Theory input for vector-boson scattering

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Key process to investigate electroweak symmetry breaking

Crucial role of Higgs boson

Possibility to measure SM parameters

→ Higgs width: [Campbell, Ellis; 1502.02990]

Window to new physics

High multiplicity process

...
Evidence by ATLAS and CMS at Run-I for $W^\pm W^\pm$

[1405.6241, 1611.02428, 1410.6315]

Measurement by ATLAS and CMS at run-II for $W^\pm W^\pm$

[CMS-PAS-SMP-17-004; 1709.05822], [ATLAS-CONF-2018-030]

Evidence by CMS at Run-II for ZZ [1708.02812]

Observation by ATLAS and CMS at Run-II for WZ

Outline

→ Motivation for this presentation:
  Overview of theory input for VBS in the SM

- NLO predictions
- Quality of the VBS approximation
- Beyond fixed order (parton shower)
Example of $pp \rightarrow \mu^+ \nu_\mu e^+ \nu_e jj$

→ All partonic channels to be taken into account:
  • $uu \rightarrow \mu^+ \nu_\mu e^+ \nu_e dd$
  • $u\bar{d} \rightarrow \mu^+ \nu_\mu e^+ \nu_e s\bar{c}$
  • $uc \rightarrow \mu^+ \nu_\mu e^+ \nu_e sd$
  • $d\bar{d} \rightarrow \mu^+ \nu_\mu e^+ \nu_e \bar{u} \bar{u}$
  • $u\bar{d} \rightarrow \mu^+ \nu_\mu e^+ \nu_e d\bar{u}$
  • $u\bar{s} \rightarrow \mu^+ \nu_\mu e^+ \nu_e d\bar{c}$
  • $\bar{s}\bar{d} \rightarrow \mu^+ \nu_\mu e^+ \nu_e \bar{u}\bar{c}$

→ Tree amplitudes of order $\mathcal{O}(g^6)$ and $\mathcal{O}(g_s^2 g^4)$
• LO contributions at: $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha_s \alpha^5)$, and $\mathcal{O}(\alpha_s^2 \alpha^4)$
→ EW contribution/signal, interference, and QCD contribution/background
→ Example of $W^+W^+$:

[Figure showing $\sigma$ (fb) per bin ($m_{jj}, \Delta y_{jj}$):
$\alpha^6$, $\alpha_s \alpha^5$, $\alpha_s^2 \alpha^4$]

[Ballestrero, MP et al.; 1803.07943]

• The contributions have different kinematic

• **Need for exclusive cuts to enhance the EW contribution**
→ typical cuts are $m_{jj}$ and $|\Delta y_{jj}|$.

→ Need for reliable theoretical predictions: higher orders, estimate of approximations, parton shower, ...

Common feature of all VBS signatures
NLO computations (1)

- $W^\pm W^\pm$
  - NLO QCD to EW-induced process in VBS approximation
    [Jäger, Oleari, Zeppenfeld; 0907.0580], [Denner, Hošeková, Kallweit; 1209.2389]
  - NLO QCD to QCD-induced process [Melia et al.; 1007.5313, 1104.2327], [Campanario et al.; 1311.6738]
  - Matching to parton shower [Jäger, Zanderighi; 1108.0864], [Melia et al.; 1102.4846]
    → Available in VBFNLO or POWHEG-BOX
  - Full NLO QCD and EW to EW- and QCD-induced process
    [Biedermann, Denner, MP; 1611.02951, 1708.00268]

- $W^\pm Z$
  - NLO QCD to EW-induced process in VBS approximation
    [Bozzi et al.; hep-ph/0701105]
  - NLO QCD to QCD-induced process [Campanario et al.; 1305.1623]
    → Available in VBFNLO
  - Preliminary results for NLO EW to EW-induced process
NLO computations (2)

- $W^{+}W^{-}$
  - NLO QCD to EW-induced process in VBS approximation
    [Jäger, Oleari, Zeppenfeld; hep-ph/0603177]
  - NLO QCD to QCD-induced process
    [Melia et al.; 1104.2327], [Greiner et al.; 1202.6004]
  - Matching to parton shower
    [Jäger, Zanderighi; 1301.1695], [Rauch, Plätzer; 1605.07851]
  → Available in VBFNLO or Powheg-Box

- $ZZ$
  - NLO QCD to EW-induced process in VBS approximation and matching to parton shower
    [Jäger, Karlberg, Zanderighi; 1312.3252]
  - NLO QCD to QCD-induced process
    [Campanario et al.; 1405.3972]
  → Available in VBFNLO or Powheg-Box
All processes known at NLO QCD accuracy matched to PS ...  
... in VBS approximation  
... for both QCD-/EW-induced process  
  - all available in VBFNLO (apart from QCD-induced $W^+W^-$)  
  - partially available in Powheg-Box  
  - possible to generate in MG5_aMC@NLO or Sherpa  

NLO EW corrections only known for $W^+W^+$  
(only preliminary for WZ)  
Full NLO computation only known for $W^+W^+$
NLO corrections

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

$\mathcal{O}(\alpha^7)$ $\mathcal{O}(\alpha^6)$ $\mathcal{O}(\alpha_s\alpha^5)$ $\mathcal{O}(\alpha_s^2\alpha^4)$

EW QCD EW QCD EW QCD

NLO contributions at $\mathcal{O}(\alpha^7)$, $\mathcal{O}(\alpha_s\alpha^6)$, $\mathcal{O}(\alpha_s^2\alpha^5)$, and $\mathcal{O}(\alpha_s^3\alpha^4)$

→ Order $\mathcal{O}(\alpha_s\alpha^6)$ and $\mathcal{O}(\alpha_s^2\alpha^5)$: QCD and EW corrections mix

→ At NLO: meaningless distinction between EW signal and QCD background

→ Combined measurement

Common feature to all VBS signatures
NLO corrections - $W^+W^+$

Calculation of both NLO QCD and EW corrections to

$$pp \rightarrow \mu^+\nu_\mu e^+\nu_ejj$$

→ **NLO fiducial cross sections:** (normalised to $\sigma_{LO}$)

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

[Biedermann, Denner, MP; 1708.00268]

→ Large EW corrections at $O(\alpha^7)$
→ Negative corrections at $O(\alpha_s\alpha^6)$
→ Photon PDF contribution at NLO (not included in NLO definitions):

$+1.50\%$ with LUXqed [Manohar et al.; 1607.04266]
NLO corrections - $W^+W^+ /$ Separated contributions

[\text{Biedermann, Denner, MP; 1708.00268}]

→ Clear hierarchy of LO contributions

→ Different behaviour of the NLO corrections (normalised to the full LO)
NLO corrections - $W^+W^+$ / Combined predictions

Large negative corrections for the full process
Corrections dominated by EW correction to EW process
Bands do not overlap

[Biedermann, Denner, MP; 1708.00268]
Cross section:

<table>
<thead>
<tr>
<th>Order</th>
<th>Cross Section [fb]</th>
<th>Corrections [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO $O(\alpha^6)$</td>
<td>0.2362</td>
<td></td>
</tr>
<tr>
<td>NLO EW $O(\alpha^7)$</td>
<td>0.1899</td>
<td>−19.6%</td>
</tr>
</tbody>
</table>

[Denner, Dittmaier, Maierhöfer, MP, Schwan] Preliminary

Differential distribution:

[Denner, Dittmaier, Maierhöfer, MP, Schwan] Preliminary

Also large corrections!
NLO EW corrections to VBS

- Electroweak corrections:
  - Leading behaviour: Sudakov logarithms, \( \log^2 \left( \frac{Q^2}{M_W^2} \right) \)
  - Usually in the tail of the distributions (suppressed)
  - Usually small for total cross section
  - Usually smaller than the QCD corrections

- Large corrections not due to VBS cuts

- Using leading logarithm approximation [Denner, Pozzorini; hep-ph/0010201]
  for \( W^+W^+ \rightarrow W^+W^+ \) (or \( WZ \rightarrow WZ \))
  - Good approximation of the full calculation
  - Large corrections explained by the scale of the scattering process and the quantum numbers of the particles involved

Large NLO EW corrections:
Intrinsic feature of VBS at the LHC
Common feature of all VBS signatures

- EW corrections $\mathcal{O}(\alpha^7)$ large with respect to LO $\mathcal{O}(\alpha^6)$
  $\rightarrow$ Intrinsic feature of VBS at the LHC
- Correction of $\mathcal{O}(\alpha_s \alpha^6)$ are expected to be of comparable size
- Small but not negligible photon contribution
- The size of $\mathcal{O}(\alpha_s^3 \alpha^4)$ depends strongly on the size of the QCD-induced process at LO
VBS approximation

→ **VBS approximation:**

Neglecting $s$-channel contributions and $t/u$ interferences

Implemented in POWHEG and VBFNLO (possibly including $s$-channel)

![Diagram of VBS process]

Source: Giovanni Pelliccioli

Common feature of all VBS signatures

→ **Extension to NLO**

Implemented in POWHEG and VBFNLO (possibly including $s$-channel)

→ **Comparison against full computations at NLO**

has never been performed before [Ballestrero, MP et al.; 1803.07943]
Quality of the VBS approximation (LO)

For low $m_{jj}$ and low $\Delta y_{jj}$, significant $s$-channel contributions

$\rightarrow$ tri-boson contributions with resonant $W$-boson

Good approximation in fiducial region for $W^+W^+$

$\rightarrow$ confirmed for $W^\pm Z$

[Bräuer, MP et al.; 1803.07977] (LH proceedings)
Quality of the VBS approximation (NLO)

- The approximations are in general worse at NLO
- Importance of s-channel at NLO
  → Less suppressed at NLO due to extra jet in the real
- Approximation can fail by up to 20% even in fiducial region
  → OK now for current experimental precision ...
  ... but might be important in the future
Quality of the VBS approximation (NLO)

[Ballestrero, MP et al.; 1803.07943] 

→ Differences lie outside the band
Beyond fixed order (1)

Reasonable agreement at both LO (left) and NLO (right) for observables defined at LO

→ **NB:** input parameters (masses, widths, PDF, scales) all set to common values

[Ballestrero, MP et al.; 1803.07943]
Very large differences for observables related to the third jet (only defined at NLO)

Different treatment of recoil in PYTHIA

Also observed by CMS in VBF-Z production [CMS; 1712.09814]

Also observed for WZ at LO [Bräuer, MP et al.; 1803.07977] (LH proceedings)
Summary

Presentation mainly based on $W^\pm W^\pm$ (with some $WZ$)

- Full NLO corrections [Biedermann, Denner, MP; 1708.00268]
- NLO EW corrections to VBS [Biedermann, Denner, MP; 1611.02951]
- Comparison of theoretical predictions [Ballestrero, MP et al.; 1803.07943]

Common features of all VBS signatures

→ What was not covered:

- Study of gauge-boson polarisation see e.g. [Ballestrero et al.; 1710.09339]
  Effort in in VBSCan network
  Workshop in Paris (10-12 October)
  https://indico.cern.ch/event/744263/

- EFT for VBS see e.g. [Anders et al.; 1801.04203], [Kalinowski et al.; 1802.02366]
  Effort in in VBSCan network