Electroweak Corrections for off-shell W^+W^- Scattering

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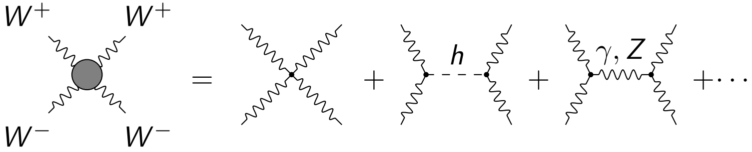
What is Vector Boson Scattering?

- interesting field to check the validity of
  - the standard model in general
  - especially electroweak symmetry breaking



- exact cancellation of unitarity-violating high-energy behaviour of longitudinal modes
- very sensitive to BSM physics
- need of precise SM predictions

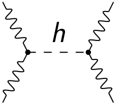
Previous work

- 2006: corrections $\mathcal{O}(\alpha_S^1\alpha^6)$ in VBS approximation [Jäger, Oleari, Zeppenfeld; arXiv:hep-ph/0603177]
- 2011/12: corrections $\mathcal{O}(\alpha_S^3\alpha^4)$ [Melia, Melnikow, Röntsch, Zanderighi; arXiv:1104.2327] [Greiner et al.; arXiv:1202.6004]
- 2013/16: corrections $\mathcal{O}(\alpha_S^1\alpha^6)$ + parton shower [Jäger, Zanderighi; arXiv:1301.1695] [Rauch, Plätzer; arXiv:1605.07851]

$\Rightarrow$ no electroweak corrections yet

Opposite sign WW scattering

- experimentally interesting
  - high cross section ($> 10\times$ larger) compared to other VBS processes $\sigma_{W^+W^-} \sim 10\,\mathrm{fb}$
  - but also large background from (misidentified) $t\bar{t}$ production $\sigma_{t\bar{t}} \sim 1\,\mathrm{nb}$ [ATLAS; arXiv:1910.08819]
  - not measured yet, measurements are forthcoming
- includes EW Higgs production via VBF and Higgs decay to W bosons
  - problematic: we cannot cut it out via physical cuts
  - interesting process also for Higgs physics

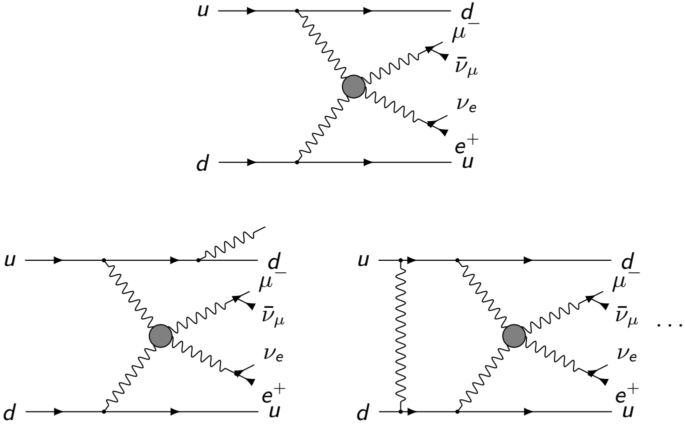


Details of the calculation

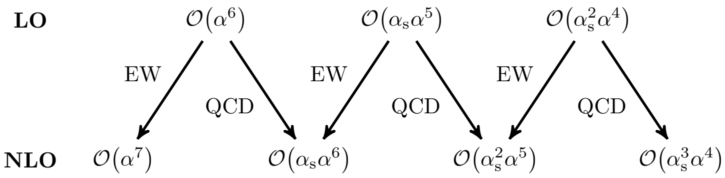
$$pp \to e^+\mu^-\nu_e\bar{\nu}_\mu jj + X$$

- Monte Carlo integration with BBMC (in-house Monte Carlo)
- calculation of matrix elements with RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati; arXiv:1605.01090] and COLLIER [Denner, Dittmaier, Hofer; arXiv:1604.06792]
    - complex-mass scheme [Denner, Dittmaier, Roth, Wackeroth; arXiv:hep-ph/9904472]
    - dimensional regularisation for IR singularities
    - renormalisation in on-shell scheme
- NLO calculation using Catani-Seymour dipoles [Catani, Seymour; arXiv:hep-ph/9605323], [Dittmaier, Kabelschacht, Kasprzik; arXiv:0802.1405]
- input:
    - pdf set NNPDF3.1luxQED [Bertone,Carrazza,Hartland,Rojo; arXiv:1712.07053]
    - running of α_S from pdfs
    - determination of α in G_μ scheme

Signal diagrams



Process structure

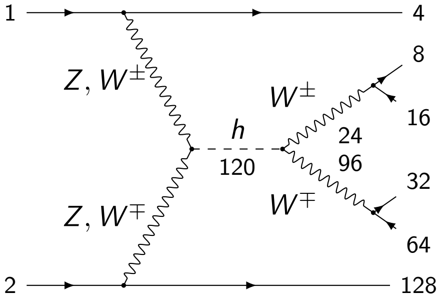


	$\sigma_{\alpha_s^0\alpha^6}$/fb	$\sigma_{\alpha_s^1\alpha^5}$/fb	$\sigma_{\alpha_s^2\alpha^4}$/fb
W^+W^+	1.4178(2)	0.004815(2)	0.17229(5)
W^+Z	0.25511(1)	0.006824(1)	1.0973(1)
ZZ	0.097683(2)	0.008628(1)	1.06248(5)
W^+W^-	2.67(3)	0.066(4)	6.93(1)

[Biedermann, Denner, Pellen; arXiv:1708.00268], [Denner, Dittmaier, Maierhöfer, Pellen, Schwan; arXiv:1904.00882], [Denner, Franken, Pellen, Schmidt; arXiv:2009.00411], [Denner, Franken, Schmidt; in prep.]

The Higgs resonance (I)

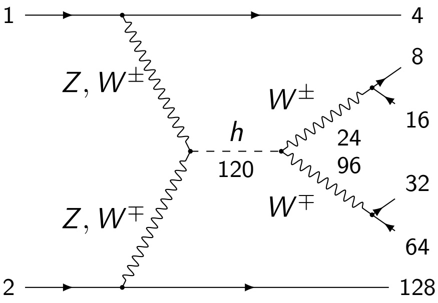
- first appearance in the fiducial phase space region:



with its very sharp resonance peak

- problem of our Monte Carlo: mapping of invariants in fixed order back-to-front $s_{24} \to s_{96} \to s_{120}$

The Higgs resonance (II)



- both W bosons mapped resonant $\Rightarrow$ h almost never resonant

$$s_{16} = (p_8 + p_{16})^2 \approx m_W^2, \quad s_{96} = (p_{32} + p_{64})^2 \approx m_W^2$$

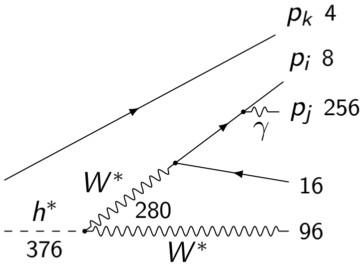
$$\Rightarrow \qquad s_{120} > \left(\sqrt{s_{24}} + \sqrt{s_{96}}\right)^2 > m_H^2 \text{ mostly}$$

The Higgs resonance (III)

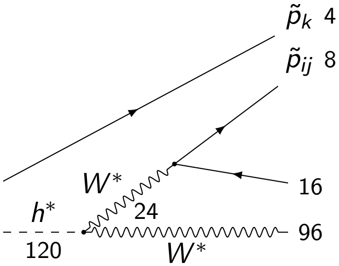
- problem enhanced at NLO in Catani-Seymour algorithm:
  - used to subtract divergencies in collinear and soft regions
  - redistributes momenta of emitter p_i, emissus p_j and some spectator p_k to a reduced $n-1$ particle PS with momenta $\tilde{p}_{ij}, \tilde{p}_k$
  - normally no severe impact on "non-dangerous" PSP ...
  - ... but it may shift the momenta in the reduced PS to the Higgs resonance
    $\Rightarrow$ real ME and subtracted ME do not match
- Monte Carlo signature: events with extremely large weights
  $\Rightarrow$ unstable integration

The Higgs resonance (IV)

real ME $\Rightarrow$ subtracted ME



$\Rightarrow$



$s_{280} \approx m_W^2, s_{96} \approx m_W^2 \quad \Rightarrow \quad \tilde{s}_{24} \not\approx m_W^2, s_{96} \approx m_W^2$

$s_{376} > m_H^2 \quad \Rightarrow \quad \tilde{s}_{120} \approx m_H^2$ possible

depending on the combination of momenta of emitter, emissus and spectator, formerly non-resonant particles can become resonant

Solution

- introduction of additional integration channels
- 3 steps:
  - determine all (free) s-channel invariants back to front
  - separate massive and massless s-channel invariants
  - do a cyclic permutation of massive s-channel invariants

$$(s_{96} \to s_{280} \to s_{376}), \quad (s_{280} \to s_{376} \to s_{96}), \quad (s_{376} \to s_{96} \to s_{280})$$

- for every possibly resonant propagator: at least 1 integration channel that maps this propagator first
- let the channel weight optimisation do the rest
  $\Rightarrow$ dominant integration channels with resonant Higgs

General setup

- simulate pp collider at $\sqrt{s} = 13\,\mathrm{TeV}$
- only light jets; b-jet veto
- cluster jets with anti-kT algorithm [Cacciari, Salam, Soyez; arXiv:0802.1189], resolution parameter $R = 0.4$
- consider only particles with $|y| < 5$ for recombination
- recombination $j\gamma \to j, \ell\gamma \to \ell$, resolution parameter $R = 0.4$
- use scales $\mu_\mathrm{F} = \mu_\mathrm{R} = \sqrt{p_{\mathrm{T},j_1} p_{\mathrm{T},j_2}}$

Two experimental cut setups

inspired by	**"VBS setup"** [CMS; priv. conv.]	**"Higgs setup"** [CMS; arXiv:1806.05246]
$p_{\mathrm{T},\ell\ell}$	$> 30\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$
$p_{\mathrm{T},j1}, p_{\mathrm{T},j2}$	$> 30\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$
$p_{\mathrm{T},\ell 1}$	$> 25\,\mathrm{GeV}$	$> 25\,\mathrm{GeV}$
$p_{\mathrm{T},\ell 2}$	$> 13\,\mathrm{GeV}$	$> 10\,\mathrm{GeV}$
$p_{\mathrm{T,miss}}$	$> 20\,\mathrm{GeV}$	$> 20\,\mathrm{GeV}$
$\Delta R_{j\ell}$	> 0.4	> 0.4
$\Delta R_{\ell\ell}$	–	> 0.4
$m_{\ell\ell}$	$> 50\,\mathrm{GeV}$	$> 12\,\mathrm{GeV}$
$\lvert y_\ell \rvert$	< 2.4	< 2.4
$\lvert y_j \rvert$	< 4.5	< 4.7
M_{jj}	$> 300\,\mathrm{GeV}$	$> 400\,\mathrm{GeV}$
$\lvert \Delta y_{jj} \rvert$	> 2.5	> 3.5
$m_{\mathrm{T},4\ell}$	–	$\in [60\,\mathrm{GeV}, 125\,\mathrm{GeV}]$
$\lvert z^*_{\ell jj} \rvert$	–	< 0.5
jet veto: $p_{\mathrm{T},j3}$	–	$< 30\,\mathrm{GeV}$

Two experimental cut setups

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$p_{\mathrm{T},j1}$, $p_{\mathrm{T},j2}$	$> 30\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$
$p_{\mathrm{T},\ell 1}$	$> 25\,\mathrm{GeV}$	$> 25\,\mathrm{GeV}$
$p_{\mathrm{T},\ell 2}$	$> 13\,\mathrm{GeV}$	$> 10\,\mathrm{GeV}$
$p_{\mathrm{T,miss}}$	$> 20\,\mathrm{GeV}$	$> 20\,\mathrm{GeV}$
$\Delta R_{j\ell}$	> 0.4	> 0.4
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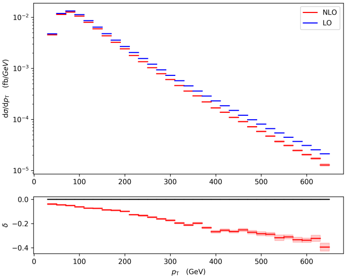
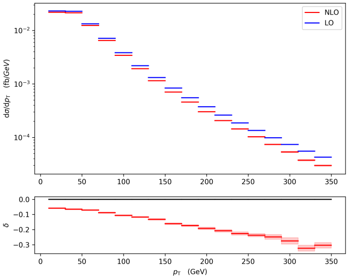
Differential distributions (I) – preliminary

(a) p_{T,j_1}



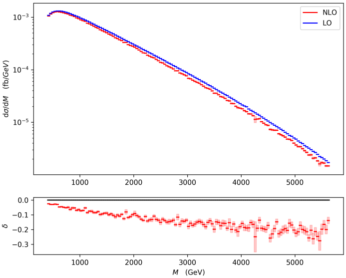
(b) p_{T,e^+}



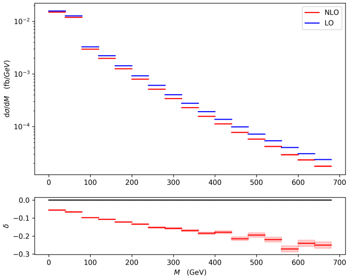
- typical VBS signature: large corrections (up to -40%) at high energies due to Sudakov logarithms

Differential distributions (II) – preliminary

(a) $M_{j_1 j_2}$



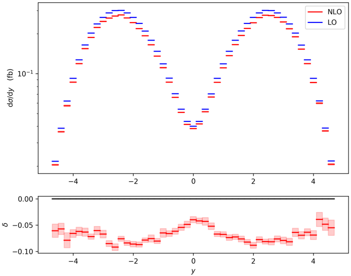
(b) $M_{e^+\mu^-}$



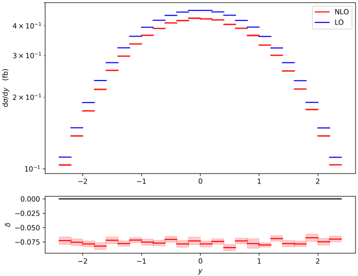
- same behaviour of the corrections, but: bulk of the cross section at low lepton invariant masses

Differential distributions (III) – preliminary

(a) y_{j_1}



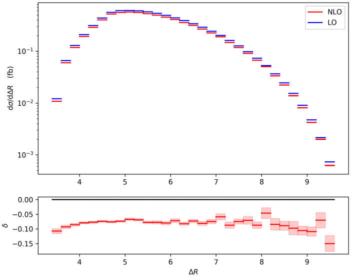
(b) y_{e^+}



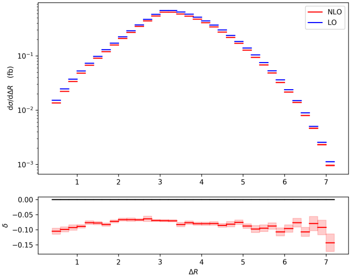
- small jet rapidities very suppressed
- corrections in lepton rapidity almost constant

Differential distributions (IV) – preliminary

(a) $\Delta R_{j_1 j_2}$



(b) $\Delta R_{j_1 e^+}$



- again typical VBS signatures: clearly separated particles

Electroweak corrections in different VBS processes

	$\sigma_{\alpha^6}/\text{fb}$	$\delta\sigma_{\alpha^7}/\text{fb}$	$\delta\sigma_{\alpha^7}/\sigma_{\alpha^6}$
W^+W^+	1.4178(2)	−0.2169(3)	−15.3%
W^+Z	0.25511(1)	−0.04091(2)	−16.0%
ZZ	0.097683(2)	−0.015573(5)	−15.9%
W^+W^- (Higgs setup)	1.5322(2)	−0.115(3)	−7.5%

[Biedermann, Denner, Pellen; arXiv:1708.00268], [Denner, Dittmaier, Maierhöfer, Pellen, Schwan; arXiv:1904.00882], [Denner, Franken, Pellen, Schmidt; arXiv:2009.00411], [Denner, Franken, Schmidt; in prep.]

Summary & outlook

- W^+W^- scattering is *"different"* from other VBS processes
- Higgs resonance plays an important role
  - has severe impact on the behaviour of NLO cross sections
  - different setups for Higgs and VBS
- we plan to investigate a further setup in which we eliminate the Higgs resonance
- checks against other Monte Carlos (MoCaNLO) ongoing
- better statistics, additional setups and other orders in α_S coming soon

Stay tuned ;-)

SM input parameters

$$
\begin{aligned}
m_W^{\mathrm{OS}} &= 80.379\,\mathrm{GeV} & \Gamma_W^{\mathrm{OS}} &= 2.085\,\mathrm{GeV} \\
m_Z^{\mathrm{OS}} &= 91.1876\,\mathrm{GeV} & \Gamma_Z^{\mathrm{OS}} &= 2.4952\,\mathrm{GeV} \\
m_h &= 125.0\,\mathrm{GeV} & \Gamma_h &= 4.07 \cdot 10^{-3}\,\mathrm{GeV} \\
G_\mu &= 1.16638 \cdot 10^{-5}\,\mathrm{GeV}^{-2} & \alpha_S(m_Z^2) &= 0.118
\end{aligned}
$$

Definition of non-standard cut variables

$$z^*_{\ell jj} = \frac{y_\ell - \frac{y_{j_1}+y_{j_2}}{2}}{y_{j_1} - y_{j_2}}$$

$$m_{\mathrm{T},4\ell} = \sqrt{2 p_{\mathrm{T},\ell\ell} p_{\mathrm{T,miss}} [1 - \cos \Delta\phi_{\Sigma_{\ell\ell}\Sigma_{\nu\nu}}]}$$