

# Electroweak corrections to vector-boson scattering

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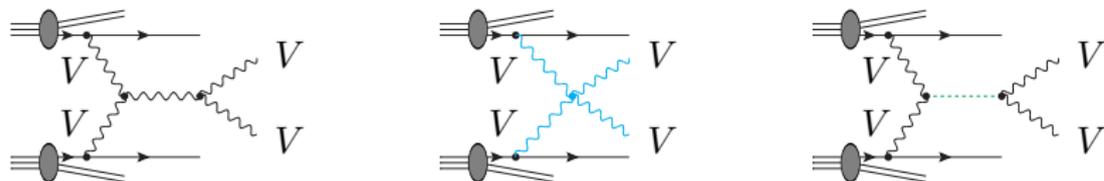
*in collaboration with B. Biedermann and M. Pellen*

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**Radcor conference 2017, St. Gilgen, September 26, 2017**

- 1 Introduction
- 2 Complete NLO corrections to  $pp \rightarrow \mu^+ \nu_\mu e^+ \nu_e jj$
- 3 Large NLO EW corrections to VBS
- 4 Conclusion

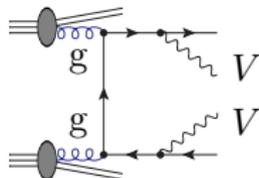
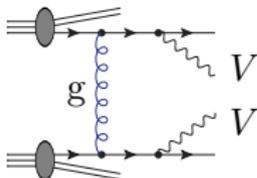
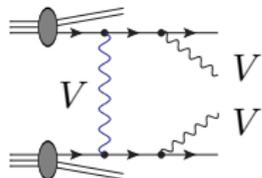
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Physics issues of vector-boson scattering (VBS): ( $V = W, Z$ )

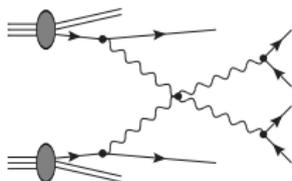
- crucial test of electroweak (EW) symmetry breaking mechanism  
Higgs boson important for unitarity of process
- search for anomalous quartic-gauge-boson couplings  
 sensitivity grows with energy of vector bosons  
 $\hookrightarrow$  EW corrections (EWC) significant  $\propto \alpha \log^2(E/M_W)$
- experimental signature
  - two forward/backward jets at large rapidities
  - large rapidity separation between jets
  - large di-jet invariant mass
  - final-state vector bosons in central region
- VBS purely EW process ( $\mathcal{O}(\alpha^4)$  for stable  $V$ s)

Final state:  $VV + 2j$  ( $4l + 2j$ )

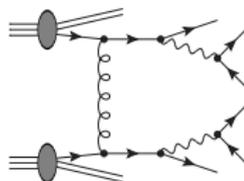


- **Full EW process** ( $\mathcal{O}(\alpha^4)$  for stable  $V$ s as above)  
not separable from VBS
- **QCD process** ( $\mathcal{O}(\alpha_s^2 \alpha^2)$  for stable  $V$ s)  
gauge-invariant contribution
- **interferences** between EW and QCD contributions  
( $\mathcal{O}(\alpha_s \alpha^3)$  for stable  $V$ s)  
appear only for channels with identical or weak-isospin partner quarks
- **gluonic channels** for neutral final states
- **irreducible background can be suppressed by cuts** on  $M_{jj}$  and  $|\Delta y_{jj}|$

EW production:  $\mathcal{O}(\alpha^6)$



QCD-induced production:  $\mathcal{O}(\alpha_s^2 \alpha^4)$



- full LO predictions: Ballestrero, Franzosi, Maina '10 (PHANTOM)
- NLO QCD corrections to EW diagrams:
  - Jäger, Oleari, Zeppenfeld (+ Bozzi) '06, '07, '09 (VBFNLO);
  - Denner, Hosekova, Kallweit '12
  - PS matching: Zanderighi, Jäger '11, '13 + Karlberg '14 ( $W^+W^+, W^+W^-, ZZ$ )
  - Rauch, Plätzer '16 ( $W^+W^-$ )
- NLO QCD corrections to QCD diagrams:
  - Melia, Melnikov, Rötsch, Zanderighi '10, '11; Greiner et al. '12;
  - Campanario, Kerner, Ninh, Zeppenfeld '13, '14 (VBFNLO)
  - PS matching: Melia, Nason, Rötsch, Zanderighi '11 ( $W^+W^+$ )
- NLO EW corrections
  - for on-shell VBS: Denner, Dittmaier, Hahn '97; Denner, Hahn '98
  - first results for a full  $2 \rightarrow 6$  process: Denner et al. '16, '17

Process:  $pp \rightarrow W^+W^+jj \rightarrow \ell^+\nu_\ell\ell'^+\nu_{\ell'}jj$

- **distinct signature: same-sign di-leptons +  $\cancel{E}_T$  + 2 jets**  
same-sign leptons reduce SM background significantly
- no contributions of gluonic channels
- **largest cross section ratio EW to QCD production**  
EW production mode dominates QCD production for VBF cuts
- **experimental evidence:**  
ATLAS '14, '16 ( $4.5\sigma$  for WWjj,  $3.6\sigma$  for EW contribution)  
CMS '14 ( $2.0\sigma$  for WWjj,  $1.9\sigma$  for EW contribution)  
**observation:** CMS '16  $5.5\sigma$  for EW WWjj
- background for New Physics leading to same-sign lepton final states



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## Recent calculation Biedermann, Denner, Pellen '17

LO EW process:  $pp \rightarrow \mu^+ \nu_\mu e^+ \nu_e jj$   $\mathcal{O}(\alpha^6)$ 

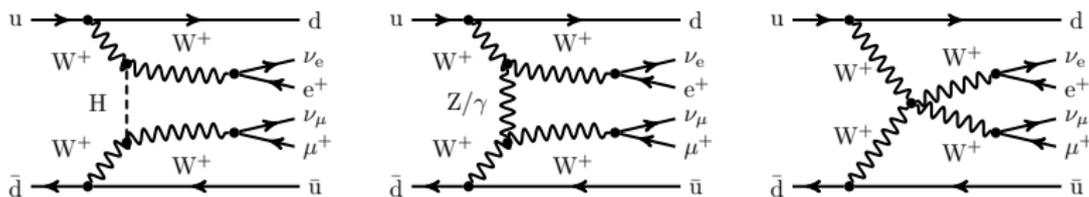
- all partonic channels included

$uu \rightarrow \mu^+ \nu_\mu e^+ \nu_e dd$	$(t, u)$	[67%]	$uc \rightarrow \mu^+ \nu_\mu e^+ \nu_e ds$	$(t)$	[6%]
$cc \rightarrow \mu^+ \nu_\mu e^+ \nu_e ss$	$(t, u)$		$u\bar{d} \rightarrow \mu^+ \nu_\mu e^+ \nu_e s\bar{c}$	$(s)$	
$u\bar{d} \rightarrow \mu^+ \nu_\mu e^+ \nu_e d\bar{u}$	$(t, s)$	[16%]	$u\bar{s} \rightarrow \mu^+ \nu_\mu e^+ \nu_e d\bar{c}$	$(t)$	[4%]
$c\bar{s} \rightarrow \mu^+ \nu_\mu e^+ \nu_e s\bar{c}$	$(t, s)$		$c\bar{d} \rightarrow \mu^+ \nu_\mu e^+ \nu_e s\bar{u}$	$(t)$	[4%]
$\bar{d}\bar{d} \rightarrow \mu^+ \nu_\mu e^+ \nu_e \bar{u}\bar{u}$	$(t, u)$		$c\bar{s} \rightarrow \mu^+ \nu_\mu e^+ \nu_e d\bar{u}$	$(s)$	
$\bar{s}\bar{s} \rightarrow \mu^+ \nu_\mu e^+ \nu_e \bar{c}\bar{c}$	$(t, u)$		$\bar{d}\bar{s} \rightarrow \mu^+ \nu_\mu e^+ \nu_e \bar{u}\bar{c}$	$(t)$	

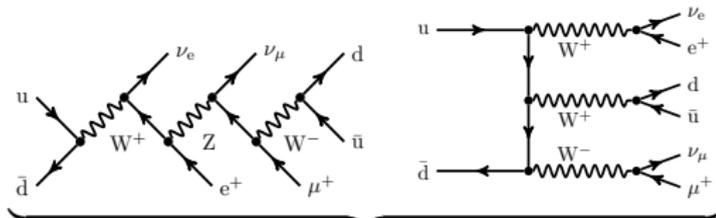
(kinematic channels) [contribution to cross section]

- no bottom-induced contributions (no final state top quarks)
- real corrections upon adding additional photon/gluon
- photon/gluon-induced contributions upon crossing photon/gluon
- complete matrix elements taken into account

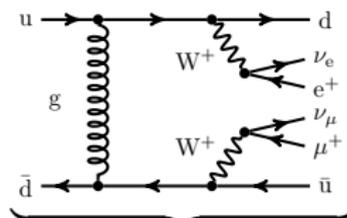
Vector-boson scattering (VBS) topologies:  $\mathcal{O}(g^6)$  all  $t$  channel



irreducible background to VBS:



EW background  $\mathcal{O}(g^6)$ ,  $s$  channel



QCD background  $\mathcal{O}(g_S^2 g^4)$   
only  $t$  channel

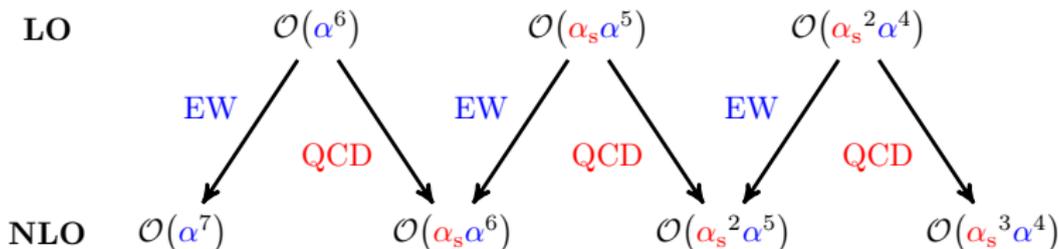
$t$  channel: incoming quarks/antiquarks connected to outgoing quarks/antiquarks

$u$  channel: exchange identical quarks/antiquarks

$s$  channel: incoming quark and anti-quark connected

all boson propagators time like

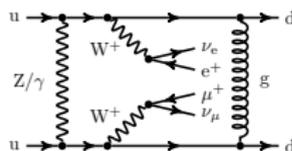
- LO:
- $\mathcal{O}(\alpha^6)$ : EW contribution including VBS and irred. background
  - $\mathcal{O}(\alpha_s \alpha^5)$ : interference between different kinematic channels
  - $\mathcal{O}(\alpha_s^2 \alpha^4)$ : irreducible QCD background



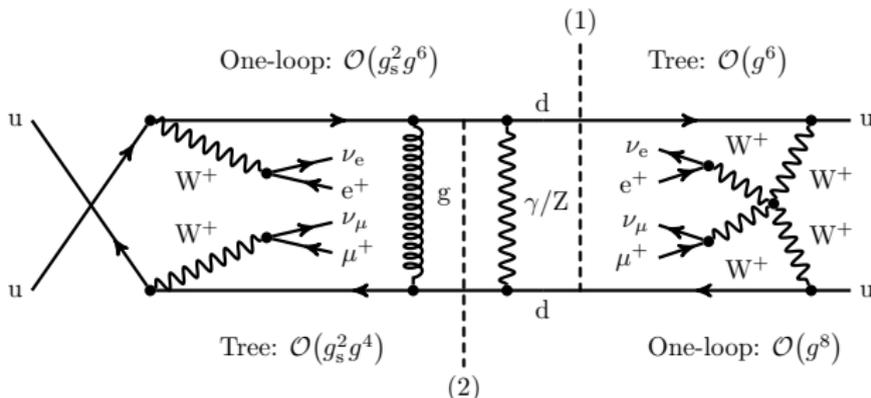
- NLO:
- $\mathcal{O}(\alpha^7)$ : EW corrections to EW LO process
  - $\mathcal{O}(\alpha_s \alpha^6)$ : QCD corrections to LO EW and EW corrections to LO interference
  - $\mathcal{O}(\alpha_s^2 \alpha^5)$ : EW corrections to LO QCD and QCD corrections to LO interference
  - $\mathcal{O}(\alpha_s^3 \alpha^4)$ : QCD corrections to QCD LO process

## Virtual diagrams mix QCD and EW corrections:

- EW correction to LO QCD amplitude
- QCD correction to LO EW amplitude



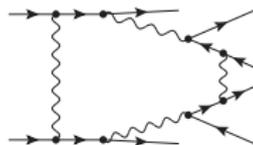
⇒ QCD and EW corrections mix at  $\mathcal{O}(\alpha_s \alpha^6)$  and  $\mathcal{O}(\alpha_s^2 \alpha^5)$



- (1) QCD corrections to EW LO cross section
- (1) EW corrections to interference between LO QCD and EW
- (2) EW correction to LO EW amplitude interfered with QCD amplitude

⇒ separation into QCD and EW is not well-defined at NLO

- Complete one-loop matrix elements included  $\mathcal{O}(\alpha^7)$ ,  $\mathcal{O}(\alpha_s \alpha^6)$ ,  $\mathcal{O}(\alpha_s^2 \alpha^5)$   $\mathcal{O}(\alpha_s^3 \alpha^4)$  terms
- on-shell renormalization scheme
- $G_\mu$  scheme for electromagnetic coupling:



$$\alpha_{G_\mu} = \frac{\sqrt{2}G_\mu M_W^2}{\pi} \left( 1 - \frac{M_W^2}{M_Z^2} \right)$$

absorbs running of  $\alpha$  to EW scale and universal corrections  $\propto m_t^2$

- complex-mass scheme for vector-boson resonances

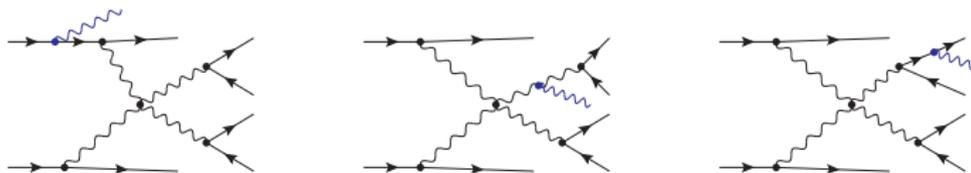
Denner, Dittmaier, Roth, Wackerroth, Wieders '99, '05

complex poles:  $\mu_W^2 = M_W^2 - iM_W\Gamma_W$ ,  $\mu_Z^2 = M_Z^2 - iM_Z\Gamma_Z$

$\Rightarrow$  complex EW mixing angle

$\Rightarrow$  gauge-invariant amplitudes

- all matrix elements calculated with **RECOLA** Actis et al. '13, '16 and **COLLIER** Denner, Dittmaier, Hofer '16



## soft and collinear singularities

- Catani–Seymour dipole subtraction     Catani, Seymour '96; Dittmaier '99
- recombination of collinear parton–photon/gluon and lepton–photon pairs (jet clustering)
  - ⇒ cancellation of singularities from soft and final-state collinear photon/gluon emission
- initial-state collinear singularities cancelled by  $\overline{\text{MS}}$  redefinition of PDFs

phase-space integration with multi-channel Monte Carlo programs  
(e.g. MOCANLO [Feger](#))

- **Tree-level matrix elements and LO hadronic cross section**  
 successfully compared with MG5@NLO Alwall et al. '14
- **IR-singularities, Monte Carlo integration**
  - variation of  $\alpha$  parameter in subtraction terms Nagy, Trócsányi '98
  - variation of IR scale
  - two independent implementations of Monte Carlo integration
- **one-loop matrix elements**
  - comparison against double-pole approximation  
 for two dominant partonic channels ( $uu, u\bar{d}$ )  
 agreement within 1%
  - $\mathcal{O}(\alpha_s^3 \alpha^4)$  contributions for  $uu$  channel compared against MG5@NLO
  - RECOLA has been checked for many other processes

Energy: 13 TeV

## PDFs

NNPDF3.0QED [Ball et al. '13, '14](#)

factorization and renormalization scales:  $\mu_F = \mu_R = \sqrt{p_{T,j_1}, p_{T,j_2}}$

## recombination / jet clustering

anti- $k_T$  algorithm with  $R = 0.4$  [Cacciari, Salam, Soyez '08](#)

recombination of photons with charged partons with  $R = 0.1$

cuts: inspired by [ATLAS 1405.6241, 1611.02428](#) and [CMS 1410.6315](#)

$$p_{T,\ell} > 20 \text{ GeV}, \quad |y_\ell| < 2.5, \quad \Delta R_{j\ell} > 0.3$$

$$p_{T,j} > 30 \text{ GeV}, \quad |y_j| < 4.5, \quad \Delta R_{\ell\ell} > 0.3$$

$$E_{T,\text{miss}} > 40 \text{ GeV}$$

for 2 leading jets:  $M_{jj} > 500 \text{ GeV}, \quad |\Delta y_{jj}| > 2.5$  (VBF cuts)

$$\Delta R_{ij} = \sqrt{(\Delta y_{ij})^2 + (\Delta \phi_{ij})^2}$$

Scale uncertainty:

$$\sigma_{\text{LO}} = 1.6383(2)_{-9.44(2)\%}^{+11.66(2)\%} \text{ fb}$$

central scale scaled by factors

$$(\xi_{\text{fac}}, \xi_{\text{ren}}) \in \{ (1/2, 1/2), (1/2, 1), (1, 1/2), (1, 1), (1, 2), (2, 1), (2, 2) \}$$

results for separate orders:

order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s \alpha^5)$	$\mathcal{O}(\alpha_s^2 \alpha^4)$	sum
$\sigma_{\text{LO}}$ [fb]	1.4178(2)	0.04815(2)	0.17229(5)	1.6383(2)

- LO EW contribution dominates (87%) (owing to VBS cuts)
- QCD-induced contribution 10%
- interference 3% (larger for individual channels)

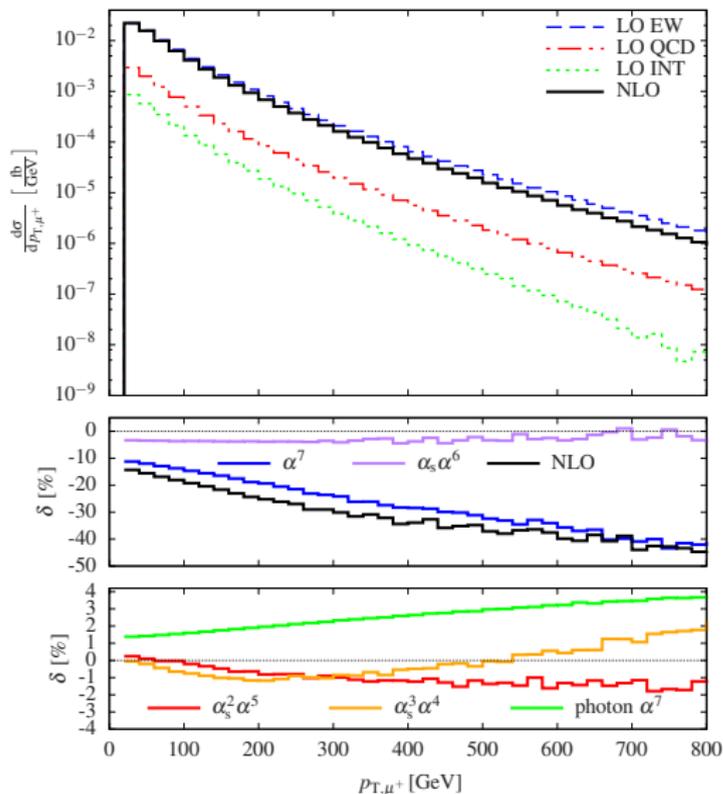
Scale uncertainty reduced by factor 5:

$$\sigma_{\text{NLO}} = 1.3577(7)_{-2.7(1)\%}^{+1.2(1)\%} \text{ fb}$$

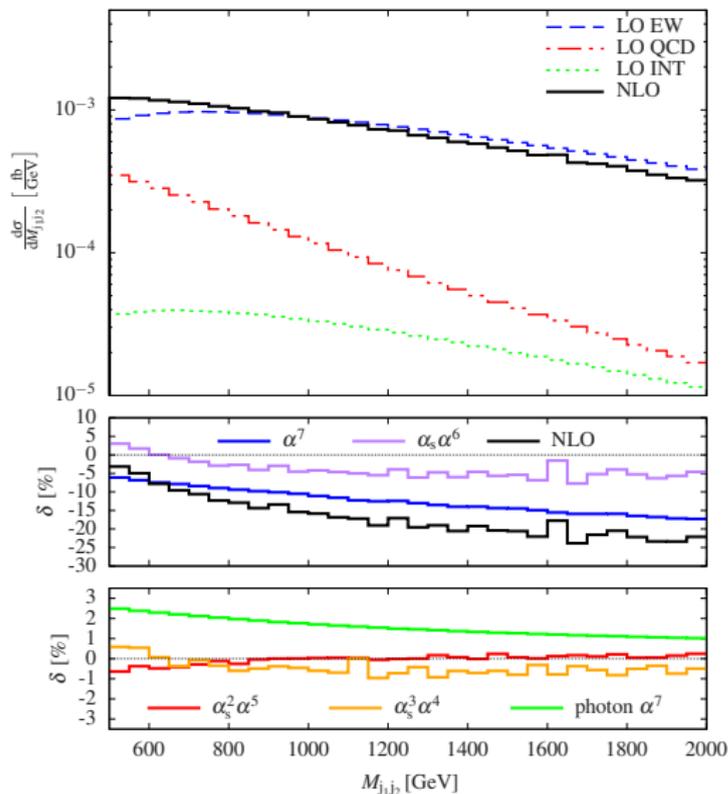
results for separate orders:

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s \alpha^6)$	$\mathcal{O}(\alpha_s^2 \alpha^5)$	$\mathcal{O}(\alpha_s^3 \alpha^4)$	Sum
$\delta\sigma_{\text{NLO}}$ [fb]	-0.2169(3)	-0.0568(5)	-0.00032(13)	-0.0063(4)	-0.2804(7)
$\delta\sigma_{\text{NLO}}/\sigma_{\text{LO}}$ [%]	<b>-13.2</b>	-3.5	0.0	-0.4	-17.1

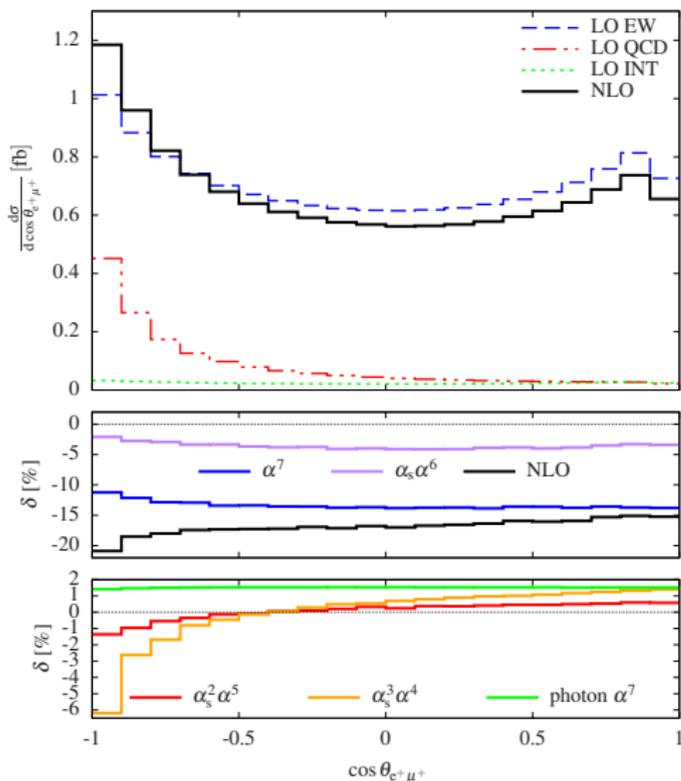
- **surprisingly large EW corrections at  $\mathcal{O}(\alpha^7)$**
- **small negative corrections at  $\mathcal{O}(\alpha_s \alpha^6)$ :**
  - ~ 0.6% difference with respect to VBS approximation  
 (neglecting  $s$ -channel and  $t$ -/ $u$ -channel interferences)  
 tuned comparison against Denner et al. '12 and Jäger et al. '09  
 and VBS approximation in RECOLA
- very small  $\mathcal{O}(\alpha_s^2 \alpha^5)$  and  $\mathcal{O}(\alpha_s^3 \alpha^4)$  corrections (LO suppressed)
- photon-induced contribution at NLO +1.5% with LUXqed Manohar et al. '16  
 (not included in NLO cross section, dominated by  $\mathcal{O}(\alpha^7)$ )



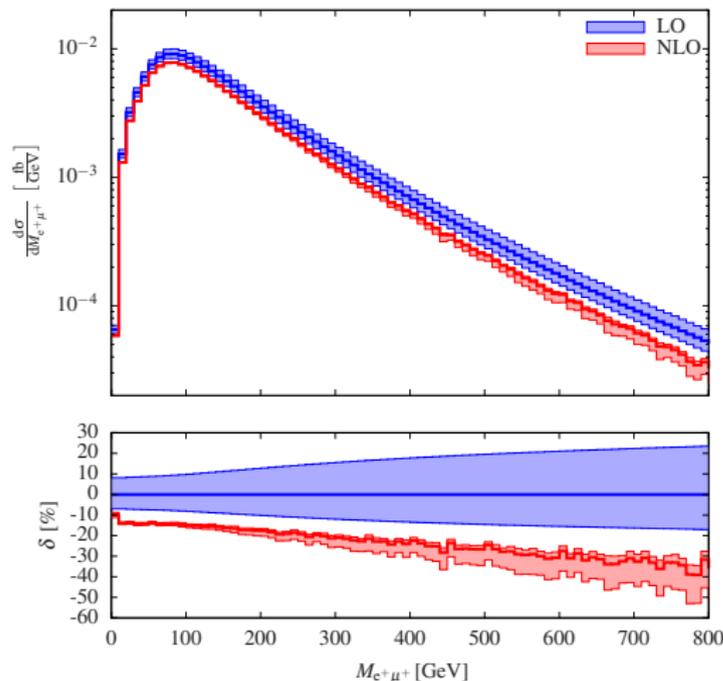
- EW contribution dominates everywhere
- $\mathcal{O}(\alpha^7)$   $-40\%$  at 800 GeV (Sudakov logarithms)
- $\mathcal{O}(\alpha_s \alpha^6)$   $-4\% - 0\%$
- $\mathcal{O}(\alpha_s^2 \alpha^5)$ ,  $\mathcal{O}(\alpha_s^3 \alpha^4)$  between  $-2\%$  and  $+2\%$  cancelling for large  $p_{T,\mu^+}$
- photon-induced corrections increase to  $4\%$  at  $p_{T,\mu^+} = 800$  GeV



- Large cross section also for high  $M_{jj}$
- QCD-induced contrib. drops much faster
- $\mathcal{O}(\alpha^7)$   $-6\%$   $-17\%$
- $\mathcal{O}(\alpha_s \alpha^6)$   $+5\%$   $-5\%$
- $\mathcal{O}(\alpha_s^2 \alpha^5)$ ,  $\mathcal{O}(\alpha_s^3 \alpha^4)$  tiny
- photon-induced corrections decrease with  $M_{jj}$



- LO QCD produces dominantly back-to-back charged leptons  
 $\Rightarrow$  relatively large fraction for small  $\cos \theta_{e^+ \mu^+}$
- $\mathcal{O}(\alpha^7)$  between  $-11\%$  and  $-14\%$
- $\mathcal{O}(\alpha_s \alpha^6)$  between  $-3\%$  and  $-4\%$
- $\mathcal{O}(\alpha_s^3 \alpha^4)$  reaches  $-6\%$  for small  $\cos \theta_{e^+ \mu^+}$  (enhanced LO)



- scale uncertainty decreases significantly from LO to NLO
- NLO scale uncertainty band outside LO scale uncertainty band owing to large EW corrections not included in QCD scale uncertainty  
⇒ need to include EWC

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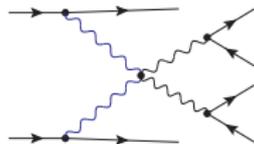
Process:  $pp \rightarrow \mu^+ \nu_\mu e^+ \nu_e jj$

EW contributions only,  $\mu_F = \mu_R = M_W$

Biedermann, Denner, Pellen '17

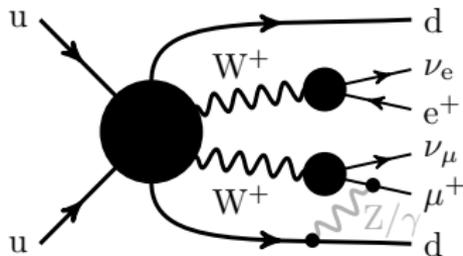
$\sigma^{\text{LO}}$ [fb]	$\sigma_{\text{EW}}^{\text{NLO}}$ [fb]	$\delta_{\text{EW}}$ [%]
1.5348(2)	1.2895(6)	-16.0

- **surprisingly large EW corrections for fiducial cross section**
- large EWC arise from bosonic virtual corrections
- leading behaviour of EWC usually dominated by Sudakov logarithms,  $\log^2 \left( \frac{Q^2}{M_W^2} \right)$ 
  - appear usually in the tails of distributions (suppressed)
  - usually small for total cross section
- **large corrections not due to VBS cuts**  
 remove  $m_{jj} > 500 \text{ GeV}$  and  $|\Delta y_{jj}| > 2.5$   
 relax  $p_{T,j}$  and  $E_{T,\text{miss}} \Rightarrow$  still large EWC  
 $\Rightarrow$  **intrinsic feature of VBS process**



## Leading contribution in expansion about poles of $W$ resonances

- factorisable corrections: production  $\times$  decay
- nonfactorisable corrections *Accomando et al. '04, Dittmaier, Schwan '15*

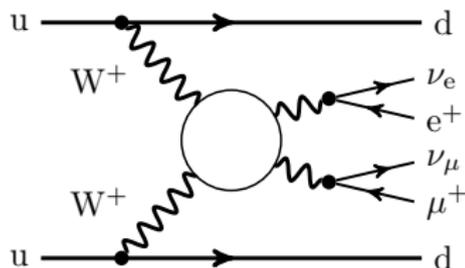


- DPA only applied to virtual corrections
- DPA agrees within 1% with full calculation
- EWC dominated by factorisable corrections (95%)

large corrections driven by  $WW$  scattering process?

## Effective vector-boson approximation (EVBA)

- EVBA reduces discussion to  $W^+W^+ \rightarrow W^+W^+$
- crude approximation but sufficient to understand dominant effects



## leading-logarithmic approximation for $WW \rightarrow WW$ Denner, Pozzorini '00

$$\sigma_{LL} = \sigma_{LO} \left[ 1 - \frac{\alpha}{4\pi} 4C_W^{ew} \log^2 \left( \frac{Q^2}{M_W^2} \right) + \frac{\alpha}{4\pi} 2b_W^{ew} \log \left( \frac{Q^2}{M_W^2} \right) \right]$$

$$C_W^{ew} = \frac{2}{s_w^2}, \quad b_W^{ew} = \frac{19}{6s_w^2}$$

(double EW logs, collinear single EW logs, and single logs from parameter renormalisation included) (angular-dependent logarithms omitted)

## Simple formula for total cross section

$$\sigma_{\text{LL}} = \sigma_{\text{LO}} \left[ 1 - \frac{\alpha}{4\pi} 4C_{\text{W}}^{\text{ew}} \log^2 \left( \frac{Q^2}{M_{\text{W}}^2} \right) + \frac{\alpha}{4\pi} 2b_{\text{W}}^{\text{ew}} \log \left( \frac{Q^2}{M_{\text{W}}^2} \right) \right]$$

- for  $Q = \langle m_{4\ell} \rangle \sim 390 \text{ GeV}$  (from MC run)

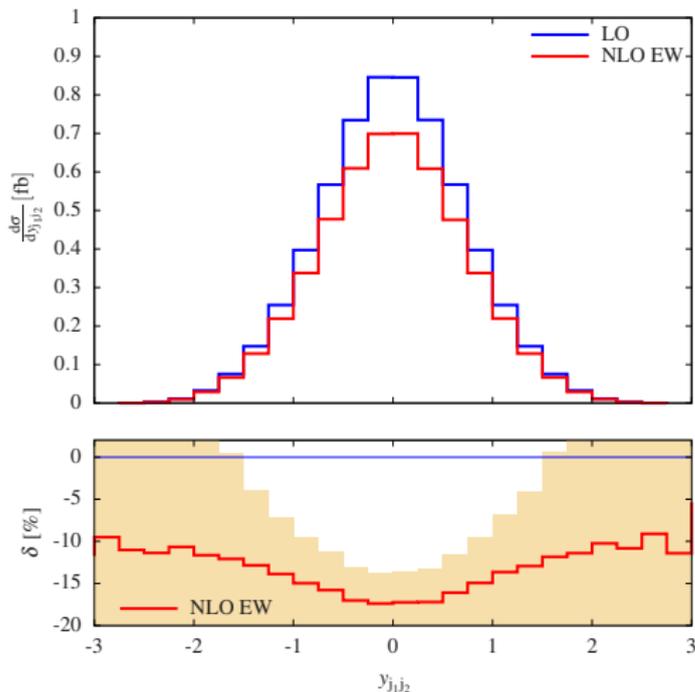
$$\delta_{\text{EW}}^{\text{LL}} = -16\% (!)$$

## surprisingly good agreement with complete calculation

⇒ corrections 3–4 times larger than for  $q\bar{q} \rightarrow W^+W^+$

- $C^{\text{ew}}$  larger for bosons than fermions
- $\langle m_{4\ell} \rangle$  larger for VBS (massive  $t$ -channel exchange Denner, Hahn '97)  
 $\langle m_{4\ell} \rangle \sim 250 \text{ GeV}$  for  $q\bar{q} \rightarrow W^+W^+$
- less cancellation between double and single logs

large NLO EW corrections intrinsic feature of VBS



Biedermann et al. '17

- $y_{j_{1j_2}} \approx 0$ :  
two jets back-to-back,  
VBS configuration  
⇒ bulk of cross section  
EWC  $\sim -16\%$
- band:  $\pm 1/\sqrt{N_{\text{obs}}}$   
for  $3000 \text{ fb}^{-1}$   
⇒ EWC necessary for  
adequate predictions



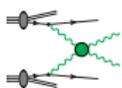
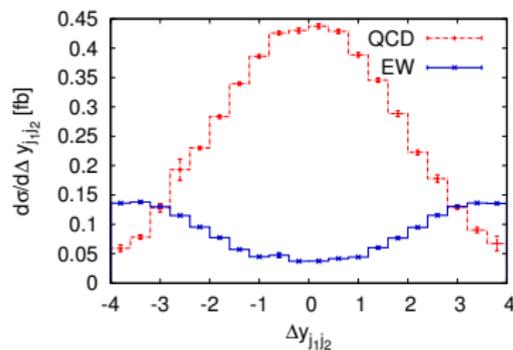
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- Complete NLO QCD and EW corrections calculated for  $pp \rightarrow \mu^+ \nu_\mu e^+ \nu_e jj$  Biedermann, Denner, Pellen 1708.00268
- matrix elements from RECOLA and loop integrals from COLLIER complete irreducible background included
- DPA provides approximation within 1%
- **-13% EW corrections for fiducial cross section**  
intrinsic feature of VBS process  
result from Sudakov logarithms in combination with large scale of WW scattering process and large vector-boson couplings  
Biedermann, Denner, Pellen 1611.02951
- EW corrections in distributions even larger  
-40% for  $p_{T,j_1} = 800$  GeV
- predictions available in terms of flexible MC programs



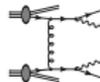
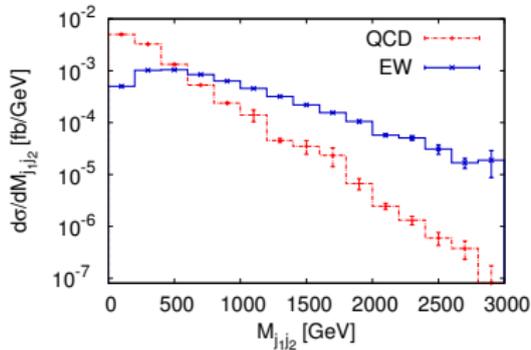
5 Backup

Jäger, Zanderighi '11

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

EW production:

- large rapidity separation  $\Delta y_{jj}$
- dominant for large  $M_{jj}$
- $\sigma_{EW}^{\text{inclusive}} = 1.10 \text{ fb}$
- $\sigma_{EW}^{\text{VBFcuts}} = 0.201 \text{ fb}$



QCD production:

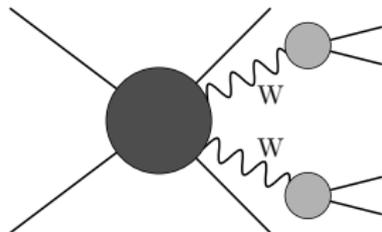
- small rapidity separation  $\Delta y_{jj}$
- prefers small  $M_{jj}$
- $\sigma_{QCD}^{\text{inclusive}} = 2.12 \text{ fb}$  **192%**
- $\sigma_{QCD}^{\text{VBFcuts}} = 0.0074 \text{ fb}$  **3.7%**

VBF cuts:  $M_{jj} > 600 \text{ GeV}$ ,  $|\Delta y_{jj}| > 4$ ,  $y_{j_1} \times y_{j_2} < 0$

Leading order:

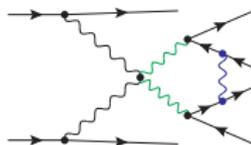
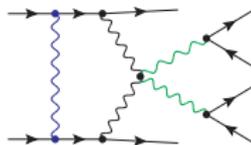
$$\mathcal{M}_{\text{LO,DPA}}^{qq \rightarrow WW qq \rightarrow 4f qq} = \sum_{\lambda_{W_1}, \lambda_{W_2}} \frac{[\mathcal{M}_{\text{LO}}^{qq \rightarrow WW qq}(\lambda_{W_1}, \lambda_{W_2}) \mathcal{M}_{\text{LO}}^{W \rightarrow 2f}(\lambda_{W_1}) \mathcal{M}_{\text{LO}}^{W \rightarrow 2f}(\lambda_{W_2})]_{\text{on-shell}}}{(p_{W_1}^2 - M_W^2 + iM_W \Gamma_W)(p_{W_2}^2 - M_W^2 + iM_W \Gamma_W)}$$

- only contributions with two resonant W bosons  $\Rightarrow$  dominant contribution
- momenta in numerator projected on shell  $\Rightarrow$  gauge invariance



## NLO:

- **factorisable corrections:**  
 corrections to production  
 or decay matrix elements
- **non-factorisable corrections:**  
 IR-singular corrections connecting  
 production and decay  
 $\Rightarrow$  universal correction factors  
 Denner et al. '00; Accomando et al. '04;  
 Dittmaier, Schwan '15



## Implementation

- DPA applied only to squared matrix element for (subtracted) virtual corrections
- leading order and real corrections treated exactly
- phase-space integration treated exactly
- naive error estimate:  $\mathcal{O}(\Gamma_W/M_W) \times \delta_{EW} \sim \mathcal{O}(0.2\%)$
- DPA worse, where non-doubly-resonant contributions sizeable