VECTOR BOSON FUSION AND NLO QCD CORRECTIONS

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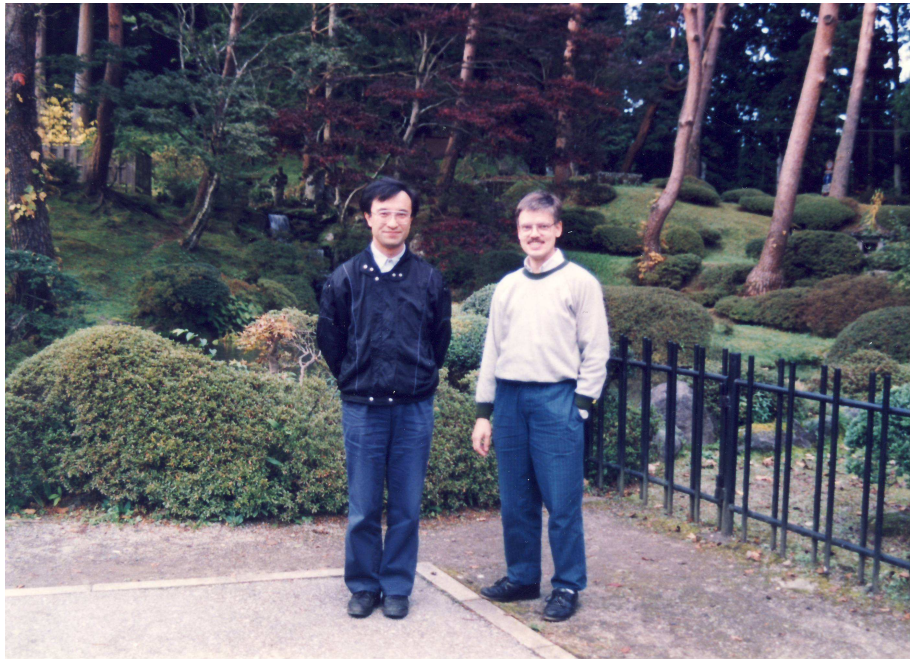
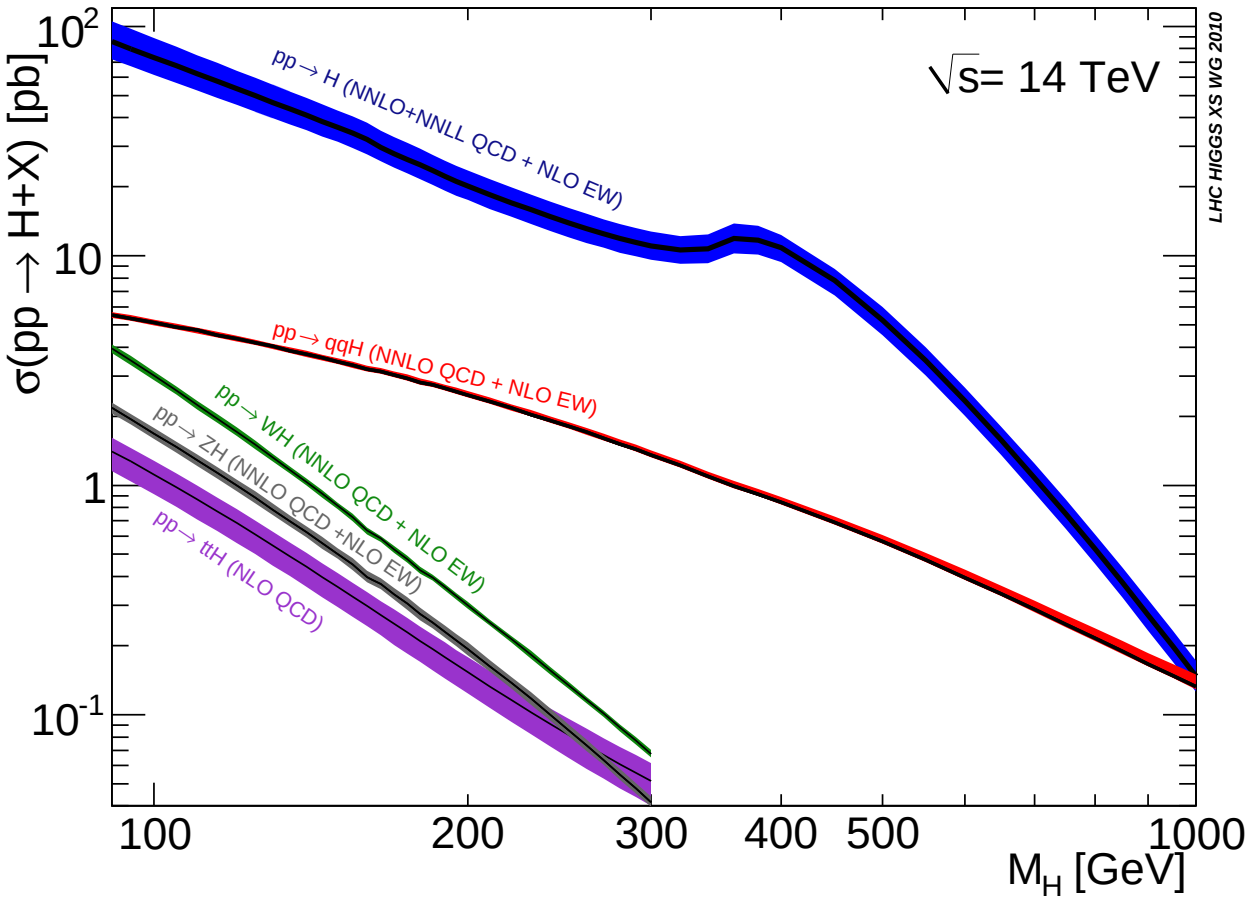
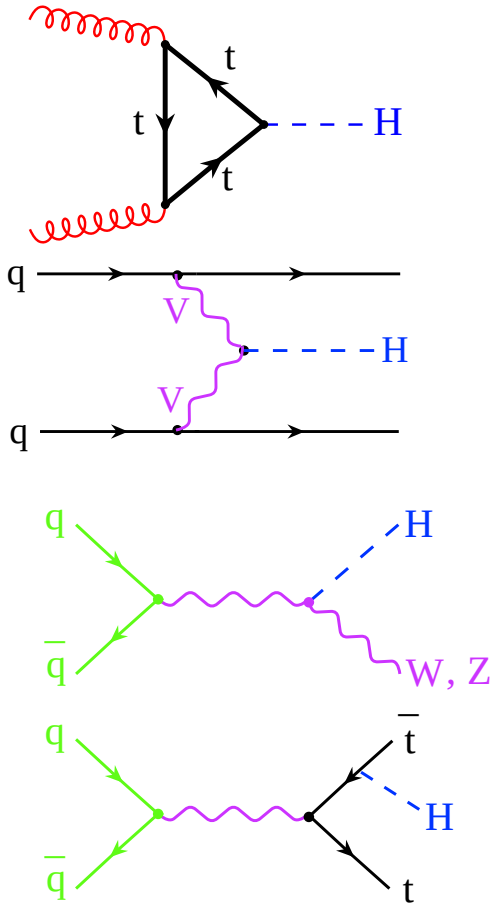
- Higgs prodcution at LHC
- Vector Boson Fusion
- NLO QCD corrections to VVjj production
- Effective Lagrangians and VBF

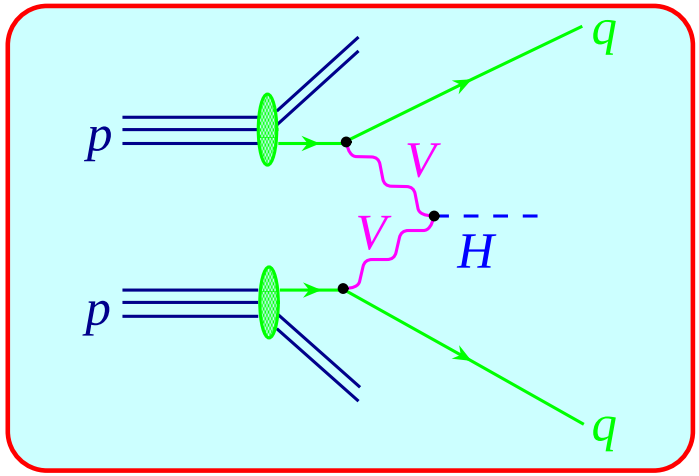


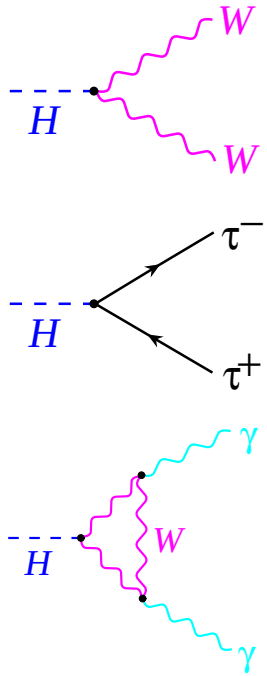
Higgs production at the LHC





Vector Boson Fusion





$m_H > 120$ GeV

$m_H < 140$ GeV

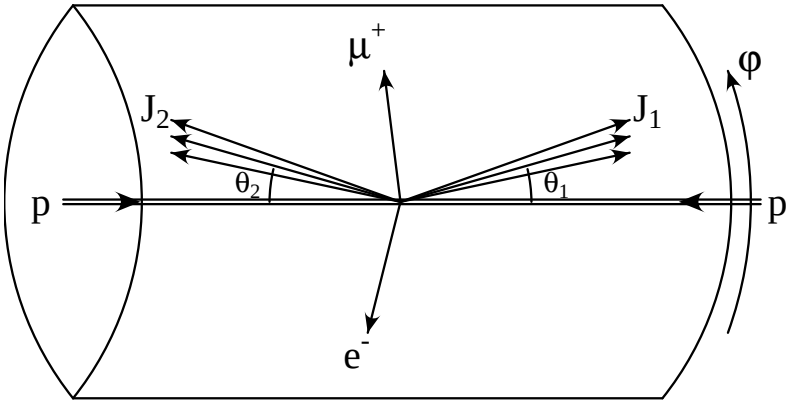
$m_H < 150$ GeV

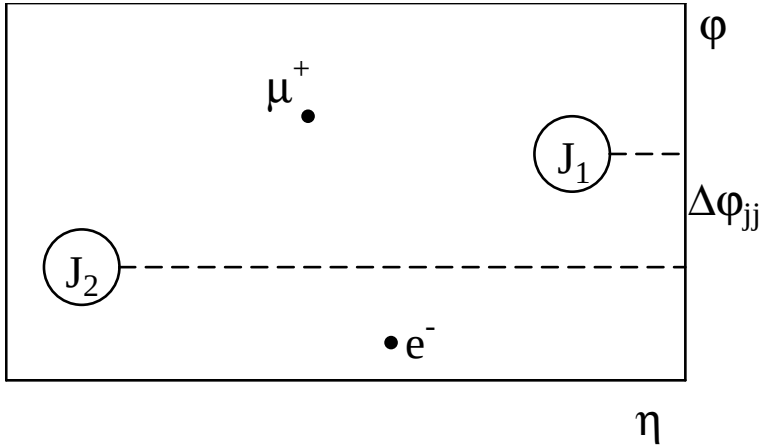
[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .]

First consideration of $h \to \gamma\gamma$ in VBF in 1997 Rainwater, D.Z, hep-ph/9712271

Semileptonic tau signal for $h \to \tau\tau$ in VBF in 1998 Rainwater, D.Z, Hagiwara, hep-ph/9808468

VBF signature



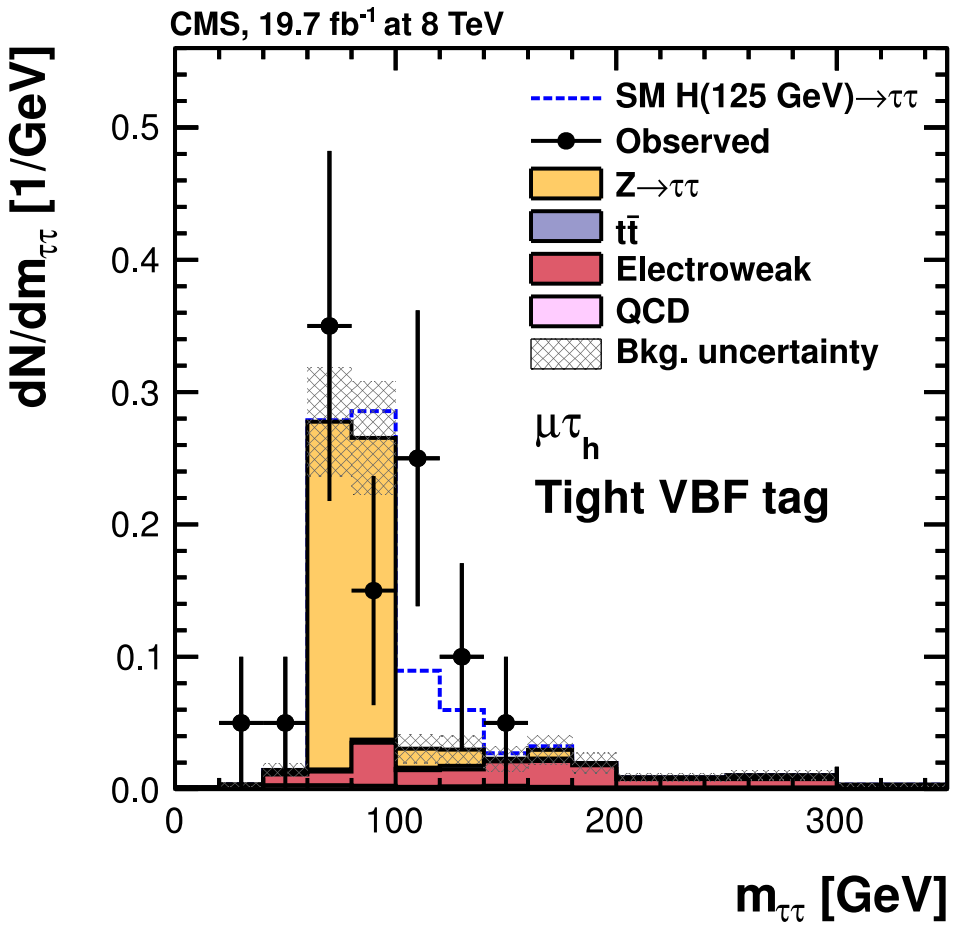


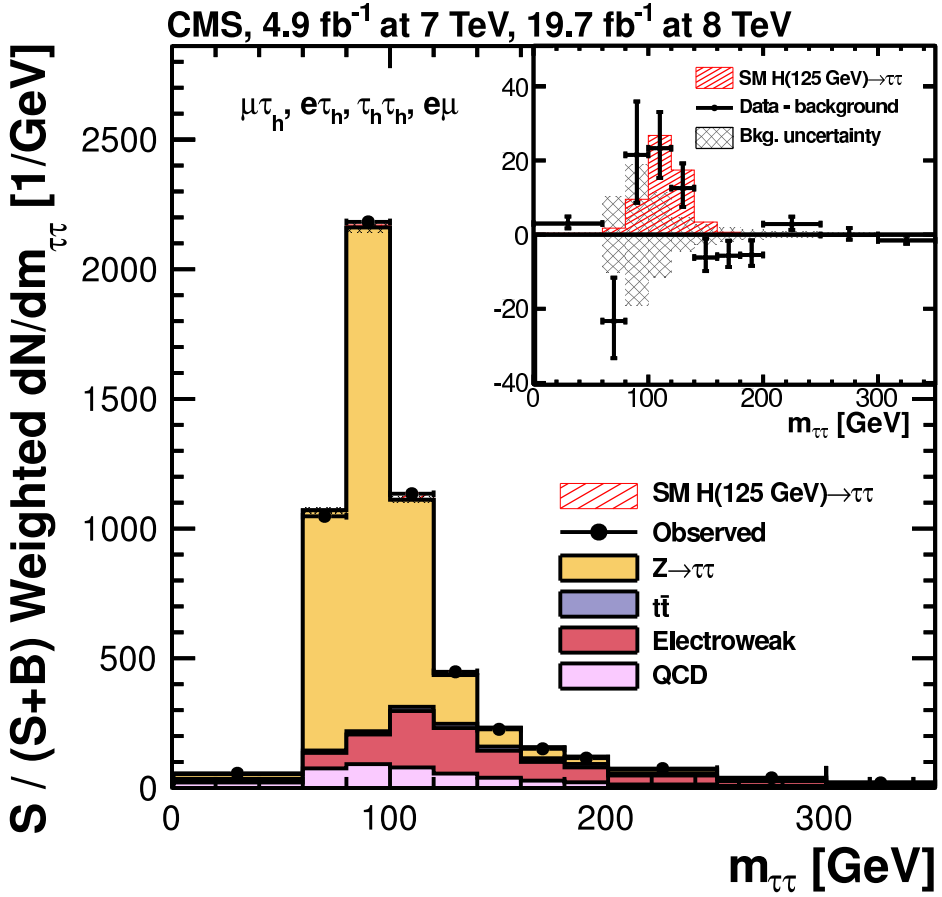
Characteristics:

- 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 with $p_T > 20$ GeV and $|\eta| < 2.5$)

Higgs decay to tau pairs

Most sensitive search channel is via VBF. Of course, experiments consider all...

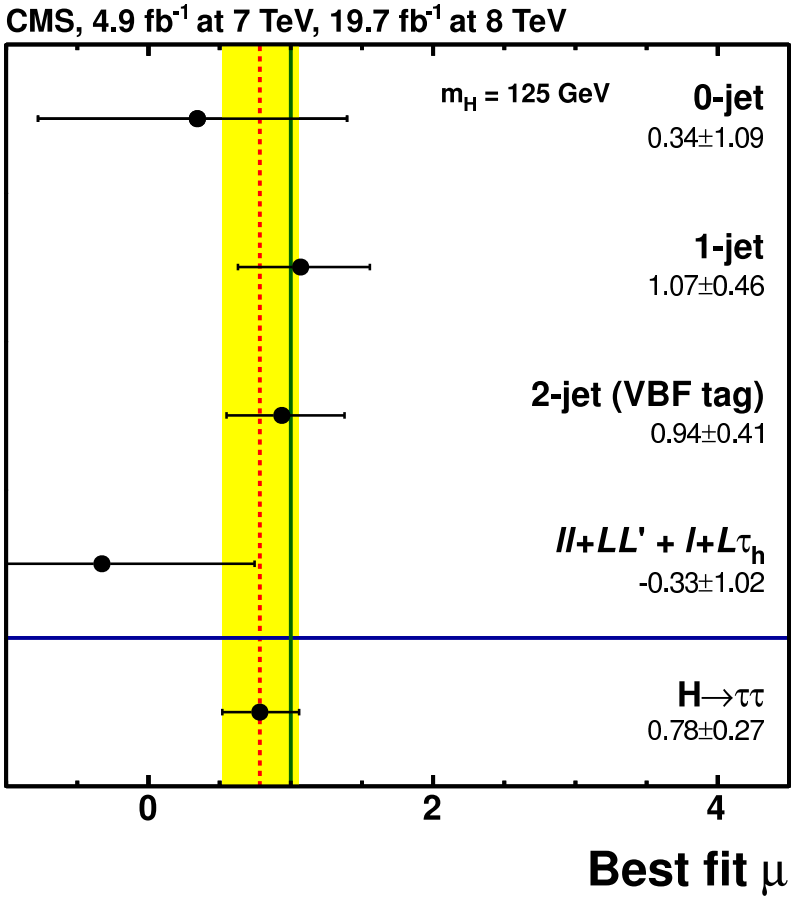




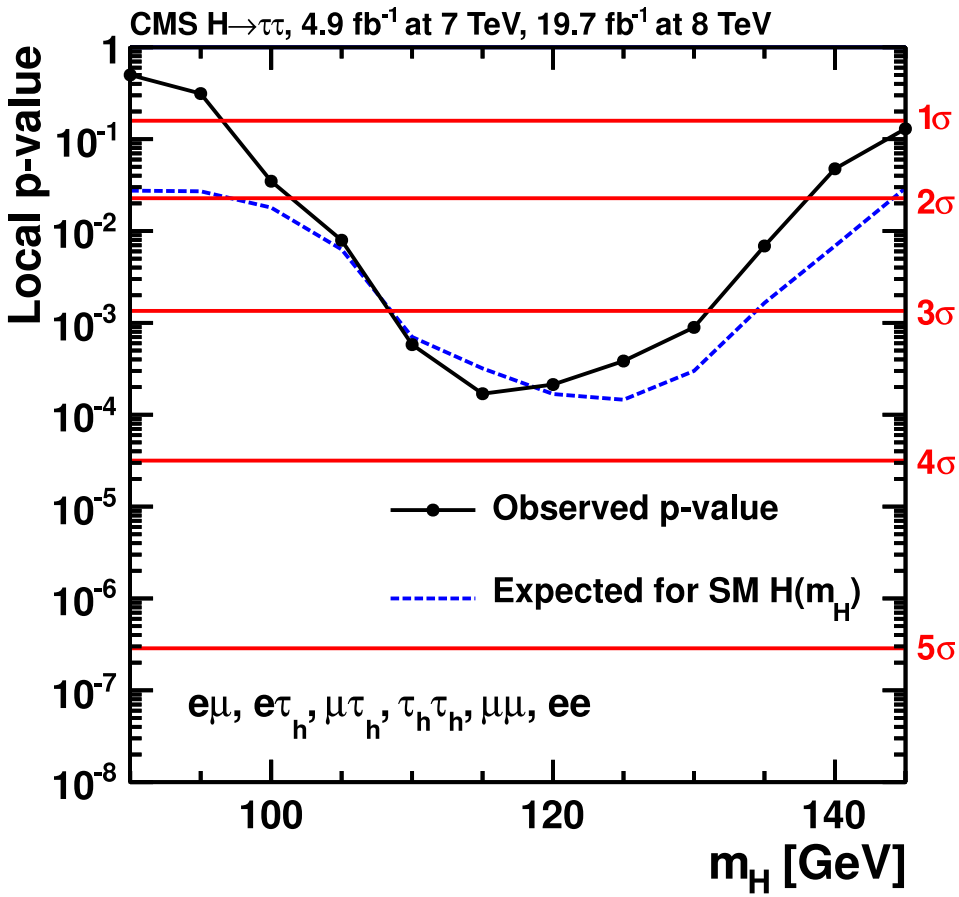
Clearly visible indication for Higgs decay to tau-lepton pairs around 120 GeV

Comparison of $\tau\tau$ signal with SM expectation

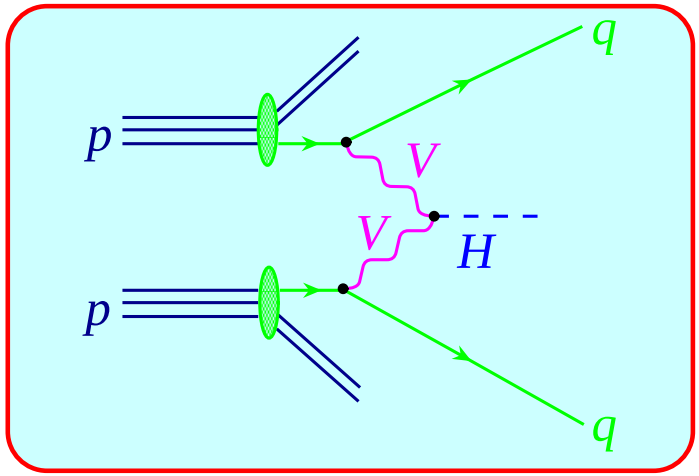
Best fit of signal strength

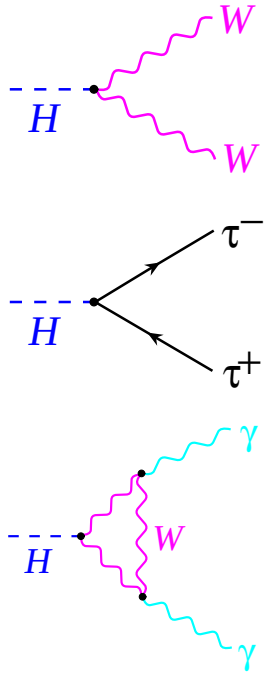


Probability of background fluctuation



Vector Boson Fusion





$m_H > 120$ GeV

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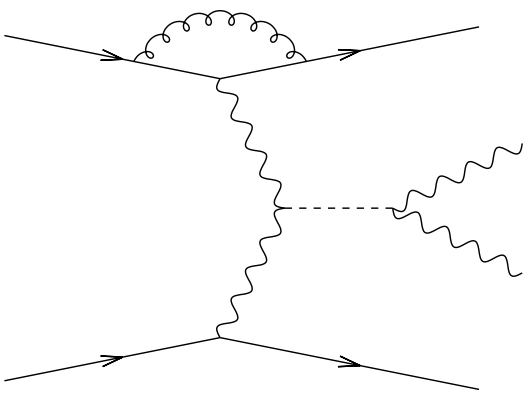
Most measurements can eventually be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \times$ BR, of order 10%.

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

NLO QCD correction to VBF 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

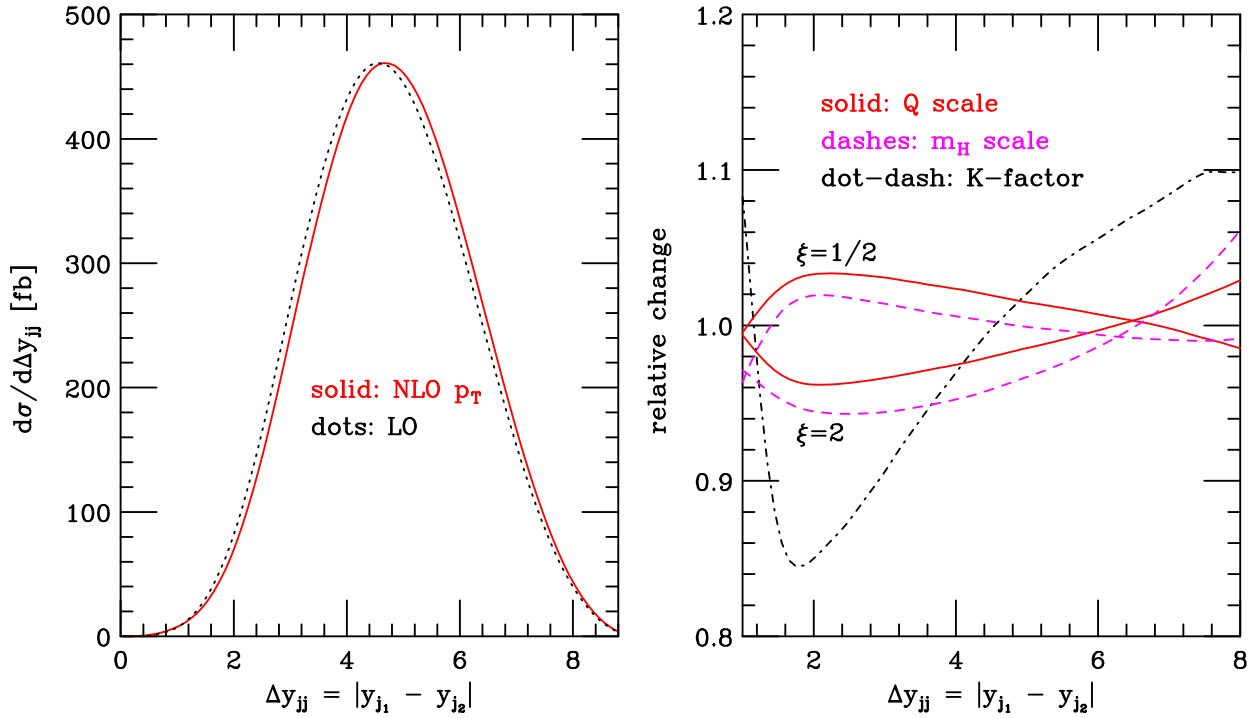
Remaining virtual corrections are accounted for by trivial factor multiplying Born cross section

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

- 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

Size of NLO QCD corrections

- Small QCD corrections of $\mathcal{O}(10\%)$
- Tiny scale dependence at NLO
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- K-factor is phase space dependent
- QCD corrections under excellent control
  confirmed by NNLO corrections to inclusive VBF cross section
  Bolzoni, Maltoni, Moch, Zaro arXiv:1003.4451
- Need electroweak corrections for 5% uncertainty
  Ciccolini, Denner, Dittmaier, 0710.4749
  Figy, Palmer, Weiglein arXiv:1012.4789



$m_H = 120$ GeV, typical VBF cuts

Limitations of the $qq \to qqH$ picture

Forget $m_h \approx 125$ GeV for the moment .... what would happen for a heavy Higgs?
At $m_H >$ few hundred GeV (for say $\Gamma_H/m_H > 0.1$) we need to take interference with continuum electroweak into account

Implication:

- Consider full processes $qq \to qqVV$ or $qq \to qq\bar{f}_1 f_2 \bar{f}_3 f_4$
- s-channel Higgs exchange graph with inverse propagator

$$\Delta_H(s) = s - s_H = s - m_H^2 + i m_H \Gamma_H$$

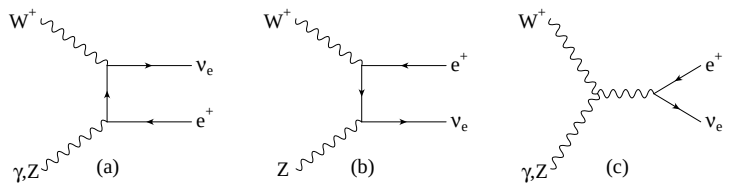
  is just one contribution.

Even with $m_h = 125$ GeV resonance, with couplings somewhat different from SM prediction, sizable deviations from SM weak-boson-scattering are possible
$\Longrightarrow$ Need precise SM predictions, i.e. at least NLO QCD corrections to weak boson scattering

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

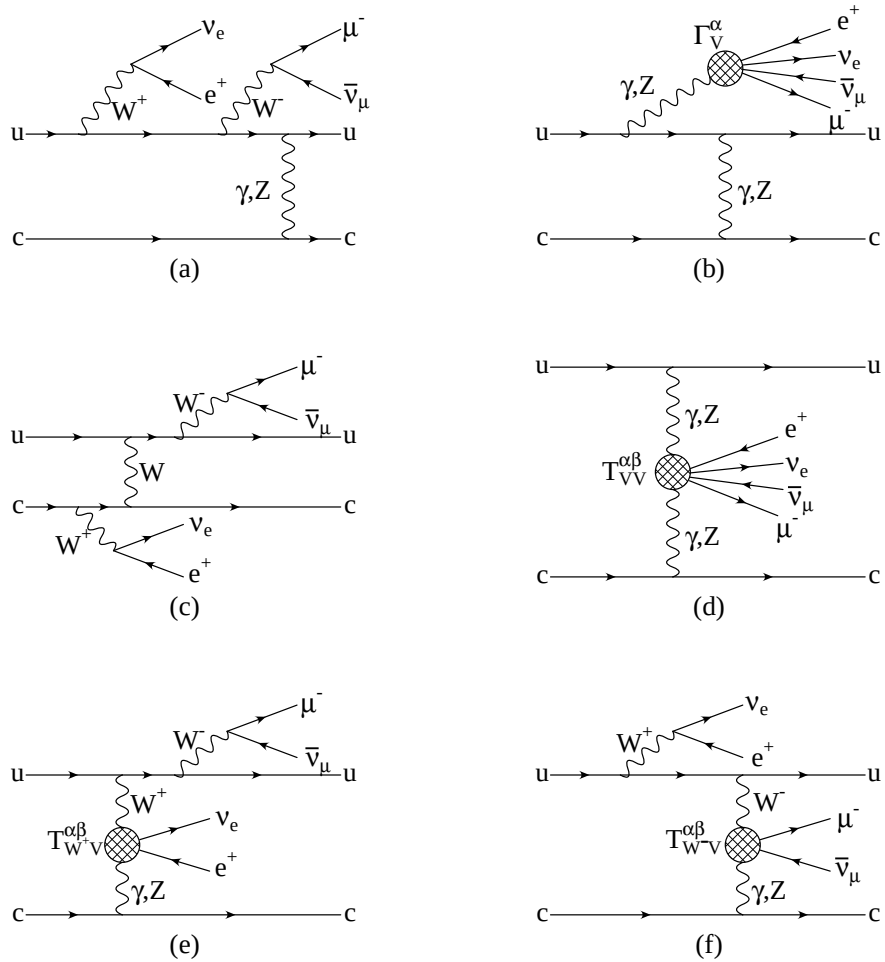
- example: WW production via VBF with leptonic decays: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\Longrightarrow$ 181 Feynman diagrams at LO
- CC $\Longrightarrow$ 92 Feynman diagrams at LO

Use modular structure, e.g. leptonic tensor



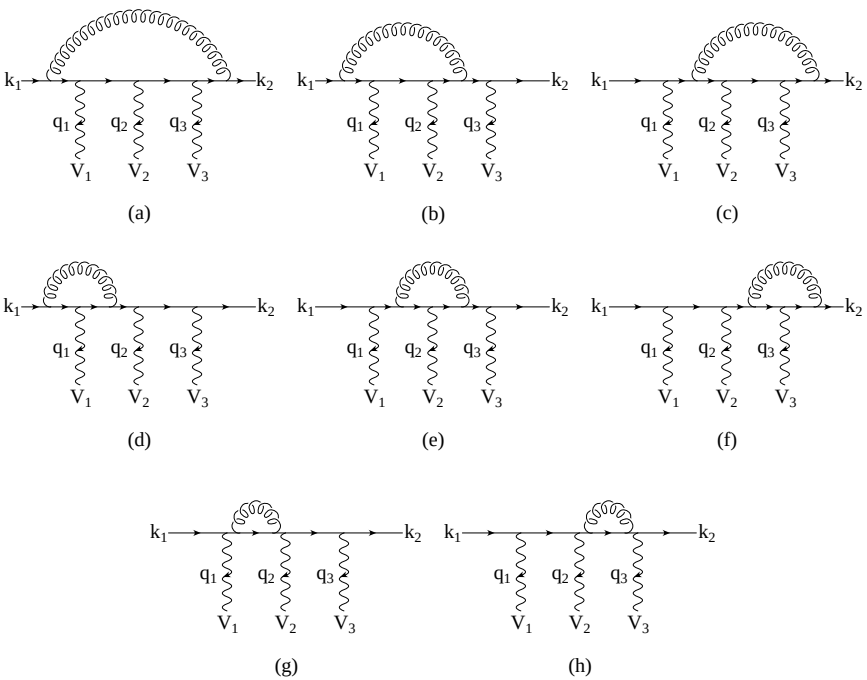
Calculate once, reuse in different processes

Speedup factor $\approx$ 70 compared to 2005 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

$$\mathcal{M}_V^{(i)} = \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\text{virt}}\right] + \widetilde{\mathcal{M}}^{(i)}_{V_1 V_2 V_3, \tau}(q_1, q_2, q_3) + \mathcal{O}(\epsilon)$$

- 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

Most challenging for virtual: pentagon corrections

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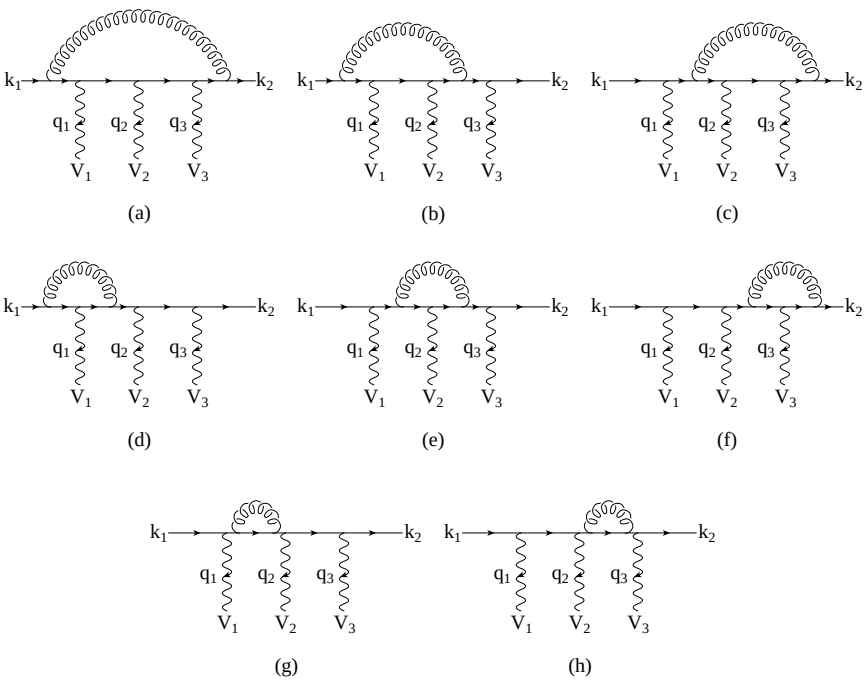

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Helicity amplitude techniques

Amplitude techniques which are used in VBFNLO were developed by Kaoru Hagiwara and myself in the late 80's

Helicity Amplitudes for Heavy Lepton Production in e^+e^- Annihilation
Nucl. Phys. **B274** (1986) 1

Amplitudes for Multi-Parton Processes Involving a Current at e^+e^-, $e^\pm p$, and Hadron Colliders
Nucl. Phys. **B313** (1989) 560

Formalism uses direct multiplication of γ-matrices in the Weyl-basis

- Very efficient for virtual as well as real emission amplitudes
- Formalism is basis for HELAS routines and, thereby, MadGraph
- Allows for iterative construction of amplitudes, especially for real emission contributions.

Phenomenology: Size of NLO corrections to VBS

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

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

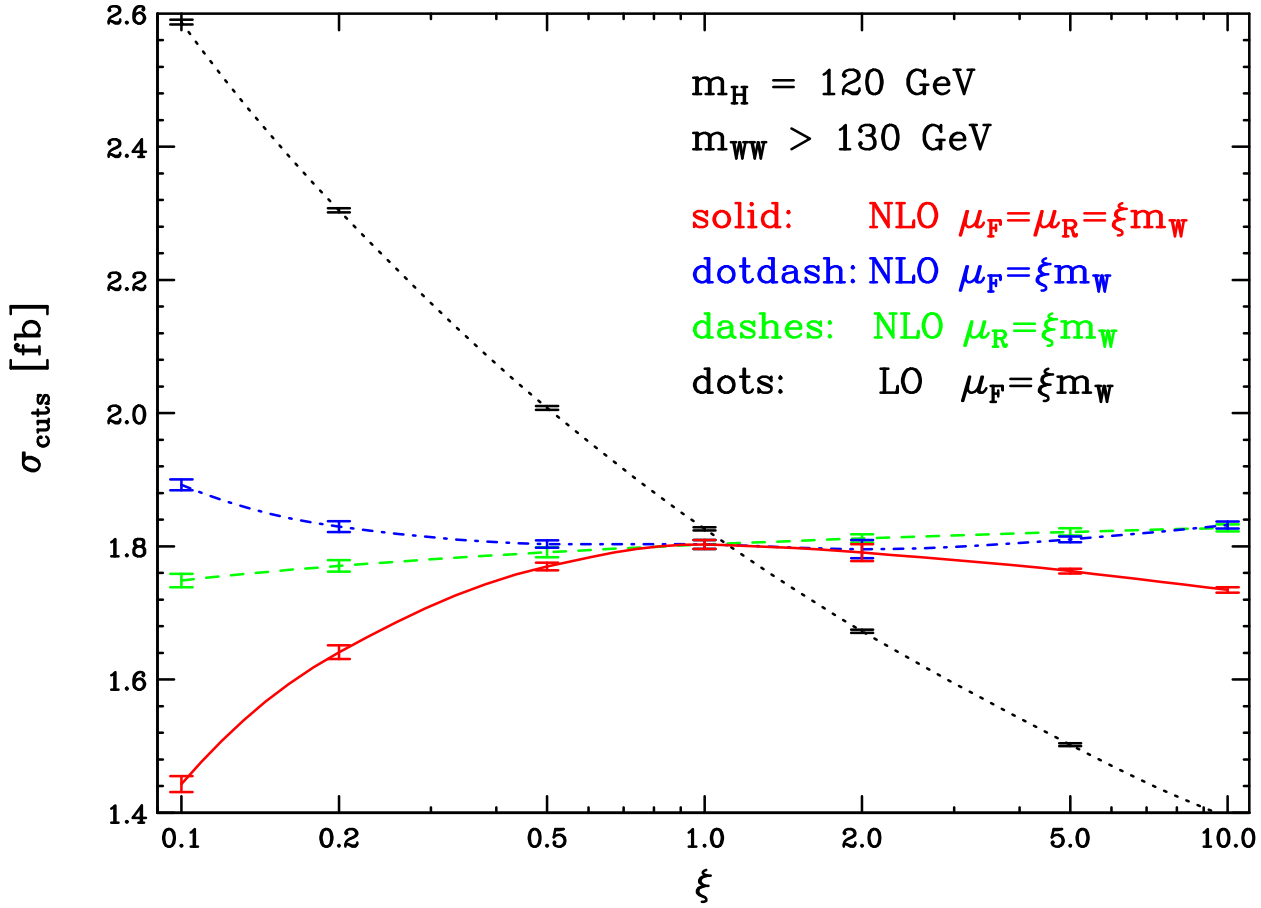
For scale dependence studies we have considered

$\mu = \xi\, m_V$ 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

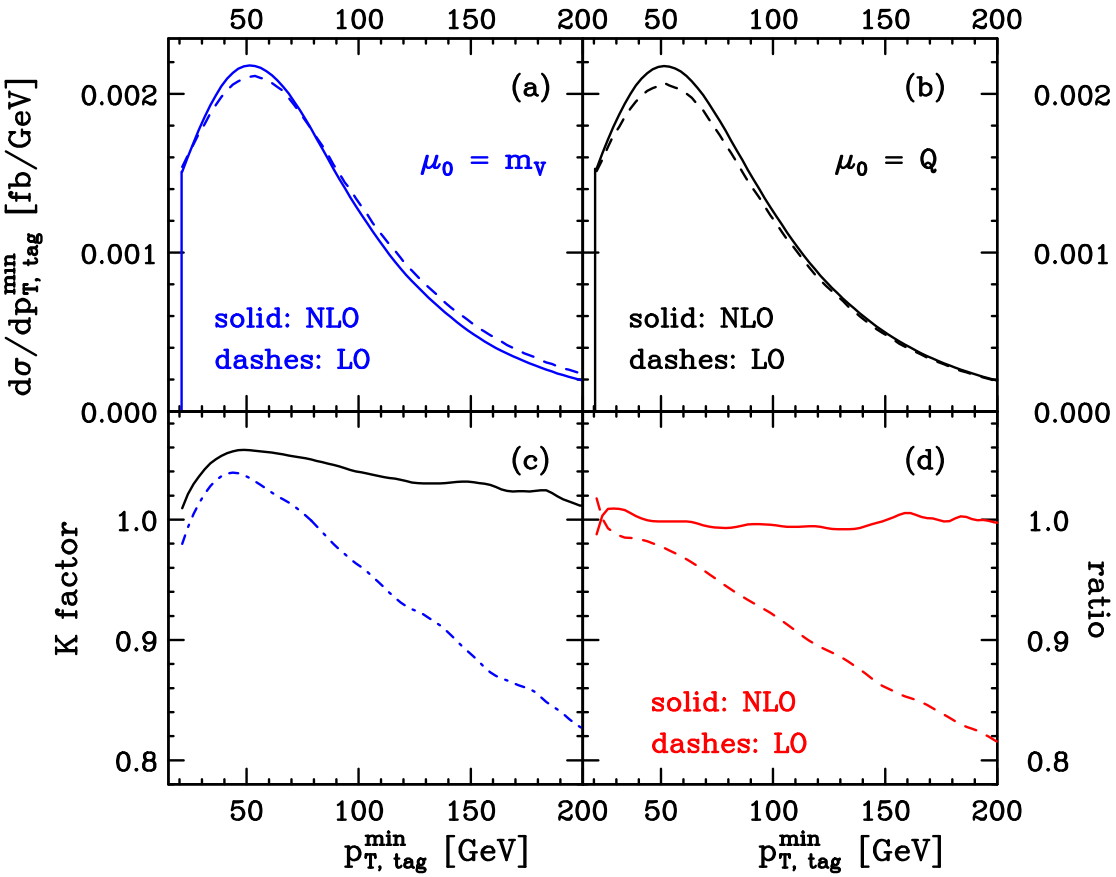
Stabilization of scale dependence at NLO

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

NLO corrections to VBF processes 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 ($qq \to qqV$)

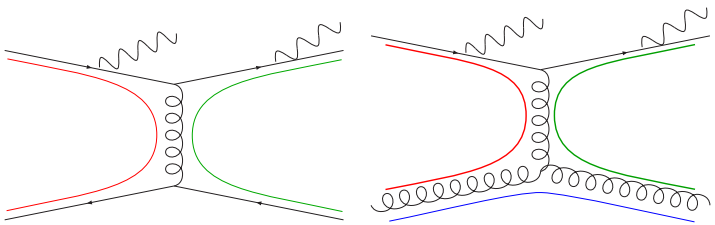
  Oleari, DZ

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

  Jäger, Oleari, DZ

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

Example of 2→4 process at NLO: QCD $WZjj$ production

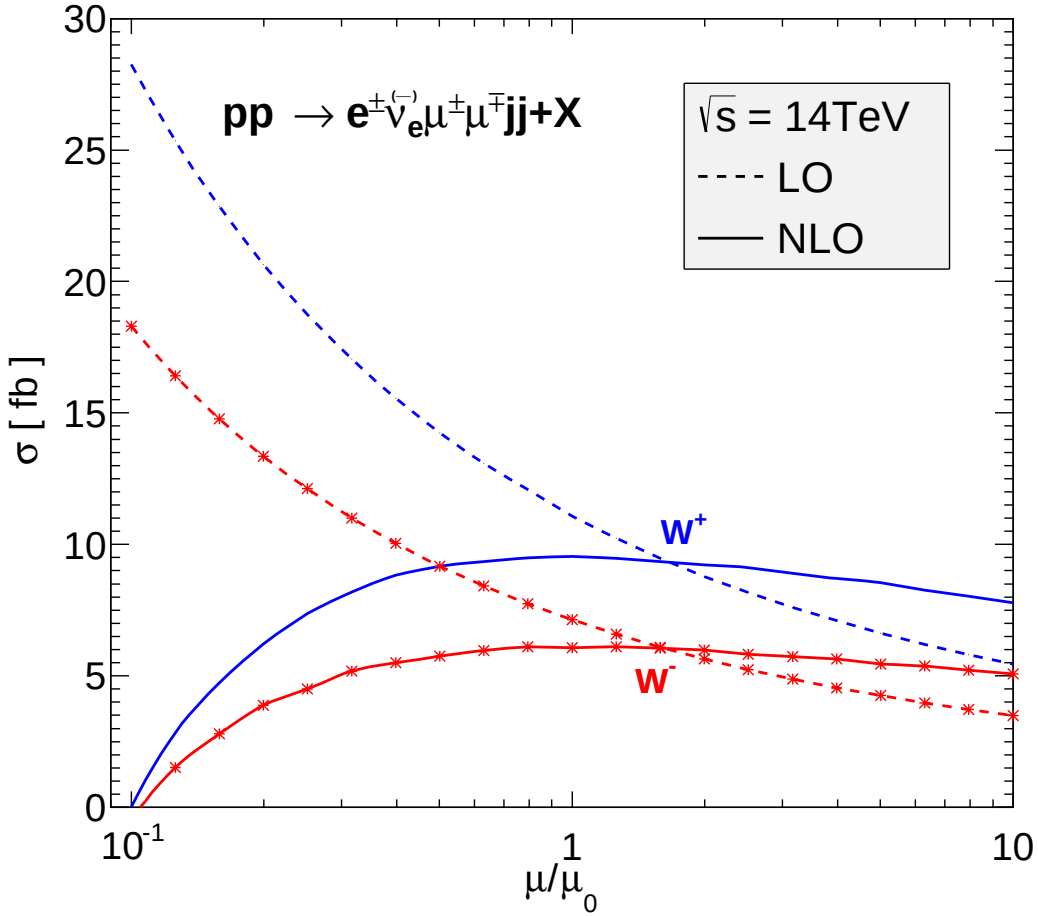


- 4 flavour scheme
- Cuts:

  $p_{Tj} > 20$ 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, $NF = 4$

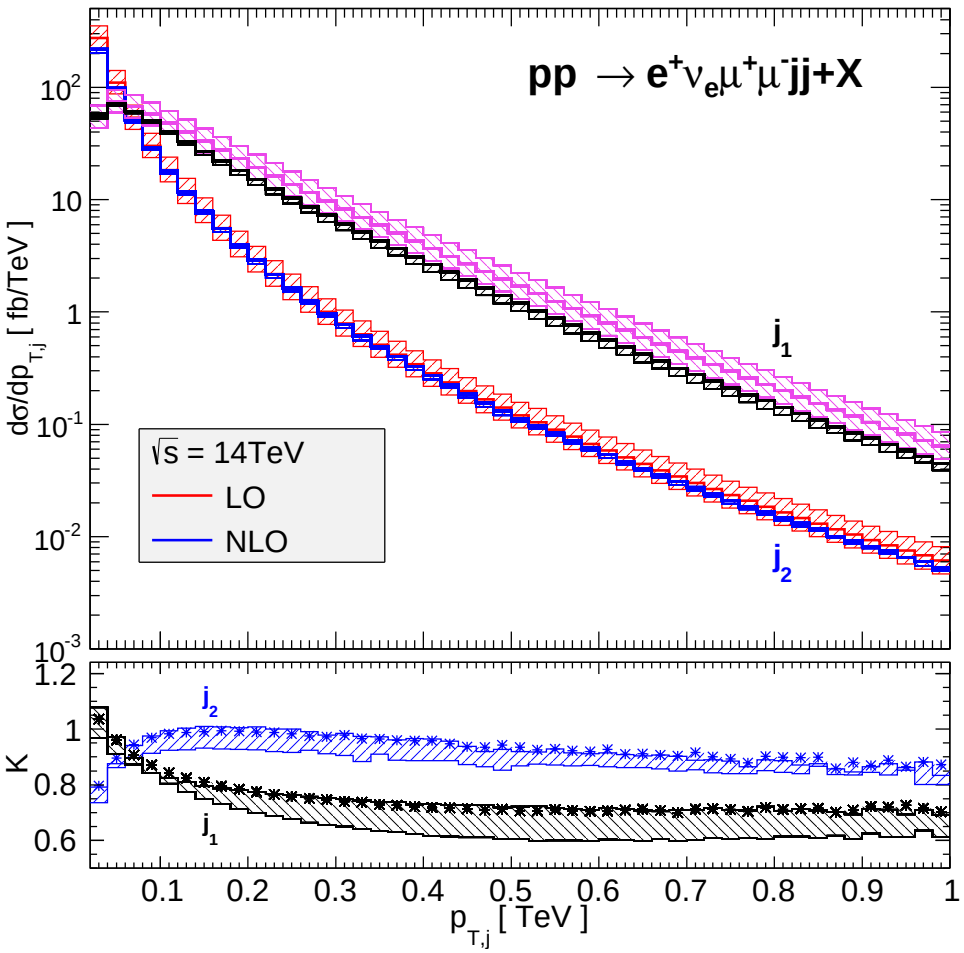
scale dependence: $\mu_0 = \left(\sum p_{T,\text{jet}} + E_{T,W} + E_{T,Z}\right)/2$



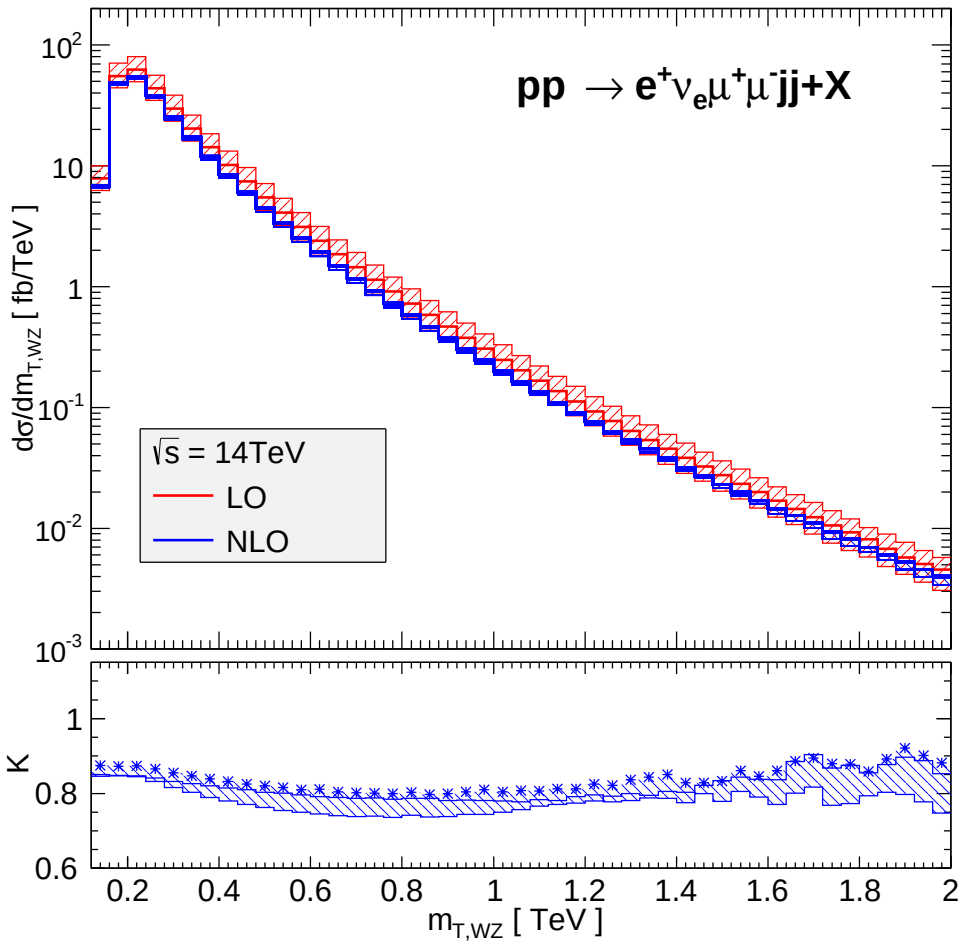
Work with Matthias Kerner, Paco Campanario, Ninh Duc Le: arXiv:1305.1623

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

Extensions in 2014 update of VBFNLO

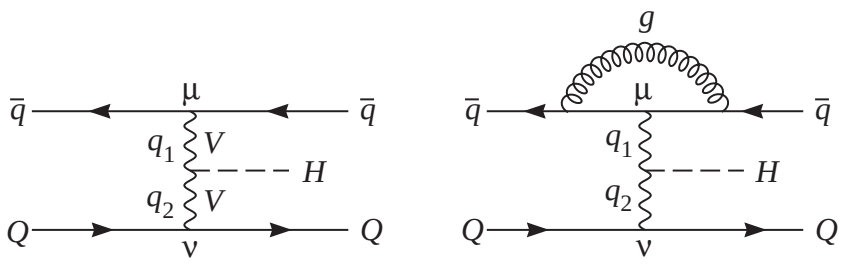
Additional NLO QCD corrected processes implemented in 2014 release:

- 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 $VV \to VV$ scattering processes.

Also completed now are $ZZjj$ and $Z\gamma jj$ production at order $\alpha^2\alpha_s^3$

Tensor structure of the HVV coupling

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



(a) (b)

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

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

Connection to effective Lagrangian

We need model of the underlying UV physics to determine the form factors $a_i(q_1, q_2)$

Approximate its low-energy effects by an effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{f_{WW}}{\Lambda^2}\phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi + \frac{f_\phi}{\Lambda^2}\left(\phi^\dagger\phi - \frac{v^2}{2}\right)(D_\mu\phi)^\dagger D^\mu\phi + \cdots + \sum_i \frac{f_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

Gives leading terms for form factors, e.g. for hWW coupling

$$a_1 = \frac{2m_W^2}{v}\left(1 + \frac{f_\phi}{\Lambda^2}\frac{v^2}{2} + c_W^{(1)}\frac{f_W}{\Lambda^2}(q_1^2 + q_2^2) + \cdots\right) + \sum_i c_i^{(1)}\frac{f_i^{(8)}}{\Lambda^4}v^2q^2 + \cdots$$

$$a_2 = c^{(2)}\frac{f_{WW}}{\Lambda^2}v + \sum_i c_i^{(2)}\frac{f_i^{(8)}}{\Lambda^4}vq^2 + \cdots$$

$$a_3 = c^{(3)}\frac{\tilde{f}_{WW}}{\Lambda^2}v + \sum_i c_i^{(3)}\frac{\tilde{f}_i^{(8)}}{\Lambda^4}vq^2 + \cdots$$

Describe same physics (for a particular vertex) by taking some minimal set of effective Lagrangian coefficients f_i as form factors

Work with Kaoru on effective Lagrangian

- Most general parameterization of WWV vertex and W-pair production at LEP
  Hagiwara, Hikasa, Peccei, D.Z, Probing the Weak Boson Sector in $e^+e^- \to W^+W^-$
  Nucl. Phys. **B282** (1987) 253
- Loop effects of WWV anomalous couplings in an SU(2)xU(1) invariant effective Lagrangian setting: no strong model-independent constraints from precision observables like S,T,U
  Hagiwara, Ishihara, Szalapski, D.Z., Low Energy Effects of New Interactions in the Electroweak Boson Sector, Phys. Rev. **D48** (1993) 2182
- Effective Lagrangian effects on Higgs production and decay
  Hagiwara, Szalapski, D.Z., Anomalous Higgs Boson Production and Decay
  Phys. Lett. **B318** (1993) 155

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

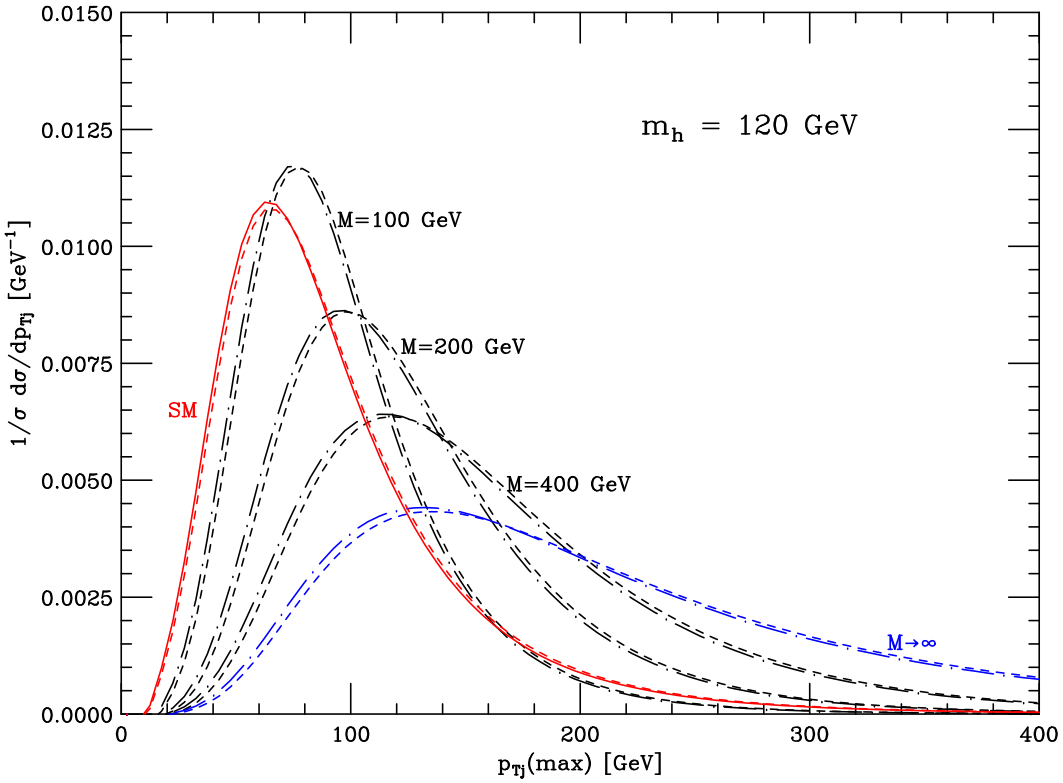
Remember to choose form factors in anom_HVV.dat

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

Jet transverse momentum

Form factors affect momentum transfer and thus jet transverse momenta (Here: a_2 only)

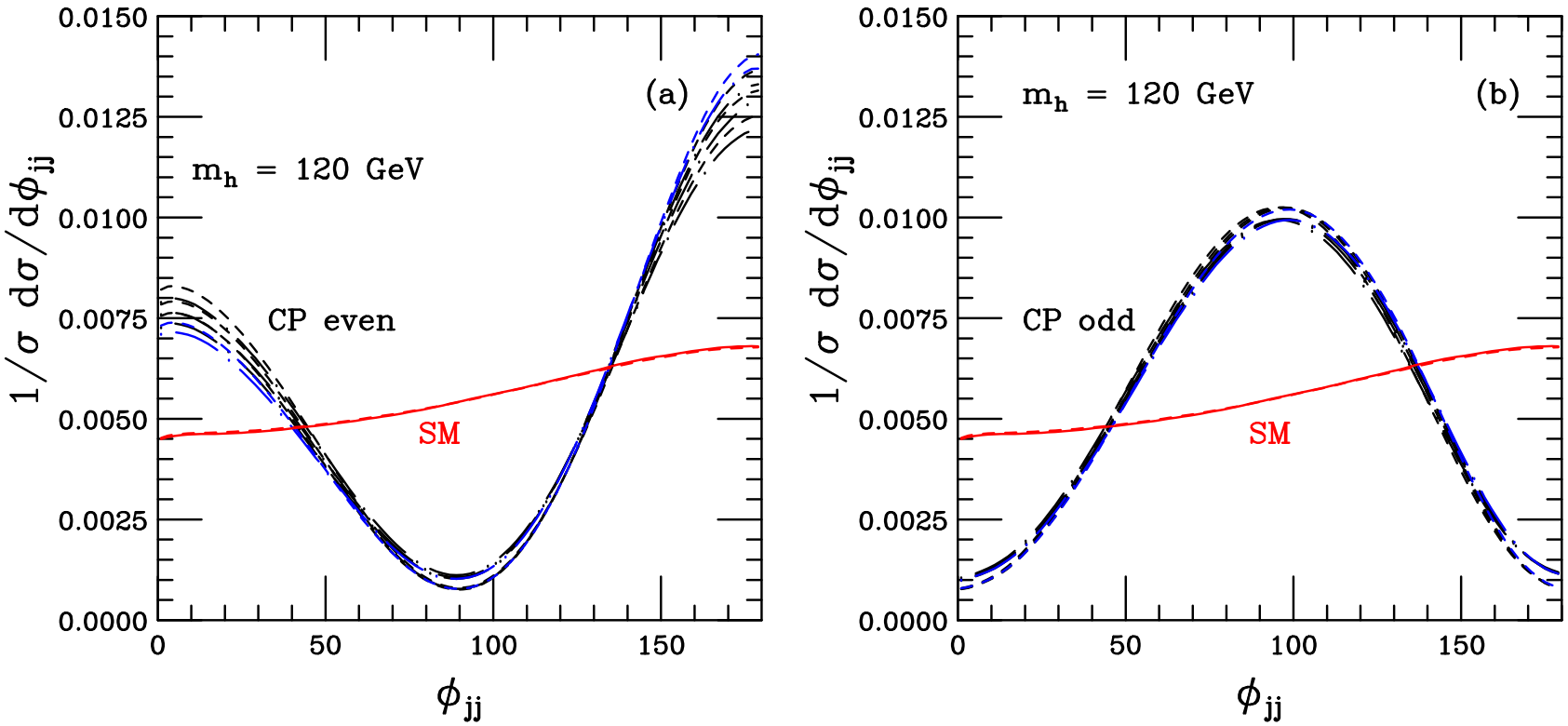
Figy, DZ hep-ph/0403297



- 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.

Same physics in decay plane correlations for $h \to ZZ^* \to 4$ leptons

Size estimates for a_2 terms

a_2 for the four HVV combinations can be derived from effective Lagrangian

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} HZ_{\mu\nu}Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} HW^+_{\mu\nu}W^{\mu\nu}_- + \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} HZ_{\mu\nu}A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} HA_{\mu\nu}A^{\mu\nu}$$

- SU(2) multiplets in triangle graphs producing these effective couplings tend to produce all four of same order of magnitude
- However
  - $H \to ZZ \to 4\ell$ and $H \to WW \to \ell^+\ell^-\nu\bar{\nu}$ partial widths are strongly suppressed by being off-shell and by small leptonic branching ratios
  - No such suppressions for $H \to \gamma\gamma$

  $\Longrightarrow$ Need $g_{5e}^{HZZ} \approx g_{5e}^{HWW} \approx 1000\, g_{5e}^{H\gamma\gamma}$ in absence of SM a_1 term
- $HZ\gamma$ coupling must also be suppressed (would see on-shell $H \to Z\gamma \to \ell^+\ell^-\gamma$ otherwise)

$\Longrightarrow$ Substantial fine tuning needed

$\Longrightarrow$ Loop induced HWW and HZZ couplings, i.e. a_2 or a_3 couplings as primary origin of observed $H \to WW$ and $H \to ZZ$ decays are highly unlikely

Conclusions

- Vector boson fusion and vector boson scattering are important processes which will give valuable information on EW symmetry breaking in run II of the LHC and beyond
- NLO QCD corrections are now known for these signal processes but also for the dominant $VVjj$ QCD backgrounds
- Effective Lagrangians and anomalous couplings are again emerging as extremely useful tools to parameterize our knowledge of Higgs couplings and vector boson scattering

Thank you, Kaoru, for many years of delightful collaboration on many of these topics

Backup

Vector boson scattering

The $m_h \approx 125$ GeV Higgs will unitarize $VV \to VV$ scattering provided it has SM hVV couplings

$\Longrightarrow$Check this by either

- precise measurements of the hVV couplings at the light Higgs resonance
- measurement of $VV \to VV$ differential cross sections at high p_T and invariant mass

Full $qq \to qqVV$ with VV leptonic and semileptonic decay is implemented in VBFNLO with NLO QCD corrections and large set of dimension 6 and 8 terms in the effective Lagrangian

Going beyond dimension 6

Reason for dimension 8 operators like

$$\begin{aligned}
\mathcal{L}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]
\end{aligned}$$

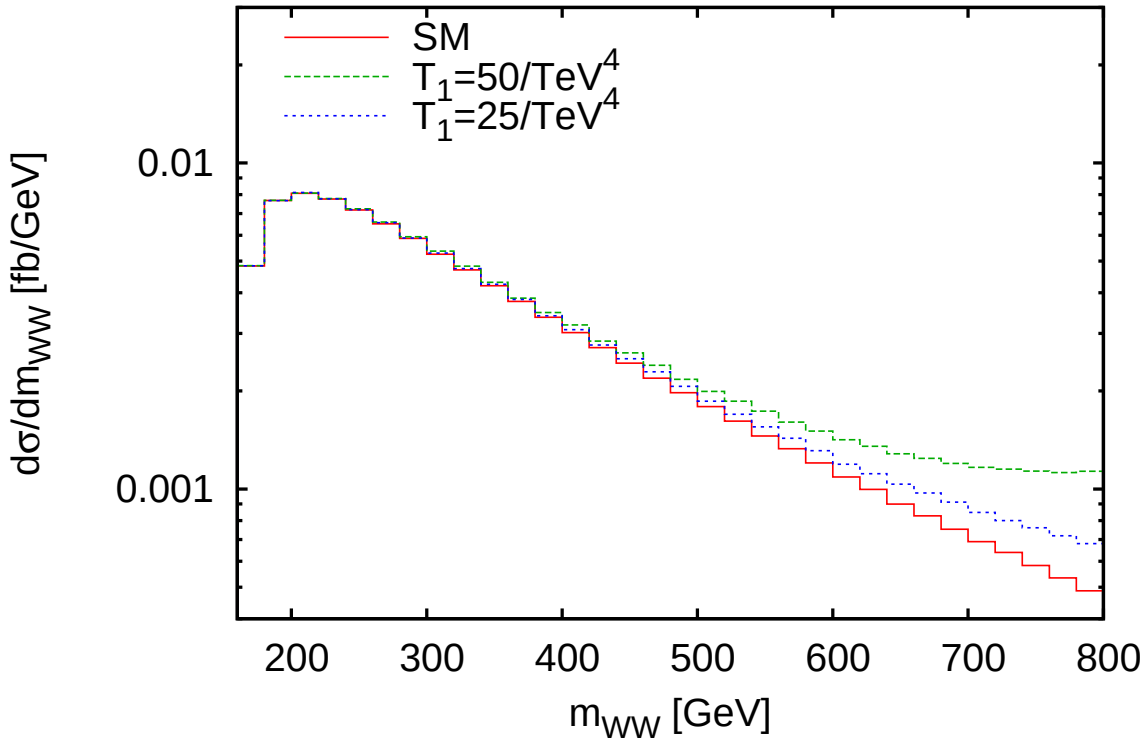
- Dimension 6 operators only do not allow to parameterize VVVV vertex with arbitrary helicities of the four gauge bosons

For example: $\mathcal{L}_{S,0}$ is needed to describe $V_L V_L \to V_L V_L$ scattering

- New physics may appear at 1-loop level for dimension 6 operators but at tree level for some dimension 8 operators

$VV \to W^+W^-$ with dimension 8 operators

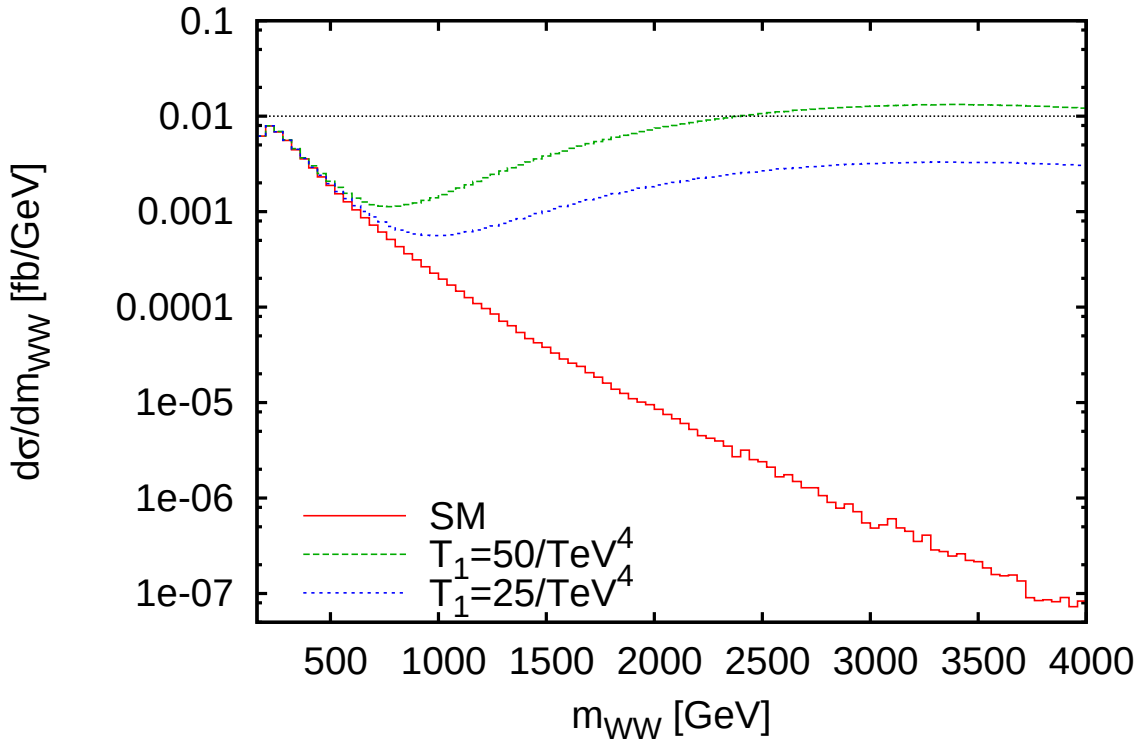
Effect of $\mathcal{L}_{eff} = \frac{f_{M,1}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$
with $T_1 = \frac{f_{M,1}}{\Lambda^4}$ constant on $pp \to W^+W^- jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- Small increase in cross section at high WW invariant mass??

$VV \to W^+W^-$ with dimension 8 operators

Effect of constant $T_1 = \frac{f_{M,1}}{\Lambda^4}$ on $pp \to W^+W^- jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- Huge increase in cross section at high m_{WW} is completely unphysical
- Need form factor for analysis or some other unitarization procedure