SM PHYSICS AND BEYOND IN VBFNLO

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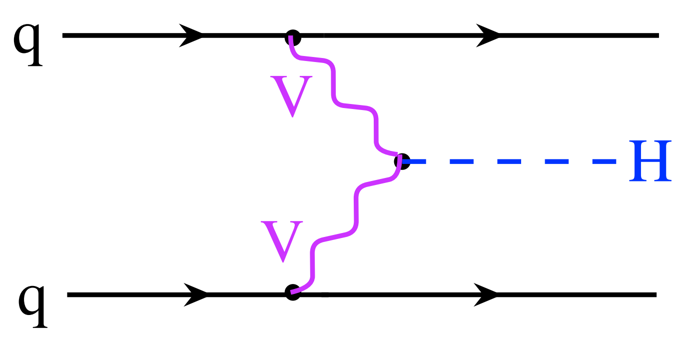
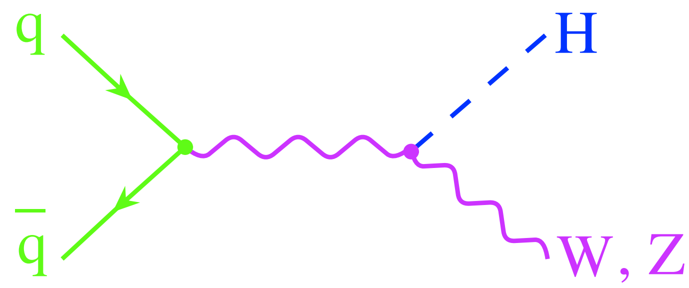
- NLO QCD corrections to VBF and VBS
- Other processes in VBFNLO
- Central Jet Veto
- Interface to Parton Shower
- Anomalous couplings in VBF and $VV \rightarrow VV$ scattering

Introduction/Motivation

Vector boson fusion $(qq \to qqH, qq \to qqV)$ and vector boson scattering $(qq \to qqVV)$ are expected to provide prime information on the dynamics of electroweak symmetry breaking at the LHC

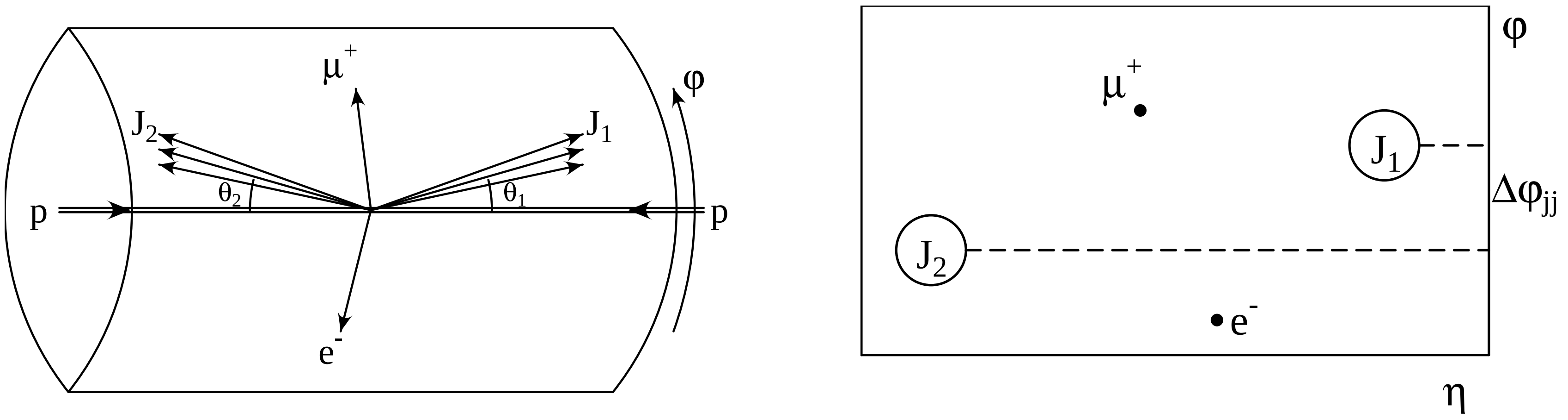


Information on hVV and hff couplings is augmented by study of VH production



- We have calculated NLO QCD corrections for these and a variety of other processes 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/

VBF and VBS 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
  $\Longrightarrow$ Enhance signal contributions by "VBF cuts", e.g.

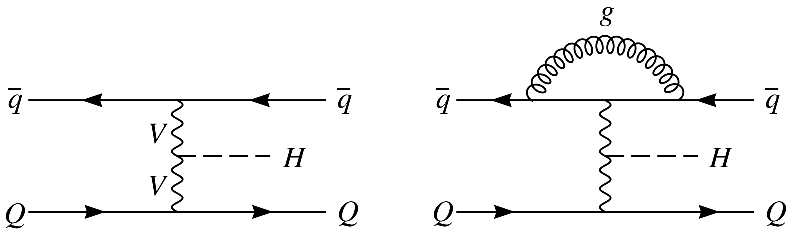
$$m_{jj} > 600\,\text{GeV} \qquad\qquad |y_{j_1} - y_{j_2}| > 4$$

- Higgs/V/VV decay products between tagging jets

Generic features of NLO QCD corrections to VBF and VBS

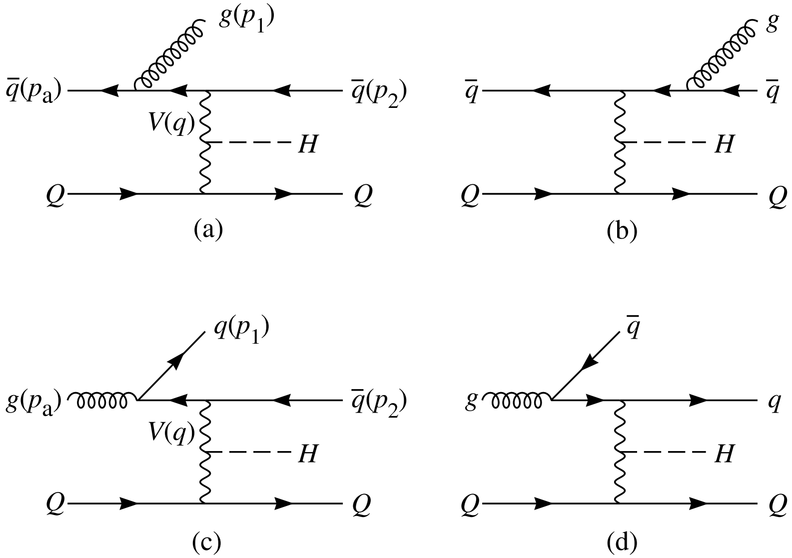
t-channel color singlet exchange $\Longrightarrow$ QCD corrections to different quark lines are independent

Born and vertex corrections to upper line



No t-channel gluon exchange at NLO

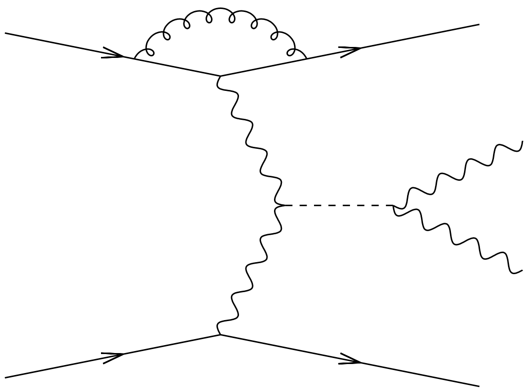
real emission contributions: upper line



Treat s-channel contributions (here VH production with $V \to jj$ decay)
and QCD processes (e.g. $VVjj$ production at order $\alpha_s^2\alpha^2$) as separate processes.
Neglect interference for identical fermions: small effects in phase space where VBF/VBS is visible
Features are generic for all VBF/VBS processes

Virtual corrections: 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

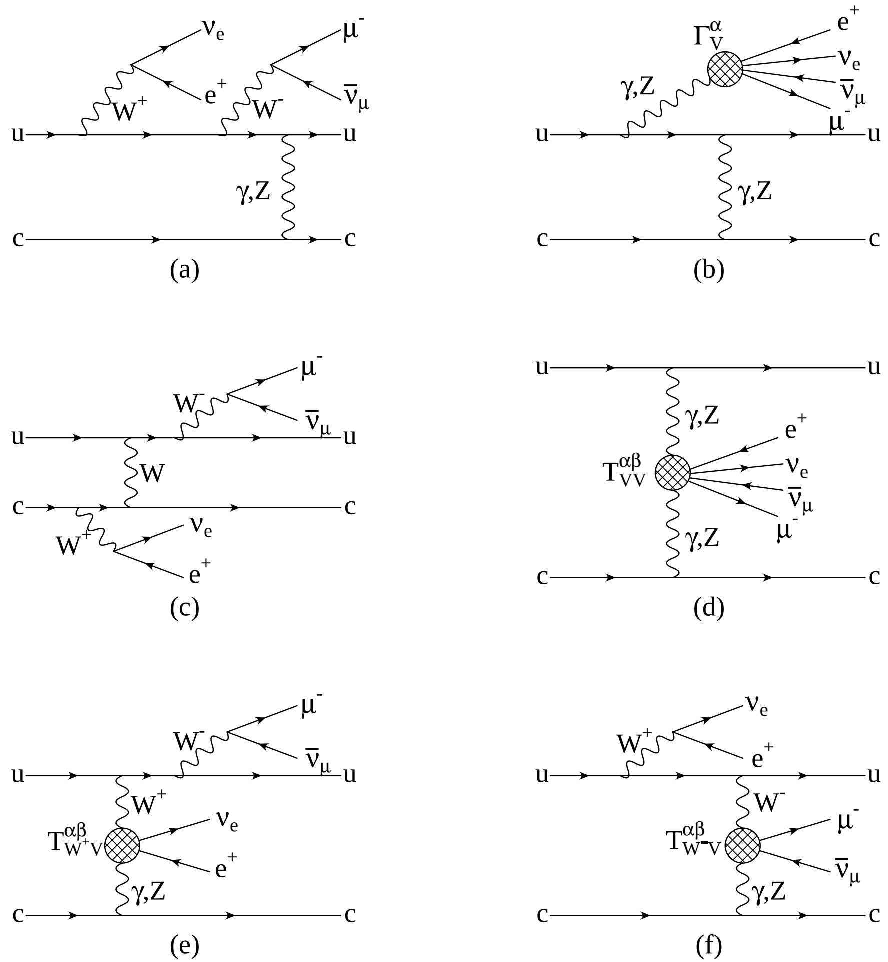
Remaining virtual corrections are accounted for by trivial factor multiplying Born cross section

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

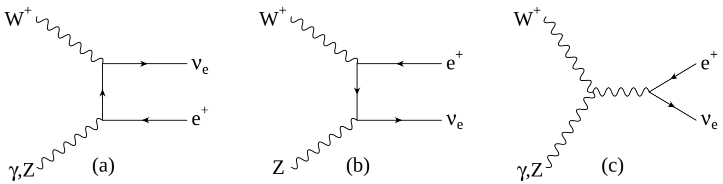
- Factor 2 for corrections to upper and lower quark line
- Same factor to Born cross section absorbs most of the virtual corrections for other VBF processes

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

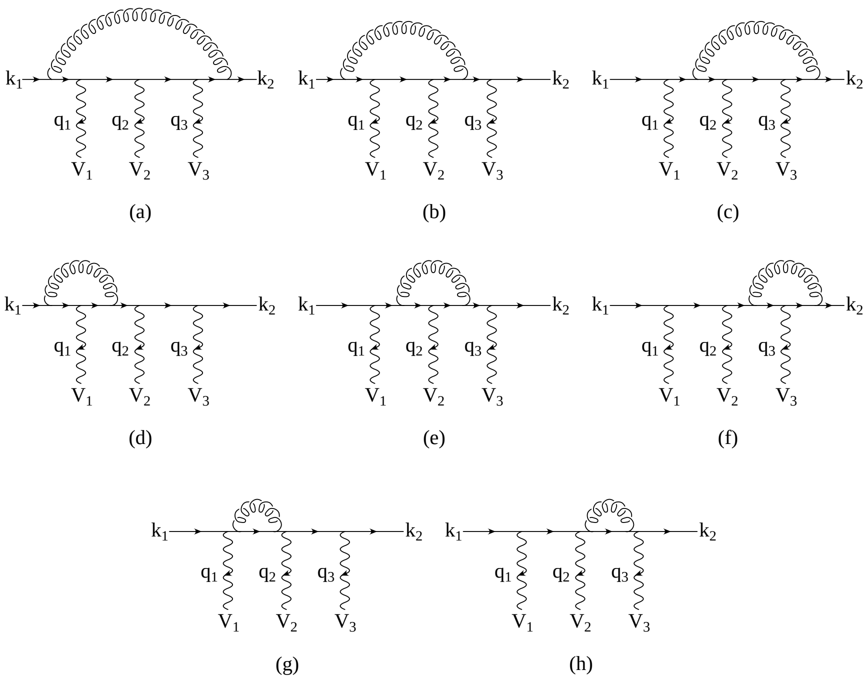


Calculate once, reuse in different processes

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

Most complex 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

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

- 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

Some 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

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

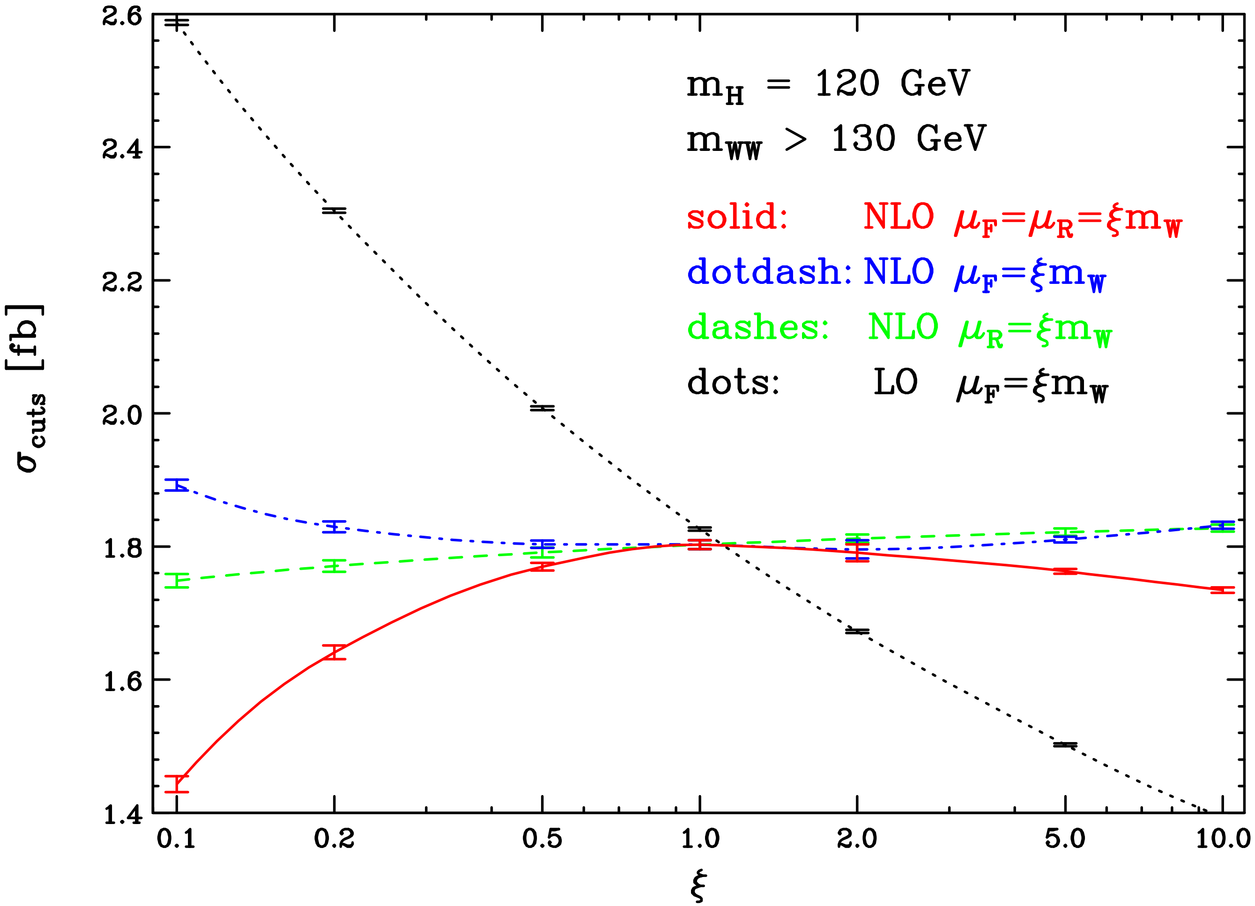
For scale dependence studies we have considered

$\mu = \xi\, m_V$ 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

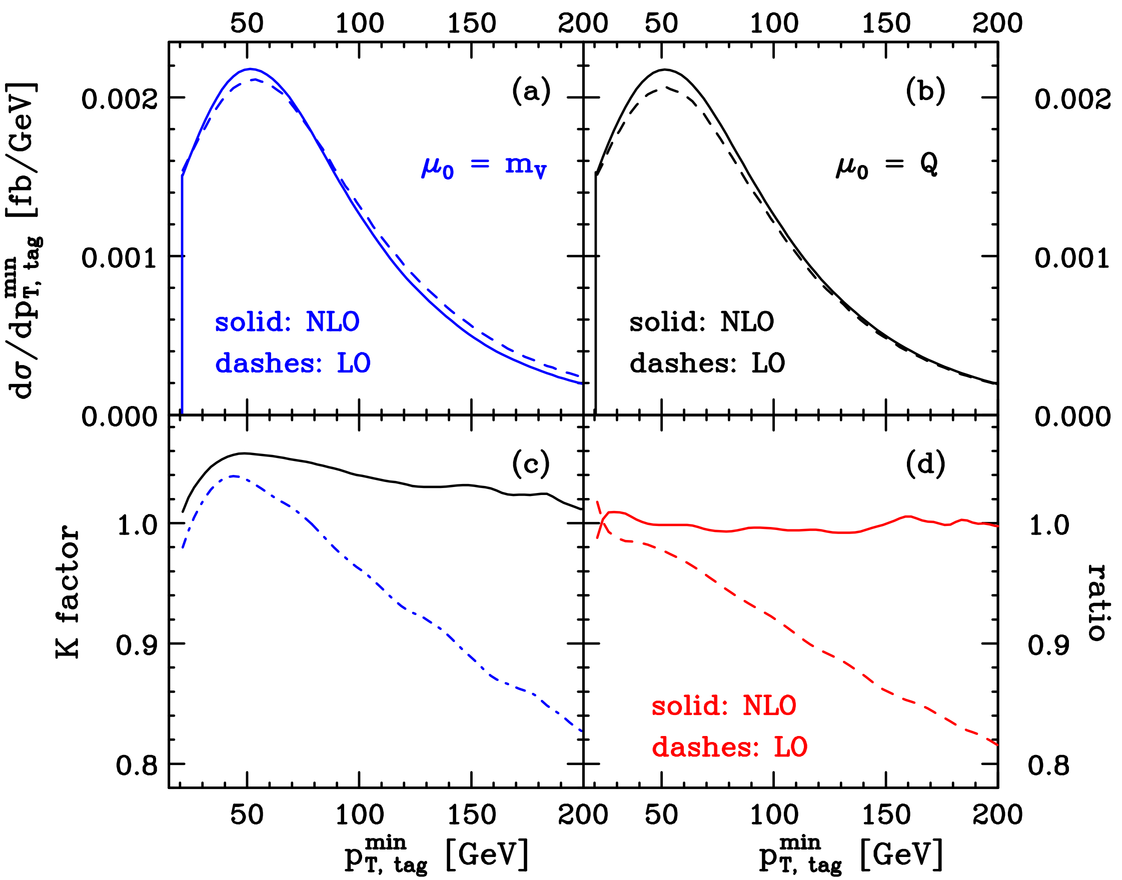
Stabilization of scale dependence at NLO

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

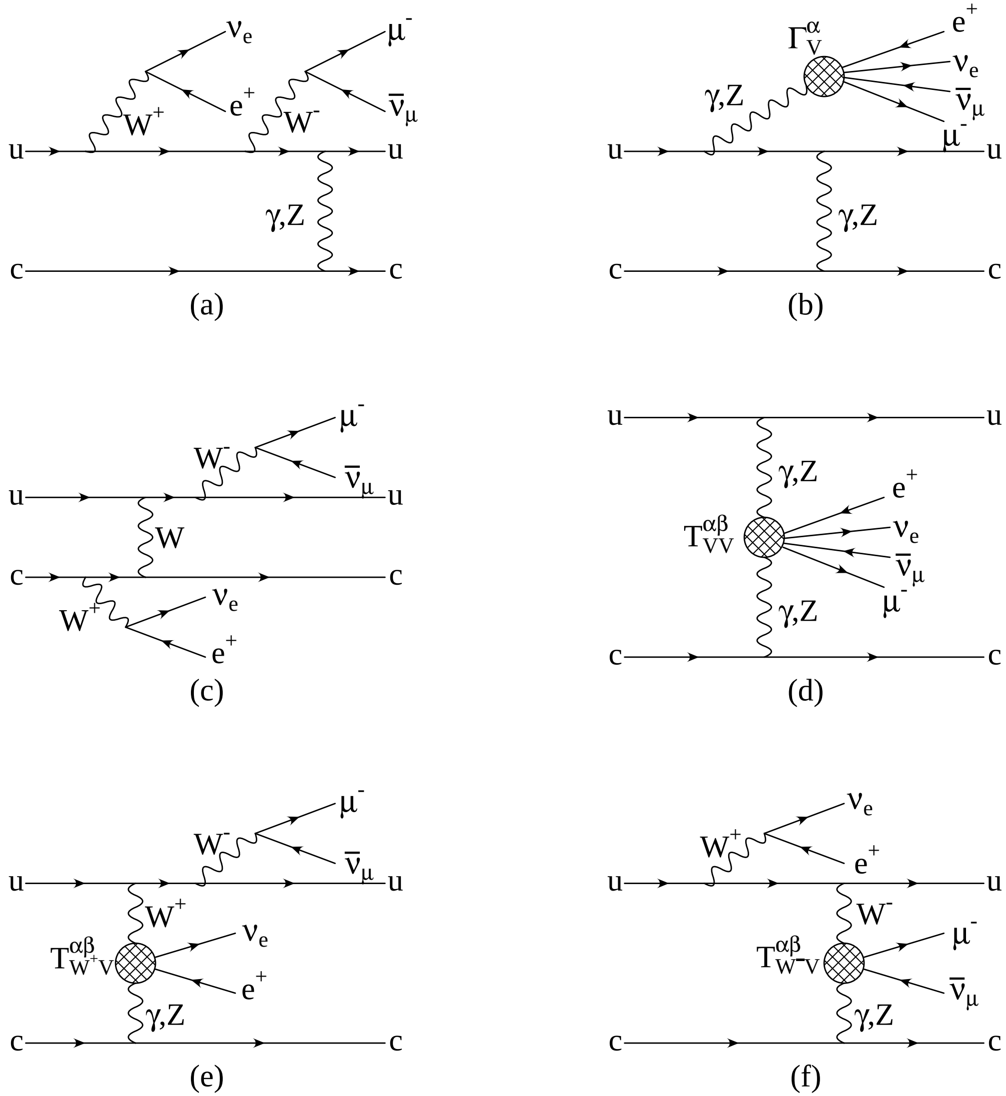


- Shape comparison LO vs. NLO depends on scale
- Scale choice $\mu = Q$ produces approximately constant K-factor
- Ratio of NLO curves for different scales is unity to better than 2%: scale choice matters very little at NLO

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

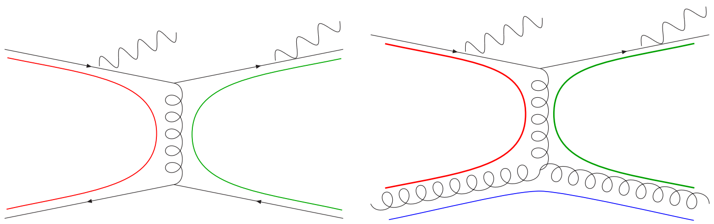
- BSM effects like anomalous couplings and heavy vector resonances

Extensions in 2012 update of VBFNLO

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

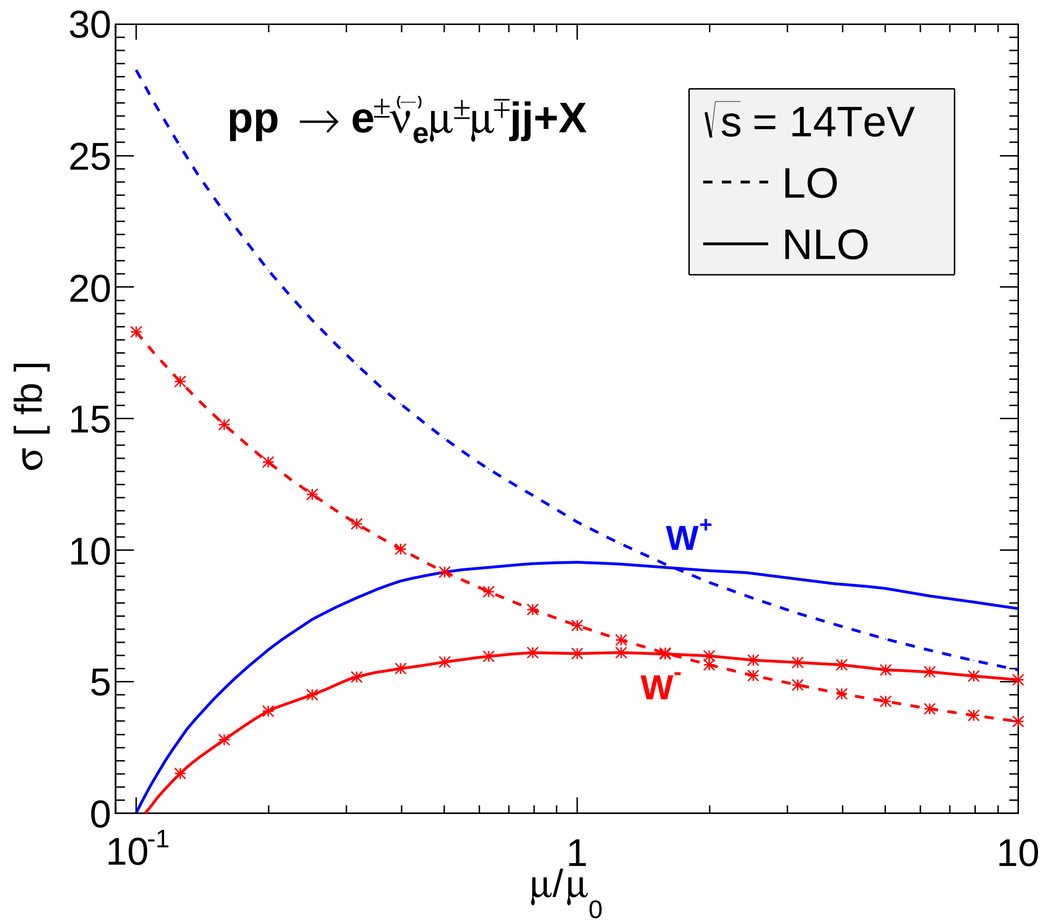
- $W\gamma\gamma j$ production as first true 2→4 process
- Triple weak boson production is now complete: all $V_1V_2V_3$ production processes for any $V_i = W^\pm, Z, \gamma$
- Same sign WW scattering in VBF: W^+W^+jj final states
- Diboson production processes (WZ, $W\gamma$, ZZ, $Z\gamma$ and $\gamma\gamma$) 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, $NF = 4$

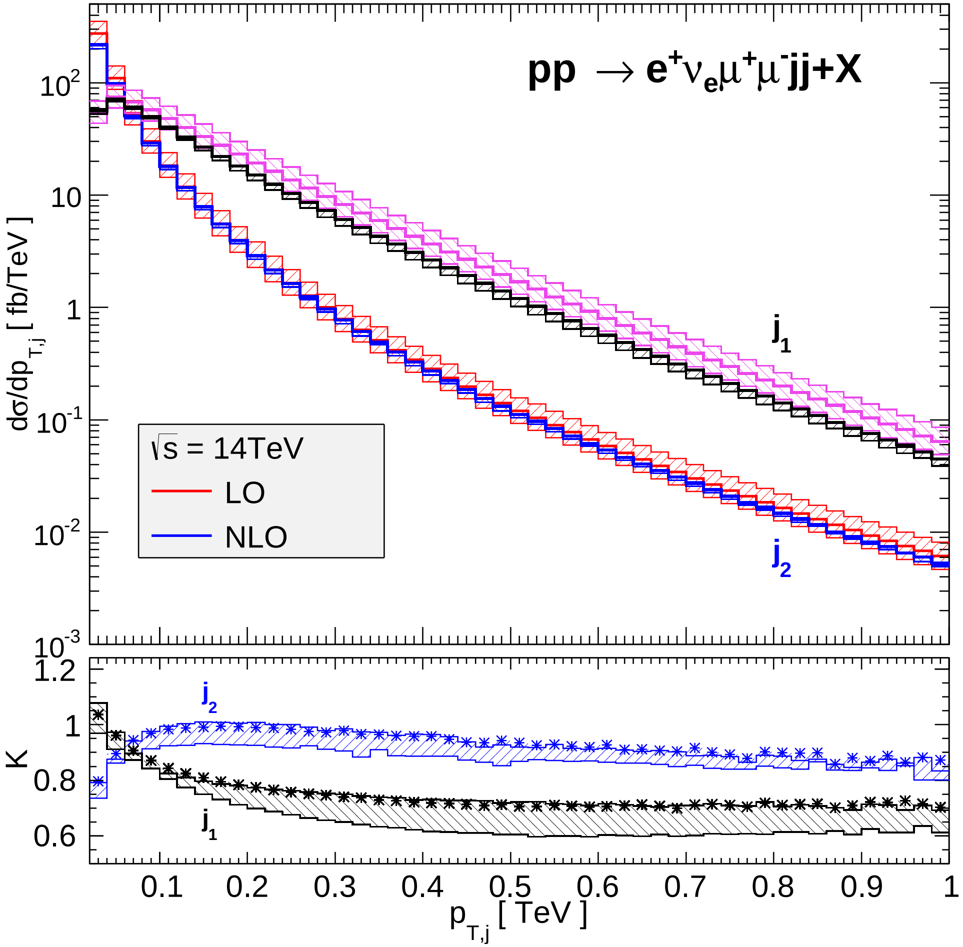
scale dependence: $\mu_0 = \left(\sum p_{T,\text{jet}} + E_{T,W} + E_{T,Z}\right)/2$



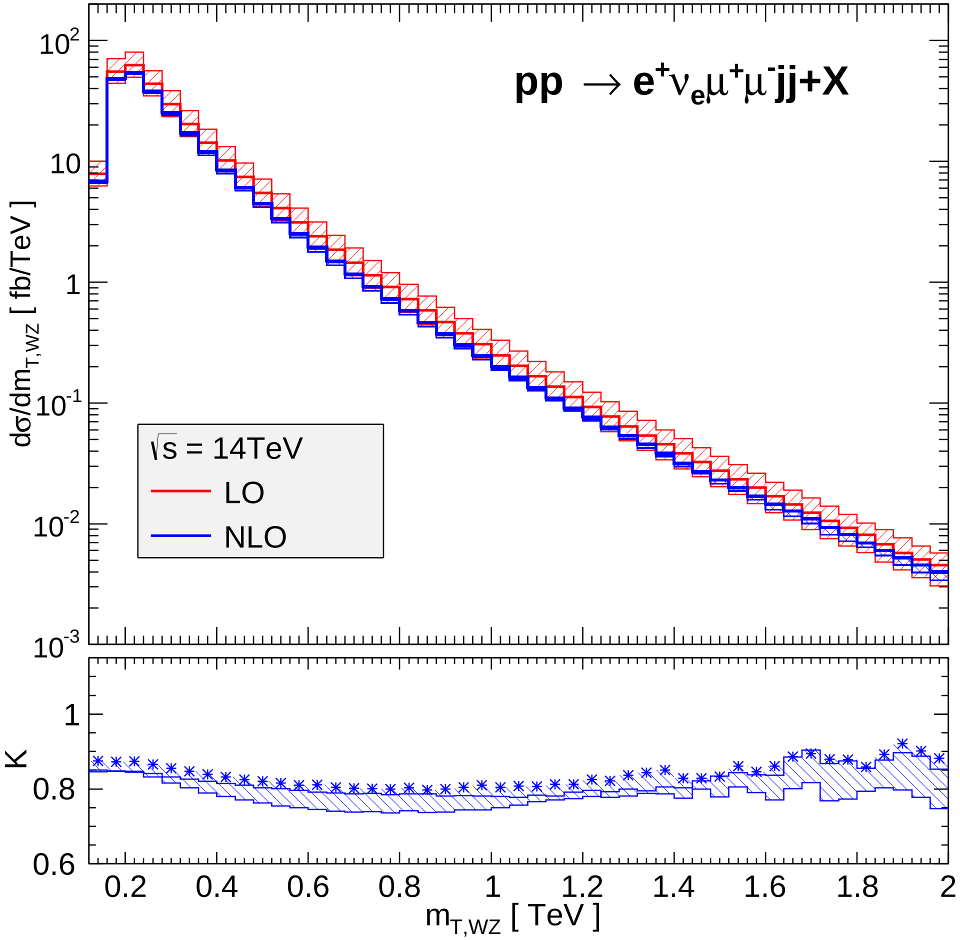
Work with Matthias Kerner, Paco Campanario, Ninh Duc Le: arXiv:1305.1623

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

Further 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

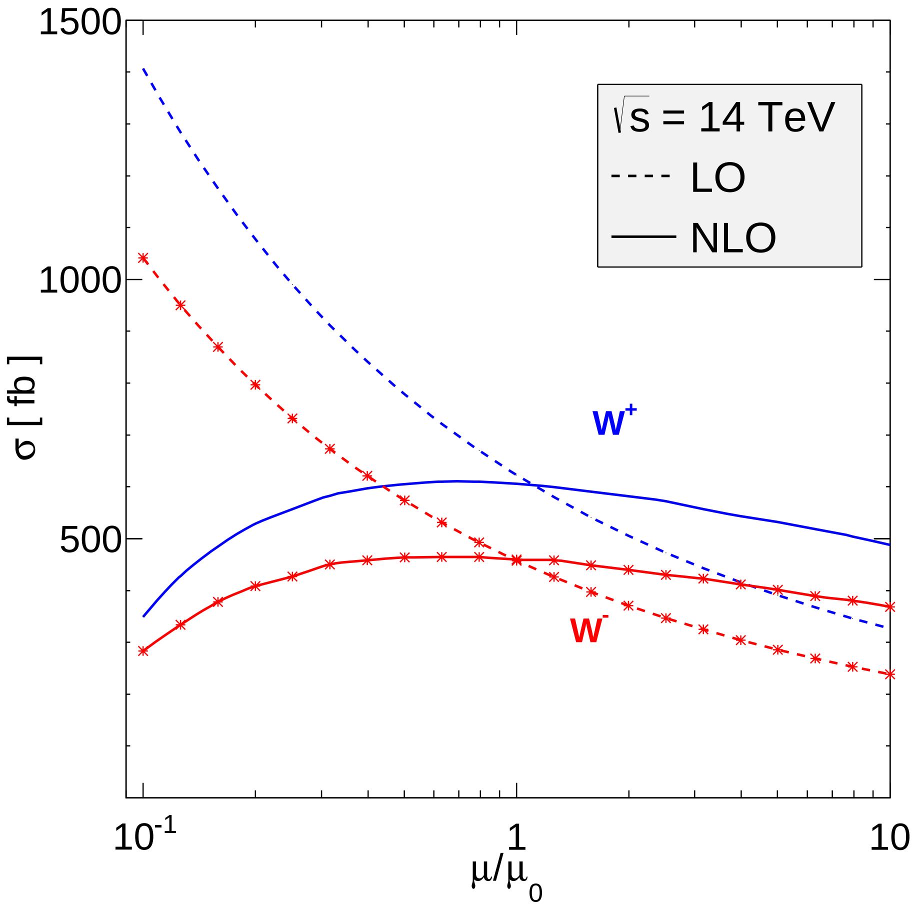
anti-k_T with $R = 0.4$

photon isolation $\delta_0 = 0.7$ (Frixione)

- PDF: MSTW2008
- Scale:

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

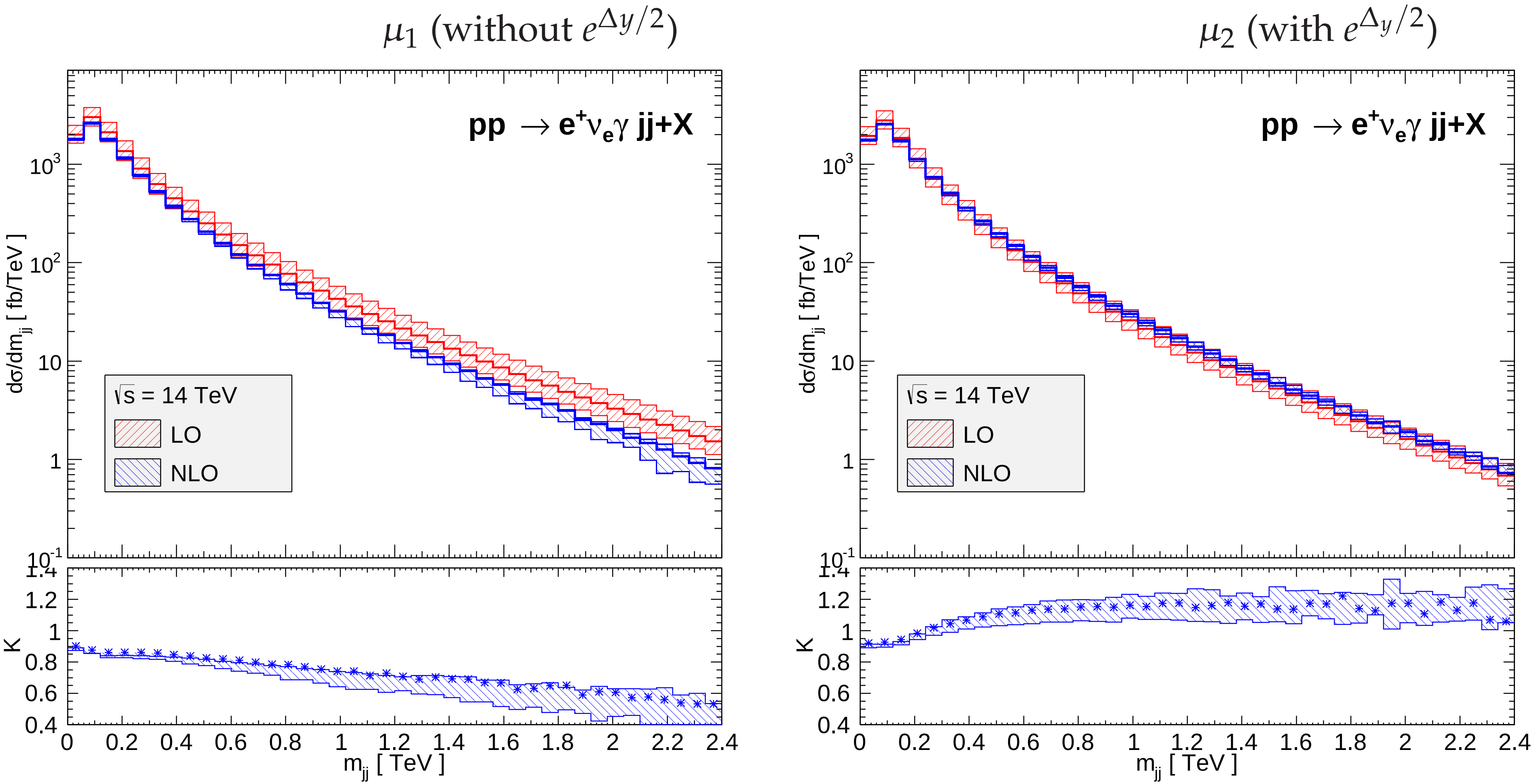
with $E_{T,W} = \sqrt{p_{T,W}^2 + m_W^2}$, $y_{12} = \frac{y_1 + y_2}{2}$



→ Scale dependence reduced

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

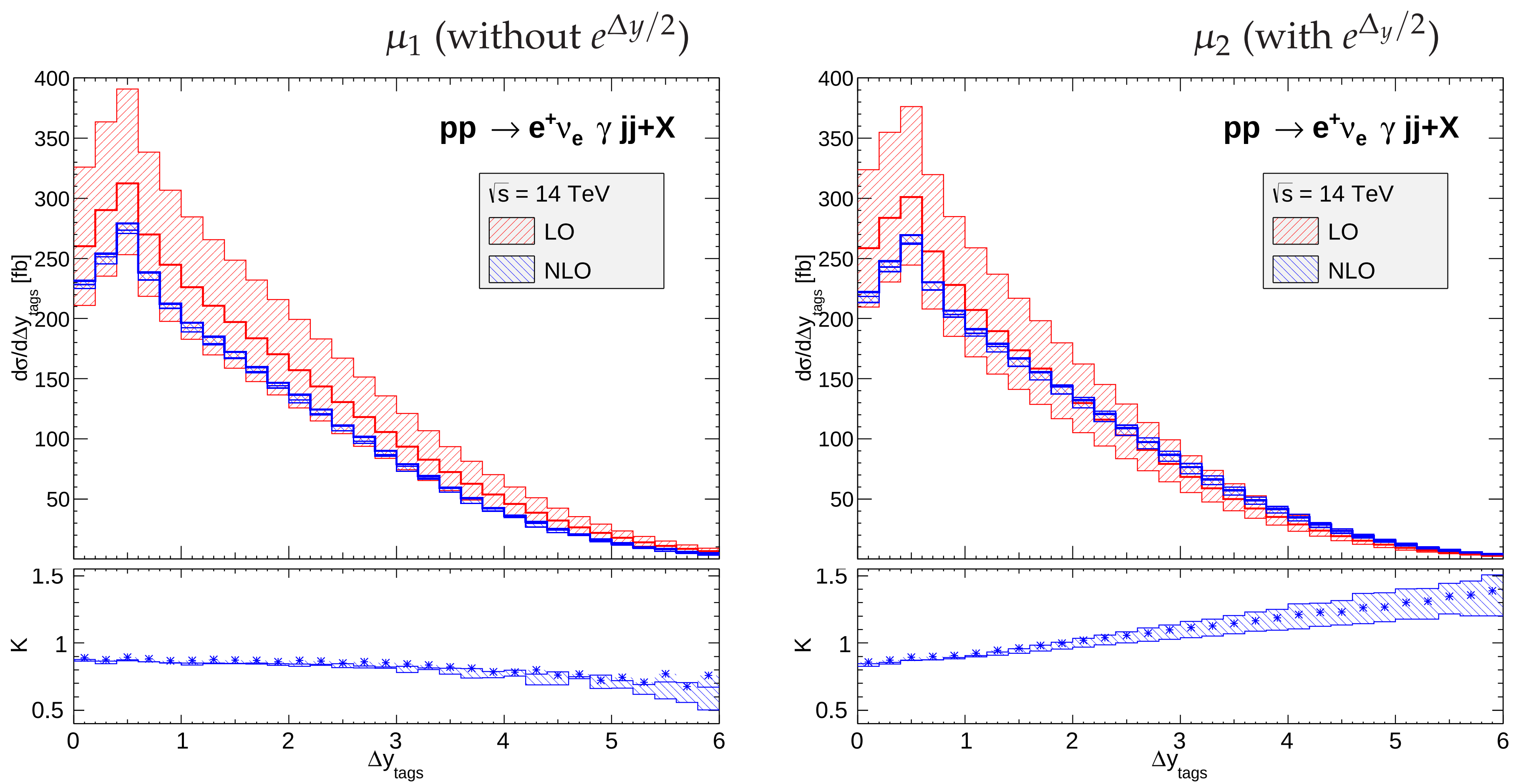
$W\gamma jj$ distributions: dijet invariant mass



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



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

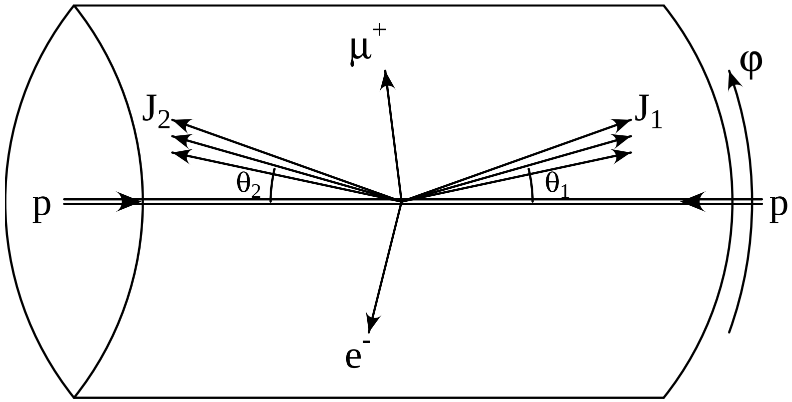
large Δy: $\quad m_{jj} \approx \sqrt{p_{T1} p_{T2}}\, e^{\Delta y/2} \quad < \quad \mu_2 \approx \frac{p_{T1}+p_{T2}}{2}\, e^{\Delta y/2}$

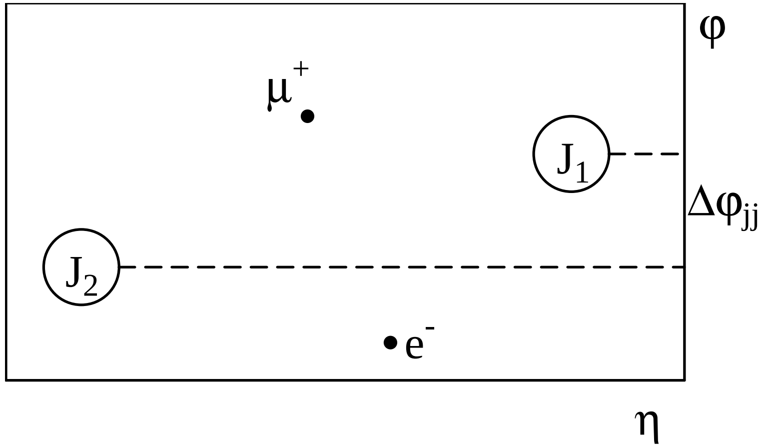
Some extensions in 2014 and 2015 updates of VBFNLO

Additional NLO QCD corrected processes

- QCD $WZjj$ and $ZZjj$ production at order $\alpha^2\alpha_s^3$
- $W\gamma jj$ and $Z\gamma jj$ 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)
- 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.
- BLHA interface of VBS processes with parton shower in VBFNLO 3.0.0 β

VBF signature





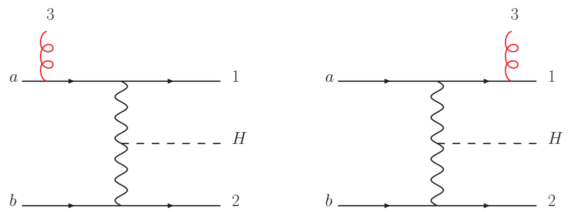
Characteristics:

- 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 between tagging jets)

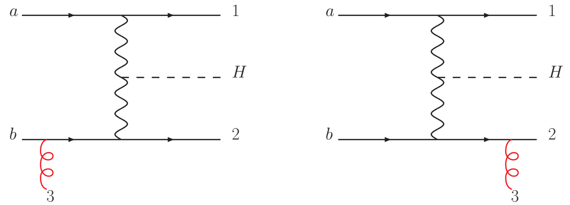
VBF $hjjj$ production

- Born: 3 final state partons + Higgs via VBF

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

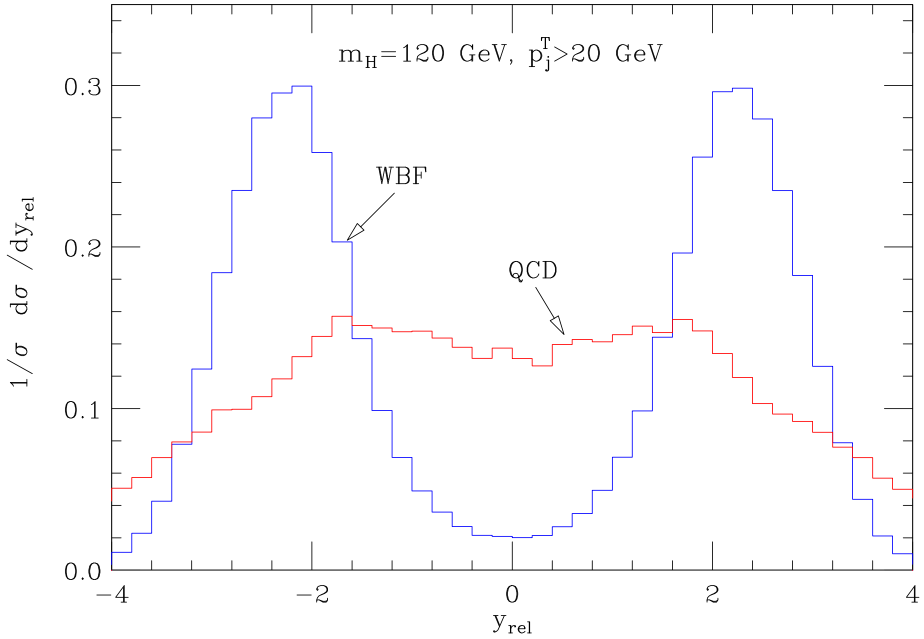


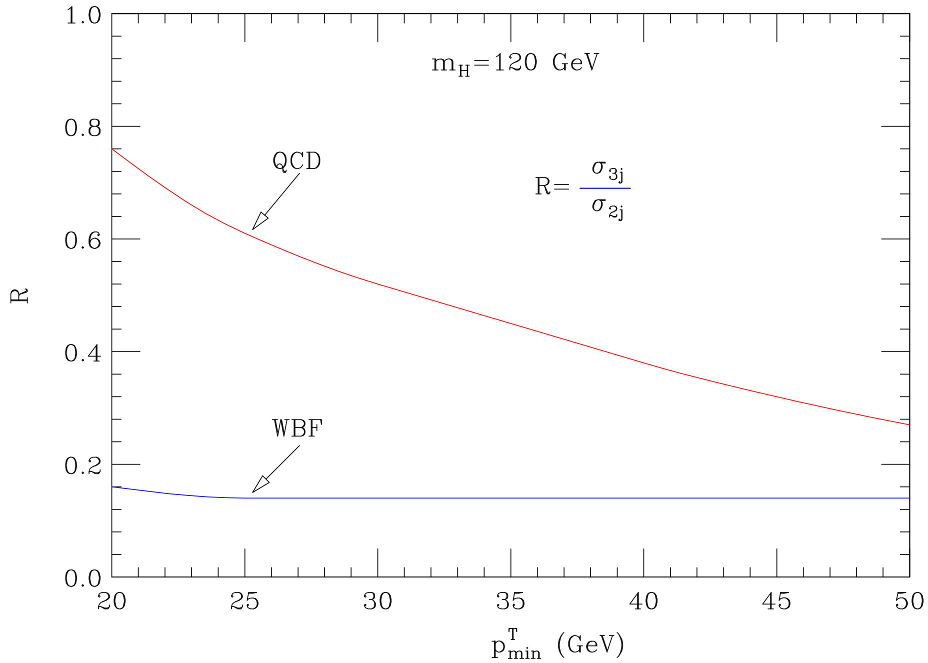
$$+ \; \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \Big[\mathcal{M}_{B,2b} : \Big]$$



- No interference between upper and lower set of Feynman graphs due to color structure
- Two emission graphs off upper quark line interfere destructively for gluon emission at larger angles than scattered quark
- Anlogous for gluon emission off lower quark line
- $\Longrightarrow$ Little gluon radiation in rapidity region between the two quark jets

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





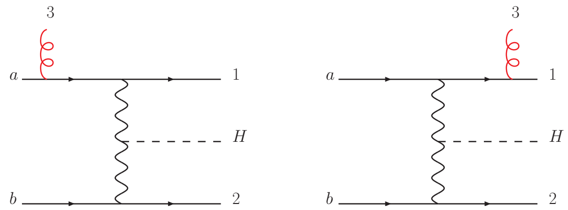
[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- 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 $hjjj$ production and NLO corrections

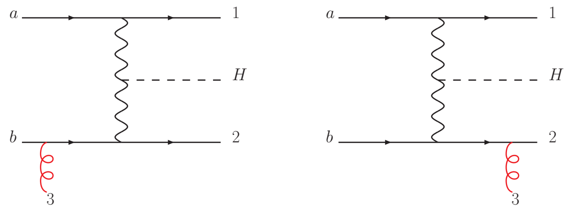
- Born: 3 final state partons + Higgs via VBF

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



$$\Big]$$

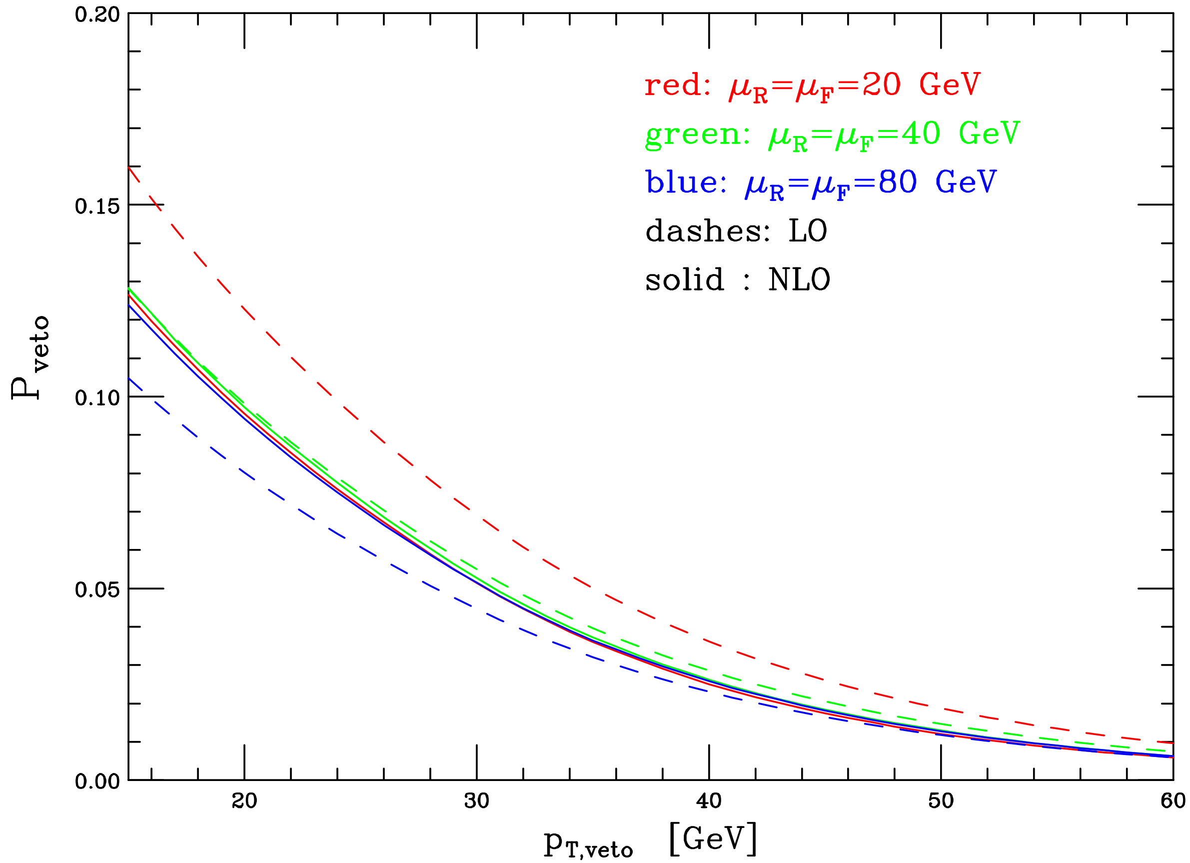
$$+ \delta_{i_1 i_a} t^{a_3}_{i_2 i_b}\Big[\mathcal{M}_{B,2b}:$$



$$\Big]$$

- 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
    (consistent with full NLO calculation by Campanario, Figy, Plätzer, Sjodahl)

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

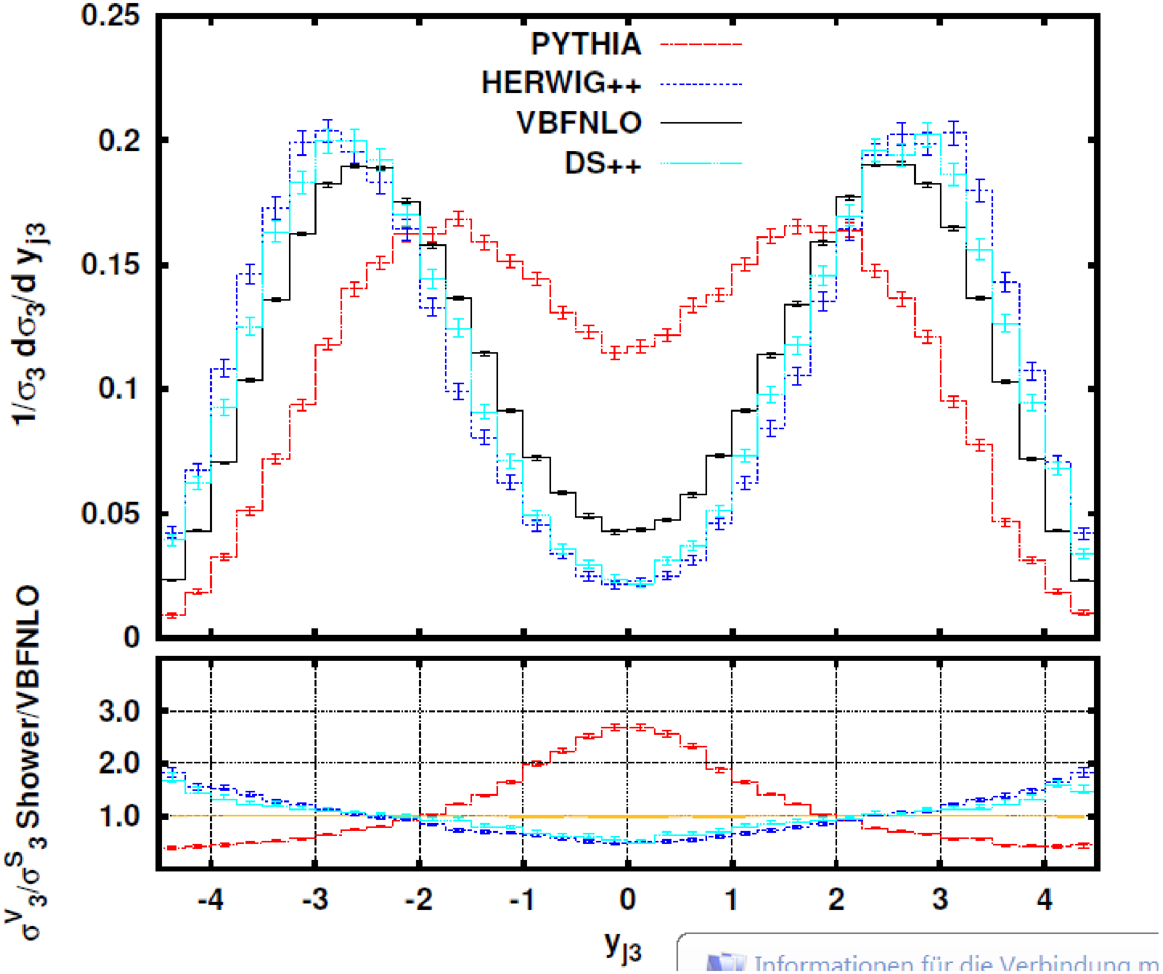
Veto jets beyond fixed order

Interface of NLO calculations with Herwig and PYTHIA via Powheg Box
has been implemented by Franziska Schissler

- How well can "veto jets" be modeled directly by parton shower approach?
- Differences between basic shower models
  (PYTHIA vs. default Herwig shower vs. dipole shower)
- Improvements when adding true NLO corrections

Veto jet distribution: LO $qq \to qqh$ matrix elements

Schissler thesis, 2014



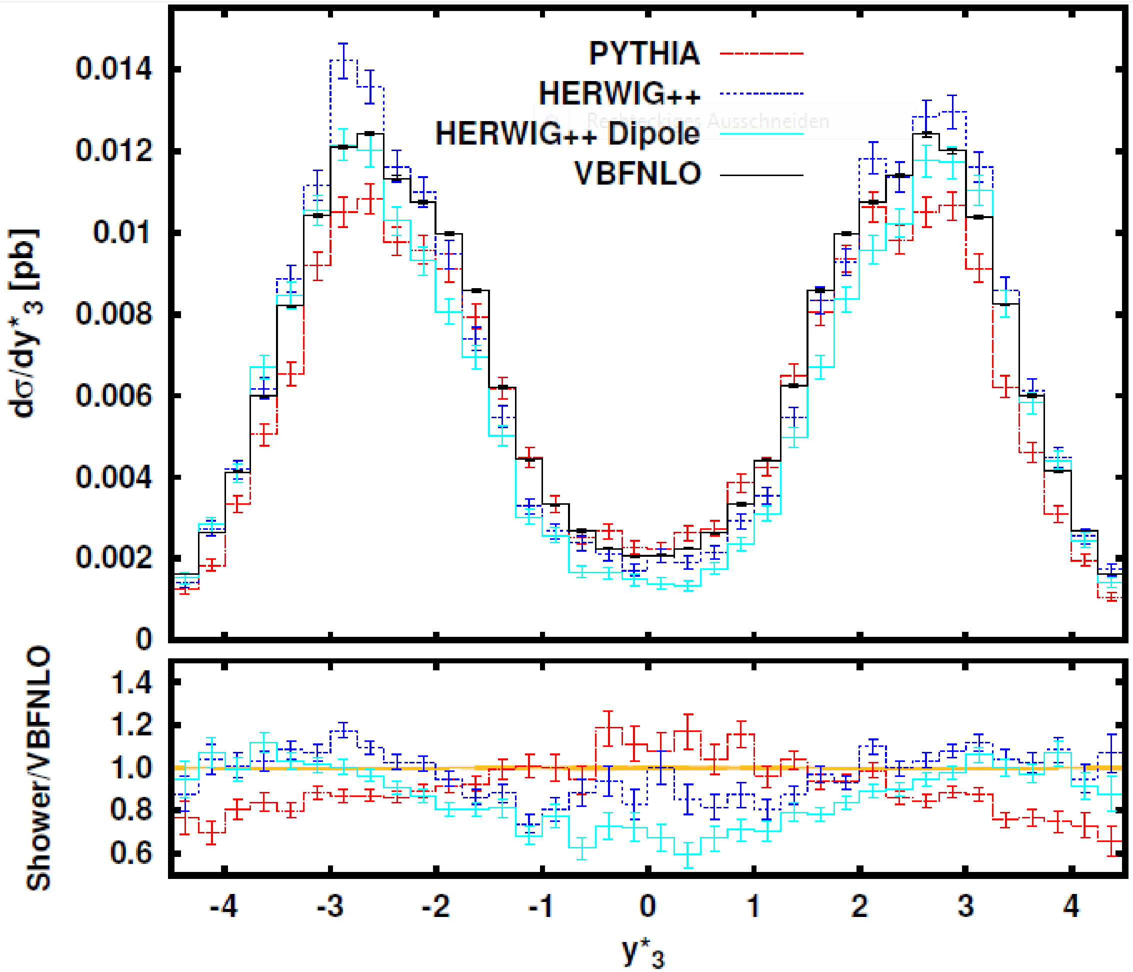
Pure parton-shower generation of central jets does not produce reliable results

Collinear approximation inherent in PS approach is not valid in veto region for VBF events

Extra parton must be included in hard matrix element

Veto jet distribution: VBF $Wjjj$ production at LO

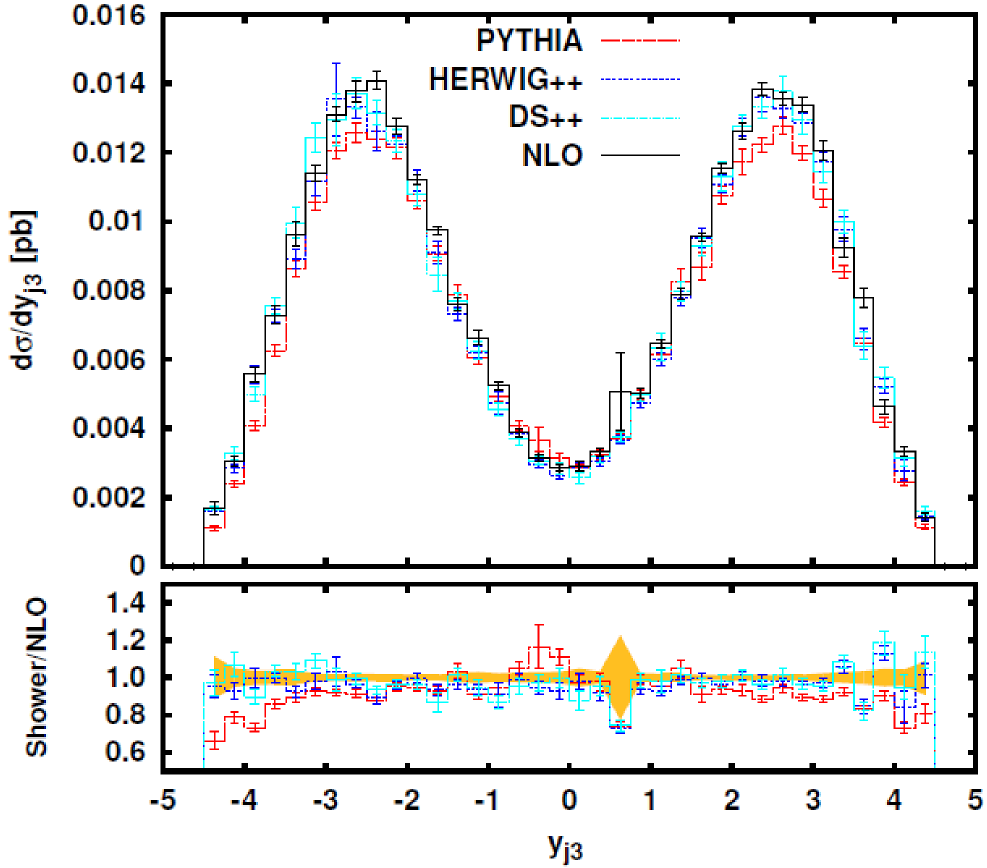
Schissler,DZ arXiv:1302.2884



Inclusion of third parton at ME level produces reasonable agreement between NLO Vjj calculations and parton shower programs

Veto jet distribution: VBF $hjjj$ production at NLO

Jäger, Schissler,DZ arXiv:1405.6950



Further improvement with NLO $hjjj$ calculation matched to PS programs

Reliable simulation of veto jet candidates is possible but requires matrix elements with sufficiently high parton multiplicity

BLHA Interface

Interface NLO program with parton-shower MC [Arnold, Plätzer, Rauch et al.]
well-defined standard: Binoth Les Houches Accord (BLHA)

Motivation: Combine advantages of NLO calculations and parton shower

NLO calculation

- normalization correct to NLO
- additional jet at high-p_T accurately described
- theoretical uncertainty reduced

Parton shower

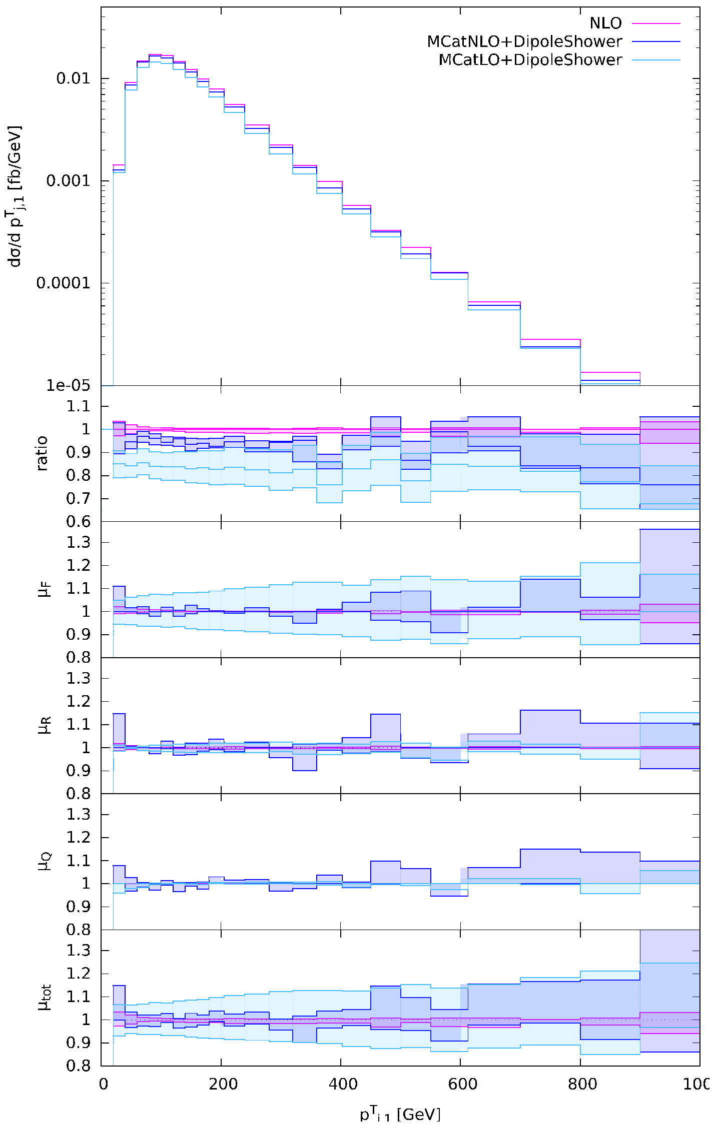
- Sudakov suppression at small p_T
- events at hadron level possible

$\Rightarrow$ Interface VBFNLO with parton shower $\rightarrow$ BLHA interface (work by Michael Rauch)
$\rightarrow$ First tests: Herwig 7 package Matchbox as MC program [Gieseke, Plätzer]

Two parton showers: angular-ordered and Catani-Seymour dipoles

Matching methods: MC@NLO and POWHEG

VBF-W^+W^- + parton shower



For p_{T,j_1}, comparison of:

- pure NLO
- NLO+PS (MC@NLO+dipole shower)
- LO+PS (dipole shower)

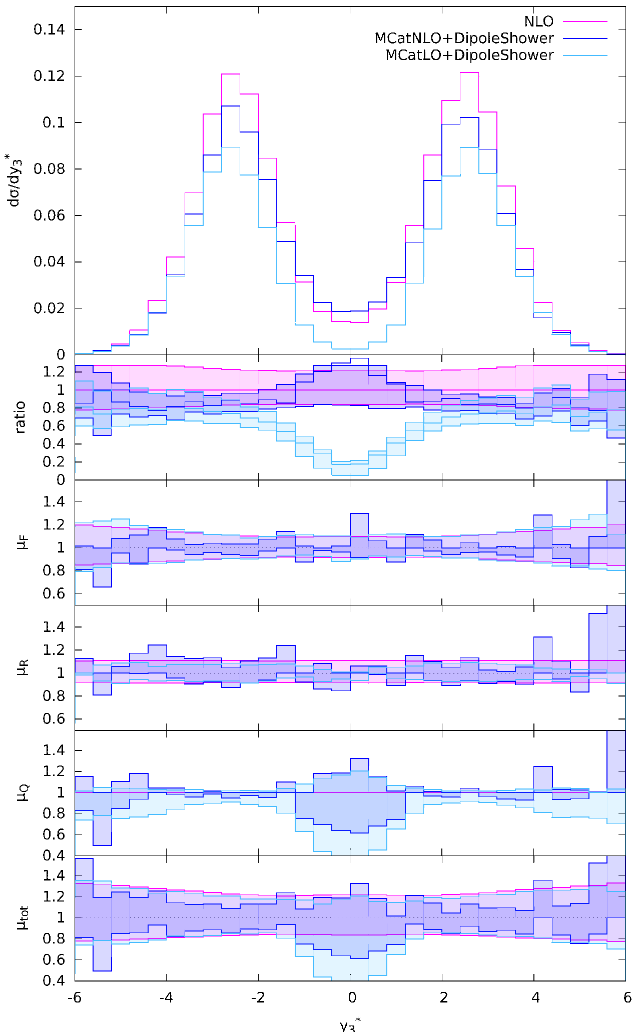
Panels:

- differential c.s.
- ratio of c.s. and total scale variation ($\mu_0 = p^T_{j,1}$)
- individual variation of μ_F, μ_R, μ_Q (shower scale)
- total variation $\mu_i/\mu_0 \in [\frac{1}{2}; 2]$

Inclusion of parton shower:

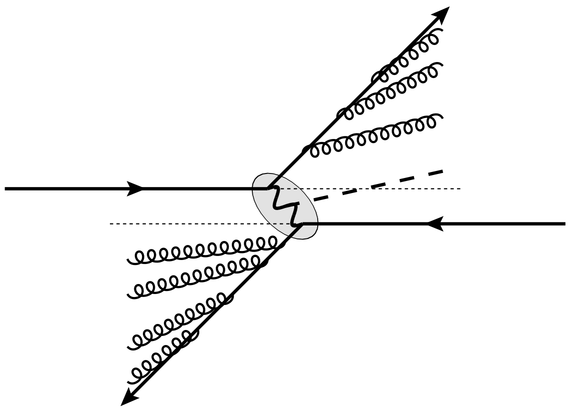
- smaller c.s. (additional splittings)
- larger uncertainties (add. shower scale)

VBF-W^+W^- + parton shower



$$y_3^* = y_3 - \frac{y_1+y_2}{2}$$

- almost no radiation generated in central region by LO+PS
- additional radiation by shower created mainly between jets and beam axis (color connections)



- $\rightarrow$ central region corrected at NLO by LO W^+W^-jjj ME
- dipole shower "interpolates" between NLO behavior in central region and shower behavior at small angles

NLO Event Output

Additional features:

- events at NLO

```
HepMC::Version 2.06.08
HepMC::IO_GenEvent-START_EVENT_LISTING
E 1 -1 1.0000000000000000e+02 1.1426144356896106e-01 8.0545791941901580e-03 0 -1 5 10003 10006 0 1 9.6574119350375395e-05
N 1 "0"
U GEV MM
C 1.2003526218804084e+00 1.2429340593057579e+04
F 2 -2 1.9944966561722052e-01 5.4752809081600089e-03 1.0000000000000000e+02 4.8837107666330770e-01 7.0773553098927189e-01 0 0
V -1 0 0 0 0 0 0 2 0
P 10001 24 -4.5106124574613865e+01 2.1914561871288999e+01 4.8707785224913533e+02 4.8305712963914090e+02 -8.0096530215583300e+01 11 0 0 -5 0
[...]
```

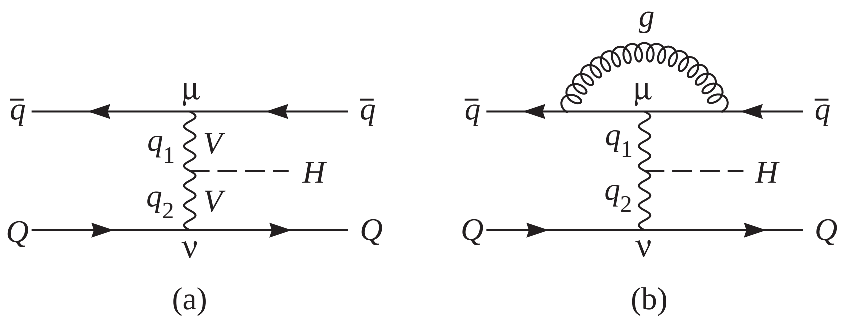
- BLHA interface completely following Les Houches standard
  $\longrightarrow$ also working with other MC generators (e.g. Sherpa)

  $\leftrightarrow$ when using BLHA v1 with VBF processes, care needs to be taken to use the VBF approximation also in the MC generator

- other process classes will follow (e.g. QCD-VVjj)

Tensor structure of the HVV coupling

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



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

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

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

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

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

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

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

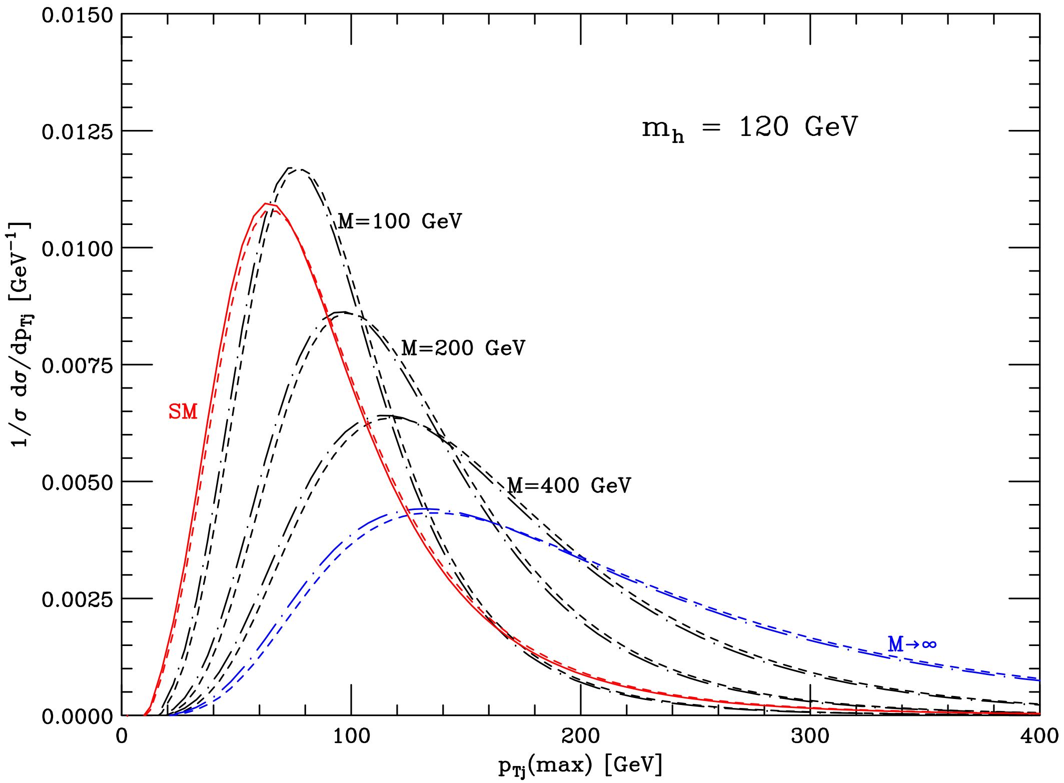
$$F_1 = \frac{M^2}{q_1^2 - M^2} \frac{M^2}{q_2^2 - M^2} \qquad \text{or} \qquad F_2 = -2\, M^2\, C_0\left(q_1^2, q_2^2, (q_1 + q_2)^2, M^2\right)$$

- Anomalous couplings implemented in VBFNLO for VBF and VBS, for VV, VVj, VVV, and other production processes

$qq \to qqH$: jet transverse momentum

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

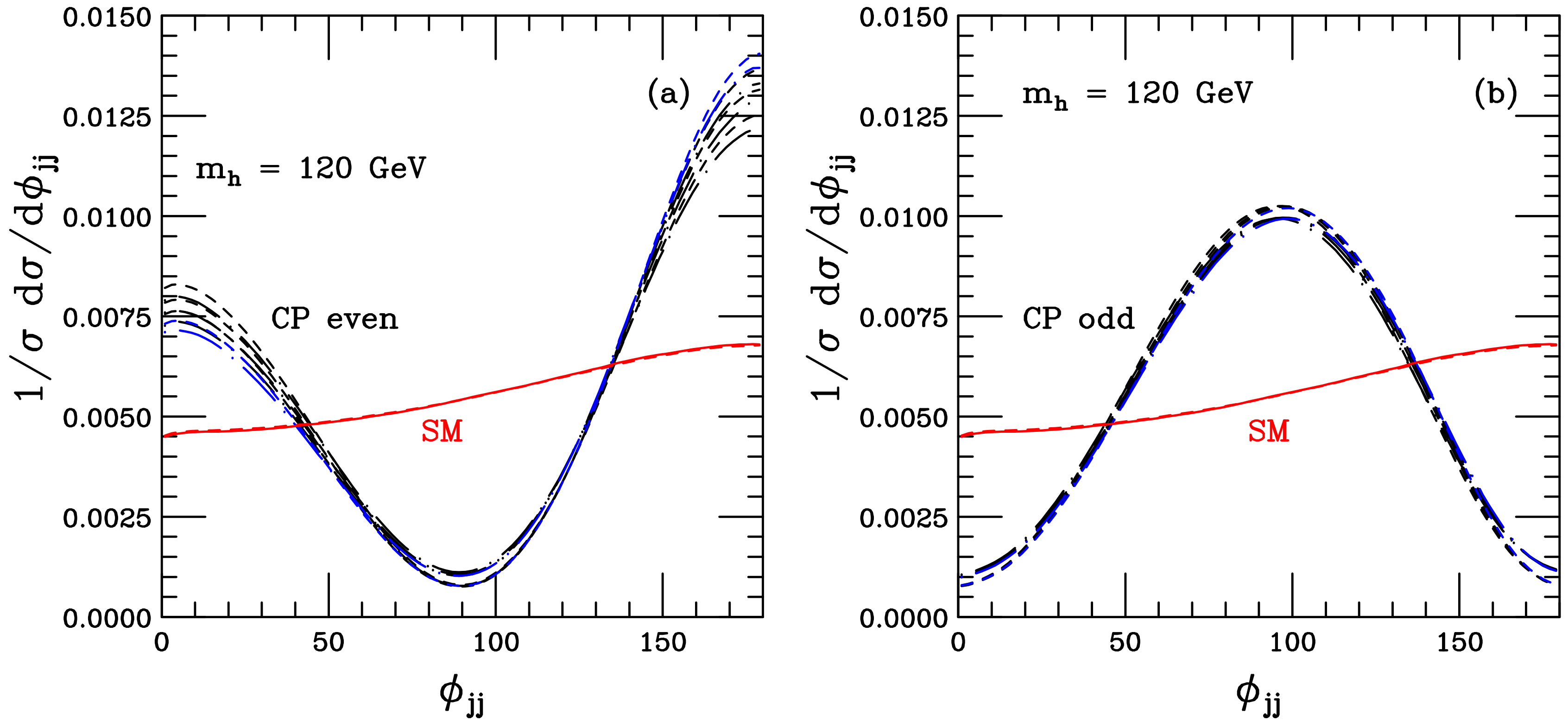
Figy, DZ hep-ph/0403297



- 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

Vector boson scattering

The $m_h = 125$ 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

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

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

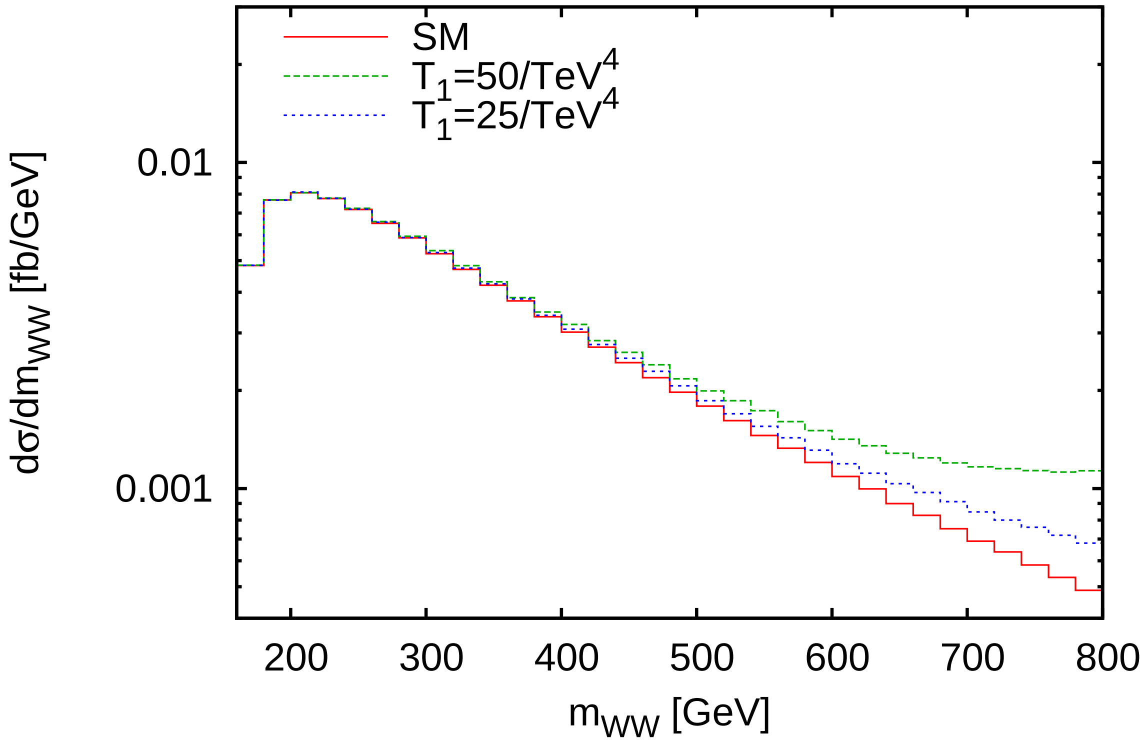
For example: $\mathcal{L}_{S,0}$ is needed to describe $V_L V_L \to V_L V_L$ scattering

- 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 $\mathcal{L}_{eff} = \frac{f_{M,1}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$

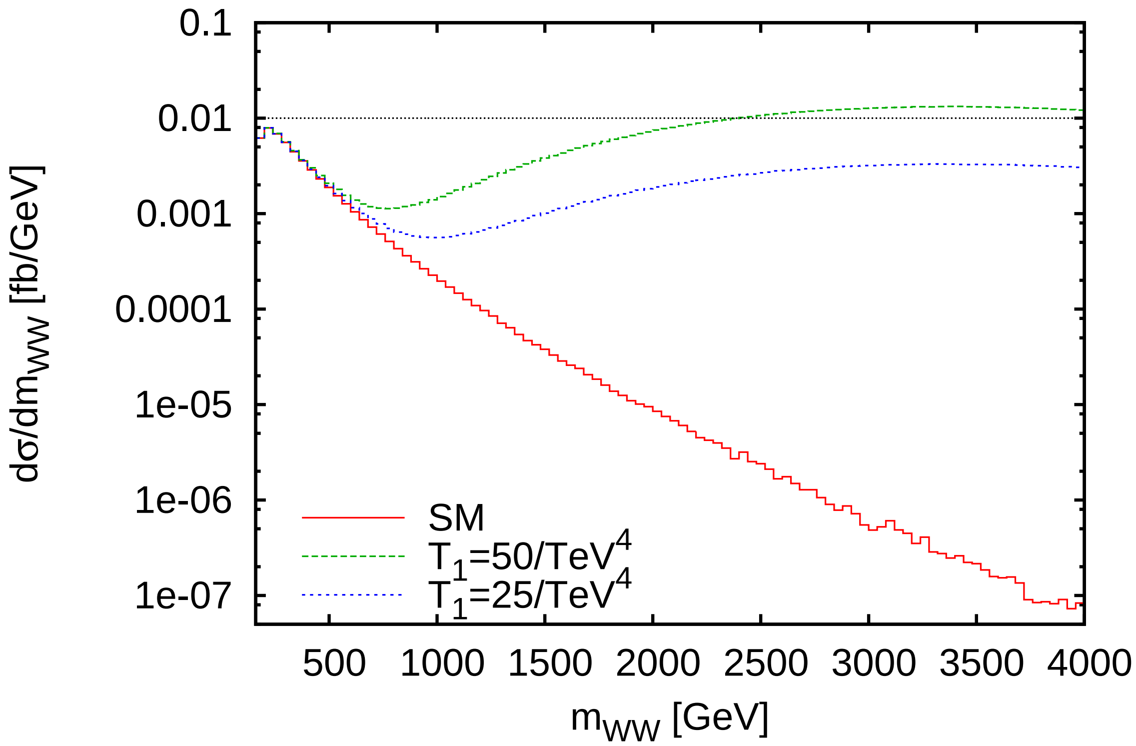
with $T_1 = \frac{f_{M,1}}{\Lambda^4}$ constant on $pp \to W^+W^- jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



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

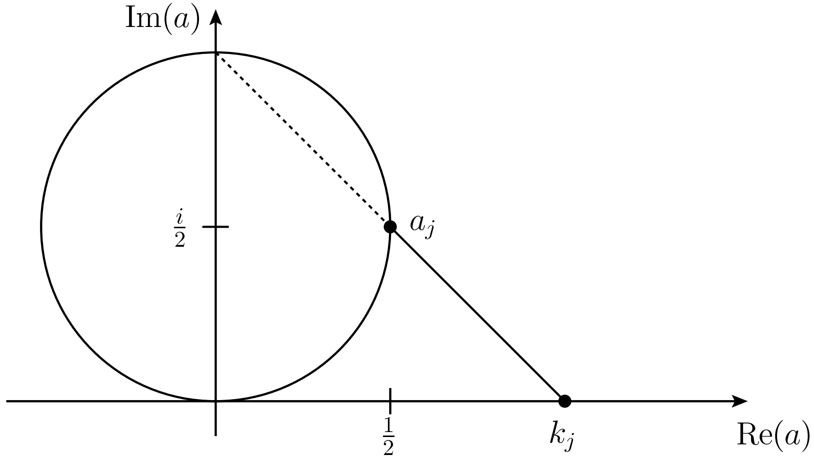
$VV \to W^+W^-$ with dimension 8 operators

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
  K-matrix unitarization for $V_LV_L \to V_LV_L$ scattering in VBFNLO 3.0.0 β (Max Löschner)

K matrix unitarization

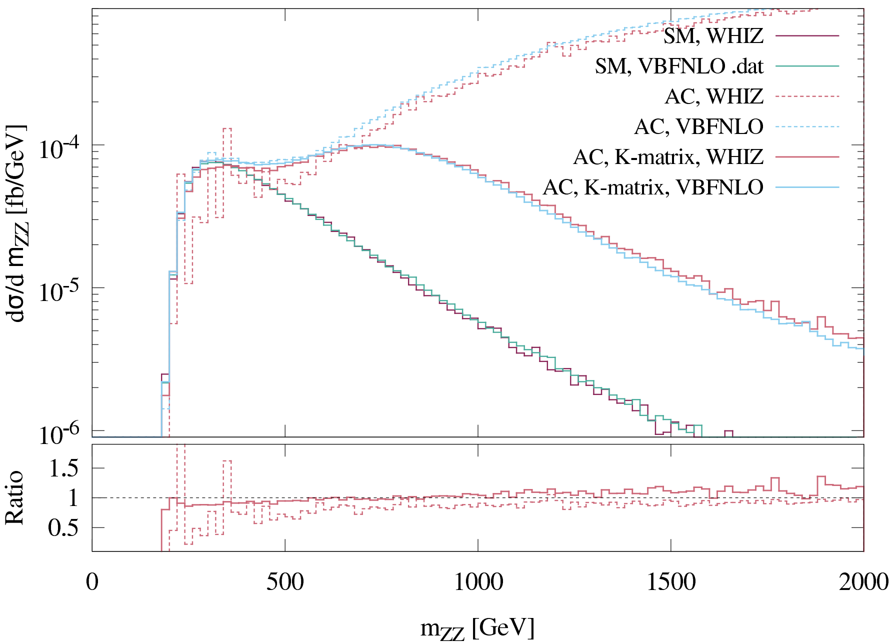


Project amplitude k_j, which exceeds (tree-level) unitarity, back onto Argand circle
→ K matrix unitarized amplitude a_j

[VBFNLO implementation: Löschner, Perez;

following: Alboteanu, Kilian, Reuter]

Comparison with Whizard, which has this method already implemented: [Kilian, Ohl, Reuter, Sekulla, et al.]



Example: VBF-ZZ ($e^+e^-\mu^+\mu^-$)

good agreement between both codes for longitudinal ops. at LO
→ can now generate distributions also at NLO via VBFNLO

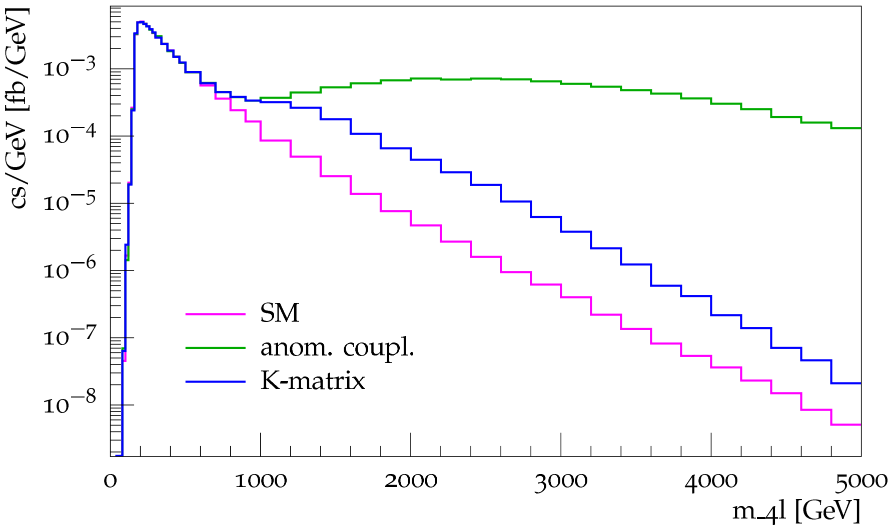
Extension to mixed and transverse operators not straight-forward
→ work ongoing

Combination with Parton Shower

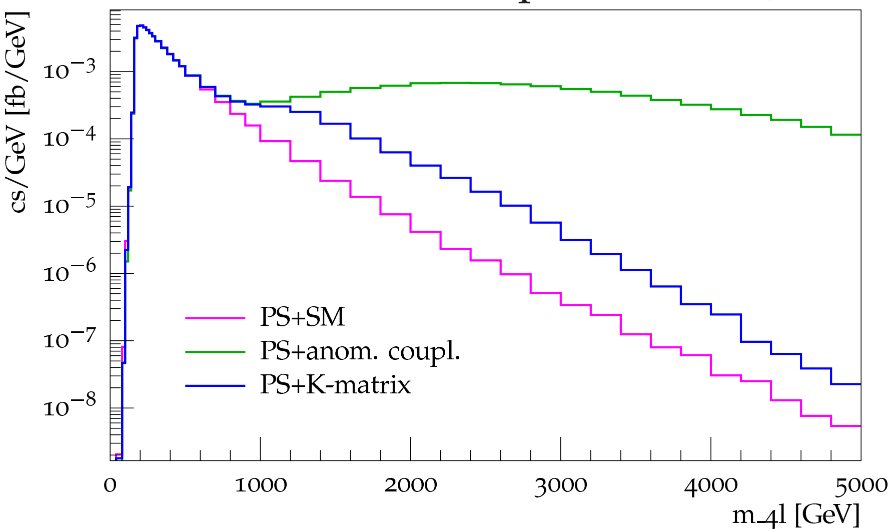
Can also combine K-matrix in setup with parton shower [VBFNLO3&Herwig7]

Example: VBF-W^+W^+ ($pp \to e^+\nu_e\,\mu^+\nu_\mu\,jj$)
anom. coupl.: $f_{S,1}/\Lambda^4 = 100$ TeV^{-4}

fixed-order NLO



NLO+PS (MC@NLO + dipole shower)



No significant shape changes in $d\sigma/dm_{4\ell}$ when switching on PS

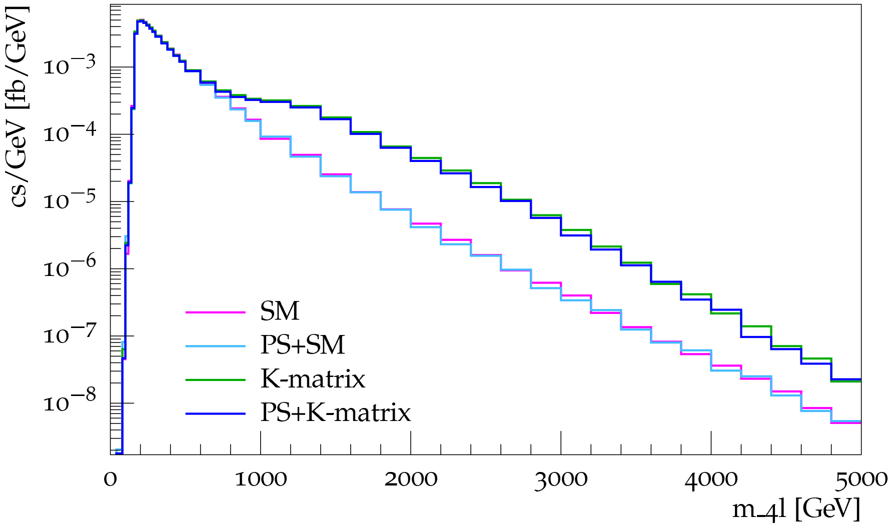
(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix))

W^+W^+: Combination with Parton Shower

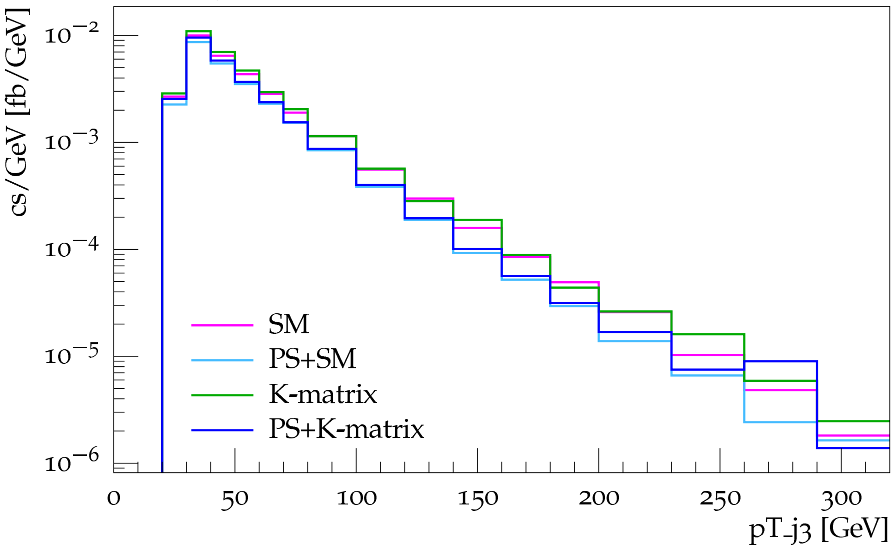
Can also combine K-matrix in setup with parton shower [VBFNLO3&Herwig7]

anom. coupl.: $f_{S,1}/\Lambda^4 = 100$ TeV^{-4}

$m_{4\ell}$ – Comparison



$p^T_{j,3}$ – Comparison



No significant shape changes in $m_{4\ell}$ when switching on PS

(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix))

$\leftrightarrow$ $p^T_{j,3}$ more sensitive to parton-shower effects since it is LO distribution

Conclusions

- VBFNLO provides NLO QCD corrections for a host of processes, from VBF and VBS, over VVV production, to production $VVjj$ final states via gluon exchange
- VBFNLO now also provides interface to event generators for VBF/VBS. Other process classes will follow
- Model independent parameterizations of deviations from the SM are provided
- Form factors or some other unitarization procedure cannot be avoided when using effective Lagrangians for VV scattering at the LHC
- NLO corrections and their implementation have been a 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, M. Löschner, G. Perez, S. Plätzer, S. Prestel, H. Rzehak, F. Schissler, M. Spannowsky, Ninh Duc Le, R. Roth, N. Kaiser, O. Schlimpert