Production of multiple electroweak bosons: theoretical status

Ansgar Denner

Universität Würzburg

Standard Model @ LHC 2013

Freiburg, April 9, 2013

Outline

- Relevance of multiple electroweak boson production and perturbative corrections
- Vector-boson pair production
- Vector-boson pair production with additional jets
- Triple vector-boson production
- Vector-boson + jet production
- Summary

Relevance of multiple vector-boson production

- probe non-Abelian structure of the SM
  (compare WW production at LEP2)
- sensitive to (anomalous) triple and quartic vector-boson couplings
- subject to unitarity cancellations in SM at high energies
  $\Rightarrow$ enhanced sensitivity to deviations from SM
- probe dynamics of longitudinal massive gauge bosons
  $\Rightarrow$ window to Higgs mechanism
- important background processes to
  - Higgs production with decay into vector-boson pairs
  - searches for new physics with leptons and $\not{E}_{\mathrm{T}}$ signatures
    (e.g. production of supersymmetric particles)

$\Rightarrow$ precise theoretical predictions required!
for test of SM and search for physics beyond

Relevance of higher-order corrections

Process class: $\mathrm{pp} \to$ weak vector bosons $\quad \mathrm{W}, \mathrm{Z}, (\gamma)$

vector bosons decay: leptonic $V \to \bar{l}l'$, hadronic $V \to \bar{q}q'$

QCD corrections:

- for leptonic decays: only production corrected
- generic size: $\mathcal{O}(\alpha_\mathrm{s}) \sim 10\%$
  enhanced by logarithms and new channels $\Rightarrow 25\text{–}100\%$
- generic size of NNLO corrections: $\mathcal{O}(\alpha_\mathrm{s}^2) \sim \mathrm{few}\%$

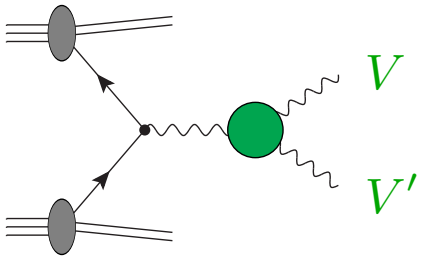
EW corrections:

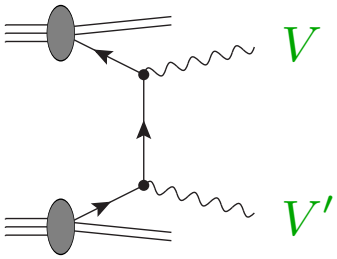
- involve full process: production and decay
  $\Rightarrow$ more complicated structure
  $\Rightarrow$ suitable approximations useful
- typical size for $\sqrt{\hat{s}} \sim M_\mathrm{Z}$: $\mathcal{O}(\alpha/\sin^2\theta_\mathrm{w}) \sim \mathrm{few}\%$
- typical size for $\sqrt{\hat{s}} \gg M_\mathrm{Z}$: $\mathcal{O}(\alpha/\sin^2\theta_\mathrm{w})\ln^2\left(M_\mathrm{W}^2/\hat{s}\right) \sim \mathcal{O}(10-50\%)$
  Sudakov logarithms of universal origin

Vector-boson pair production

Vector-boson pair production

Leading order:





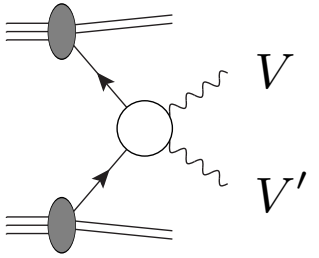
$V, V' = \mathrm{Z}, \mathrm{W}^{\pm}(, \gamma)$

only $q\bar{q}'$ initial states

triple-gauge-boson couplings

NLO-QCD corrections for stable vector bosons

- $\mathrm{pp} \to \mathrm{ZZ}$ Ohnemus, Owens '91; Mele, Nason, Ridolfi '91
- $\mathrm{pp} \to \mathrm{W}^{\pm}\mathrm{Z}$ Ohnemus '91; Frixione, Nason, Ridolfi '92
- $\mathrm{pp} \to \mathrm{W}^{+}\mathrm{W}^{-}$ Ohnemus '91; Frixione '93

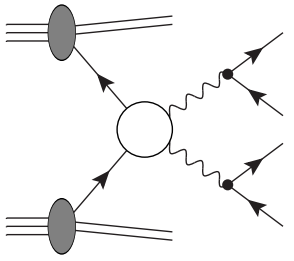


NLO-QCD corrections including leptonic decays:

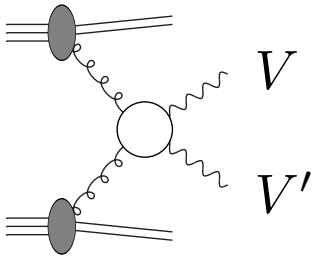
$\Rightarrow$ realistic cuts, spin correlations, off-shell effects

VV production below threshold ($\Rightarrow$ Higgs background)

- phenomenological results:
  Ohnemus '94; Dixon, Kunszt, Signer '99; Campbell, Ellis '99
- analytical amplitudes: Dixon, Kunszt, Signer '98
- public Monte Carlo code MCFM: Campbell, Ellis '99



Gluon-induced contributions



occur first at one-loop level
formally of NNLO but
enhanced by large gluon luminosity

calculations

- stable vector bosons:

  Dicus, Kao, Repko '87; Glover, van der Bij '89, Kao, Dicus '91

- inclusion of off-shell effects:

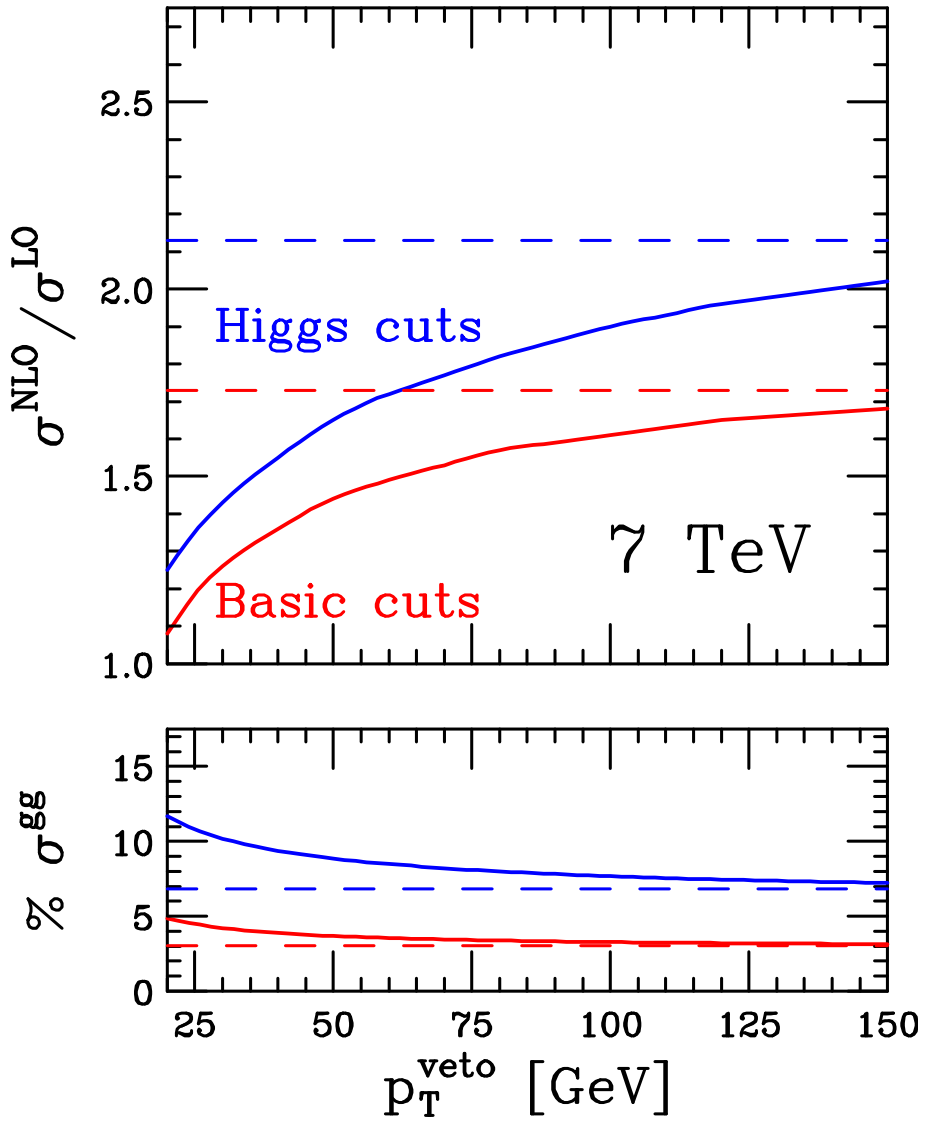
  Matsuura, van der Bij '91; Binoth, Ciccolini, Kauer, Krämer '05,'06; Binoth, Kauer, Mertsch '08, Campbell, Ellis, Williams '11

results

- relative contribution depends strongly on cuts
  - 4% for total cross section
  - up to $30-35\%$ after "Higgs cuts" Dührssen, Jakobs, van der Bij, Marquard '05
    Binoth, Ciccolini, Kauer, Krämer '06
- enhanced by jet veto

NLO-QCD for $pp \to WW \to e^+\nu_e\mu^-\bar{\nu}_\mu$

Campbell, Ellis, Williams '11



K factor as function of jet veto

- sizeable and cut-dependent NLO corrections $50-100\%$
- larger corrections for "Higgs cuts"
- K-factor can be reduced by imposing a jet veto
- gluon-induced contributions are enhanced by a jet veto

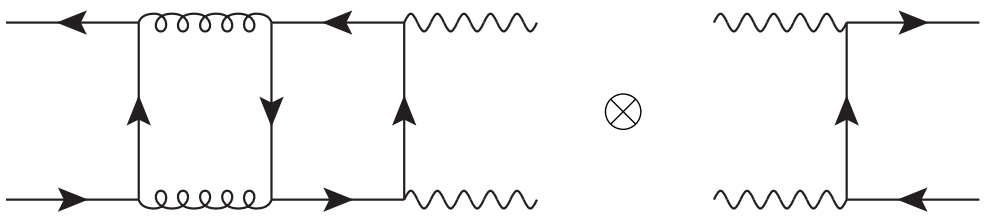
Basic cuts: $p_T^l > 20\,\text{GeV}, \quad |\eta_l| < 2.5$
$E_T^{\text{miss}} > 20\,\text{GeV}$

Higgs cuts: $m_{ll} > 20\,\text{GeV}, \quad \Delta\phi_{ll} < 60^\circ$
$p_T^{l,\text{max}} > 30\,\text{GeV}, \quad p_T^{l,\text{min}} > 25\,\text{GeV}$

NNLO-QCD corrections

Only small part of NNLO-QCD corrections available:
virtual corrections: Chachamis, Czakon, Eiras '08

- two-loop and one-loop-squared corrections
- for $\mathrm{W}^+\mathrm{W}^-$ final state in $q\bar{q}$ annihilation
- in the high-energy limit (all invariants $\gg M_{\mathrm{W}}^2$)



complicated calculation at technical frontier

real corrections:
NLO calculations for VVj (see below) constitute real part of NNLO for VV

QCD-Parton-shower matching

NLO-QCD merged to parton-shower codes PYTHIA, HERWIG, SHERPA

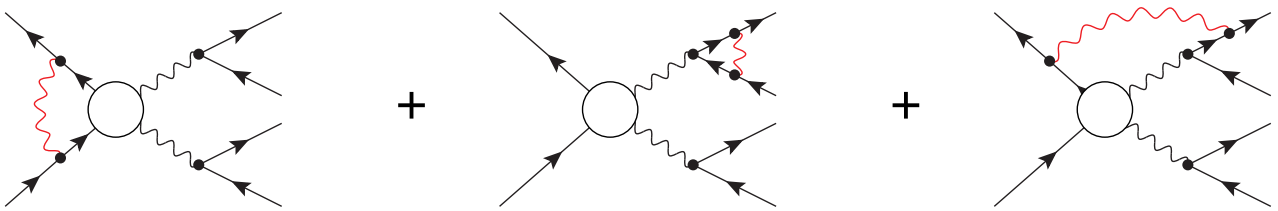
- MC@NLO in HERWIG — Frixione, Webber '06
- POWHEG in HERWIG++ — Hamilton '10
- POWHEG in SHERPA — Höche, Krauss, Schönherr, Siegert '10
- POWHEG-BOX — Melia, Nason, Röntsch, Zanderighi '11
- aMC@NLO in HERWIG and PYTHIA6 — Frederix et al. '11

Results for $\mathrm{e}^+\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-$, $\mathrm{e}^+\mathrm{e}^-\mu^+\mu^-$ final states at $7\,\mathrm{TeV}$: Frederix et al. '11

- $+40\%$ NLO corrections (size depends strongly on cuts, energy, process)
- distributions are generally rescaled, some nontrivial kinematic effects
- NLO scale uncertainty 2% for qq, qg channels, 20% for gg channel
- PDF uncertainty $\sim 2\%$
- effects of parton shower generally small
  apart from few distributions where differences are expected ($p_{\mathrm{T}4l}$)

EW corrections

More complicated than QCD corrections ⇒ approximations used

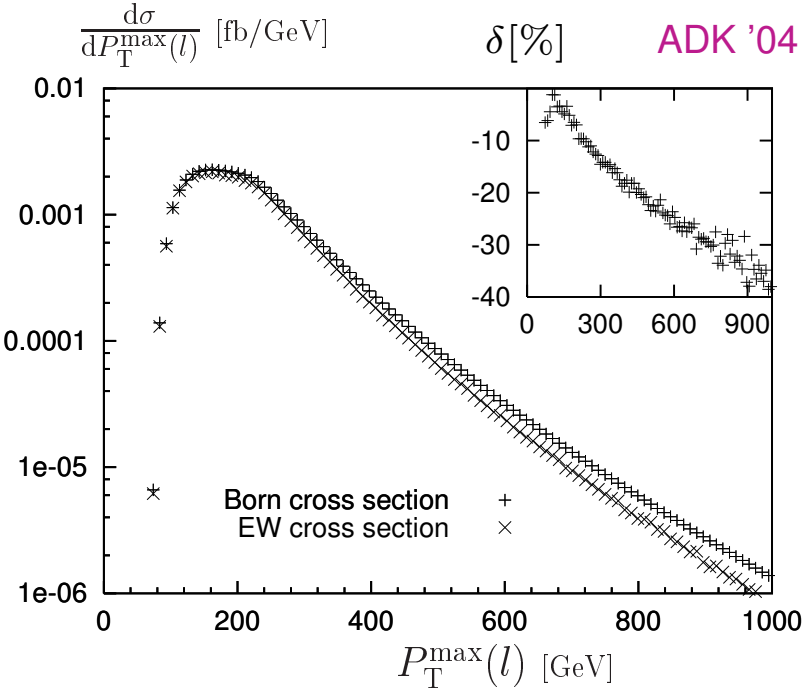


Accomando, Denner, Pozzorini '01
Accomando, Denner, Kaiser '04

- double-pole approximation for vector bosons
- high-energy approximation: logarithmic corrections

result:
large negative EW corrections
(Sudakov logarithms)
for large energy scales

$\mathrm{pp} \to \mathrm{WZ} \to \mathrm{e}\nu_\mathrm{e}\mu^+\mu^-$ at $\sqrt{s} = 14\,\mathrm{TeV}$

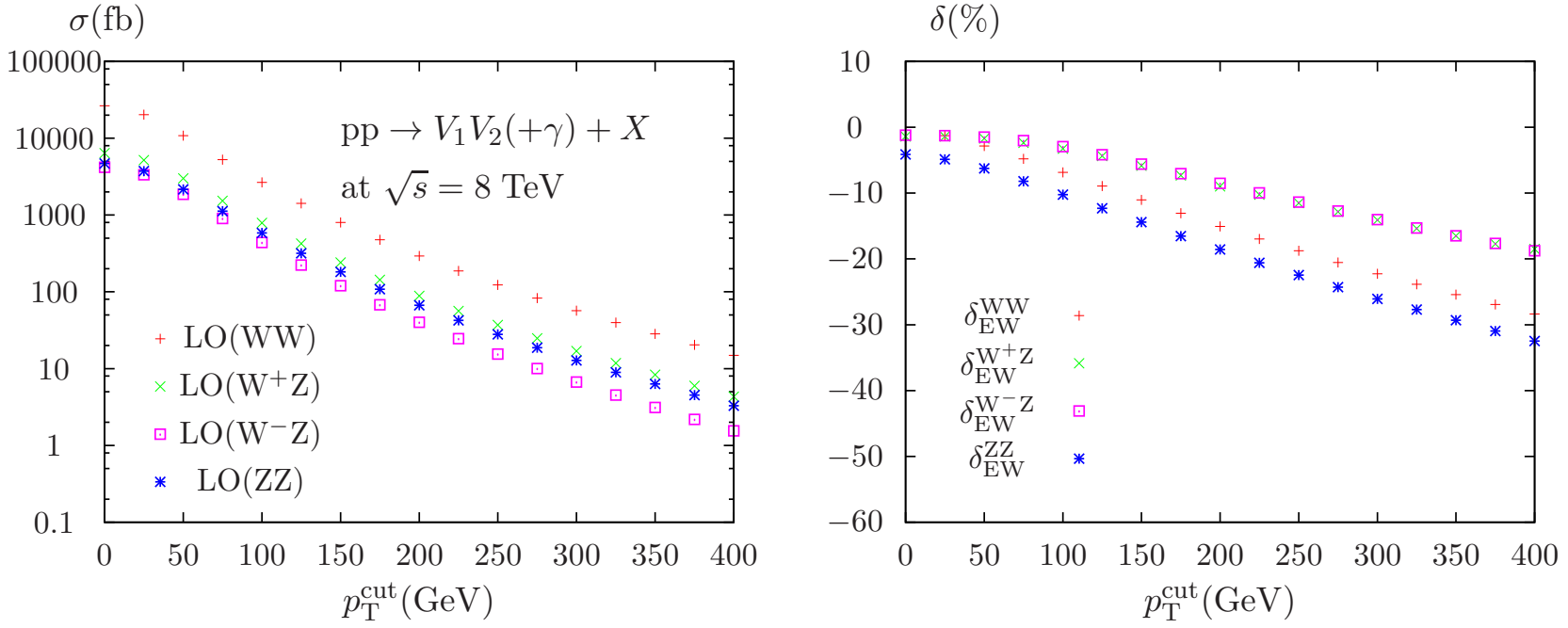


EW corrections II

Bierweiler, Kasprzik, Kühn, Uccirati '12 complementary calculation

- complete NLO EW corrections for stable $\mathrm{W}^+\mathrm{W}^-$, $\mathrm{W}^\pm\mathrm{Z}$, ZZ $(M_{VV'} > M_V + M'_V!)$
- for $\mathrm{W}^+\mathrm{W}^-$ also gg and $\gamma\gamma$-induced contributions $(\mathcal{O}(10\%))$

cross section as a function of the cut on $p_{\mathrm{T}V}$



Sudakov regime $(\hat{s}, |\hat{t}|, |\hat{u}| \gg M_{\mathrm{W}}^2)$:

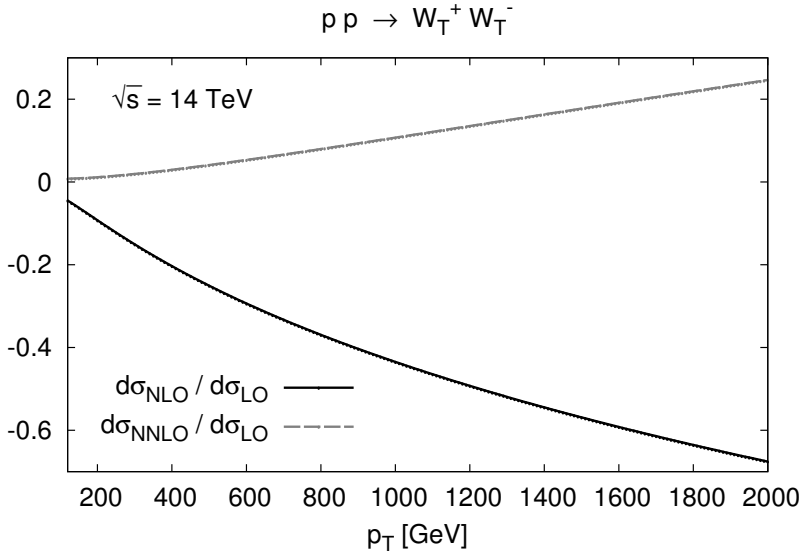
relative EW corrections of Bierweiler et al. and Denner et al. agree within few %

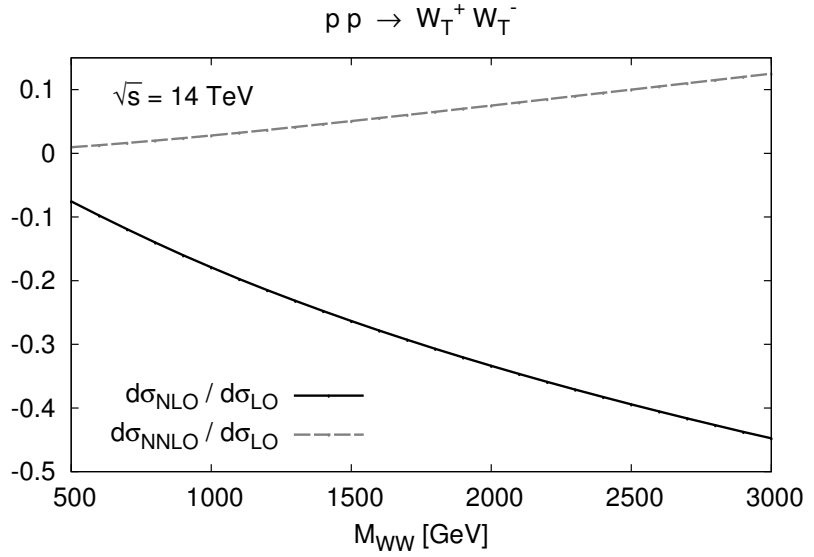
$\Rightarrow$ off-shell effects and corrections to decays small for inclusive observables

EW corrections beyond NLO

Kühn, Metzler, Penin, Uccirati '11

- NNL EW logarithms in high-energy limit for stable $\mathrm{W}^+\mathrm{W}^-$ at
  - one loop: $\alpha \ln^n(s/M_\mathrm{W}^2),\ n = 2, 1, 0$
  - and two loops: $\alpha^2 \ln^n(s/M_\mathrm{W}^2),\ n = 4, 3, 2$
- significant cancellations between LL, NLL and NNLL logarithmic corrections
- maximal effect 60% (one-loop) and 20% (two loops) at $14\,\mathrm{TeV}$ LHC





VV production: open issues

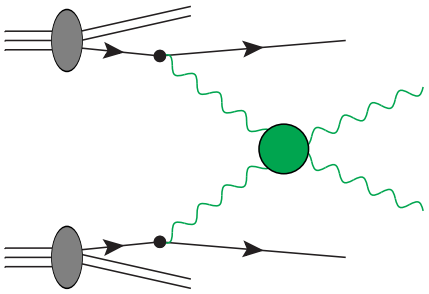
- NLO-EW corrections for full processes with decays
  in progress Dittmaier et al.
- NNLO QCD: in progress? Czakon et al.
- combination of all pieces required
  - NLO QCD
  - gg contributions
  - parton-shower matching

  } combination exists
  - NLO EW
  - NNLL EW logarithms
  - NNLO QCD?
- parton-shower matching for EW corrections

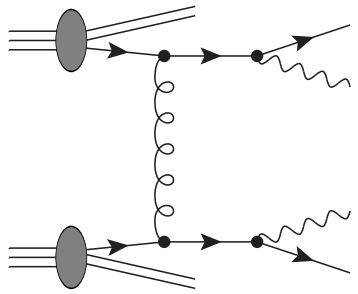
Vector-boson-pair production with two jets

Vector-boson-pair production with 2 jets

EW production: $\mathcal{O}(\alpha^4)$



QCD-induced production: $\mathcal{O}(\alpha_s^2\alpha^2)$



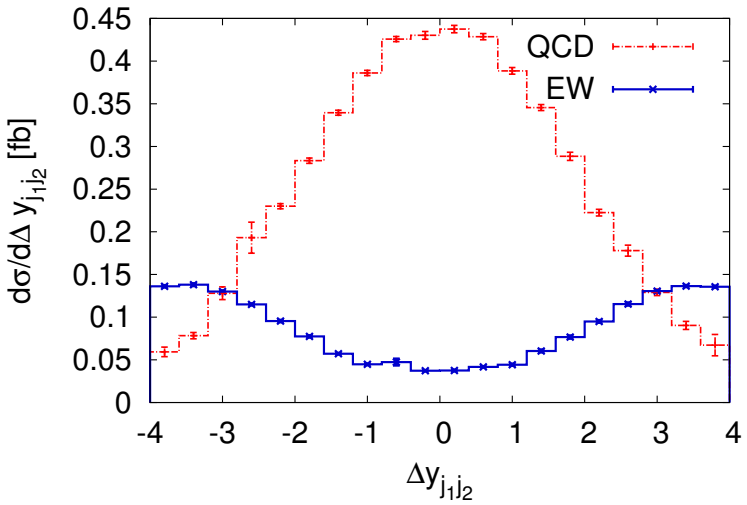
physical significance

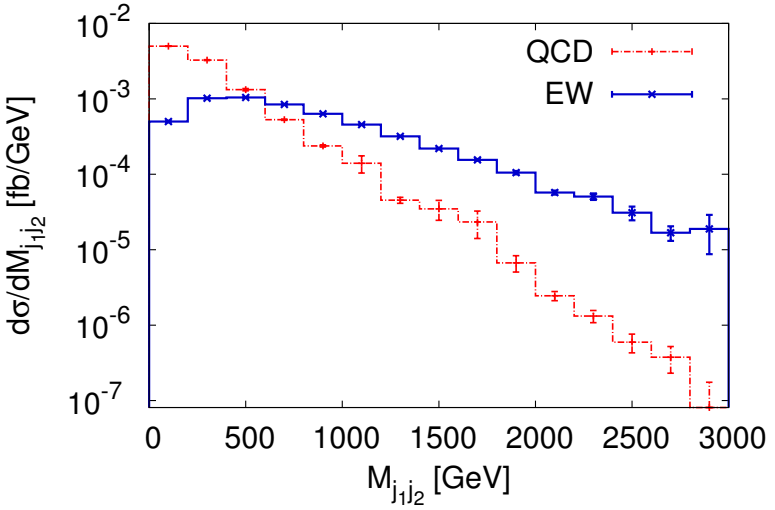
- physics is in EW production!
- EW production involves vector-boson scattering, sensitive to
  - EW symmetry breaking sector
  - Higgs boson
  - quartic vector-boson couplings
- $\mathrm{W^+W^+jj}$: distinct signature: same-sign dileptons $+ \not{E}_\mathrm{T} + 2$ jets
- background to Higgs production and BSM searches in VBF

W^+W^+jj: QCD versus EW production

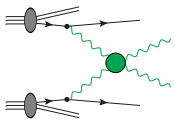
Jäger, Zanderighi '11

$\sqrt{s} = 7\,\mathrm{TeV}$, NLO QCD, basic cuts: $p_{\mathrm{T},j} > 20\,\mathrm{GeV}$



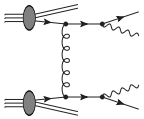


EW production:



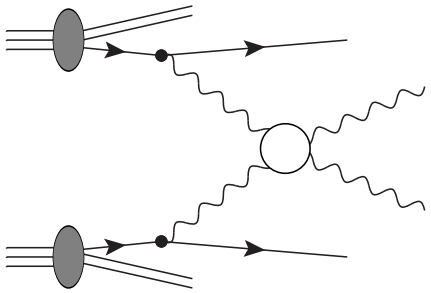
- large rapidity separation Δy_{jj}
- dominant for large M_{jj}
- $\sigma_{\mathrm{EW}}^{\mathrm{inclusive}} = 1.10\,\mathrm{fb}$
- $\sigma_{\mathrm{EW}}^{\mathrm{VBFcuts}} = 0.201\,\mathrm{fb}$

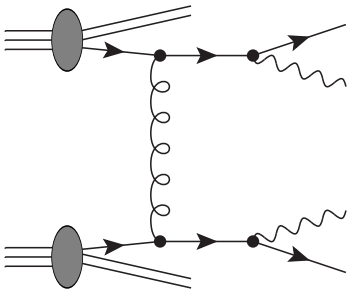
QCD-induced production:



- small rapidity separation Δy_{jj}
- prefers small M_{jj}
- $\sigma_{\mathrm{QCD}}^{\mathrm{inclusive}} = 2.12\,\mathrm{fb}$ 192%
- $\sigma_{\mathrm{QCD}}^{\mathrm{VBFcuts}} = 0.0074\,\mathrm{fb}$ 3.7%

$VV + 2$ jet production at NLO





NLO-QCD corrections including leptonic decays

- $\mathrm{pp} \to VV\mathrm{jj}$ (all channels)
  Bozzi, Jäger, Oleari, Zeppenfeld '06–'09
- $\mathrm{pp} \to \mathrm{W^+W^-jj}$ Greiner et al. '12
- $\mathrm{pp} \to \mathrm{W^+W^+jj}$
  Denner, Hošeková, Kallweit '12
- $\mathrm{pp} \to \mathrm{W^+W^+jj}$
  Melia, Melnikov, Röntsch, Zanderighi '10
- $\mathrm{pp} \to \mathrm{W^+W^-jj}$
  Melia, Melnikov, Röntsch, Zanderighi '11

parton-shower matching with POWHEG-BOX

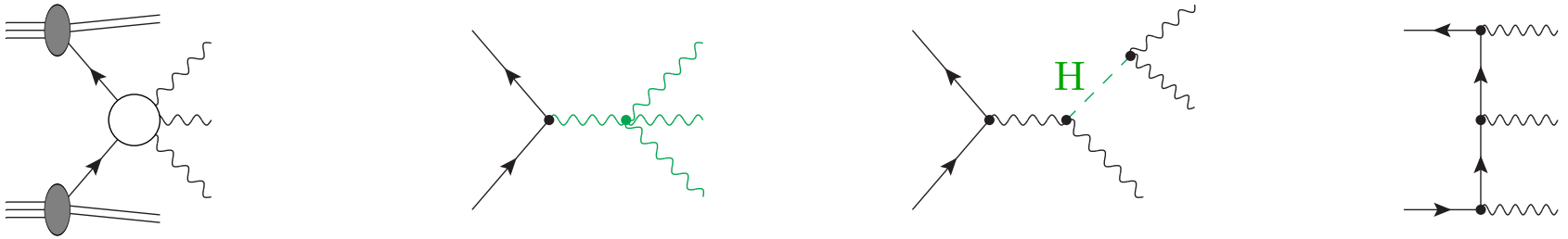
- $\mathrm{pp} \to \mathrm{W^+W^+jj}, \mathrm{W^+W^-jj}$
  Zanderighi, Jäger '11, '13
- $\mathrm{pp} \to \mathrm{W^+W^+jj}$
  Melia, Nason, Röntsch, Zanderighi '11

NLO-EW corrections exist only for $VV \to VV$: (not for full $2 \to 6$ process)

- $\mathrm{ZZ} \to \mathrm{ZZ}$ Denner, Dittmaier, Hahn '97, $\mathrm{W^+W^+} \to \mathrm{W^+W^+}$ Denner, Hahn '98
- size: $\mathcal{O}(10\text{–}100\%)$, increasing with energy

Triple vector-boson production

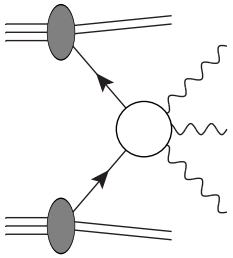
Triple vector-boson production



sensitive to triple and quartic vector-boson couplings

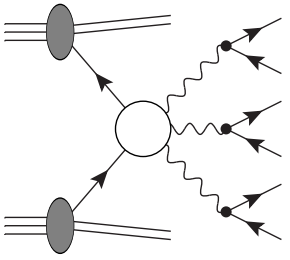
NLO calculations

on-shell vector bosons



- $pp \to ZZZ$
  Lazopoulos, Melnikov, Petriello '07
- $pp \to VVV$
  Binoth, Ossola, Papadopoulos, Pittau '08

including leptonic decays



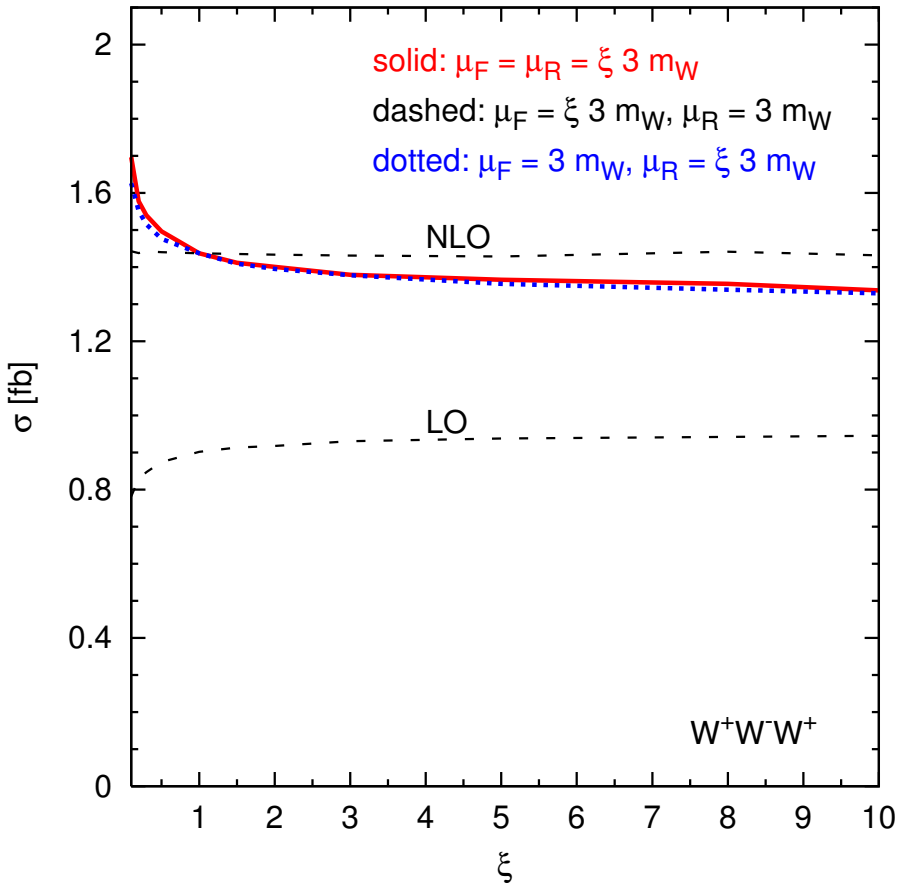
- $pp \to WWZ$
  Hankele, Zeppenfeld '07 (VBFNLO)
- $pp \to WZZ, WWW$
  Campanario et al. '08 (VBFNLO)

Triple vector-boson production: NLO-QCD results

- LO $\propto \alpha_s^0$
- NLO corrections drastically underestimated by LO scale variation
- large K factors: $1.5 - 2.2$ owing to new qg channel at NLO
- small NLO scale dependence: $\mathcal{O}(10\%)$
- K factors depend strongly on phase-space region and observable

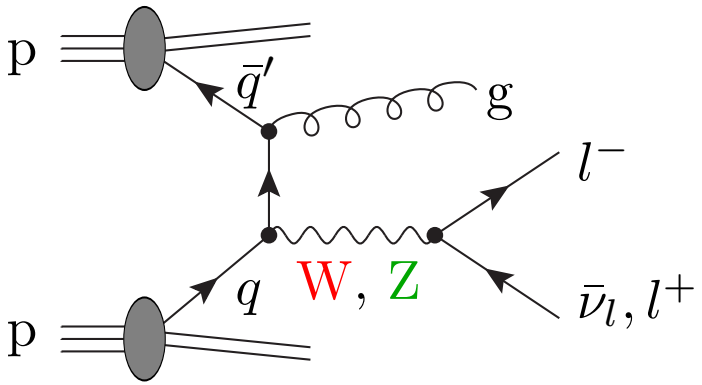
scale dependence
for $\mathrm{pp} \to \mathrm{W^+W^-W^+}$

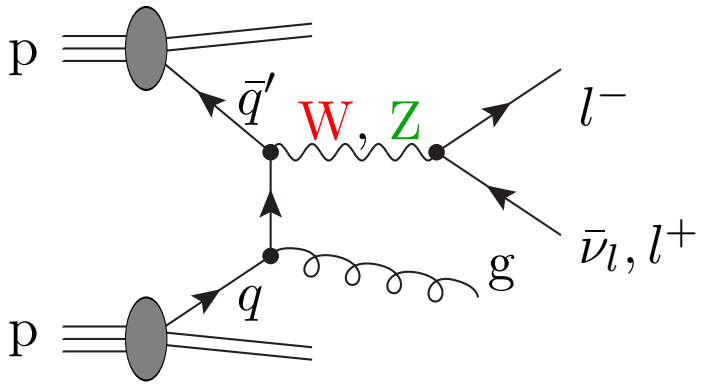
Campanario et al. '08



Vector-boson plus jet production

Vector-boson + jet production





- important contribution to single V production
  $\Rightarrow$ measurement of M_V, Γ_V, electroweak mixing angle $\sin^2\theta_{\rm eff}^{\rm lept}$
- tests of jet dynamics in QCD
- constraints on parton distribution functions (PDFs)
- source of high-energy leptons and/or missing transverse momentum
  $\Rightarrow$ background to new physics

Vector-boson + jet production

NLO-QCD corrections: Giele, Glover, Kosower '93; Campbell, Ellis '02

EW corrections

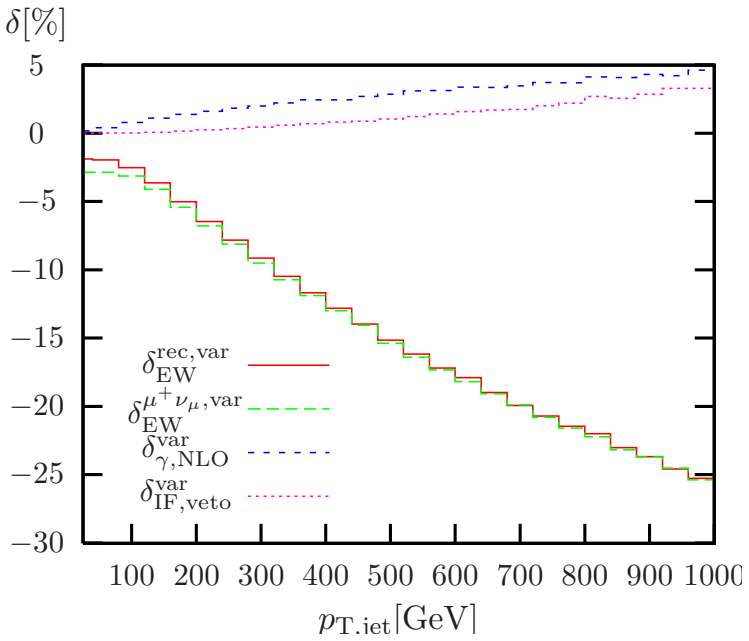
- $\mathrm{pp} \to \mathrm{Z} + \mathrm{jet} + X$
  - weak $\mathcal{O}(\alpha)$ correction (stable Z) Maina, Moretti, Ross '04
    $\delta_{\mathrm{weak}} \sim -(5\text{–}15)\%$ for $p_{\mathrm{T}} \lesssim 500\,\mathrm{GeV}$
  - (NLO + NNLL) EW corrections (stable Z) Kühn, Kulesza, Pozzorini, Schulze '04, '05
  - EW and QCD NLO corrections for $\mathrm{pp} \to \mathrm{Z} + \mathrm{jet} + X$ including leptonic decays
    $\mathrm{pp} \to \mathrm{Z} + l^+l^- + \mathrm{jet} + X$ Denner, Dittmaier, Kasprzik, Mück '11
    $\mathrm{pp} \to \mathrm{Z} + \nu\bar{\nu} + \mathrm{jet} + X$ Denner, Dittmaier, Kasprzik, Mück '12
- $\mathrm{pp} \to \mathrm{W} + \mathrm{jet} + X$
  - EW corrections for stable W: Kühn et al. '07; Hollik, Kasprzik, Kniehl '07
    $\delta_{\mathrm{weak}} \sim -30\%$ for $p_{\mathrm{T}} \sim 2000\,\mathrm{GeV}$
    photon-induced processes contribute appreciably (several $\%$ at large p_{T})
    Hollik et al. '07
  - EW and QCD NLO corrections including leptonic decays
    $\mathrm{pp} \to \mathrm{W} + l\nu + \mathrm{jet} + X$ Denner, Dittmaier, Kasprzik, Mück '10

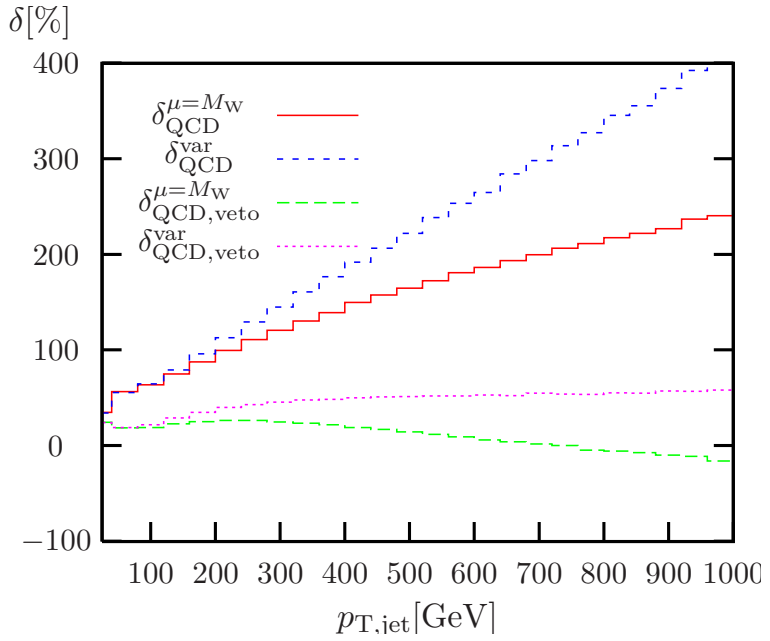
Jet transverse momentum in $pp \to W + \text{jet} + X$

EW corrections

QCD corrections

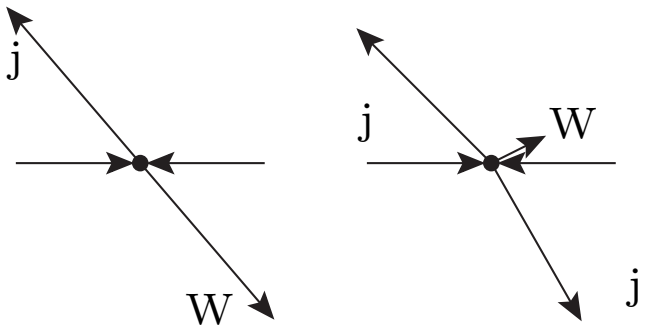
Denner, Dittmaier, Kasprzik, Mück '11





- large electroweak corrections for high p_T
  Sudakov logarithms
- 5% photon-induced corrections at $1\,\text{TeV}$
- for large $p_{T,j}$ huge QCD corrections owing to new subprocess $pp \to 2\,\text{jets} + W$
  with two opposite hard jets and soft W
  veto on 2nd jet reduces corrections considerably

LO configuration new NLO configuration



Summary

General Tools

NLO-QCD corrections available for many multi-particle processes in

- MCFM Campbell, Ellis, Williams
- VBFNLO Arnold, . . . , Zeppenfeld
- upcoming: OPENLOOPS Cascioli, Maierhöfer, Pozzorini

NLO-QCD parton-shower matching for many processes via

- POWHEG BOX Alioli, Frixione, Nason, Oleari, Re
- aMC@NLO Alwall et al.
- SHERPA Höche et al.

NLO-EW corrections

- much more complicated structure
- exist only for some processes, often based on approximations
- more calculations in progress
  in particular including vector-boson decays and off-shell effects
- separation of photons and jets needed (e.g. $\mathrm{W}\gamma/\mathrm{Wj}$)
  $\Rightarrow$ photon fragmentation function or Frixione criterion

Existing calculations

process	NLO QCD	NLO PS matching	loop induced gg contribution	NLO EW
$\gamma\gamma$	✓, NNLO	✓	✓	
$V\gamma$	✓		✓	PA
Vj	✓	✓	OS	✓
VV	✓	✓	✓	OS/PA+HEA
$\gamma\gamma\gamma$	✓			
γjj	VBF			
$V\gamma\gamma$	✓			
$V\gamma$j	✓		OS	
Vjj	VBF	✓		
VVj	✓		OS	
$VV\gamma$	✓			
VVV	✓			
VVjj	VBF,(✓)	(✓)		

OS = on-shell approximation

PA = pole approximation

VBF= vector-boson-fusion part

HEA= high-energy approximation

(✓): partial results or specific processes

$\Rightarrow$ much work to be done, in particular on EW side

Conclusions

Conclusions

Multiple vector-boson (MVB) production

- allow to test non-Abelian structure of SM
- constitute important background for Higgs and BSM production

QCD corrections

- QCD corrections large and strongly dependent on experimental set-up
- NLO-QCD corrections exist for many MVB processes
- NLO-QCD parton-shower matching is becoming standard (typically small effect)
- very few NNLO corrections known

EW NLO corrections

- typically few $\%$ to 10% $\Rightarrow$ important for precise measurements
- strongly enhanced for high energy scales $\sim 40\%$
- VV: available for on-shell vector bosons or in approximations
- not yet available for $\mathrm{pp} \to VV \to 4l$, $\mathrm{pp} \to VVV$, or $\mathrm{pp} \to \mathrm{jj}VV$

Backup slides

Input-parameter scheme

- Natural input parameters: α, M_{W}, M_{Z}, m_f, M_{H}, α_{s}
- alternative input parameter sets: G_μ instead of M_{W} or α
  G_μ no fundamental parameter, but precisely measured in μ decay
- weak mixing angle: on-shell definition $\sin\theta_{\mathrm{w}} = \sqrt{1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2}$
- definition of α
  - on-shell: $\alpha(0)$
    appropriate for external photons
  - $\alpha(M_{\mathrm{Z}})$, $\alpha(\sqrt{s})$: $\frac{\alpha(M_{\mathrm{Z}})}{\alpha(0)} \approx 1.06$
    absorbs running of α from $Q = 0$ to EW scale
    appropriate for weak bosons and internal photons
  - G_μ scheme: $\alpha_{G_\mu} = \sqrt{2} G_\mu M_{\mathrm{W}}^2 (1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2)/\pi$: $\frac{\alpha_{G_\mu}}{\alpha(0)} \approx 1.03$
    absorbs running of α from $Q = 0$ to EW scale and $\Delta\rho$ in $W f \bar{f}'$ coupling
    appropriate for W bosons

  appropriate choice of α reduces missing higher-order corrections

gauge invariance demands unique input-parameter set!

Vector-boson pair production

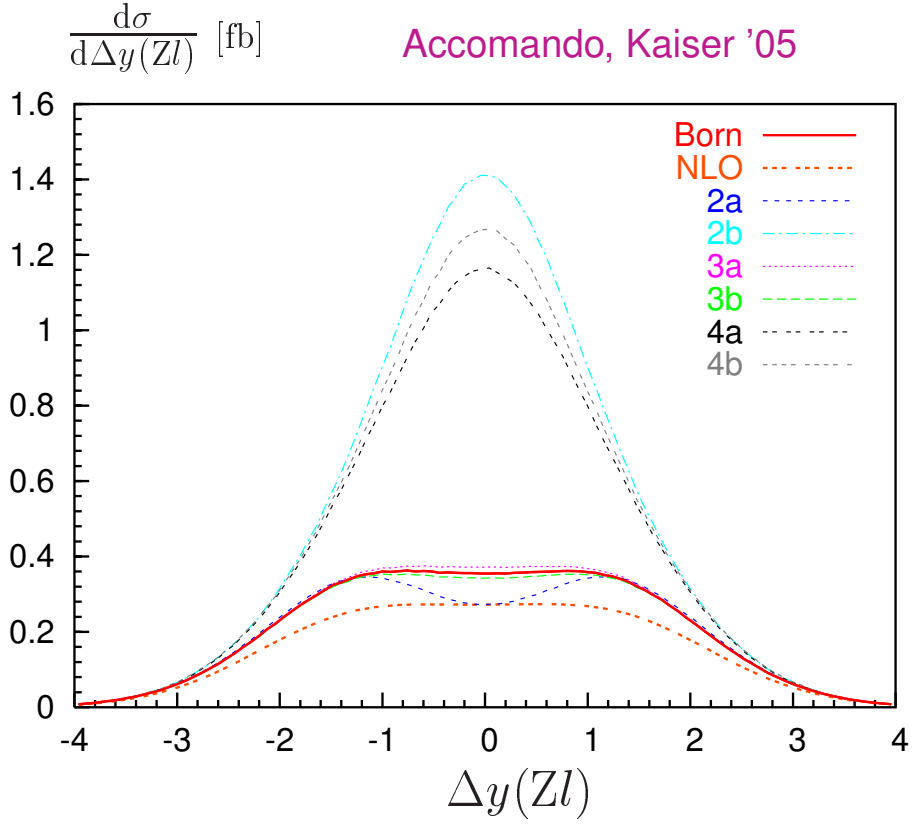
Electroweak corrections vs anomalous couplings

$pp \to WZ \to l\nu_l l'\bar{l}'$: $\sqrt{s} = 14\,\text{TeV}$

distribution in rapidity difference of Z boson and lepton from W decay $\Delta y(Zl)$

NLO = NLO electroweak: $\sim -20\%$

2a/2b: $\Delta g_1^Z = \pm 0.02$, 3a/3b: $\Delta\kappa_\gamma = \pm 0.04$, 4a/4b: $\lambda = \pm 0.02$

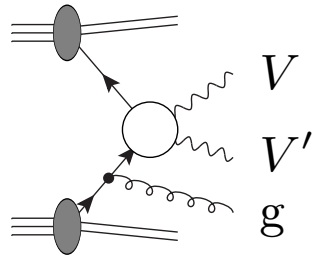


EW corrections can fake anomalous couplings

Vector-boson-pair production with one jet

Vector-boson-pair production with one jet

Large fraction of VV-pair events
exhibits additional jet activity



$\Rightarrow$ precise knowledge of VV + jet(s) production needed

calculations

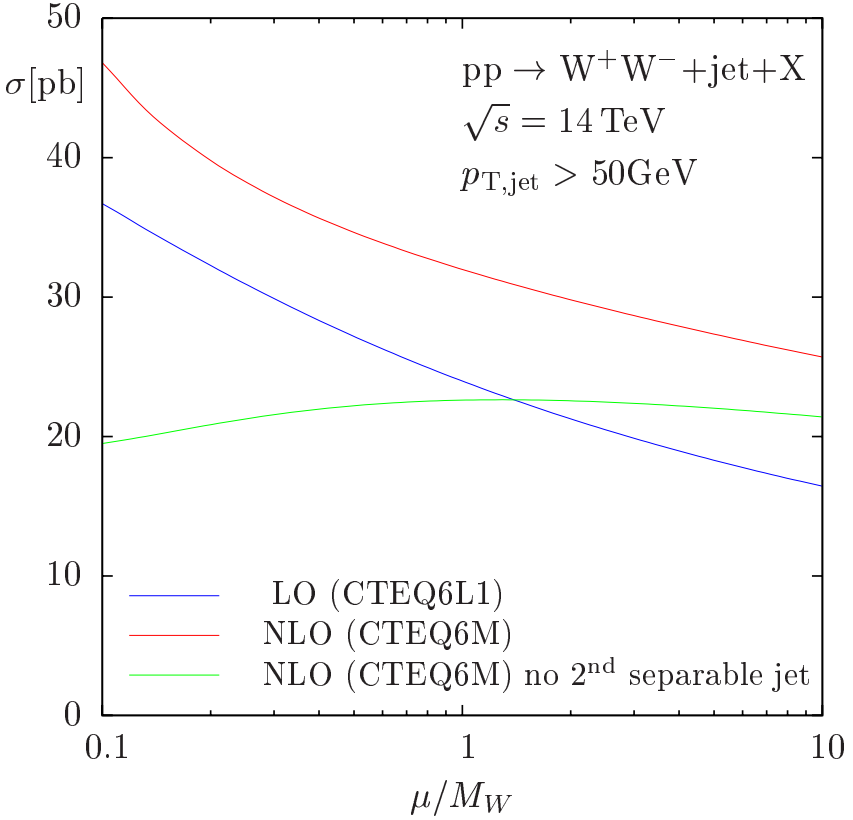
- $\mathrm{pp} \to \mathrm{W^+W^-j}$ (including leptonic decays)
  Dittmaier, Kallweit, Uwer '07, '09; Campbell, Ellis, Zanderighi '07 (MCFM)
- $\mathrm{pp} \to \mathrm{W^\pm Zj}$ (including leptonic decays and anomalous couplings)
  Campanario et al. '10 (VBFNLO)
- $\mathrm{pp} \to \mathrm{ZZj}$ (no decays)
  Binoth, Gleisberg, Karg, Kauer, Sanguinetti '10

results roughly similar as for VV production

- sizeable NLO-QCD corrections: $25{-}35\%$ for inclusive cross sections ($\mu = M_V$)
  not covered by LO scale dependence
  size depends strongly on scale, cuts, energy
- effect of NLO-QCD corrections enhanced by cuts typical for Higgs search:
  70% for typical "Higgs cuts" Campbell, Ellis, Zanderighi '07
- NLO-QCD scale uncertainty reduced by veto on second jet
  no reduction for observables characterized by large p_T values Campanario et al. '10

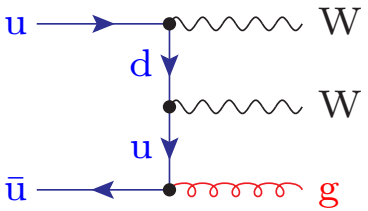
Example: scale dependence for $pp \to WWj + X$

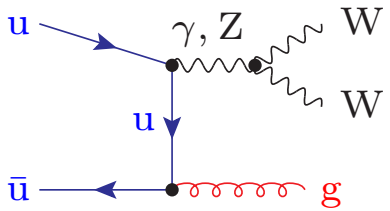
Dittmaier, Kallweit, Uwer '07



qg channel contributes 56% at NLO

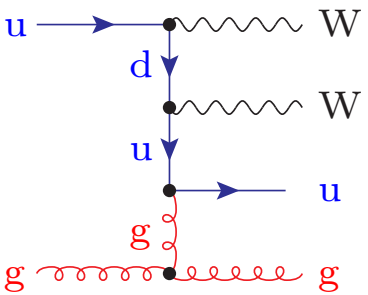
- $\sigma_{\mathrm{LO}} \propto \alpha_s$



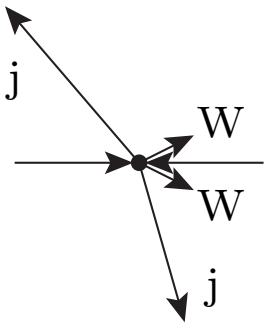


- scale dependence stabilises at NLO for genuine $\mathrm{WW} + \mathrm{j}$ production
- significant scale dependence is introduced by $\mathrm{WW} + 2\,\mathrm{j}$ (difference between green and red curves)

new diagram

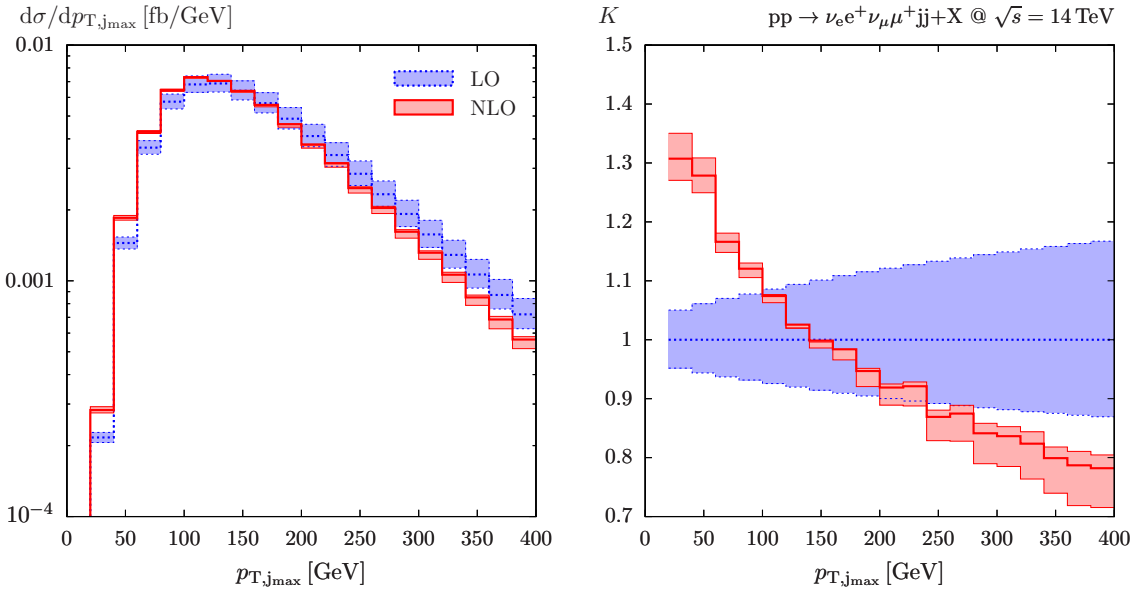


new configuration



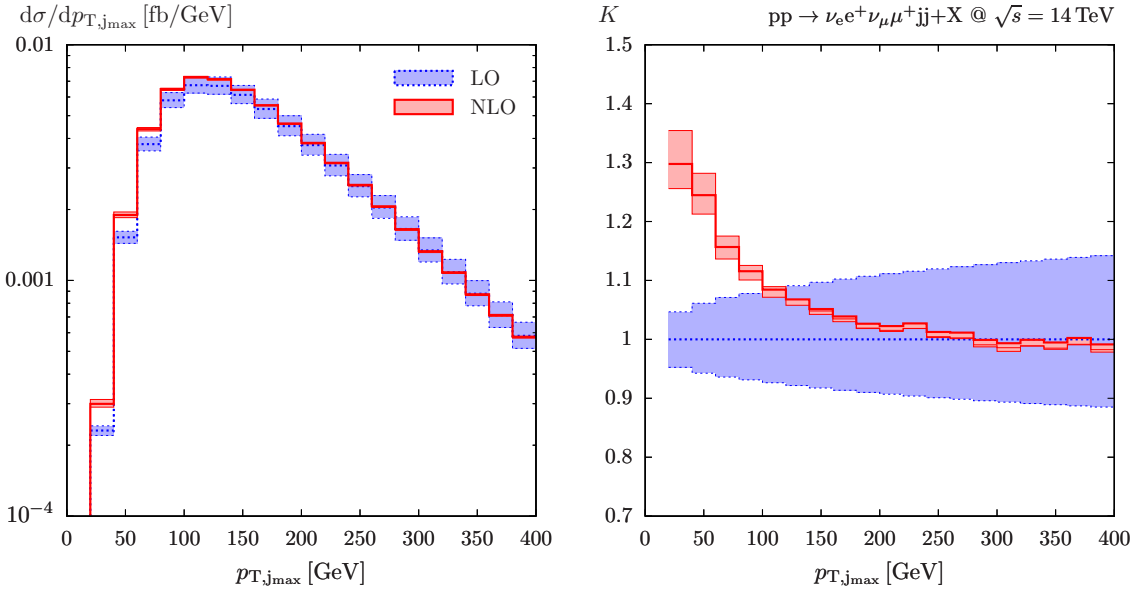
Vector-boson-pair production with two jets

NLO corrections to distribution of leading jet



Denner, Hošeková, Kallweit '12

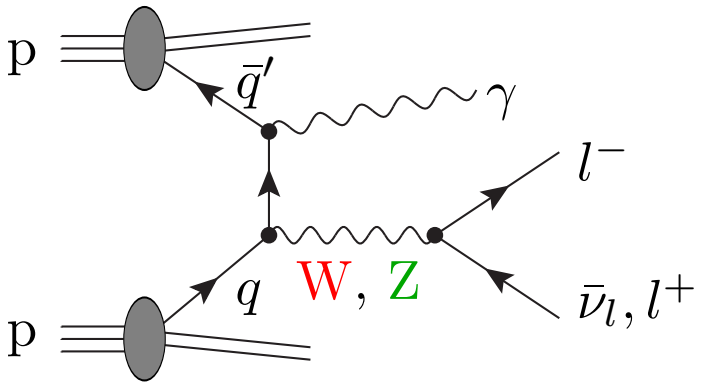
- fixed factorization scale: $\mu = M_{\mathrm{W}}$
  large negative corrections for high $p_{\mathrm{T,j_{max}}}$

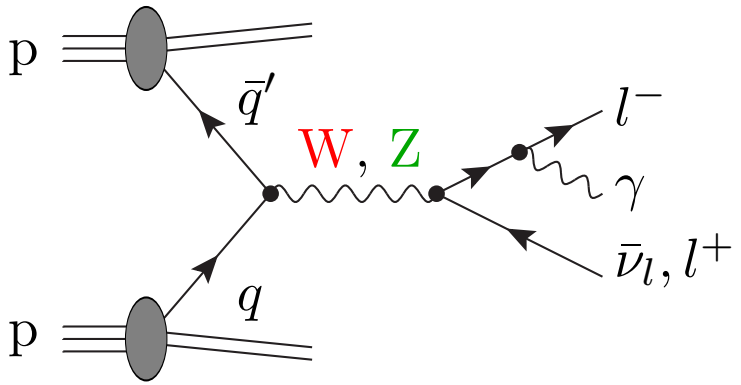


- dynamical factorization scale: $\mu = \sqrt{p_{\mathrm{T,j_1}} p_{\mathrm{T,j_2}}}$
  constant K factor for high $p_{\mathrm{T,j_{max}}}$

Vector-boson plus photon production

Vector-boson + photon production





- simplest multi-vector-boson production processes besides $\mathrm{pp} \to \gamma\gamma$
- measurement of $VV\gamma$ couplings
- background to new physics

NLO QCD corrections:

Ohnemus '93, Baur, Hahn, Ohnemus '93, De Florian, Signer '00

NLO QCD corrections $\sim 30\%$, can be enhanced by cuts

Campbell, Ellis, Williams '11

NLO-EW calculations

EW corrections:

- $\mathrm{pp}(\to \mathrm{W}\gamma) \to l\bar{\nu}\gamma + X$ Accomando, Denner, Pozzorini '01; Accomando, Denner, Meier '05
  $\mathcal{O}(\alpha)$ correction in pole approximation for W
  $\hookrightarrow\ \delta\ \sim\ -10\%\,(-27\%)$ for $p_{\mathrm{T},\gamma} \gtrsim 250\,\mathrm{GeV}\,(700\,\mathrm{GeV})$

- $\mathrm{pp} \to \mathrm{Z}\gamma + X$ Hollik, Meier '04 and $\mathrm{pp}(\to \mathrm{Z}\gamma) \to ll\gamma + X$ Accomando, Denner, Meier '05
  $\mathcal{O}(\alpha)$ correction for on-shell Z bosons / in pole approximation
  $\hookrightarrow\ \delta\ \sim\ -10\%$ for $M_{\gamma\mathrm{Z}}$ distribution

- calculation of complete $\mathcal{O}(\alpha)$ correction in progress