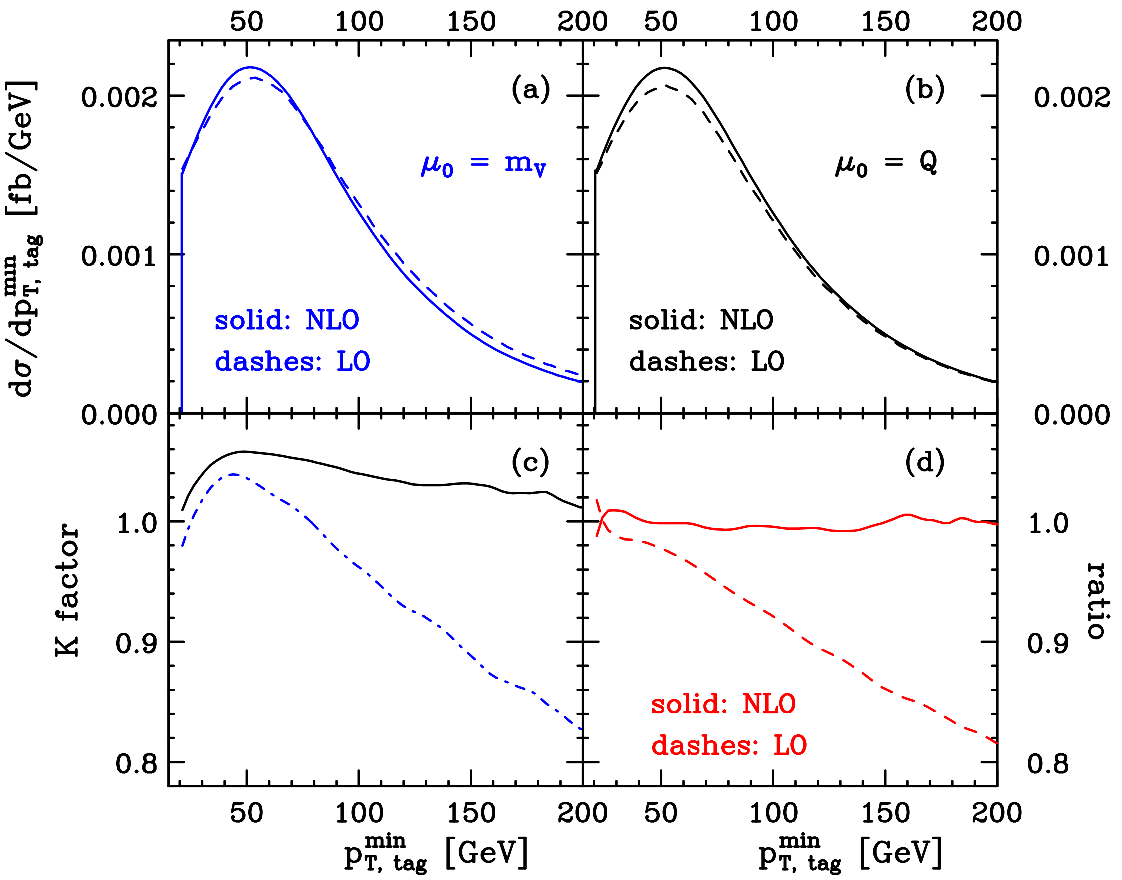
Stabilization of scale dependence at NLO

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

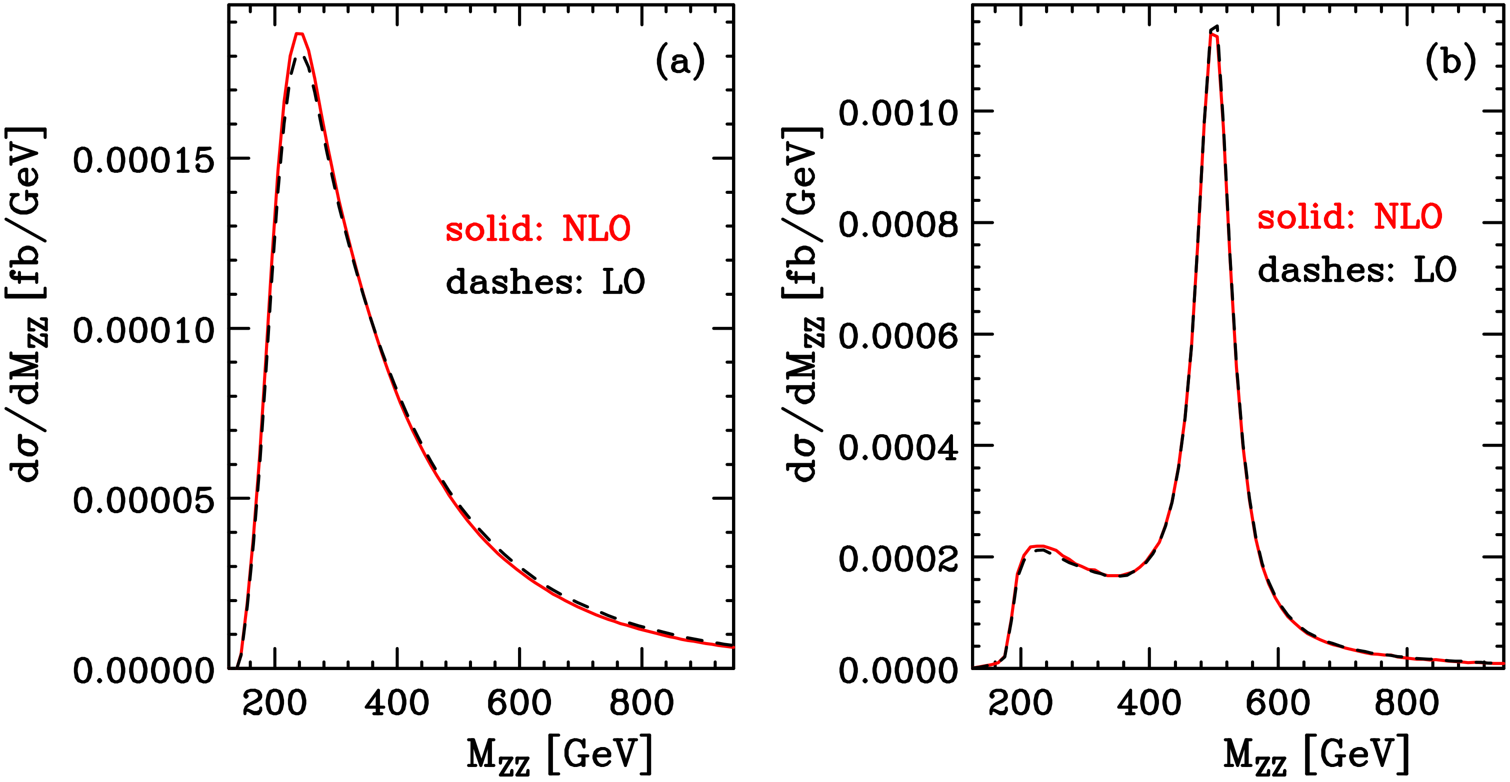


- Shape comparison LO vs. NLO depends on scale
- Scale choice $\mu = Q$ produces approximately constant K-factor
- Ratio of NLO curves for different scales is unity to better than 2%: scale choice matters very little at NLO

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

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

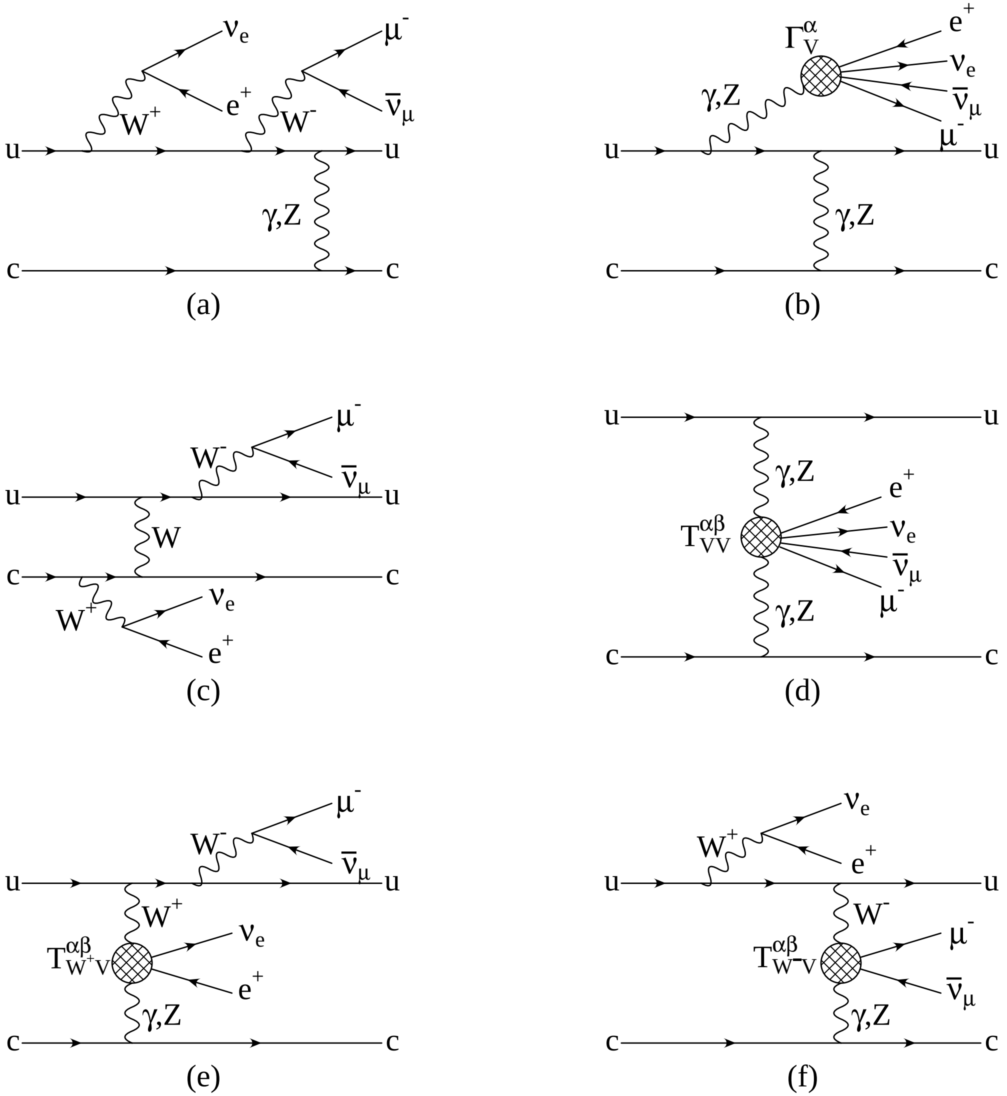
4-lepton invariant mass distribution without/with Higgs resonance



Good agreement of LO and NLO due to low scale choice $\mu = m_Z$. Alternative choice $\mu = m_H$ or $\mu = m_{4\ell}$ leads to smaller LO cross section at high $m_{4\ell}$

$qq \to qqVV$: 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 $H \rightarrow WW$ and $H \rightarrow ZZ$ contributions
  Work in collaboration with V. Hankele, S. Prestel, C. Oleari and F. Campanario

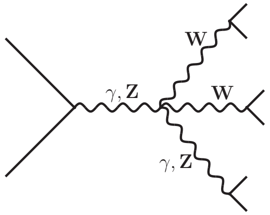
New processes which were made available in 2011 release:

- $W^+W^-\gamma$, $ZZ\gamma$ $WZ\gamma$, $W\gamma\gamma$ 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

Code is available at http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb/

VVV Production: Motivation

- Standard Model background for SUSY processes with multi-lepton + $\not{p}_T$ signature
- Possibility to obtain information about quartic electroweak couplings.



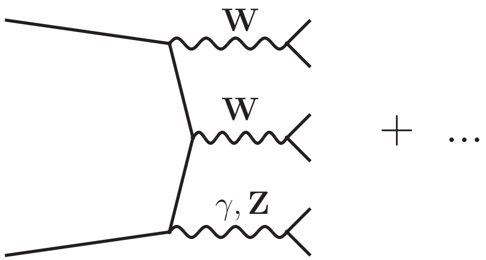
- QCD corrections to $pp \rightarrow$ VVV + X on experimentalist's wishlist:

[The QCD, EW, and Higgs Working Group: hep-ph/0604120]

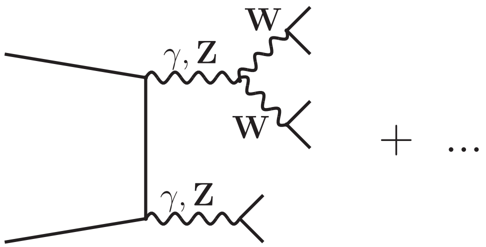
process $(V \in \{Z, W, \gamma\})$	relevant for
1. $pp \rightarrow V\,V\,\mathrm{jet}$	$t\bar{t}H$, new physics
2. $pp \rightarrow t\bar{t}\,b\bar{b}$	$t\bar{t}H$
3. $pp \rightarrow t\bar{t} + 2\,\mathrm{jets}$	$t\bar{t}H$
4. $pp \rightarrow V\,V\,b\bar{b}$	VBF$\rightarrow H \rightarrow VV$, $t\bar{t}H$, new physics
5. $pp \rightarrow V\,V + 2\,\mathrm{jets}$	VBF$\rightarrow H \rightarrow VV$
6. $pp \rightarrow V + 3\,\mathrm{jets}$	various new physics signatures
7. $pp \rightarrow V\,V\,V$	SUSY trilepton

Example: Contributions to WWZ production

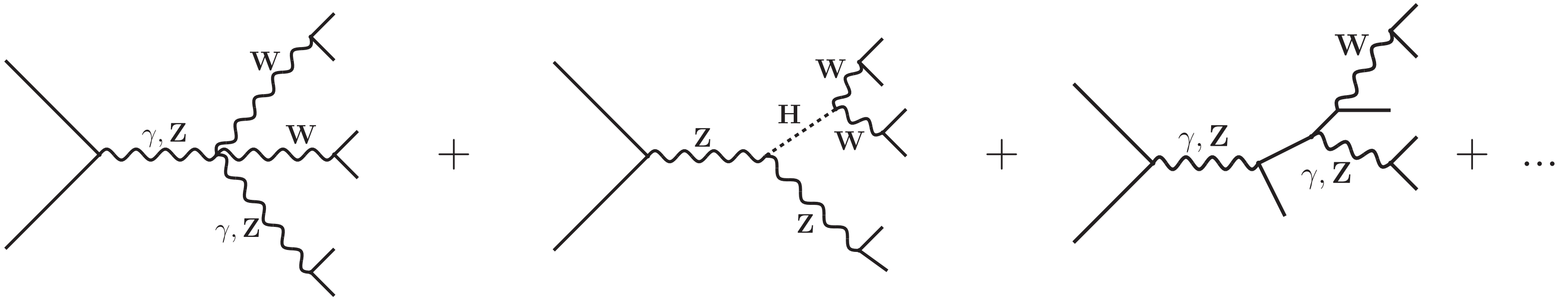
a)



b)



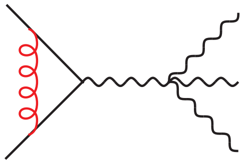
c)



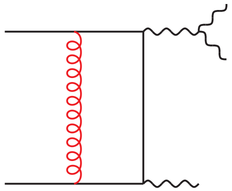
- All resonant and non-resonant matrix elements as well as spin correlations of final state leptons and Higgs contribution included.
- Interference terms due to identical particles in the final state have been neglected.
- All fermion mass effects neglected. ($H\tau\tau$-coupling = 0)

1-loop matrix elements and real emission matrix elements

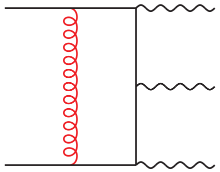
Three different topologies:



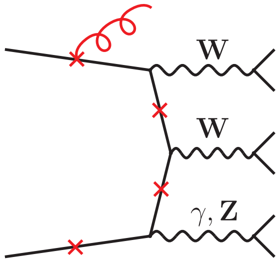
I

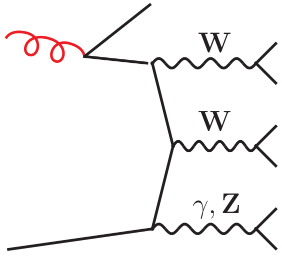


II



III





I Vertex correction proportional to Born matrix element.

II Maximally 4-point integrals appear.

III Up to five external legs (Pentagons):

- Two independent calculations.
- Numerically stable results with Denner Dittmaier method.

- Two different classes: final state gluon and initial state gluon.
- Each of them consists of several hundred Feynman-Graphs.
- Soft and collinear singularities subtracted with Catani-Seymour presription

Input variables for LHC phenomenology

- **PDFs**: CTEQ6L1 at LO and CTEQ6M, $\alpha_S(m_Z) = 0.118$ at NLO.

- **Cuts and Masses**:

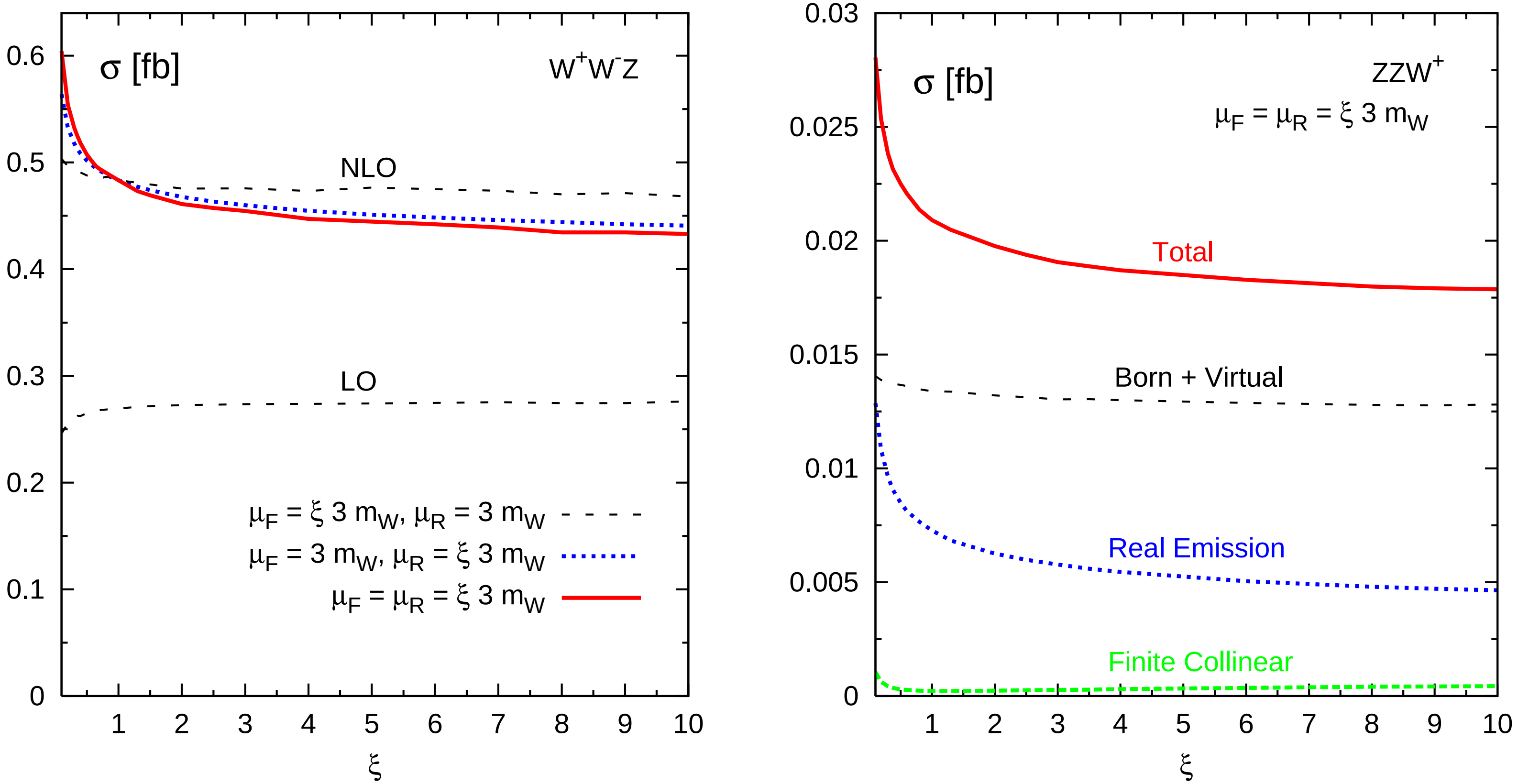
$$p_{T_\ell} > 10 \text{ GeV}, \qquad |\eta_\ell| < 2.5, \qquad m_{\ell^+\ell^-} > 15 \text{ GeV}, \qquad m_H = 120 \text{ GeV}.$$

- **Renormalization- and Factorization Scale**: $\mu_F = \mu_R = 3\, m_W$.

Following results are for electrons and/or muons in the final state:

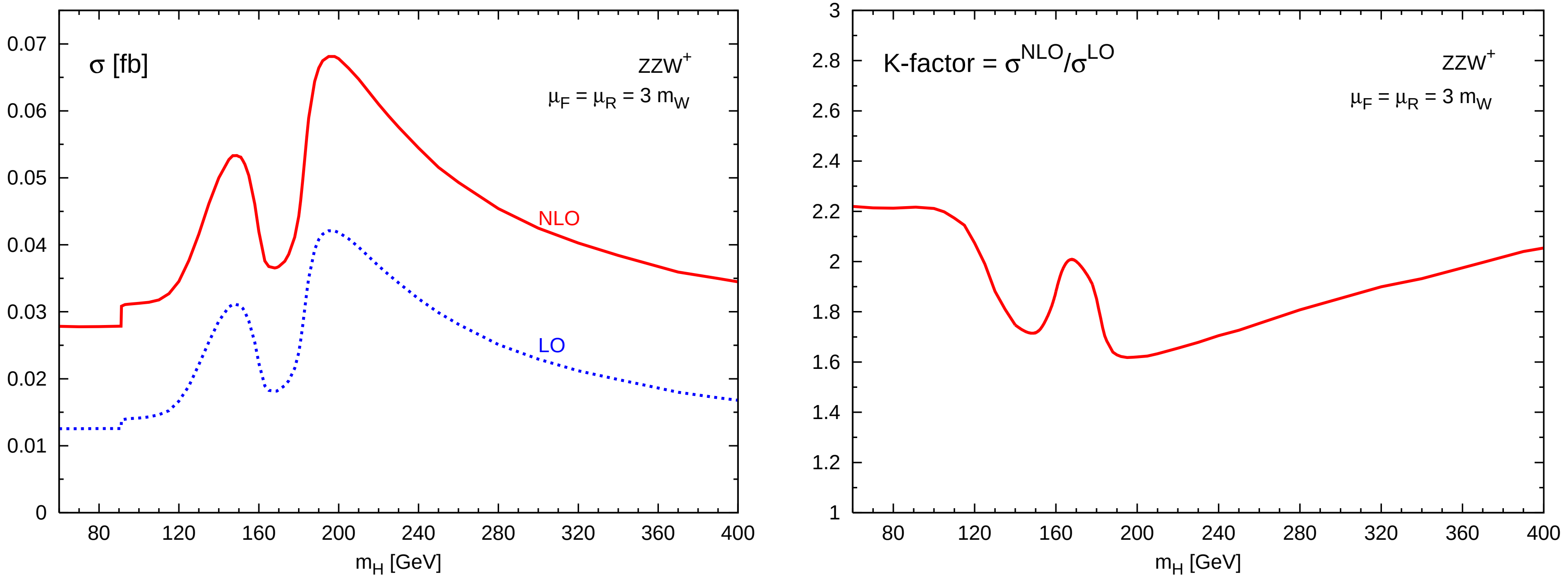
$\Longrightarrow$ Combinatorial factor of 8/4 for the $W^+W^-Z/ZZW^\pm$ production compared to three different lepton families in the final state.

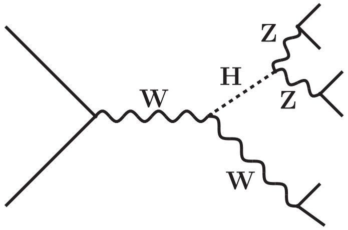
Scale Dependence



- At LO only 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.

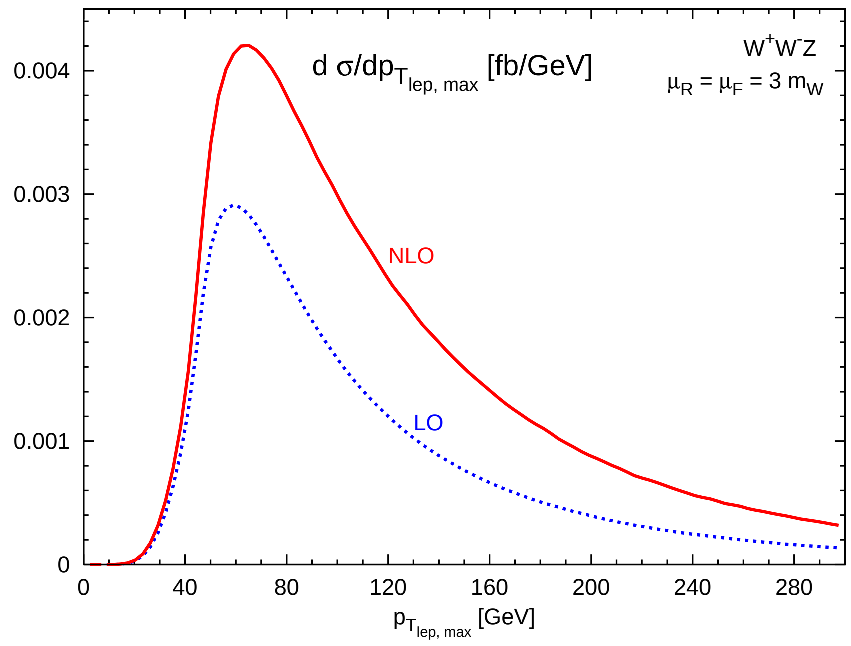
Higgs mass dependence

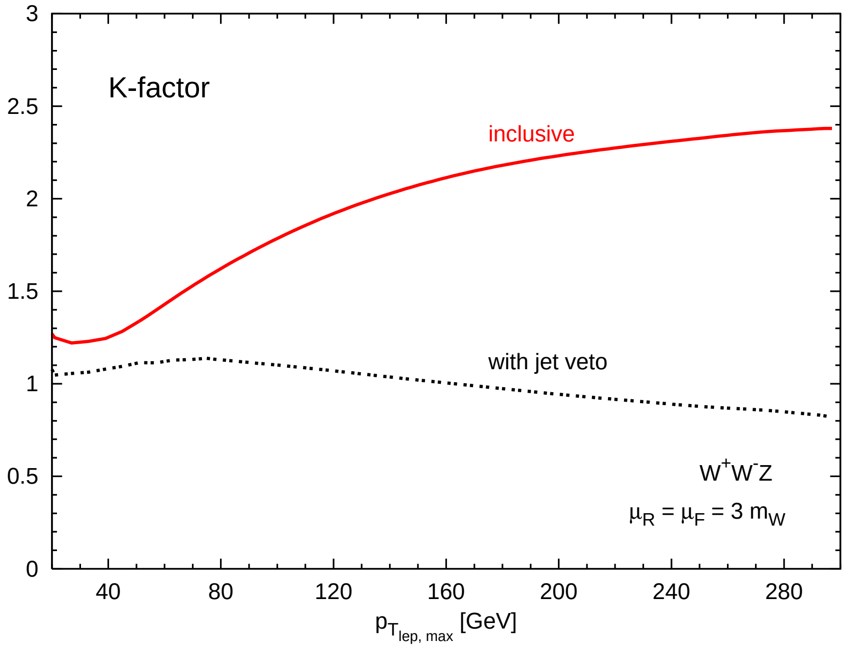




- Cross section reflects behavior of $BR(H \to ZZ)$
- K-factor is reduced by Higgs contribution.
  K-factor for $pp \to WH$ production is about K = 1.3
  $\Longrightarrow$ Different K-factor for resonance production

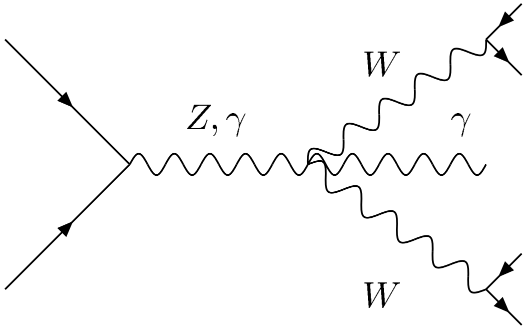
Differential cross section and K-factor for the highest-p_T-lepton



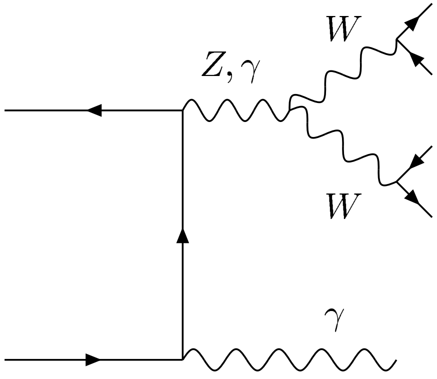


- K-factor increases with transverse momentum (p_T) by almost a factor of 2.
- Strong phase space dependence due to events with high p_T jets recoiling against the leptons.
- Veto on jets with $p_T > 50$ GeV leads to fairly flat K-factor.

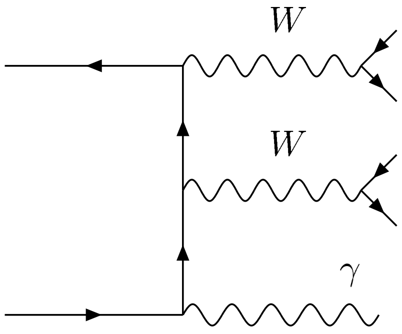
Extension to $W^+W^-\gamma$ and $ZZ\gamma$ Production



I



II



III

New elements of calculation:

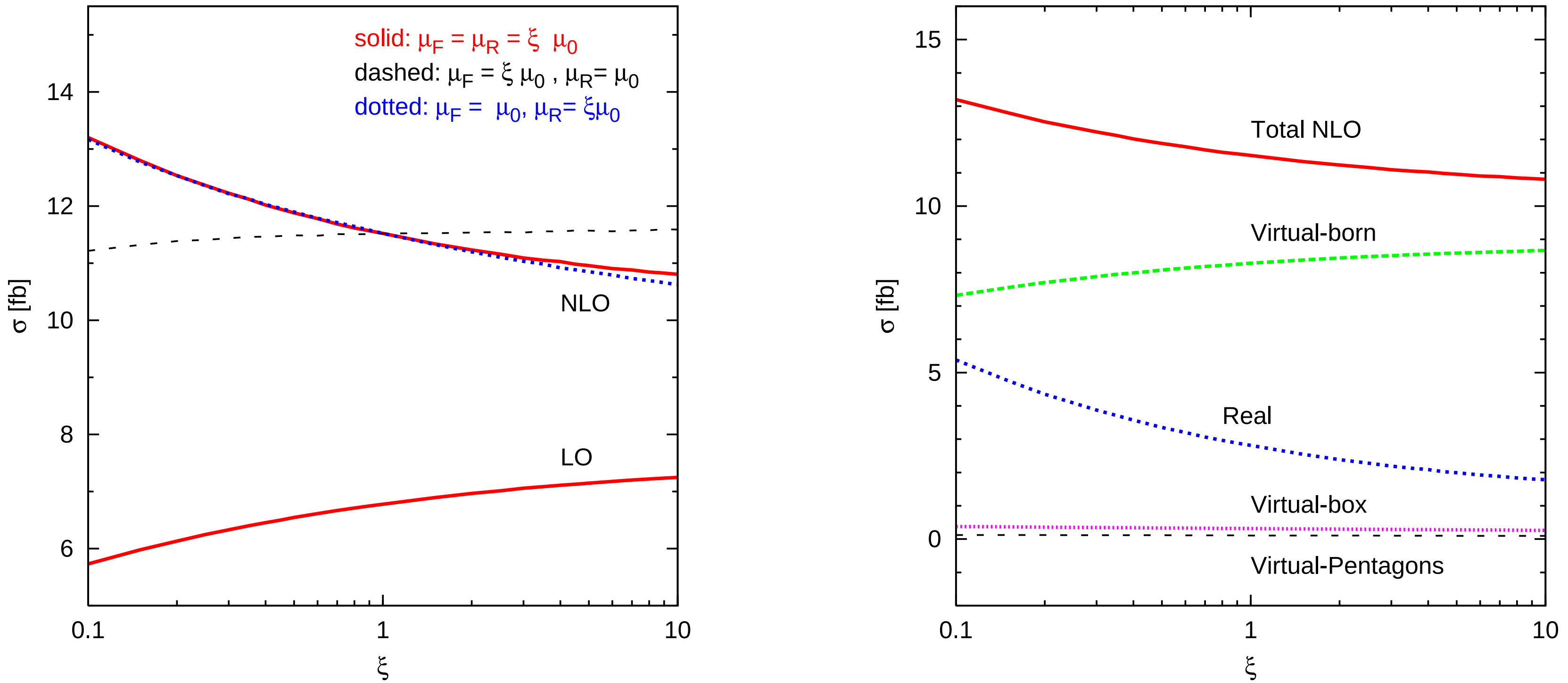
- Different infrared divergence structure of individual loop integrals but same final virtual expressions in terms of finite parts of C_{ij}, D_{ij}, and E_{ij} functions
- Photon isolation from jets for real emission contributions: use Frixione isolation

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

- Final state photon radiation becomes important: adapt phase space to this

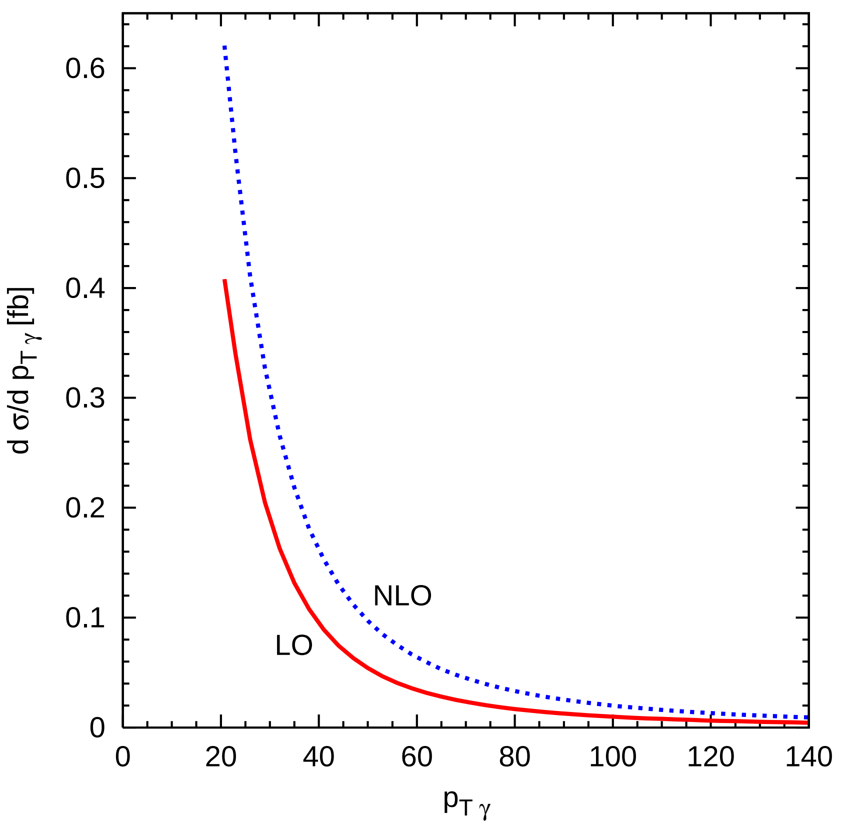
Scale dependence of integrated cross sections

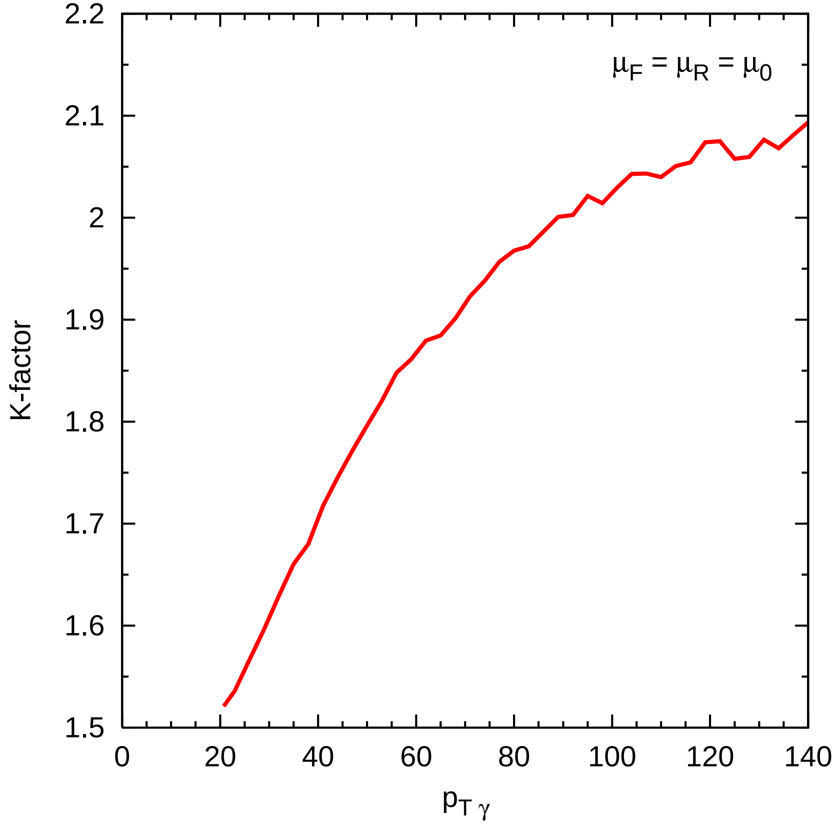
Variation of μ_F, μ_R about $\mu_0 = m_{WW\gamma}$



- Behaviour similar to VVV production: LO scale variation much smaller than NLO correction
- NLO scale dependence largely due to real emission contributions $\Longrightarrow$ jet veto will reduce it
- Box and pentagon contributions ($\tilde{\mathcal{M}}_V$ terms) are quite small: 3% and $< 1\%$ of total

NLO Corrections to Distributions: p_T of photon



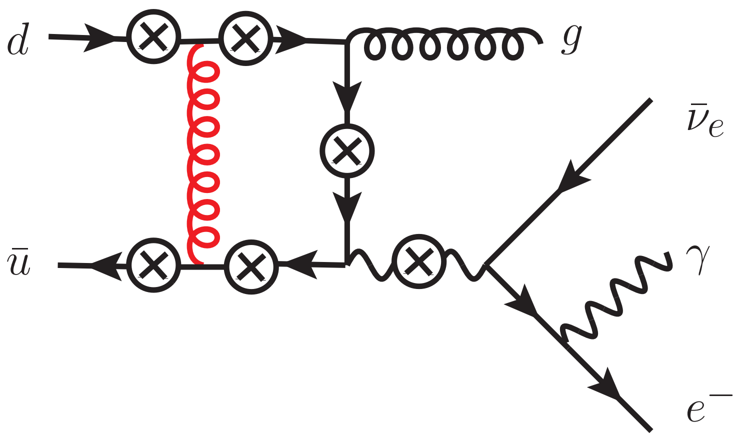


Strong phase space dependence of K-factors (depends on LO scale choice)

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

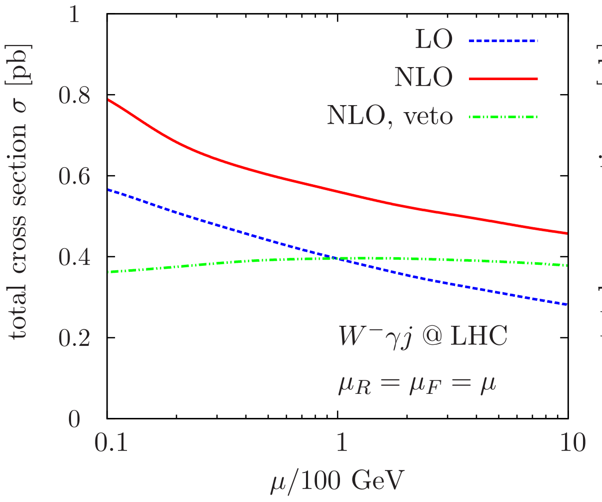
- Initial and final state photon radiation. Final radiation from lepton is important
- Virtual corrections up to pentagons
- External gluon already at tree level $\Longrightarrow$ *nonabelian* boxes with three gluon vertex
- Larger number of subtraction terms

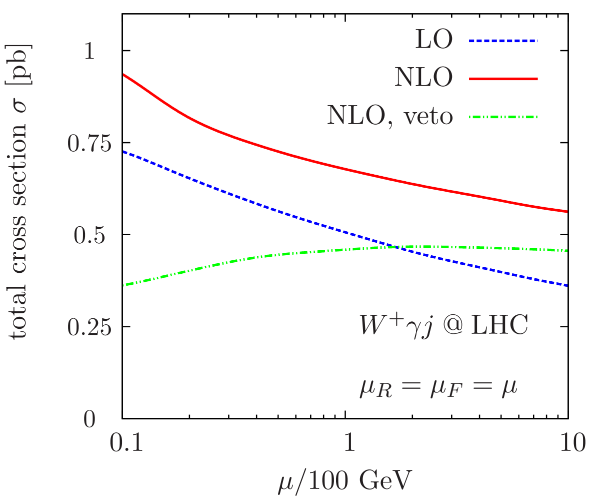
Scale dependence: LHC and Tevatron

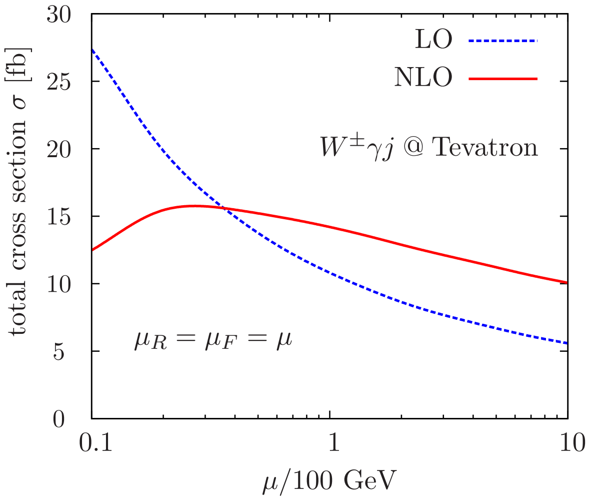
Identify lepton, photon and one or more jets with k_T-algorithm ($D = 0.7$)

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

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





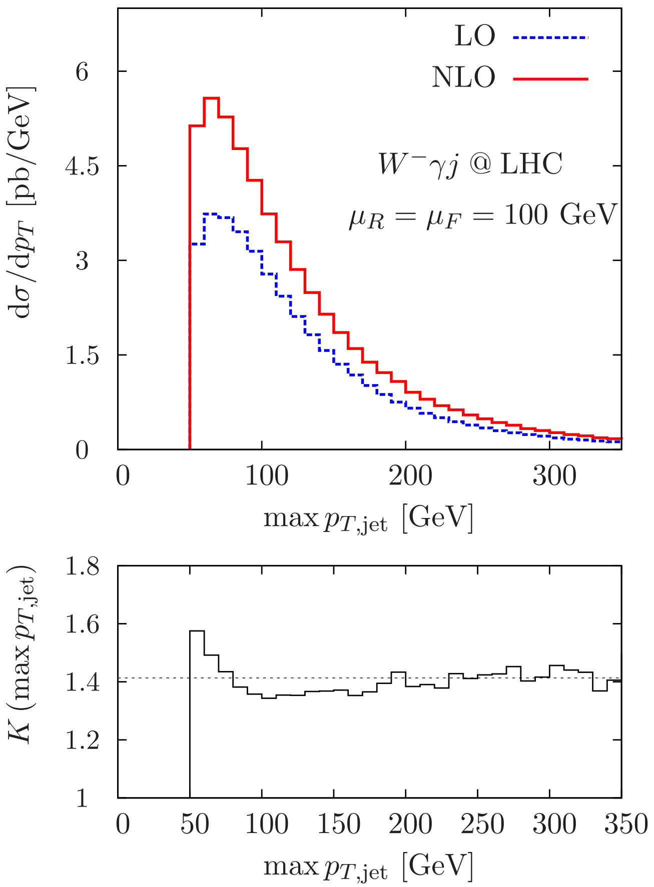


Scale variation at LHC for $\mu_F = \mu_R = 2^{\pm1} \cdot 100$ GeV: ±11% at LO reduced to ±7% at NLO

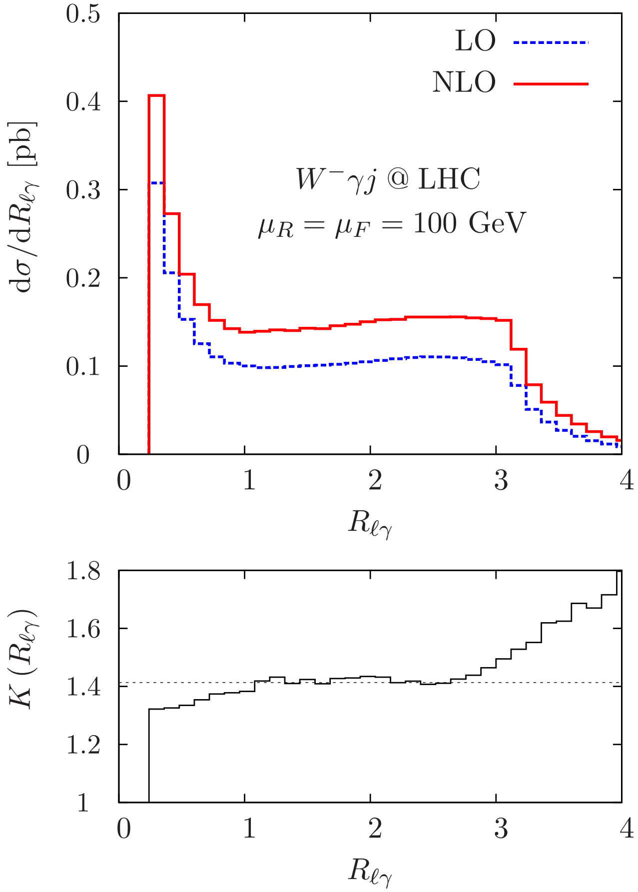
Almost flat behaviour for veto of additional jets of $p_T > 50$ GeV should be taken as accidental and not as a measure of NLO uncertainties

NLO corrections to distributions

p_T of hardest jet



lepton photon separation



- Clear shape changes of distributions when going from LO to NLO
- Average K-factor of 1.4 at LHC is significantly larger than LO scale variation

Conclusions

- VBFNLO provides NLO QCD corrections to a host of processes, in particular vector boson fusion, VVV production and VVj production
- All off-shell diagrams as well as the Higgs-contributions have been considered.
- VBFNLO also contains hjj production from gluon fusion at LO with full quark and squark mass dependence

  Code of 2011 release is available at
  http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb
- Upcoming extensions include $W\gamma\gamma$ jet production at NLO and WZ and $W\gamma$ production with anomlous triple gauge interactions
- VBFNLO is collaborative effort! Thanks to
  V. Hankele, B. Jäger, M. Worek, S. Palmer, M. Rauch, C. Oleari, K. Arnold, J. Bellm, G. Bozzi, F. Campanario, C. Englert, B. Feigl, T. Figy, J. Frank, M. Kerner, G. Klämke, M. Kubocz, S. Plätzer, S. Prestel, H. Rzehak, F. Schissler, M. Spannowsky

Backup slides

The perturbative unitarity bound

A very severe constraint on the Higgs boson mass comes from unitarity of the scattering amplitude.

$$\text{unitarity} \Longleftrightarrow \text{QM probability} < 1$$

Scattering probability bounded from above!

Considering the elastic scattering of longitudinally polarized Z bosons

$$Z_L Z_L \to Z_L Z_L$$

$$\mathcal{M} = -\frac{m_H^2}{v^2}\left[\frac{s}{s-m_H^2} + \frac{t}{t-m_H^2} + \frac{u}{u-m_H^2}\right] \qquad \text{in the } s \gg m_Z^2 \text{ limit}$$

where s, t and u are the usual Mandelstam variables.

The perturbative unitary bound on the $J = 0$ partial wave amplitude takes the form

$$s \gg m_H^2 : \qquad |\mathcal{M}_0|^2 = \left[\frac{3}{16\pi}\frac{m_H^2}{v^2}\right]^2 < 1 \qquad \Longrightarrow \qquad m_H < \sqrt{\frac{16\pi}{3}}v \approx 1\ \text{TeV}$$