.

Multi-gauge-boson production at hadron colliders

Standard Model @ LHC 2012

Copenhagen – April 2012

Barbara Jäger

Johannes Gutenberg University Mainz

Definition:

1 a : many : multiple : much <*multi*-valent>

b : more than two <*multi*-lateral>

c : more than one <*multi*-parous> <*multi*-billion>

2 : many times over <*multi*-millionaire>

Origin:

Latin, from *multus* much, many

[Merriam-Webster online dictionary]

Definition:

1 a : many : multiple : much <*multi*-valent>

b : more than two <*multi*-lateral>

c : more than one <*multi*-parous> <*multi*-billion>

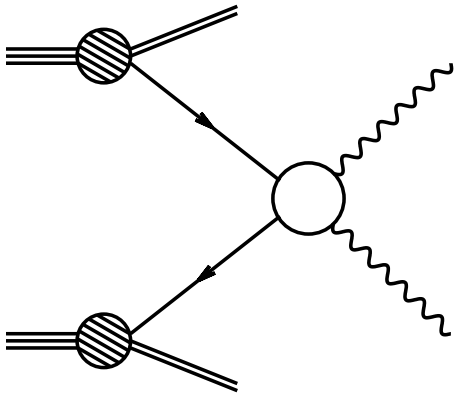
2 : many times over <*multi*-millionaire>

Origin:

Latin, from *multus* much, many

[Merriam-Webster online dictionary]

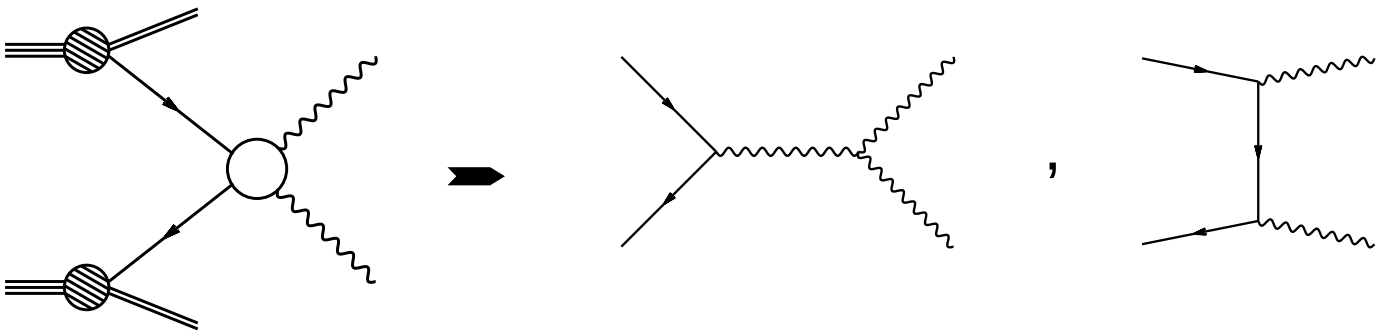
gauge-boson pair production



probe non-Abelian structure of the SM at high energies:

- (anomalous) triple-gauge-boson couplings
- dynamics of longitudinal massive gauge bosons

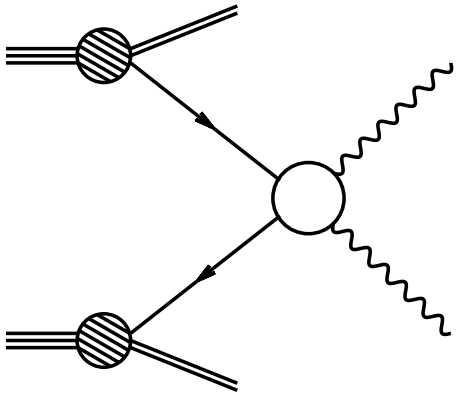
gauge-boson pair production



probe non-Abelian structure of the SM at high energies:

- (anomalous) triple-gauge-boson couplings
- dynamics of longitudinal massive gauge bosons

gauge-boson pair production

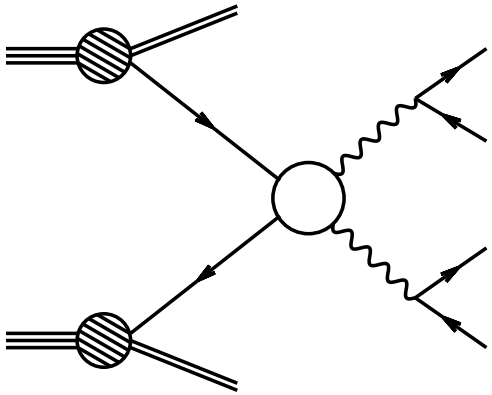


$$pp \to VV \to 4f$$

constitutes important class of
background processes to:

- the Higgs search in the mode $pp \to H \to VV \to 4f$
- new physics searches with leptons+$\not{E}_T$ signatures
  (e.g. SUSY-particle pair production)

gauge-boson pair production



$$pp \to VV \to 4f$$

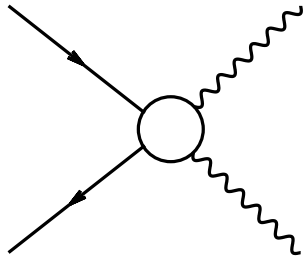
constitutes important class of
background processes to:

- the Higgs search in the mode $pp \to H \to VV \to 4f$
- new physics searches with leptons+$\not{E}_T$ signatures
  (e.g. SUSY-particle pair production)

gauge-boson pair production @ NLO QCD

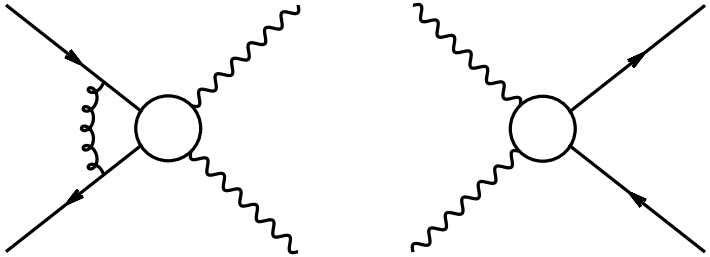
leading order contributions:

$$|\mathcal{M}_0|^2 = \left| \quad \right|^2$$

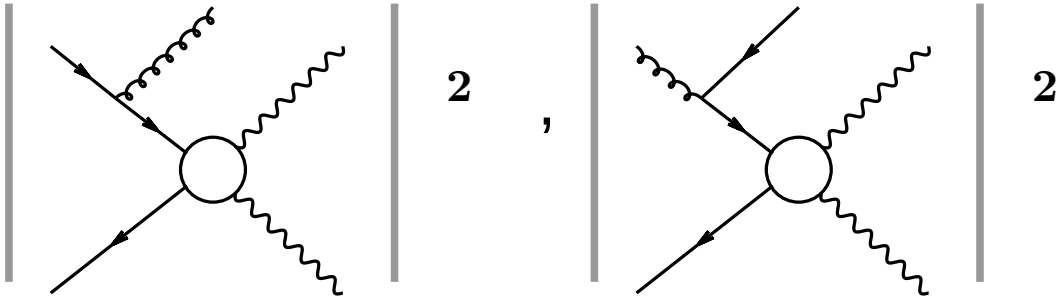


next-to-leading order QCD corrections:

virtual: $\mathcal{M}_V \mathcal{M}_0^\star =$



real: $|\mathcal{M}_R|^2 =$



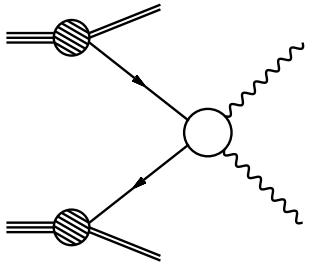
gauge-boson pair production @ NLO QCD

$h_1 h_2 \to ZZ$:

Ohnemus, Owens (1991) / Mele, Nason, Ridolfi (1991)

$h_1 h_2 \to W^{\pm} Z$:

Ohnemus (1991) / Frixione, Nason, Ridolfi (1992)



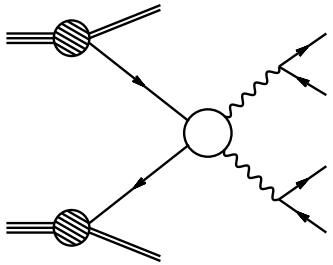
$h_1 h_2 \to W^{+} W^{-}$:

Ohnemus (1991) / Frixione (1993)

including leptonic decays:

analytical expressions:

Dixon, Kunszt, Signer (1998) / Baur, Han, Ohnemus (1996)



implementation in public code MCFM:

Campbell, Ellis (1999)

gauge-boson pair production @ NLO QCD

$$pp \to W^+(\to e^+\nu_e)W^-(\to \mu^-\overline{\nu}_\mu)$$

$\sqrt{s}$ [TeV] and cuts	σ^{LO} [fb]	σ^{NLO} [fb]	K-factor
7 (basic)	144	249	1.73
7 (Higgs)	7.14	15.19	2.13
14 (basic)	296	566	1.91
14 (Higgs)	13.7	34.7	2.53

numbers taken from MCFM: *Campbell, Ellis, Williams (2011)*

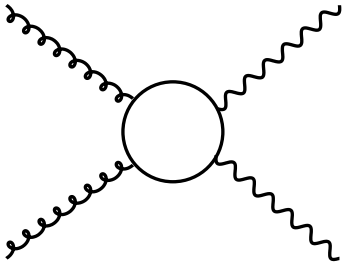
gauge-boson pair production @ NLO QCD

$$pp \to W^+(\to e^+\nu_e)W^-(\to \mu^-\overline{\nu}_\mu)$$

$\sqrt{s}$ [TeV] and cuts	σ^{LO} [fb]	σ^{NLO} [fb]	K-factor
7 (basic)	144	249	1.73
7 (Higgs)	7.14	15.19	2.13
14 (basic)	296	566	1.91
14 (Higgs)	13.7	34.7	2.53

- size of NLO-QCD corrections is large and cut-dependent
- not expected from variation of central scale
  $M_W/2 \le \mu_f \le 2M_W$ at LO ($\leftarrow$ qg channels)

gauge-boson pair production – loop contributions



gluon-induced contributions
first occur at one-loop level

considered first by

Dicus, Kao, Repko (1987); Glover, van der Bij (1989)

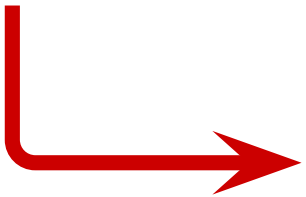
phenomenological study for the LHC:

Dührssen, Jakobs, van der Bij, Marquard (2005)

inclusion of off-shell effects and heavy-quark loops:

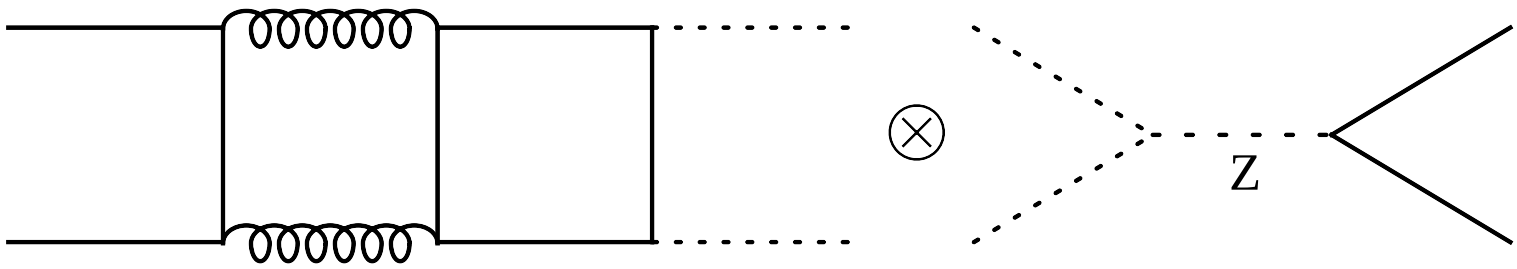
Binoth, Ciccolini, Kauer, Krämer (2005,2006);

Binoth, Kauer, Mertsch (2008)



impact depends on cuts;
can be large

gauge-boson pair production @ NNLO QCD



only small parts of the NNLO-QCD contributions have been computed:

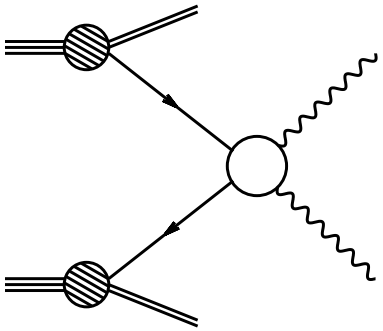
✔ two-loop and one-loop-squared virtual QCD corrections in $q\bar{q}$ annihilation in the high-energy limit (all invariants $\gg M_W^2$)

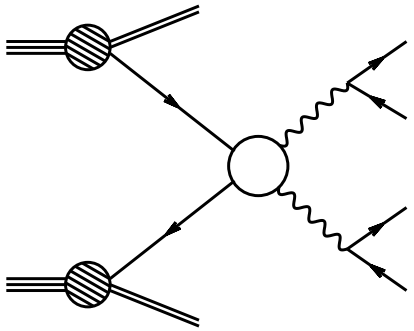
Chachamis, Czakon, Eiras (2008)

✘ no recent updates in the literature

gauge-boson pair production & parton showers

NLO-QCD calculations matched with multi-purpose parton-shower programs PYTHIA, HERWIG, SHERPA





MC@NLO:

Frixione, Webber (2002)

POWHEG:

Nason, Ridolfi (2006)

POWHEG in HERWIG++:

Hamilton (2010)

POWHEG in SHERPA:

Höche, Krauss, Schönherr, Siegert (2010)

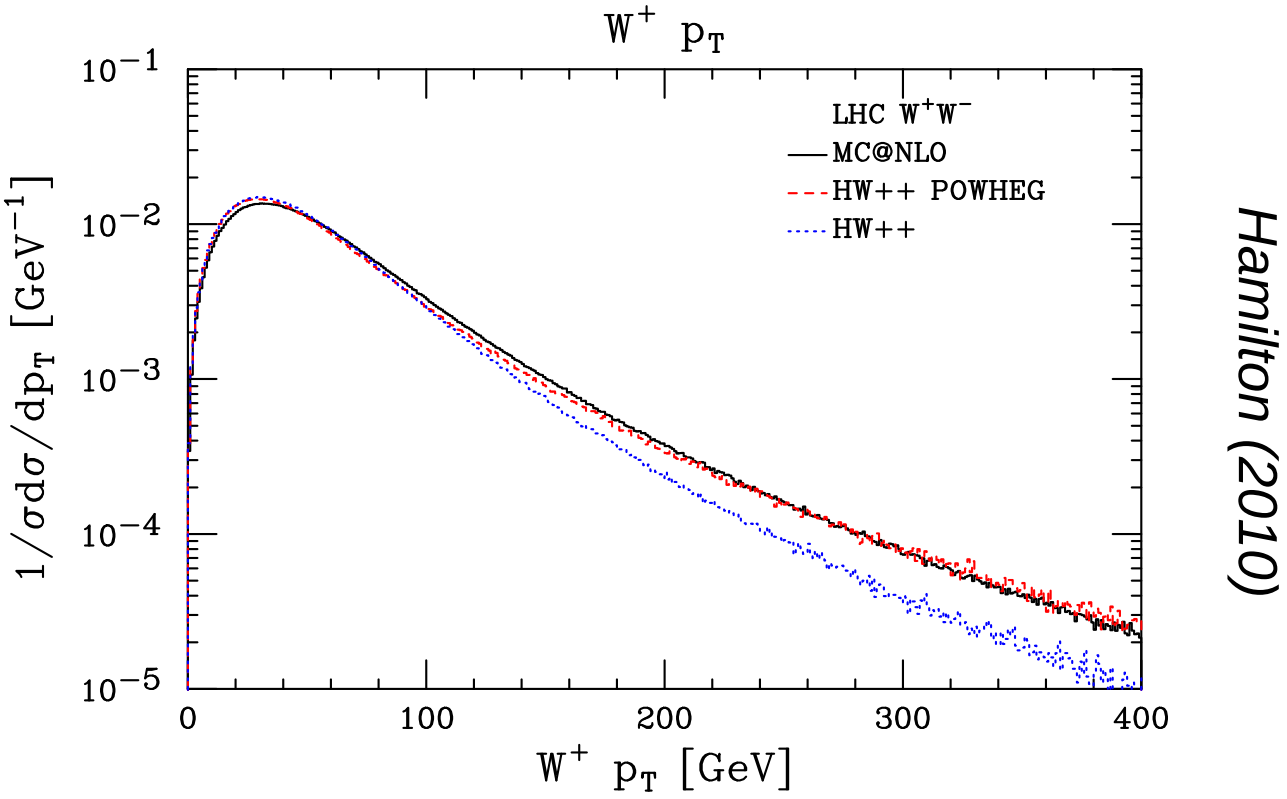
POWHEG-BOX:

Melia, Nason, Röntsch, Zanderighi (2011)

aMC@NLO:

Frederix et al. (2011)

gauge-boson pair production & parton showers

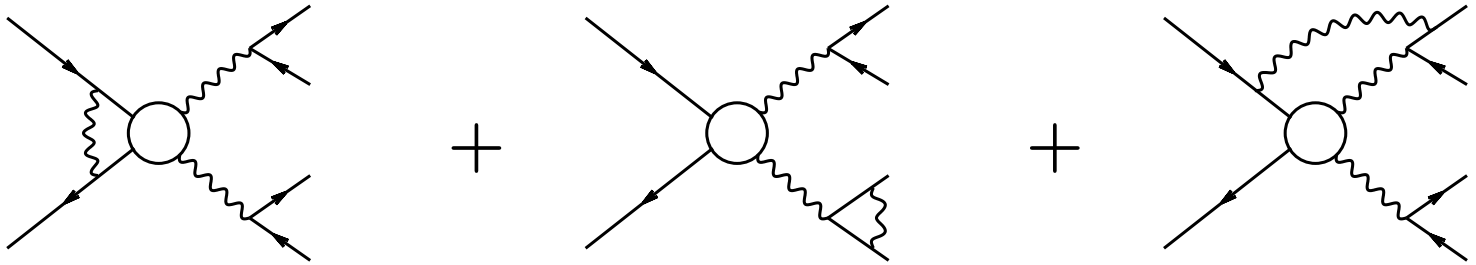


- high-p_T tails: NLO+PS deviate from LO+PS results ($\leftarrow qg$)
- mostly: agreement between different NLO+PS simulations
- deviations between MC@NLO and POWHEG
  in distributions sensitive to extra jet emission

gauge-boson pair production @ NLO EW

$pp \to VV \to$ 4 leptons: $\mathcal{O}(\alpha)$ corrections

more challenging than QCD corrections:



$\to$ employ approximations:

- retain only universal logarithms that are large at high energies
- double pole approximation for gauge bosons

Accomando, Denner, Pozzorini, Kaiser (2001-2004)

gauge-boson pair production @ NLO EW

most general contribution to Lagrangian for WWV interaction, compatible with C and P conservation:

$$\mathcal{L}_{WWV} = g_{WWV}\left[ig_1^V(W^*_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{*\,\mu}V^\nu) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + i\frac{\lambda^V}{M_W^2}W^*_{\rho\mu}W^\mu_\nu V^{\nu\rho}\right]$$

supplied by form factors to tame unitarity violations at high energies:

$$\Delta g \to \frac{\Delta g}{(1+M^2_{VV}/\Lambda^2)^2}$$

maximum deviation from SM allowed by LEP bounds:

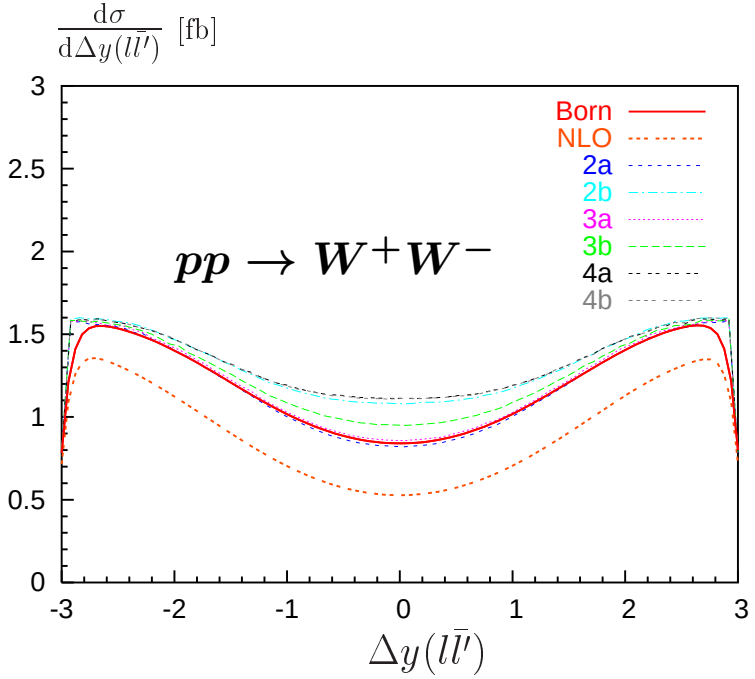
$$g_1^Z = -0.027,\ \Delta\kappa^\gamma = -0.112,\ \Delta\lambda^Z = \Delta\lambda^\gamma = -0.044$$

(SM: $g_1^V = \kappa^V = 1$ and $\lambda^V = 0$)

gauge-boson pair production @ NLO EW

parameterize new physics by anomalous triple gauge boson couplings λ, $\Delta\kappa_\gamma$, Δg_1^Z

Accomando, Kaiser (2005)



Scenario	λ	Δg_1^Z	$\Delta\kappa_\gamma$
Born/NLO EW	0	0	0
2a/2b	0	± 0.02	0
3a/3b	0	0	± 0.04
4a/4b	± 0.02	0	0

☞ EW corrections can fake anomalous triple-gauge boson couplings

gauge-boson pair production @ NNLL EW

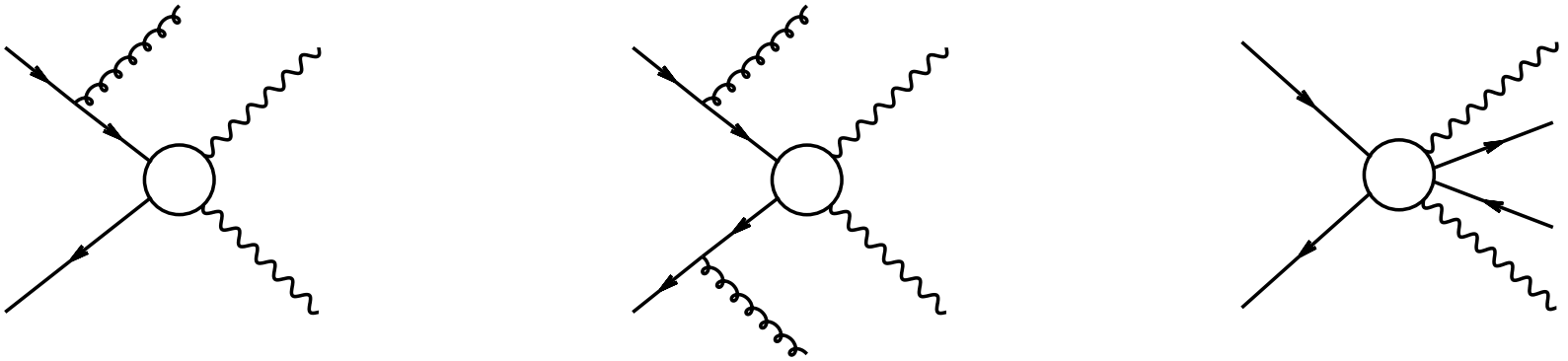
one- and two-loop electroweak corrections in
next-to-next-lo-leading logarithmic approximation
in high-energy limit

Kühn, Metzler, Penin, Uccirati (2011)

➠ maximal effect in distributions 60% (1-loop) and 20% (2-loop)

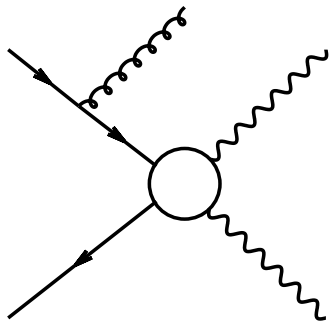
(partial compensation between
one- and two-loop contributions)

gauge-boson pairs in association with jets



- large fraction of V-pair events at the LHC exhibits additional jet activity
  $\rightarrow$ precise knowledge of $VV + \mathrm{jets}$ processes needed for:
  - extraction of EW gauge-boson couplings
  - search for Higgs bosons in GF and VBF $H \rightarrow VV$ channels
  - search for various scenarios of new physics
- important test ground for multi-particle calculations at NLO-QCD

gauge-boson pairs in association with one jet



$pp \to WWj$ (without/with leptonic decays):

Dittmaier, Kallweit, Uwer (2007);

Campbell, Ellis, Zanderighi (2007) $\to$ `MCFM`

$pp \to ZZj$ (no decays):

Binoth, Gleisberg, Karg, Kauer, Sanguinetti (2010)

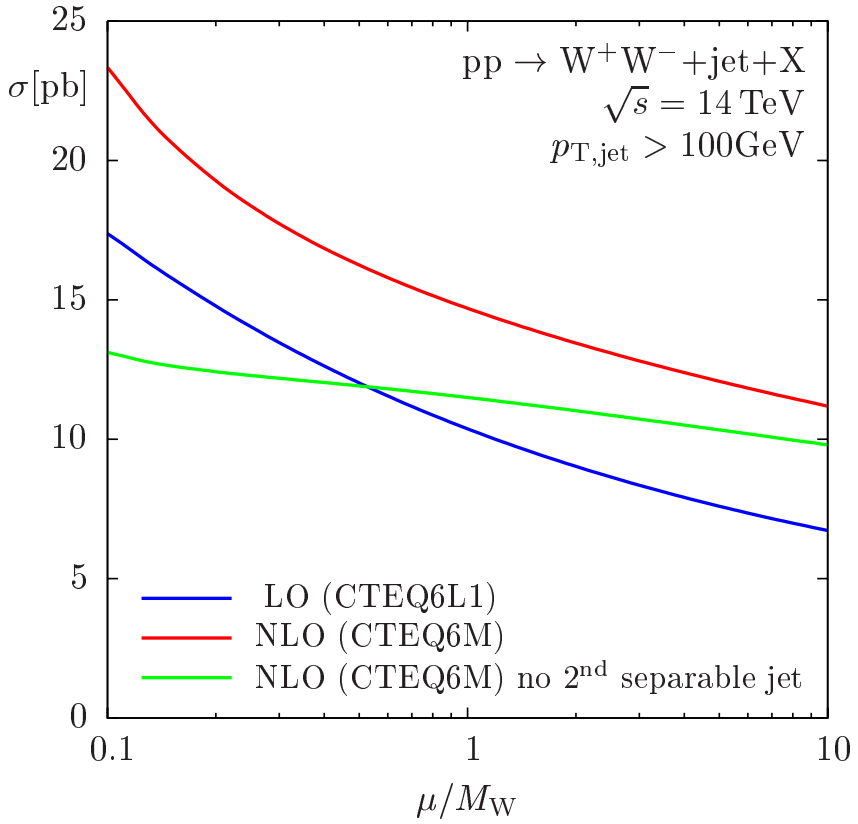
$pp \to WZj$ (including leptonic decays):

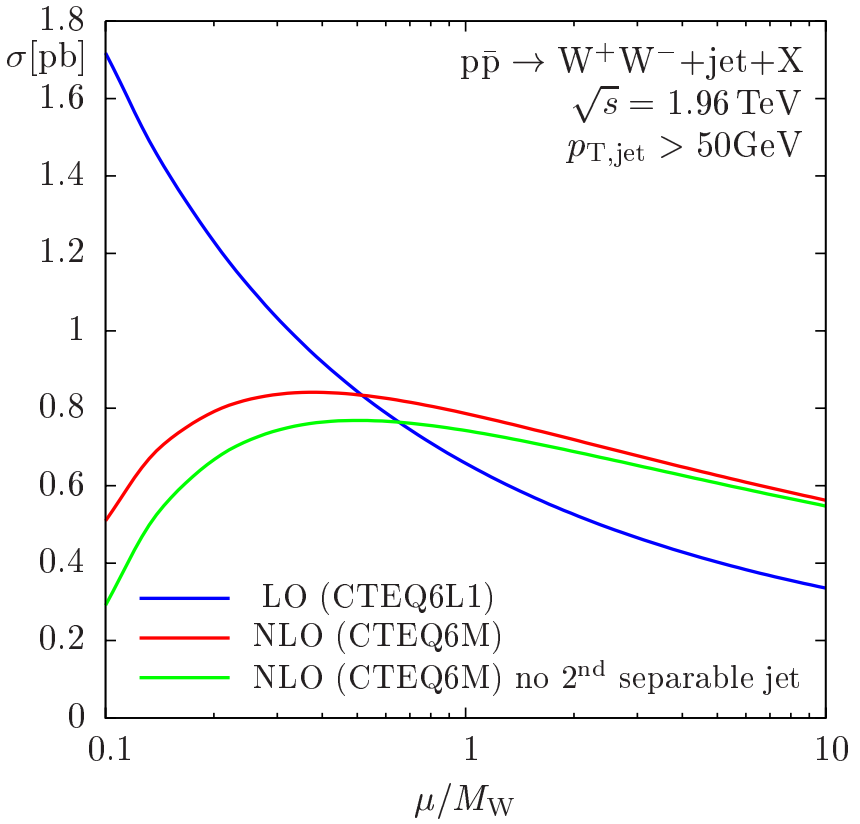
Campanario, Englert, Kallweit,

Spannowsky, Zeppenfeld (2010) $\to$ `vbfnlo`

- NLO-QCD corrections can be as large as 70%
- significant reduction of scale uncertainty at NLO-QCD
- effect of NLO-QCD corrections enhanced by cuts typical for Higgs search

gauge-boson pairs in association with jets





Dittmaier, Kallweit, Uwer (2009)

QCD corrections to x-sec can be reduced by veto on extra jet,

but: perturbative stability of differential distributions can suffer

gauge-boson pairs in association with two jets

QCD-induced production

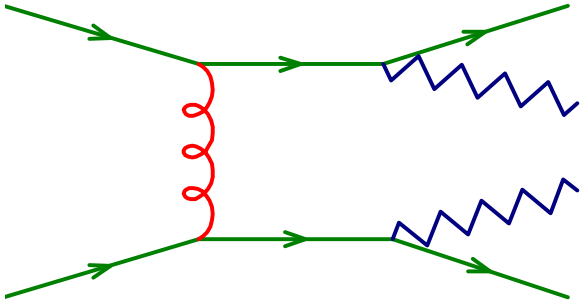
W^+W^+jj & W^+W^-jj:

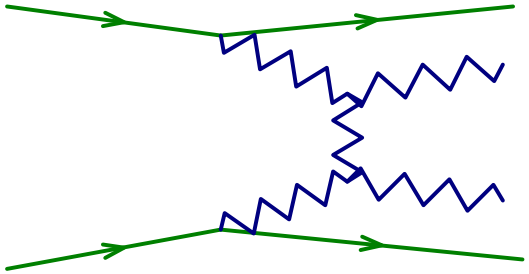
Melia, Melnikov, Rontsch, Zanderighi (2010-2011)

EW production

all $VVjj$ channels:

Bozzi, Oleari, Zeppenfeld, B.J. (2006-2009)

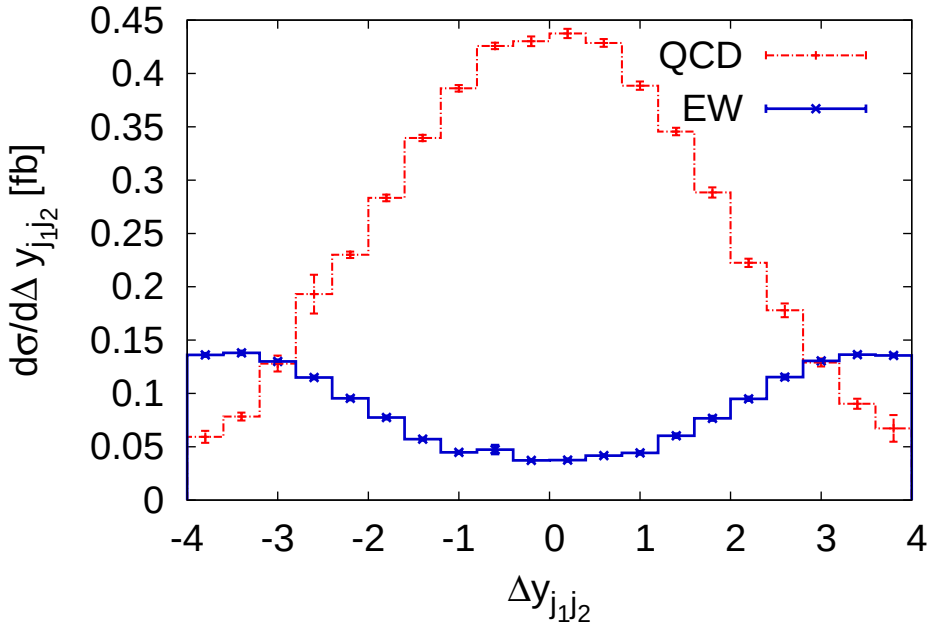


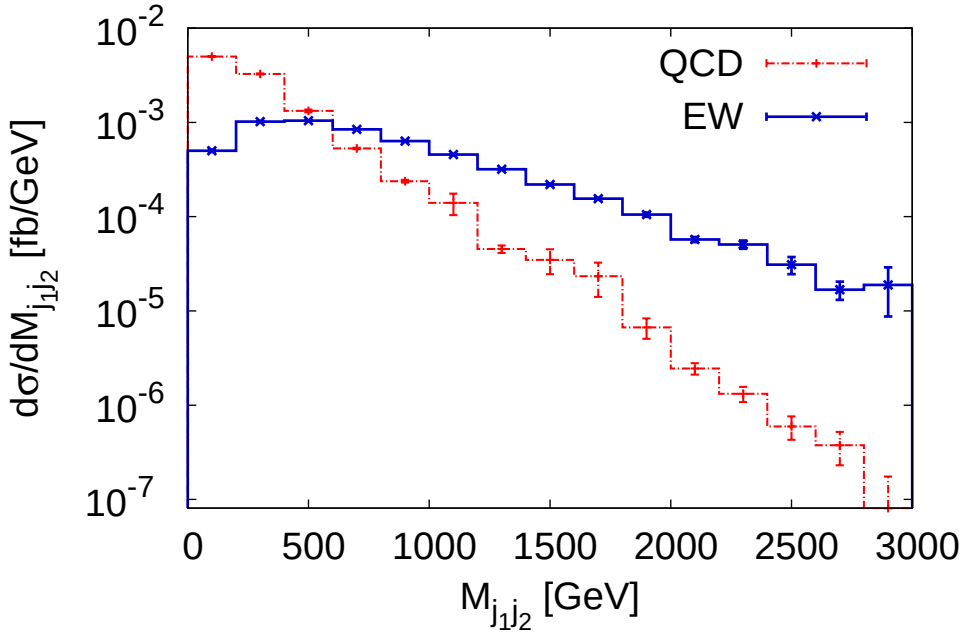


- W^+W^+jj ➠ distinct signature: same-sign leptons $+\not{E}_T+$ 2 jets
- W^+W^+jj ➠ test ground for multiple parton interactions
- $VVjj$ ➠ important backgrounds to search for Higgs and BSM in VBF channel

$pp \to W^+W^+jj$: QCD versus EW production

Zanderighi, B.J. (2011)





- $\sqrt{s} = 7$ TeV
- basic jet cuts only
- NLO-QCD accuracy

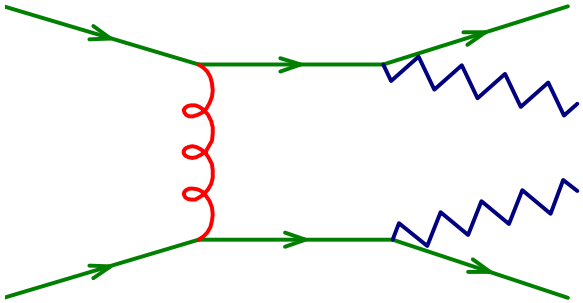
$pp \to W^+W^+jj$ in the POWHEG-BOX

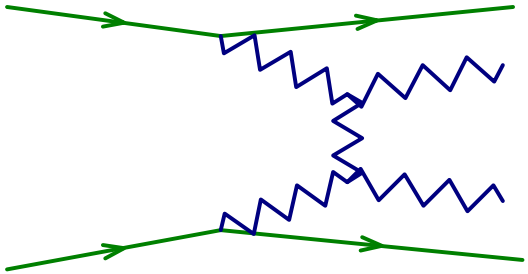
QCD-induced production

Melia, Melnikov, Rontsch, Zanderighi (2010);
Melia, Nason, Rontsch, Zanderighi (2011)

EW production

Oleari, Zeppenfeld, B.J. (2009);
Zanderighi, B.J. (2011)





NLO results with basic jet cuts only ($p_T^{\rm tag} > 20$ GeV):

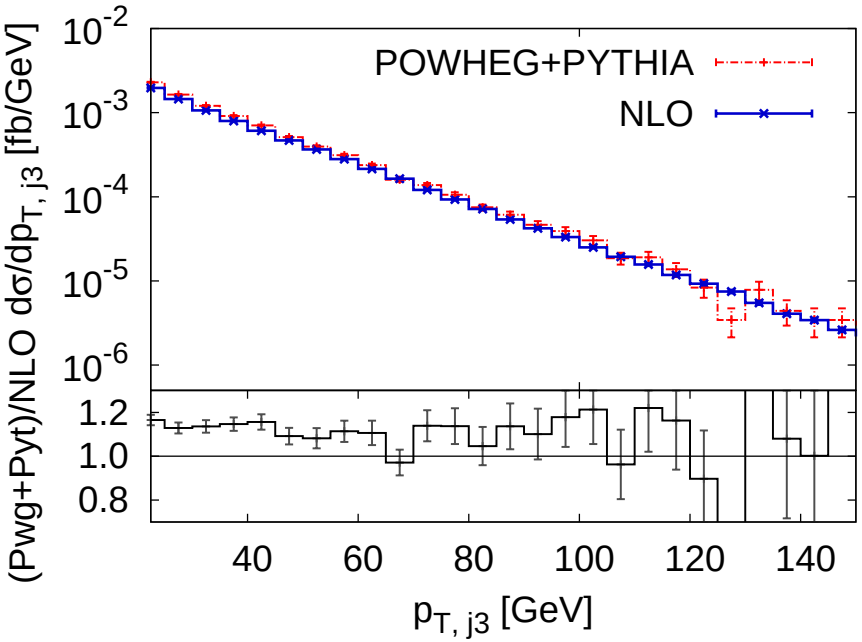
$$\sigma_{\rm QCD}^{\rm inc} = 2.12 \text{ fb} \qquad \sigma_{\rm EW}^{\rm inc} = 1.097 \text{ fb}$$

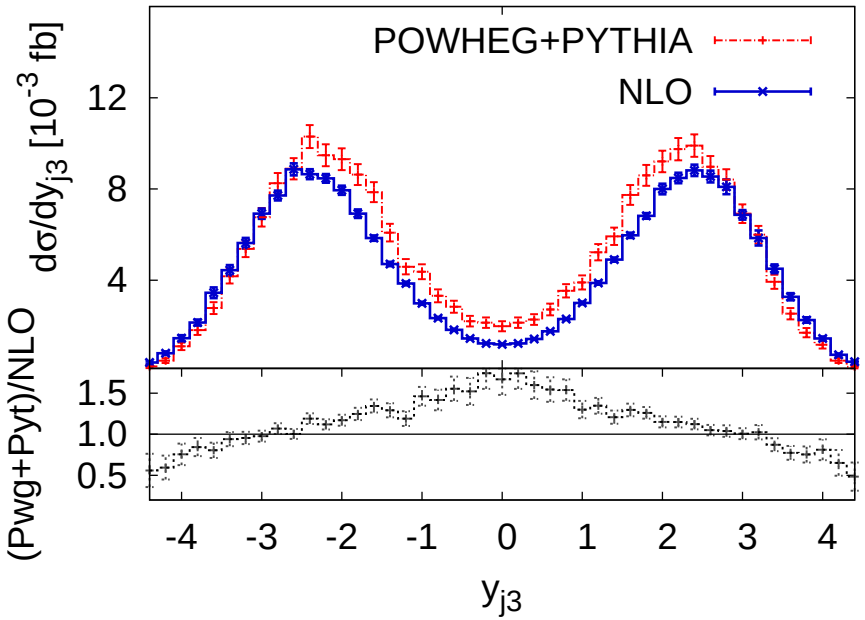
NLO results with VBF cuts:

$$\sigma_{\rm QCD}^{\rm cuts} = 0.0074 \text{ fb} \qquad \sigma_{\rm EW}^{\rm cuts} = 0.201 \text{ fb}$$

$pp \to W^+W^+jj$ in the POWHEG-BOX

Zanderighi, B.J. (2011)





good agreement between parton-level NLO calculation and POWHEG matched with PYTHIA for many observables

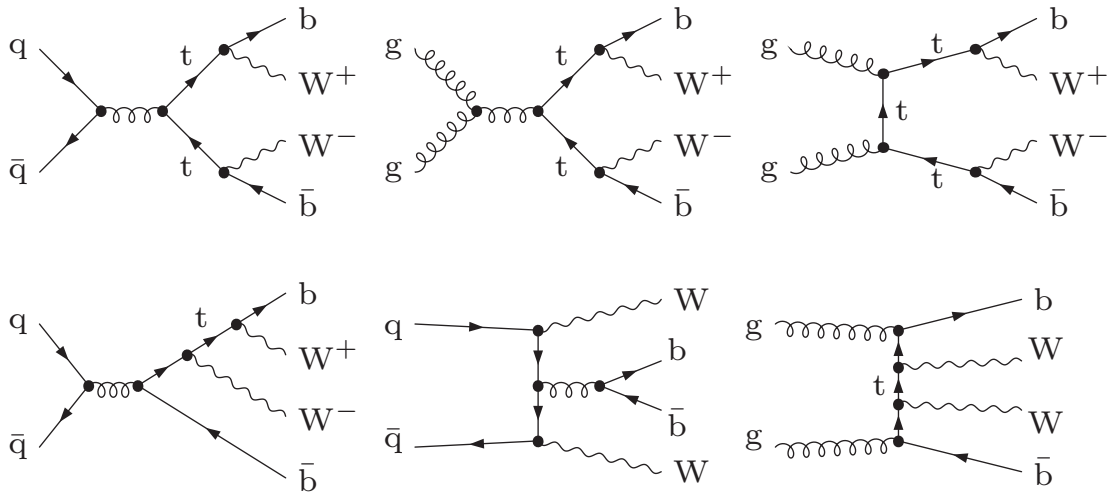
typical for VBF processes: little jet activity at central rapidities

→ exploited by central-jet veto techniques

note: parton-shower effects slightly enchance central jet activity

W pairs in association with bottom quarks

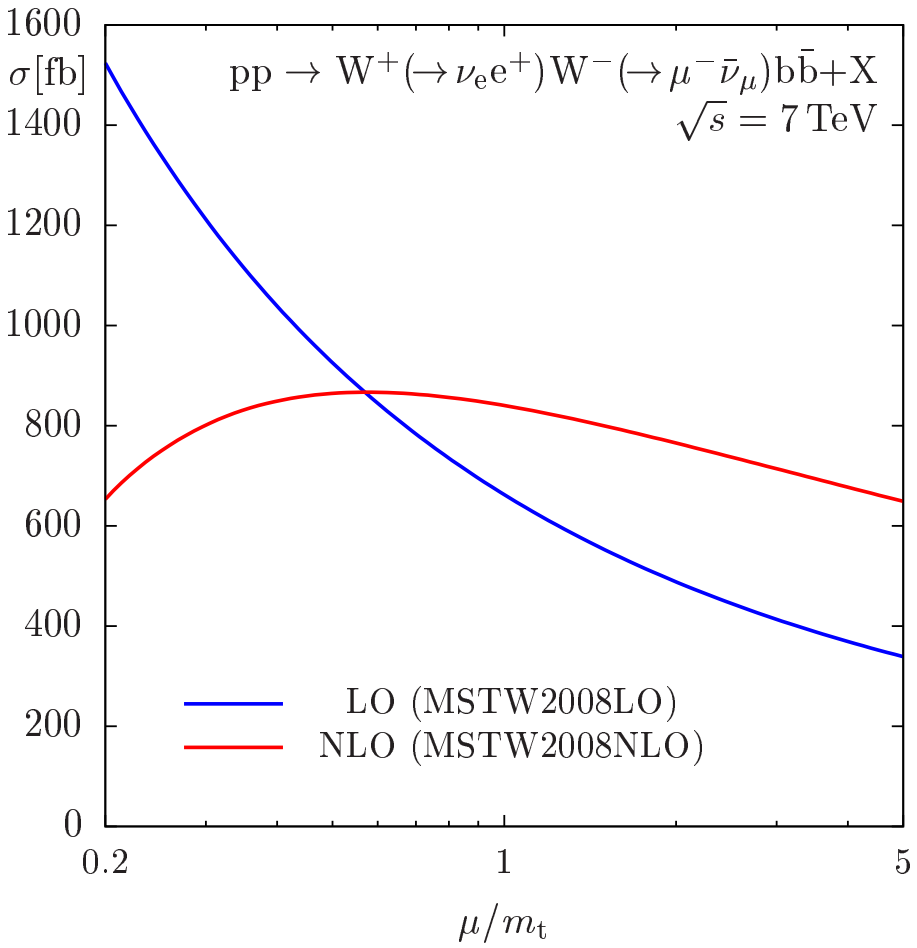
$pp \to W^+W^-b\bar{b}$ . . . complete description of
$pp \to t\bar{t}$ production and subsequent $t \to Wb$ decay,
including interferences, off-shell effects, non-resonant backgrounds



- *Denner, Dittmaier, Kallweit, Pozzorini (2010)*
- *the HELAC group: Bevilacqua et al. (2010)*

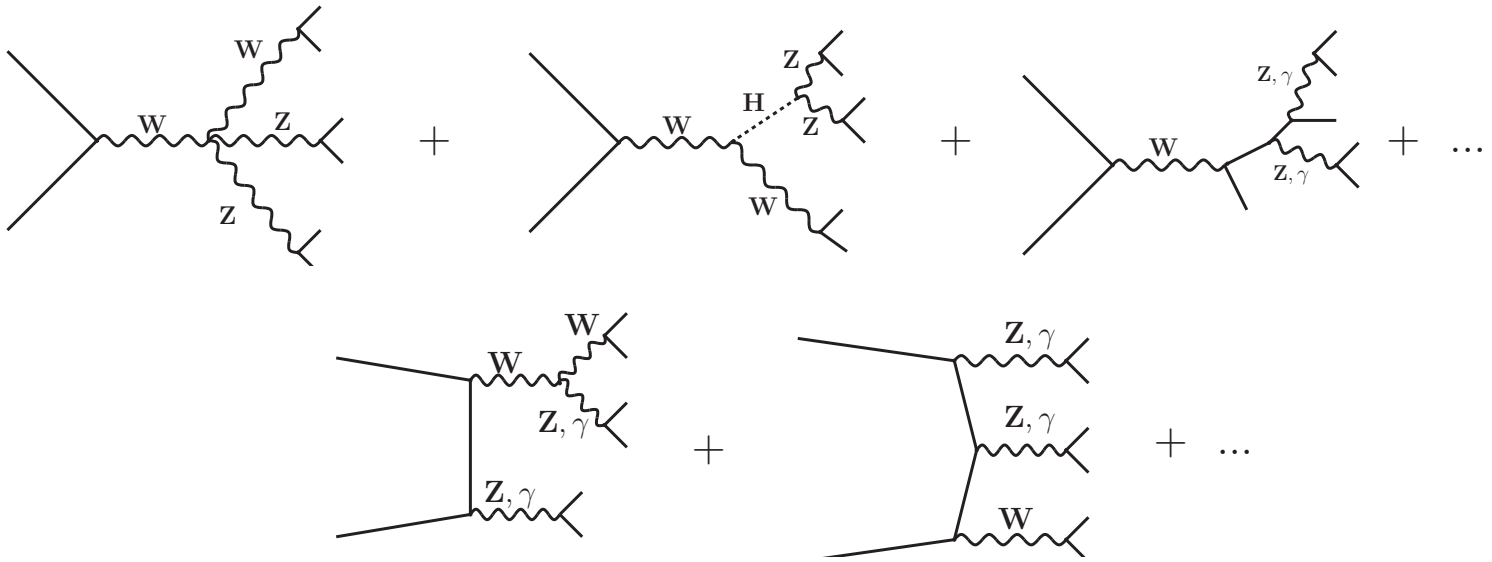
W pairs in association with bottom quarks

Denner et al. (2010)



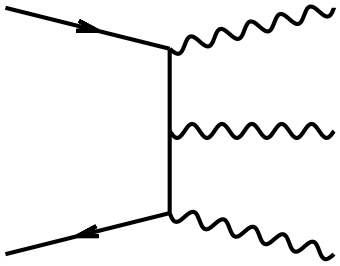
- off-shell contributions numerically relevant
  (in particular beyond LO)
- NLO-QCD corrections sizable:
  Tevatron: $\boldsymbol{K^{\mathrm{inc}} \sim 0.94}$
  LHC(7): $\boldsymbol{K^{\mathrm{inc}} \sim 1.27}$
- reduction of scale uncertainty
  ($\boldsymbol{\sim 40\% \to 9\%}$)

triboson production

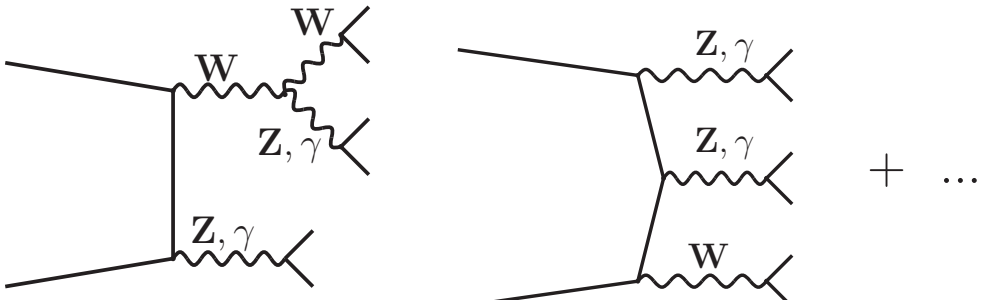


- SM background for new physics signatures with multi-leptons$+\not{p}_T$
- sensitive to (anomalous) triple and quartic gauge boson couplings
- NLO QCD corrections are large and strongly depend on observable and phase space region
(drastically underestimated by LO scale variations)

triboson production @ NLO QCD



on-shell production



including leptonic decays
and off-shell effects

$pp \to ZZZ$:
Lazopoulos, Melnikov, Petriello (2007)

$pp \to VVV$:
Binoth, Ossola, Papadopoulos, Pittau (2008)

$pp \to WWZ$:
Hankele, Zeppenfeld (2007)

$pp \to ZZW, WWW$:
Campanario, Hankele, Oleari, Prestel, Zeppenfeld (2008)

example: $pp \to W^+W^-Z$ with decays

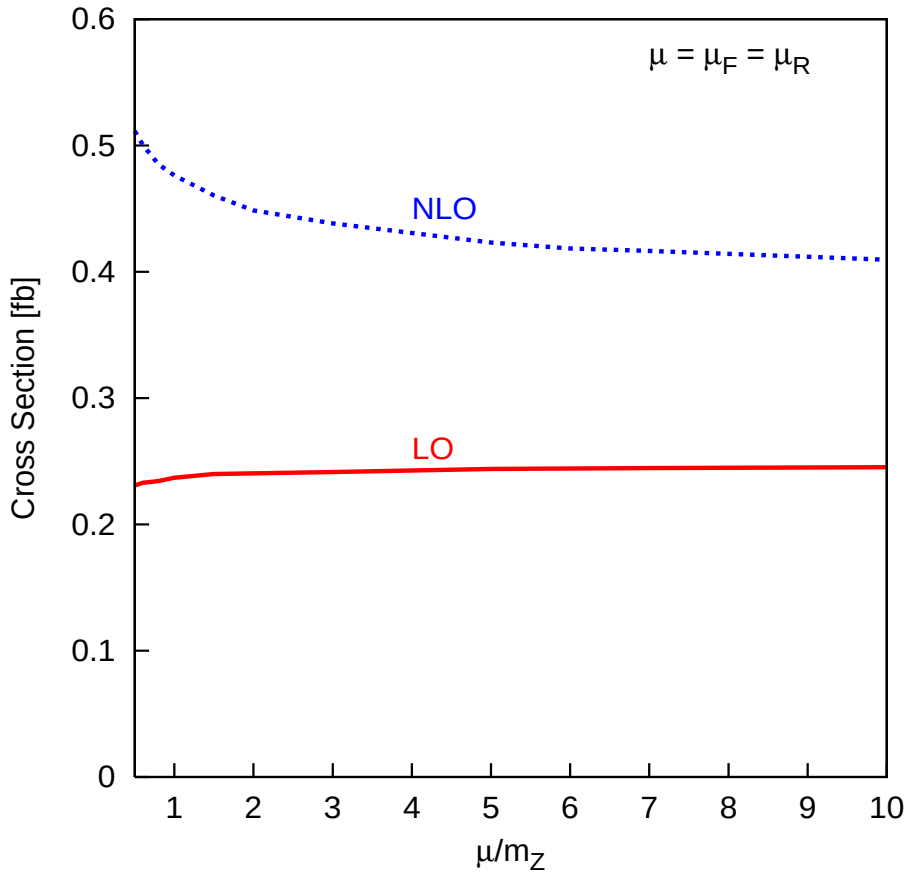
Hankele, Zeppenfeld (2007)

LO: very mild scale dependence

LO is $\mathcal{O}(\alpha_s^0)$,
PDFs probed in regions
with small μ_f dependence

but large QCD corrections with

$$\frac{\sigma^{NLO}}{\sigma^{LO}} \sim 1.7 \div 2.2$$



summary

- discussed selected processes with multiple massive weak gauge bosons at hadron colliders:

$$VV, VVj, VVjj, VVb\bar{b}, VVV$$

- provide powerful probes of the structure of the Standard Model

  e.g. triple and quartic gauge boson couplings

- serve as important backgrounds

  . . . to searches for the Higgs boson
  . . . to searches for new physics

conclusions

impact of radiative corrections can be large and dependent on experimental selection criteria

- to achieve precision required by experiment:
  - consider QCD and EW corrections
  - disregard (on-shell, high-energy, ...) approximations
  - match to parton-shower programs

- calculations for selected processes advanced, several public tools available:

`MCFM, vbfnlo, POWHEG-BOX, ...`

disclaimer:

could only touch on the subject

➠ apologies for incompleteness