Triboson production and interplay with associated Higgs production

Marek Schönherr

IPPP, Durham University

Outline

Introduction

1. Introduction
2. The trilepton channel
3. The $e^+\mu^+jj$ channel
4. Conclusions

Triboson production

Current status

- **NLO QCD** corrections known for all on-/off-shell processes

  Binoth, Ossola, Papadopoulos, Pittau '08

  Campanario, Hankele, Oleari, Prestel, Zeppenfeld '09

- **NLO QCD** on-shell $WWW + 0, 1j$ multijet merged

  Höche, Krauss, Pozzorini, MS, Thompson, Zapp '14

- **NNLO QCD** for $\gamma\gamma\gamma$

  Chawdhry, Czakon, Mitov, Poncelet '19

  Kallweit, Sotnikov, Wiesemann '20

- corrections are typically large due to gluon-induced channels opening
- beware of single-top topologies in some channels in 5F

Triboson production

Current status

- **NLO EW** corrections known for all on-shell processes
  Nhung et.al '13, Yong-Bai et.al '15, '16; Hong et.al '16
  Dittmaier, Huss, Knippen '17
- **NLO EW** corrections for off-shell *WWW* in all trilepton channels
  MS '18
- **NLO EW** corrections for off-shell *WWW* in triple pole approx.
  Dittmaier, Knippen, Schwan '19
- large photon-induced corrections,
  can compensate EW Sudakov corrections (depending on jet veto)

The trilepton channel

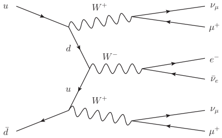
1. Introduction
2. The trilepton channel
3. The $e^+\mu^+jj$ channel
4. Conclusions

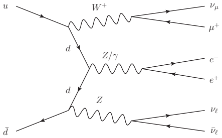
The trilepton channel

MS '18

- contribs from 0 SFOS ($e^-\mu^+\mu^+\bar{\nu}\nu\nu$), 1 SFOS ($e^-e^+\mu^+\bar{\nu}\nu\nu$) and 2 SFOS ($e^-e^+e^+\bar{\nu}\nu\nu$) processes, and $e \leftrightarrow \mu$

0 SFOS	$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	WWW	$WH[\to 2\ell 2\nu]$	WZ
1 SFOS	$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	$WWW + WZZ$	$WH[\to 2\ell 2\nu]$	WZ
	$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	WZZ	$WH[\to 2\ell 2\nu]$	WZ
	$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	WZZ	$WH[\to 2\ell 2\nu]$	WZ
2 SFOS	$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	$WWW + WZZ$	$WH[\to 2\ell 2\nu]$	WZ
	$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	WZZ	$WH[\to 2\ell 2\nu]$	WZ



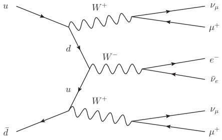


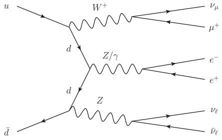
The trilepton channel

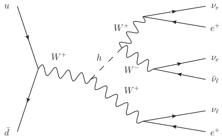
MS '18

- contribs from 0 SFOS ($e^-\mu^+\mu^+\bar{\nu}\nu\nu$), 1 SFOS ($e^-e^+\mu^+\bar{\nu}\nu\nu$) and 2 SFOS ($e^-e^+e^+\bar{\nu}\nu\nu$) processes, and $e \leftrightarrow \mu$

0 SFOS	$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	WWW	$WH[\to 2\ell 2\nu]$	WZ
1 SFOS	$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	$WWW + WZZ$	$WH[\to 2\ell 2\nu]$	WZ
	$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	WZZ	$WH[\to 2\ell 2\nu]$	WZ
	$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	WZZ	$WH[\to 2\ell 2\nu]$	WZ
2 SFOS	$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	$WWW + WZZ$	$WH[\to 2\ell 2\nu]$	WZ
	$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	WZZ	$WH[\to 2\ell 2\nu]$	WZ





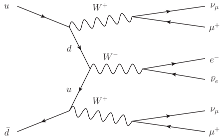


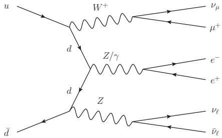
The trilepton channel

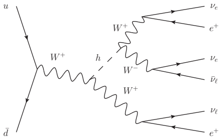
MS '18

- contribs from 0 SFOS ($e^-\mu^+\mu^+\bar{\nu}\nu\nu$), 1 SFOS ($e^-e^+\mu^+\bar{\nu}\nu\nu$) and 2 SFOS ($e^-e^+e^+\bar{\nu}\nu\nu$) processes, and $e \leftrightarrow \mu$

0 SFOS	$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	WWW	$WH[\to 2\ell 2\nu]$	WZ
1 SFOS	$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	$WWW + WZZ$	$WH[\to 2\ell 2\nu]$	WZ
	$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	WZZ	$WH[\to 2\ell 2\nu]$	WZ
	$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	WZZ	$WH[\to 2\ell 2\nu]$	WZ
2 SFOS	$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	$WWW + WZZ$	$WH[\to 2\ell 2\nu]$	WZ
	$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	WZZ	$WH[\to 2\ell 2\nu]$	WZ





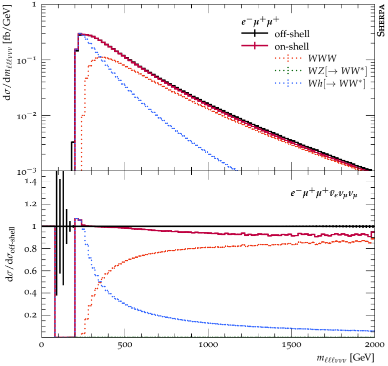


The trilepton channel

Selection	Cut	Value	
general	$p_\mathrm{T}(\ell)$	$[20\,\mathrm{GeV},\infty)$	lepton acceptance
	$y(\ell)$	$[-2.5, 2.5]$	
	$\Delta R(\ell,\ell)$	$[0.2,\infty)$	
$\not{p}_\mathrm{T} > 20$ GeV	$\Delta\phi(\not{p}_\mathrm{T},\ell\ell\ell)$	$[\frac{5}{6}\pi,\pi]$	jet veto
1, 2 SFOS	$\not{p}_\mathrm{T}$	$[50\,\mathrm{GeV},\infty)$	WZ veto
	$m_{\ell\ell}^\mathrm{SFOS}$	$[0, 70\,\mathrm{GeV}] \wedge [100\,\mathrm{GeV},\infty)$	

- cuts idealised from WWW ATLAS '16
- scale choice: $\mu = \sum m_{\mathrm{T},i}^W$ ambiguous in all channels, EW corrections largely scale independent: choose $\mu_R = \mu_F = 3\,m_W$
- use `NNPDF31_nlo_as_0118_luxqed` for reliable γPDF

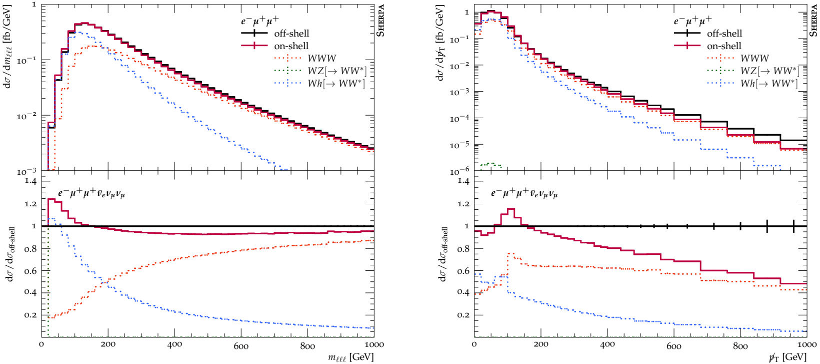
The trilepton channel – on-shell decomposition



$$m_{\ell\ell\ell\nu\nu\nu} = m_{WWW}$$

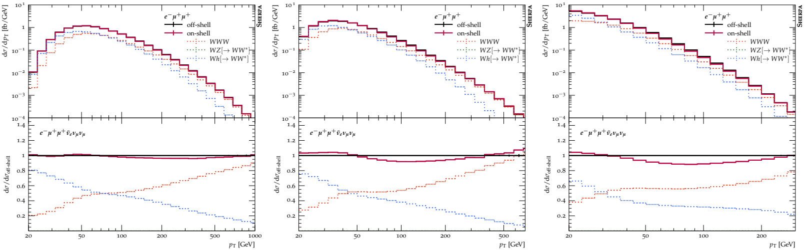
- due to presence of 3ν no W forced on-shell
- on-shell WWW not dominating for incl. xsec
- large cross section from WH, WZ negligible
- at larger m_{WWW} contribs from double (single) resonant

The trilepton channel – on-shell decomposition



- on-shell approximation reasonable for $m_{\ell\ell\ell}$
- large single and double resonant contribs for MET

The trilepton channel – on-shell decomposition

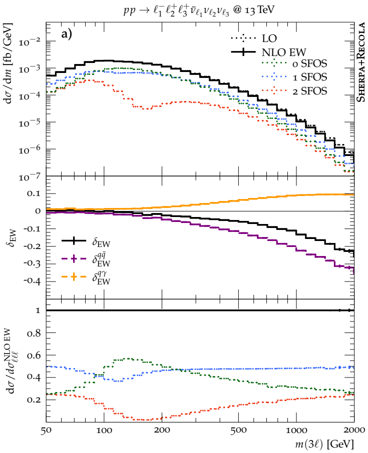


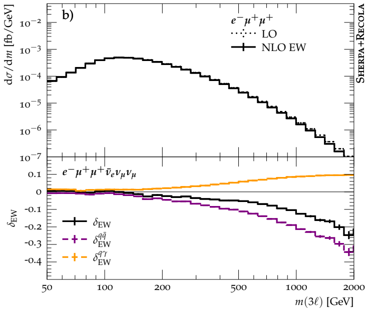
1st lepton 2nd lepton 3rd lepton

- on-shell approximation reasonable for lepton p_{T}
- moderate impact of double (single) resonant contribs

The trilepton channel – 0, 1, 2 SFOS decomposition

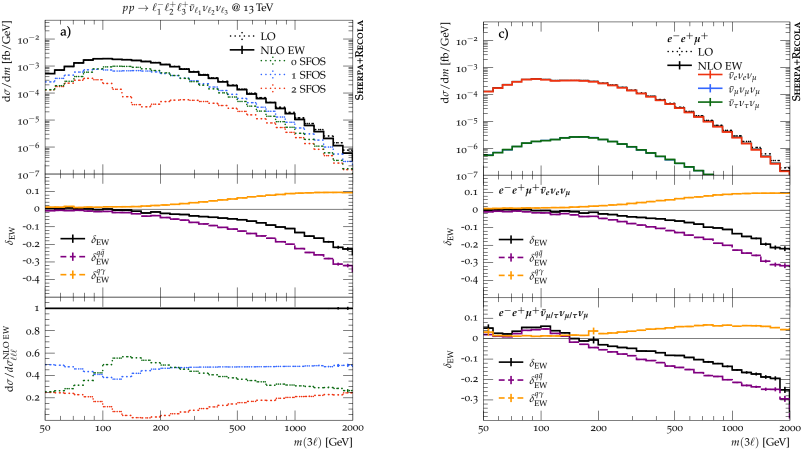
MS arXiv:1806.00307





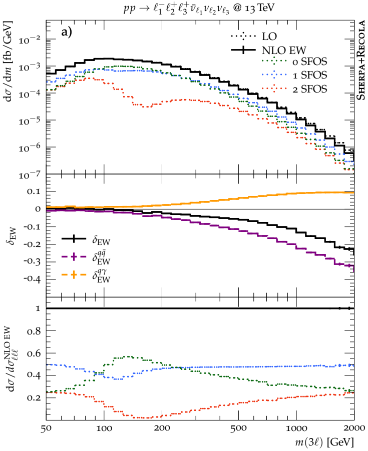
The trilepton channel – 0, 1, 2 SFOS decomposition

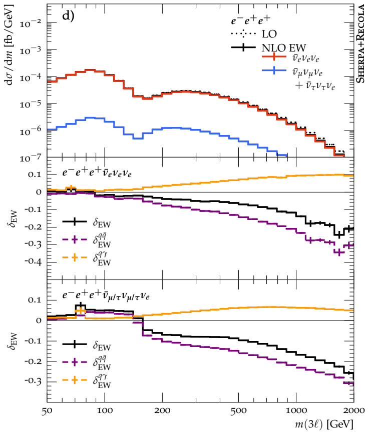
MS arXiv:1806.00307



The trilepton channel – 0, 1, 2 SFOS decomposition

MS arXiv:1806.00307





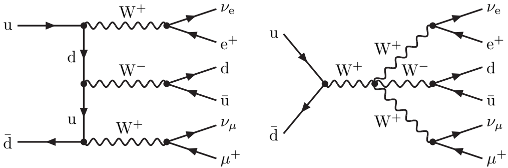
The $e^+\mu^+jj$ channel

The $e^+\mu^+$jj channel

Denner, Pellen, MS, Schumann '24

$$\mathbf{pp} \to \mathbf{e}^+\boldsymbol{\nu}_\mathbf{e}\,\boldsymbol{\mu}^+\boldsymbol{\nu}_{\boldsymbol{\mu}}\,\mathbf{jj} + \boldsymbol{X}$$

- LO contributions @ $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha_s\alpha^5)$, and $\mathcal{O}(\alpha_s^2\alpha^4)$

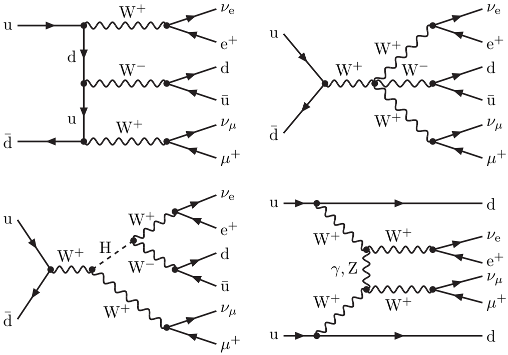


The $e^+\mu^+jj$ channel

Denner, Pellen, MS, Schumann '24

$\mathbf{pp \to e^+\nu_e\,\mu^+\nu_\mu\,jj} + X$

- LO contributions @ $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha_s\alpha^5)$, and $\mathcal{O}(\alpha_s^2\alpha^4)$

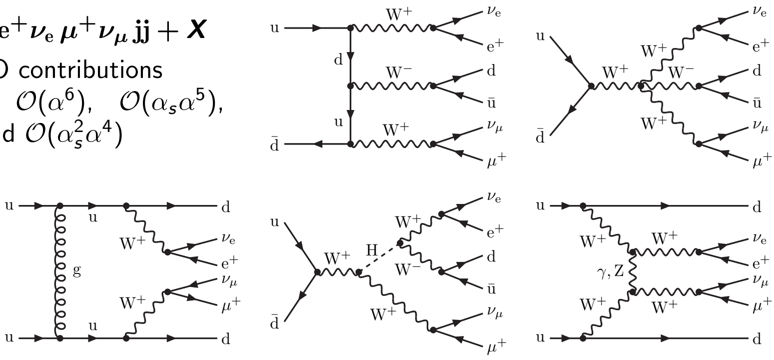


The $e^+\mu^+jj$ channel

Denner, Pellen, MS, Schumann '24

$\mathbf{pp} \to \mathbf{e^+\nu_e\,\mu^+\nu_\mu\,jj} + \boldsymbol{X}$

- LO contributions @ $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha_s\alpha^5)$, and $\mathcal{O}(\alpha_s^2\alpha^4)$

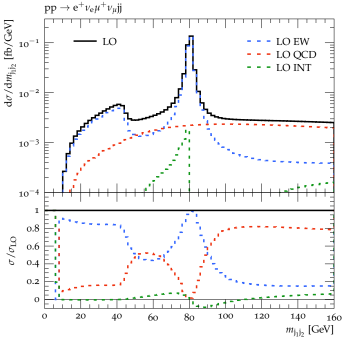


The $e^+\mu^+jj$ channel @ LO

Fiducial phase space

- contribution of individual topologies varies throughout phase space, follow *WWW* ATLAS '22
- $p_{T,\ell} > 20$ GeV, $|y_\ell| < 2.5$
  $m_{\ell\ell} \in [40, 400]$ GeV

  $p_{T,j} > 20$ GeV, $|y_j| < 4.5$
  $m_{jj} \in [0, 160]$ GeV, $|\Delta y_{jj}| < 1.5$



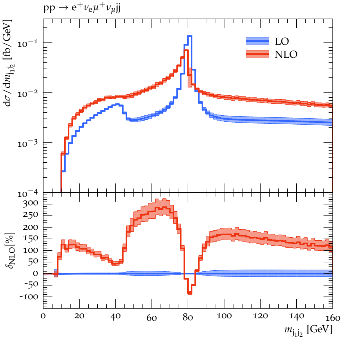
	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	sum
σ_{LO}[fb]	0.78549(9)	0.00732(1)	0.25925(3)	1.05206(9)
σ/σ_{LO}^{sum} [%]	74.7	0.7	24.6	100

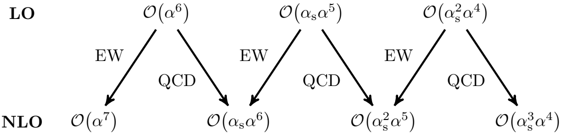
The $\mathrm{e}^+\mu^+\mathrm{jj}$ channel @ NLO

NLO corrections

- $\mathcal{O}(\alpha_s^3\alpha^4)$ pure QCD corr.
- $\mathcal{O}(\alpha_s^2\alpha^5)$ both EW and QCD corr.
- $\mathcal{O}(\alpha_s\alpha^6)$ both QCD and EW corr.
- $\mathcal{O}(\alpha^7)$ pure EW corr.

- $\mu_R = \mu_F = \sum m_T^W$
  NNPDF31_nlo_as_0118_luxqed



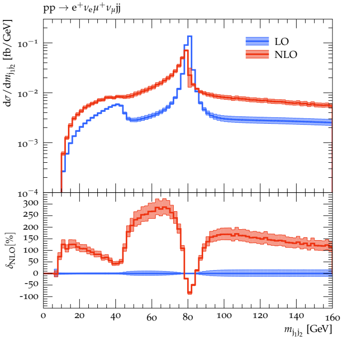


The $e^+\mu^+jj$ channel @ NLO

NLO corrections

- $\mathcal{O}(\alpha_s^3\alpha^4)$ pure QCD corr.
- $\mathcal{O}(\alpha_s^2\alpha^5)$ both EW and QCD corr.
- $\mathcal{O}(\alpha_s\alpha^6)$ both QCD and EW corr.
- $\mathcal{O}(\alpha^7)$ pure EW corr.

- $\mu_R = \mu_F = \sum m_T^W$
  NNPDF31_nlo_as_0118_luxqed



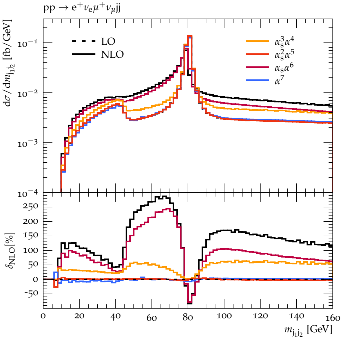
	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	sum
$\delta\sigma$[fb]	−0.035(1)	0.305(1)	−0.0032(3)	0.2260(3)	0.493(2)
$\delta\sigma/\sigma_{\text{LO}}^{\text{sum}}$ [%]	−3.4	29.0	−0.30	21.5	46.9

The $e^+\mu^+jj$ channel @ NLO

NLO corrections

- $\mathcal{O}(\alpha_s^3\alpha^4)$ pure QCD corr.
- $\mathcal{O}(\alpha_s^2\alpha^5)$ both EW and QCD corr.
- $\mathcal{O}(\alpha_s\alpha^6)$ both QCD and EW corr.
- $\mathcal{O}(\alpha^7)$ pure EW corr.

- $\mu_R = \mu_F = \sum m_T^W$
  NNPDF31_nlo_as_0118_luxqed



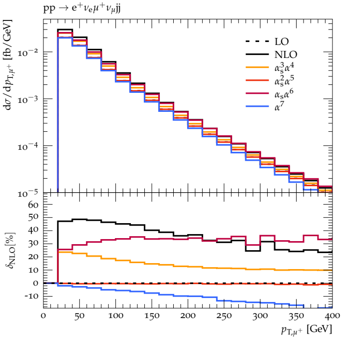
	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	sum
$\delta\sigma$[fb]	$-0.035(1)$	0.305(1)	$-0.0032(3)$	0.2260(3)	0.493(2)
$\delta\sigma/\sigma_{LO}^{sum}$ [%]	-3.4	29.0	-0.30	21.5	46.9

The $e^+\mu^+jj$ channel @ NLO

NLO corrections

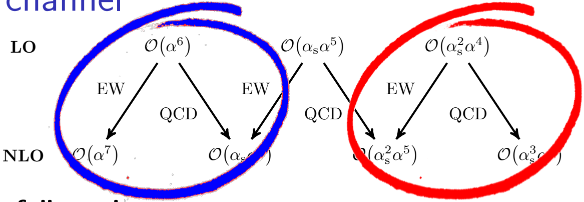
- $\mathcal{O}(\alpha_s^3\alpha^4)$ pure QCD corr.
- $\mathcal{O}(\alpha_s^2\alpha^5)$ both EW and QCD corr.
- $\mathcal{O}(\alpha_s\alpha^6)$ both QCD and EW corr.
- $\mathcal{O}(\alpha^7)$ pure EW corr.

- $\mu_R = \mu_F = \sum m_T^W$
  NNPDF31_nlo_as_0118_luxqed



	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	sum
$\delta\sigma$[fb]	−0.035(1)	0.305(1)	−0.0032(3)	0.2260(3)	0.493(2)
$\delta\sigma/\sigma_{LO}^{sum}$ [%]	−3.4	29.0	−0.30	21.5	46.9

The $e^+\mu^+jj$ channel



Decompose full result

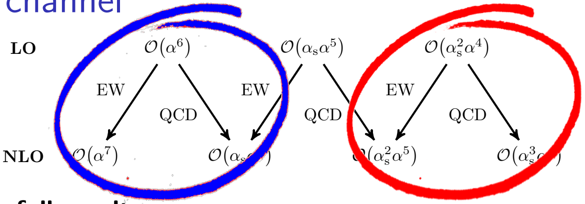
- LO inteference $\mathcal{O}(\alpha_s\alpha^5)$ (mostly) negligible, define

  EW production $\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha_s\alpha^6) + \mathcal{O}(\alpha^7)$

  QCD production $\mathcal{O}(\alpha_s^2\alpha^4) + \mathcal{O}(\alpha_s^3\alpha^4) + \mathcal{O}(\alpha_s^2\alpha^5)$

- caveat:
  $\mathcal{O}(\alpha_s^2\alpha^5)$ is still partially QCD corr. to LO interference $\rightarrow$ neglect
  $\mathcal{O}(\alpha_s\alpha^6)$ is still partially EW corr. to LO interference
  $\rightarrow$ decompose further

The $e^+\mu^+$jj channel



Decompose full result

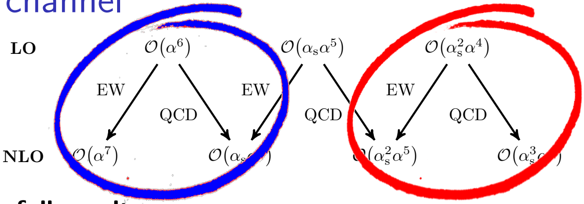
- LO inteference $\mathcal{O}(\alpha_s\alpha^5)$ (mostly) negligible, define

  EW production $\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha_s\alpha^6)+\mathcal{O}(\alpha^7)$

  QCD production $\mathcal{O}(\alpha_s^2\alpha^4)+\mathcal{O}(\alpha_s^3\alpha^4)+\mathcal{O}(\alpha_s^2\alpha^5)$

- caveat:
  $\mathcal{O}(\alpha_s^2\alpha^5)$ is still partially QCD corr. to LO interference → neglect
  $\mathcal{O}(\alpha_s\alpha^6)$ is still partially EW corr. to LO interference
  → decompose further

The $e^+\mu^+jj$ channel



Decompose full result

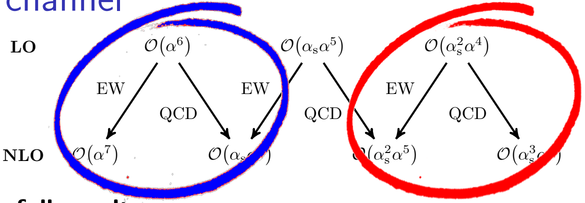
- LO inteference $\mathcal{O}(\alpha_s\alpha^5)$ (mostly) negligible, define

  EW production $\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha_s\alpha^6)+\mathcal{O}(\alpha^7)$

  QCD production $\mathcal{O}(\alpha_s^2\alpha^4)+\mathcal{O}(\alpha_s^3\alpha^4)+\mathcal{O}(\alpha_s^2\alpha^5)$

- caveat:
  $\mathcal{O}(\alpha_s^2\alpha^5)$ is still partially QCD corr. to LO interference $\rightarrow$ neglect
  $\mathcal{O}(\alpha_s\alpha^6)$ is still partially EW corr. to LO interference
  $\rightarrow$ decompose further

The $e^+\mu^+jj$ channel



Decompose full result

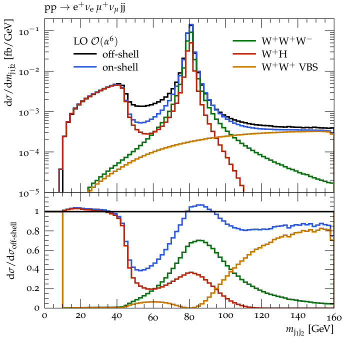
- LO inteference $\mathcal{O}(\alpha_s\alpha^5)$ (mostly) negligible, define

  EW production $\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha_s\alpha^6)+\mathcal{O}(\alpha^7)$

  QCD production $\mathcal{O}(\alpha_s^2\alpha^4)+\mathcal{O}(\alpha_s^3\alpha^4)+\mathcal{O}(\alpha_s^2\alpha^5)$

- caveat:
  $\mathcal{O}(\alpha_s^2\alpha^5)$ is still partially QCD corr. to LO interference $\rightarrow$ neglect
  $\mathcal{O}(\alpha_s\alpha^6)$ is still partially EW corr. to LO interference
  $\rightarrow$ decompose further

The $e^+\mu^+jj$ channel – on-shell decomposition @ LO



Sample decomposition

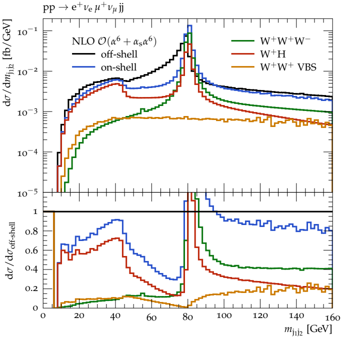
- approximate off-shell result with incoherent sum of on-shell channels using spin-correlated decays in NWA Höche et.al '14
- different on-shell channels dominant in different regions,
- WWW nowhere $\gtrsim$ 70%

$\mathcal{O}(\alpha^6)$	off shell	on shell	on-shell subprocess			
Process		sum	*WWW*	*WH*	*WZ*	VBS
σ_{LO}[fb]	0.7917	0.7738	0.4207	0.3265	$5\cdot10^{-7}$	0.0266
$\sigma/\sigma_{\text{LO}}^{\text{off shell}}$[%]	100	97.7	53.1	41.2	$7\cdot10^{-5}$	3.3

The $e^+\mu^+jj$ channel – on-shell decomposition @ NLO

Sample composition

- *WWW* contrib reduced by 4.8%
- VBS contrib increased by 4.4%, large *K*-factor driven by collinear radiation off forward jet forming new low-m_{jj} pair
- note: QCD corrections to $W \to q\bar{q}'$ decay not included here

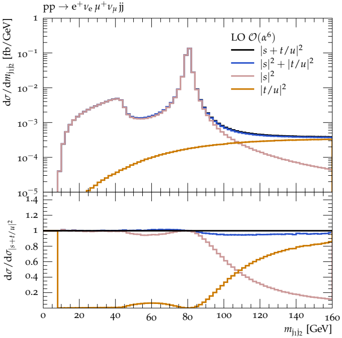


$\mathcal{O}(\alpha^6 + \alpha_s\alpha^6)$	off shell	on shell	on-shell subprocess			
Process		sum	*WWW*	*WH*	*WZ*	VBS
K_{NLO}	1.42	1.40	1.29	1.38	2.21	3.25
$\sigma/\sigma_{\text{NLO}}^{\text{off shell}}$[%]	100	96.2	48.3	40.2	$2 \cdot 10^{-6}$	7.7

The $e^+\mu^+jj$ channel – s/t-channel decomposition

Sample composition

- decompose according to s or t/u-channel jet production
  - s $WWW + WH + WZ$ (coherent)
  - t/u VBS
- otherwise completely off-shell



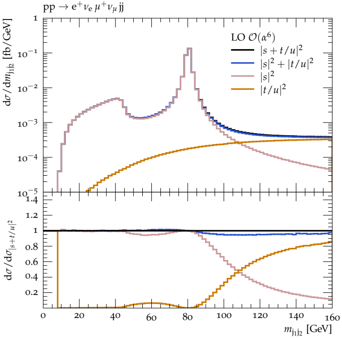
most partonic channels either s, t, or u,
decompose remaining into incoherent sum, e.g.

$$\underbrace{u d \to e^+\bar{\nu}_e \mu^+\nu_\mu d\bar{u}}_{|s+t|^2} \longrightarrow \underbrace{u d \to e^+\bar{\nu}_e \mu^+\nu_\mu s\bar{c}}_{|s|^2} + \underbrace{u s \to e^+\bar{\nu}_e \mu^+\nu_\mu d\bar{c}}_{|t|^2}$$

The $e^+\mu^+jj$ channel – s/t-channel decomposition

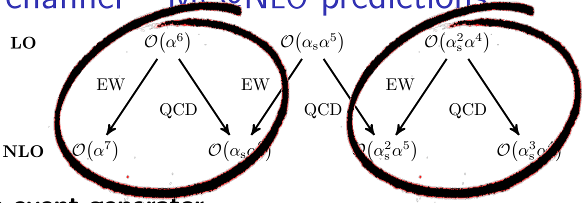
Sample composition

- decompose according to s or t/u-channel jet production
  - s $WWW + WH + WZ$ (coherent)
  - t/u VBS
- otherwise completely off-shell



$\mathcal{O}\alpha^6+\alpha_s\alpha^6$	coherent	incoherent	subchannels	
Process	$\|s+t/u\|^2$	$\|s\|^2+\|t/u\|^2$	$\|s\|^2$	$\|t/u\|^2$
σ_{NLO}[fb]	1.091	1.084	0.998	0.086
$\sigma/\sigma_{\text{NLO}}^{\text{off shell}}$[%]	100	99.4	91.5	7.9

The $e^+\mu^+jj$ channel – MC@NLO predictions



Building an event generator

- separate into QCD and EW production
- build on *s*-*t*-channel decomposition in EW production, removes EW divergences from $\mathcal{O}(\alpha_s\alpha^6)$ QCD corr. to EW prod.
  $\rightarrow$ can use traditional MC@NLO QCD as implemented in SHERPA for parton-shower matching, include EW corrections through EW_{virt} approximation

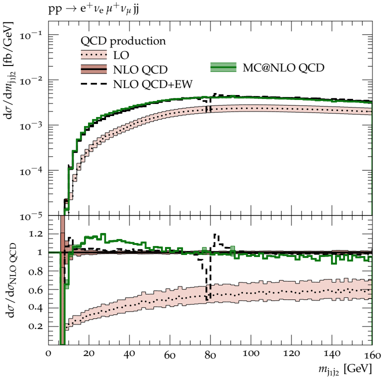
Höche, Krauss, MS, Siegert '11

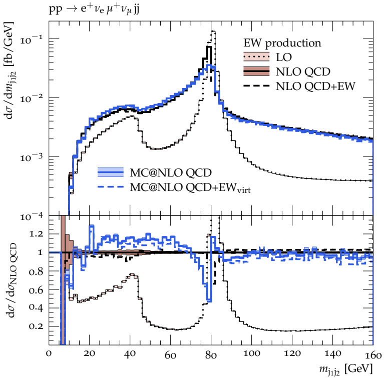
Kallweit, Lindert, Pozzorini, MS '15

Three generators: ① QCD prod., ② *s*-ch. EW prod., ③ *t*-ch. EW prod.

Denner, Pellen, MS, Schumann '24

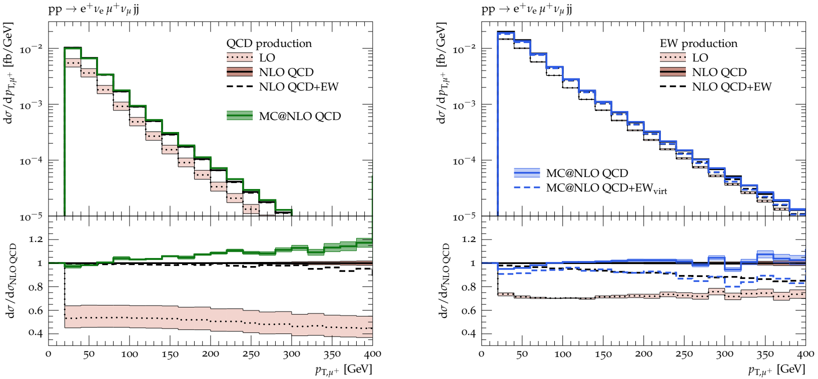
The $e^+\mu^+jj$ channel – Mc@Nlo predictions





- large beyond-NLO corrections around W resonance
- $\mathcal{O}(\alpha_s^2\alpha^5)$ has s-channel W/g interference, spurious shape feature

The $e^+\mu^+jj$ channel – MC@NLO predictions



- EW Sudakov correction for EW production well reproduced
- small corrections beyond NLO

Conclusions

- triboson signatures have to be computed off-shell due to their rich internal structure
- various resonant configurations present in (almost) all channels
  - always *WWW* and *WH* (*WZ*)
  - VBS in hadronic channels
  - *WZZ* in ≥ 1 OSSF channels
- a number of precision Monte-Carlo simulations for off-shell production exist and should be used for a reliable description
- QCD corrections are large, EW corrections are sizeable

Thank you!