The Effective-Vector-Boson Approximation at the LHC

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Higgs Couplings
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Content

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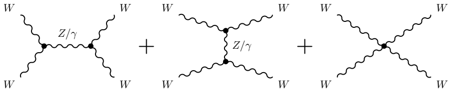
Longitudinal W-Boson Scattering

The gauge-bosons $W^{\pm}$ and Z obtain their mass and longitudinal polarisation state through EWSB.



$$\mathcal{A}(W_L W_L \to W_L W_L) \propto -s - t$$

$\rightarrow$ unitarity is violated!

Mechanism of EWSB must restore unitarity and regulate $\sigma(W_L W_L \to W_L W_L)$:

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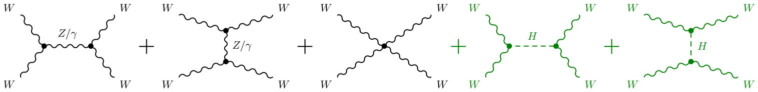

$$\mathcal{A}(W_L W_L \to W_L W_L) \propto -s - t + \frac{s^2}{s - M_H^2} + \frac{t^2}{t - M_H^2}$$

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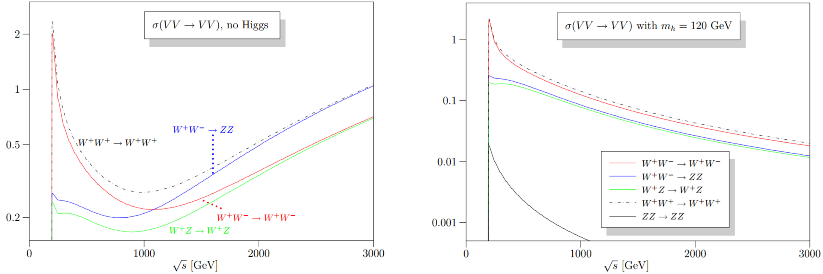
Mechanism of EWSB must restore unitarity and regulate $\sigma(W_L W_L \to W_L W_L)$:

$\rightarrow$ a light SM Higgs exactly cancels terms leading in energy

Unitarity Violation

If any or all couplings are slightly modified the cancellation fails and unitarity is violated.

Alboteanu, Kilian, Reuter '08 [arXiv:0806.4145]



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$\longrightarrow$ Any deviations from the SM represent signals of new physics.

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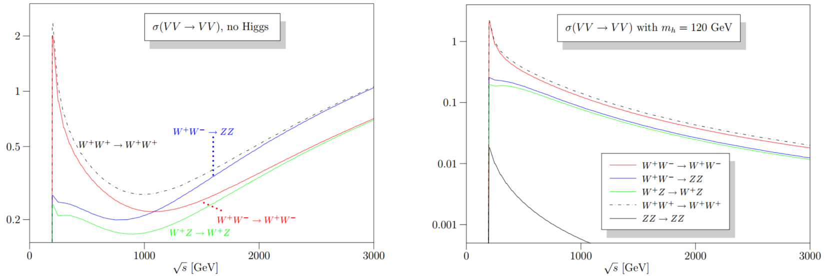

In order to restore unitarity new interactions or particles need to be introduced.

$\rightarrow$ Any deviations from the SM represent signals of new physics.

$\rightarrow$ VBS is a key tool in probing the machanism of EWSB.

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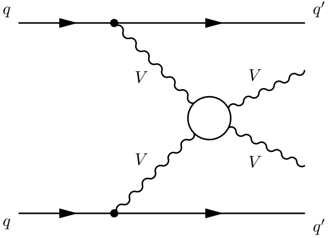
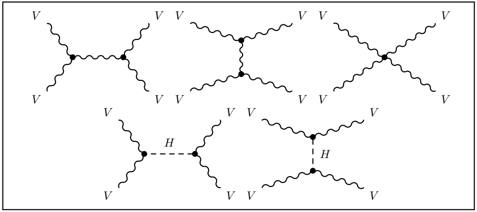
VBS at Hadron Colliders

VBS is only a non-gauge-invariant subprocess in the production of $VVjj$ final states.





$\rightarrow$ There are two main types of production modes at LO:

- EW $VVjj$ production: $\mathcal{O}(\alpha^6)$
- QCD $VVjj$ production: $\mathcal{O}(\alpha^4\alpha_s^2)$

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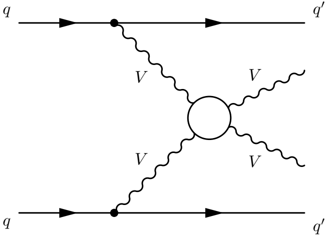

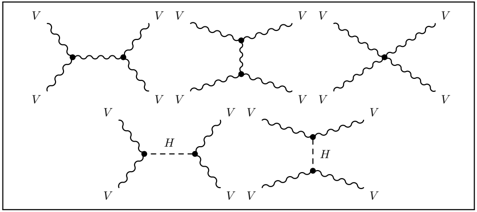

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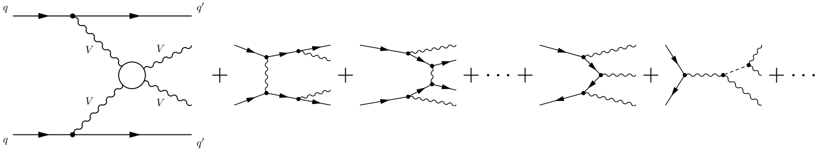
- EW $VVjj$ production: $\mathcal{O}(\alpha^6)$
- QCD $VVjj$ production: $\mathcal{O}(\alpha^4 \alpha_s^2)$
- and interferences: $\mathcal{O}(\alpha^5 \alpha_s)$ (colour and kinematically suppressed)
  $\rightarrow$ interference of both modes is negligible

Production Modes

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

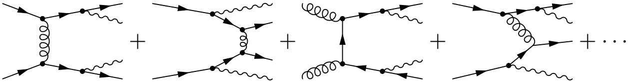
VBS diagrams

non-VBS EW diagrams



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

gauge-invariantly separable: can be suppressed by cuts



Same-Sign VBS

Vest, Anger '15

final state	VV-channel	σ^{EW} [fb]	σ^{QCD} [fb]	$\sigma^{\text{EW}}/\sigma^{\text{QCD}}$
$l^\pm l^\pm \nu\nu' jj$	$W^\pm W^\pm$	19.5	18.8	$\sim 1:1$
$l^+ l^- \nu\nu' jj$	$W^\mp W^\pm, ZZ$	93.7	3192	$\sim 1:35$
$l^+ l^- l'^\pm \nu' jj$	$W^\pm Z$	30.2	687	$\sim 1:20$
$l^+ l^- l'^+ l'^- jj$	ZZ	1.5	106	$\sim 1:70$

most promising $VVjj$ channel in terms of VBS:

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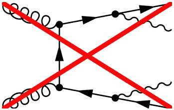

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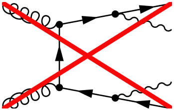

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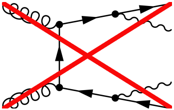

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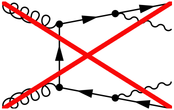

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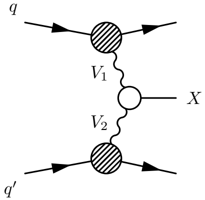
However, VBS diagrams cannot gauge-invariantly separated from non-VBS EW diagrams!

$\rightarrow$ Are there kinematic regions in which the genuine VBS process is dominant?

Content

The Effective-Vector-Boson Approximation

In the EVBA the W-Boson is treated as constituent of the quark and assumed to be on-shell. Driven by logarithmic enhancements $\log^2(M_V^2/s)$ originating from collinear vector-boson emission off the quarks, in analogy to the Weizsäcker-Williams approximation of QED[1].



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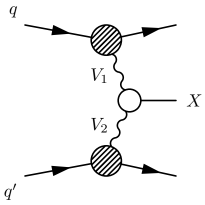

Factorization into probability densities $P_{V_1|q}(z_1)$ and $P_{V_2|q'}(z_2)$ and a hard scattering process $\sigma_{V_1 V_2 \to X}(xs)$ at reduced CM energy $\sqrt{xs}$, with $x = z_1 z_2$.

$$\sigma_{qq' \to X}(s) = \sum_{V_1, V_2} \int_{x_{\text{min}}}^{1} \mathrm{d}x \int_{z_{\text{min}}}^{1} \frac{\mathrm{d}z_1}{z_1} P_{V_1|q}(z_1) P_{V_2|q'}(x/z_1)\, \sigma_{V_1 V_2 \to X}(xs)$$

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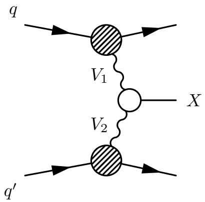

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However, naive convolution of single-vector-boson probabilities is not adequate to describe the two-vector-boson process sufficiently [2].

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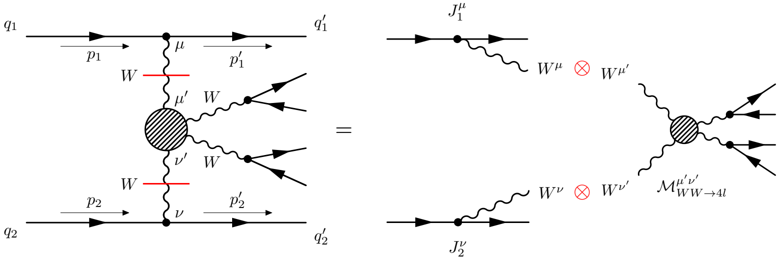
Factorisation of the Amplitude



The full amplitude reads

$$\mathcal{M}_{qq} = \sum_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} \frac{(-1)^{\lambda_1+\lambda_2}}{K_1 K_2 K_3 K_4} \mathcal{M}^{\text{prod}}_{\lambda_1} \mathcal{M}^{\text{prod}}_{\lambda_2} \times \mathcal{M}^{\text{VBS}}_{\lambda_1\lambda_2\lambda_3\lambda_4} \times \mathcal{M}^{\text{decay}}_{\lambda_3} \mathcal{M}^{\text{decay}}_{\lambda_4},$$

where we have introduced the abbreviations

$$\mathrm{i}\mathcal{M}^{\text{prod}}_{\lambda_i} = J_i^\mu \varepsilon^*_{\lambda_i,\mu}, \qquad K_i = k_i^2 - M_{\text{W}}^2, \qquad i = 1,2,$$

$$\mathrm{i}\mathcal{M}^{\text{decay}}_{\lambda_f} = J_f^\mu \varepsilon_{\lambda_f,\mu}, \qquad K_f = k_f^2 - M_{\text{W}}^2 + \mathrm{i}M_{\text{W}}\Gamma_{\text{W}}, \qquad f = 3,4.$$

On-Shell Projection

In order to guarantee gauge invariance of the amplitude we need to consider on-shell W-boson scattering.

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Where the on-shell momenta are defined as follows

$$\text{VBS}: \quad \tilde{k}^{\mu}_{12} = \frac{\sqrt{\tilde{s}}}{2}(1,0,0,\pm\beta), \qquad \tilde{k}^{\mu}_{3/4} = \frac{\sqrt{\tilde{s}}}{2}(1,\pm\beta\sin\tilde{\theta},0,\pm\beta\cos\tilde{\theta}),$$

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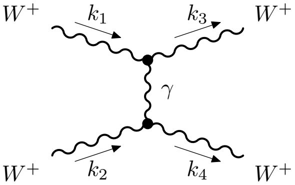
Why do we keep t and u fixed? $\rightarrow$ Appearance of a photon pole!

The Photon Pole



$$\widetilde{\mathcal{M}}^{\gamma,t} \propto \frac{1}{\tilde{t}} \qquad \tilde{t} = -\frac{\tilde{s}\beta^2}{2}(1-\cos\theta) \xrightarrow{\theta\to 0} 0,$$

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Physically a consequence of the of the infinite range of the Coulomb potential. Appears also in Møller-, Bhabha-, and in Rutherford scattering.

$\rightarrow$ either cut on scattering angle θ or fix invariants t and u in the on-shell projection.

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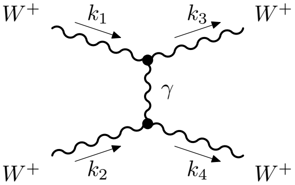

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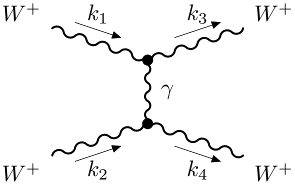

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Note: Photon pole lies outside the physical phase space of the full $2 \rightarrow 6$ process!

Numerical Results - Phase Space Cuts

We first use standard VBS cuts[3]:

- Jet recombination:

$$D = 0.7, \qquad k_\mathrm{T} \text{ algorithm.}$$

- Cuts on jets:

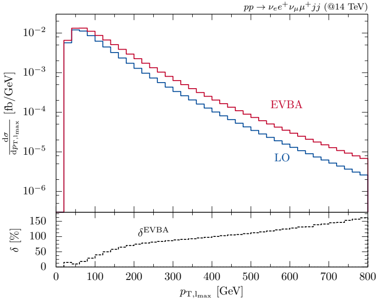
$$\begin{aligned} p_{\mathrm{T,j}} &> 20\,\text{GeV}, & |y_\mathrm{j}| &< 4.5, \\ M_\mathrm{jj} &> 600\,\text{GeV}, & y_{\mathrm{j}_1} \times y_{\mathrm{j}_2} &< 0, \\ \Delta y_\mathrm{jj} &> 4. \end{aligned}$$

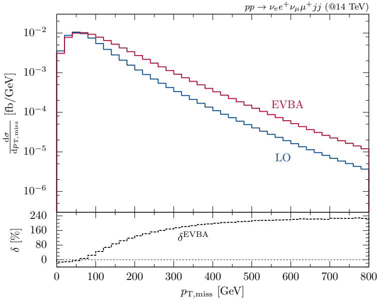
- Cuts on leptons:

$$\begin{aligned} p_{\mathrm{T,l}} &> 20\,\text{GeV}, & |y_\mathrm{l}| &< 2.5, \\ \Delta R_\mathrm{jl} &> 0.4, & y_{\mathrm{j}_\mathrm{min}} < y_\mathrm{l} &< y_{\mathrm{j}_\mathrm{max}}, \\ \Delta R_\mathrm{ll} &> 0.1. \end{aligned}$$

[3] Denner, Hosekova, Kallweit '12 [arXiv:1209.2389]

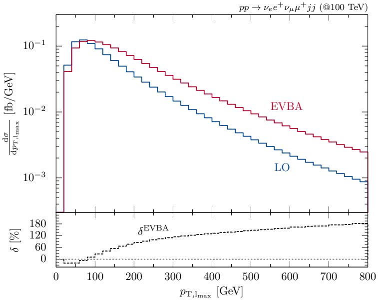
Numerical Results - EVBA I

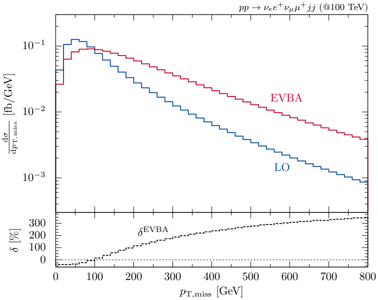




$\sqrt{s}$ [TeV]	σ_{LO} [fb]	σ_{EVBA} [fb]	δ^{EVBA}
14	1.2240(2)	1.6396(2)	34.0 %
100	19.289(3)	27.689(5)	43.6 %

Numerical Results - EVBA I





$\sqrt{s}$ [TeV]	σ_{LO} [fb]	σ_{EVBA} [fb]	δ^{EVBA}
14	1.2240(2)	1.6396(2)	34.0 %
100	19.289(3)	27.689(5)	43.6 %

Phase Space Cuts - Reloaded

We first use standard VBS cuts:

- Jet recombination:

$$D = 0.7, \qquad k_\mathrm{T} \text{ algorithm.}$$

- Cuts on jets:

$$p_{\mathrm{T,j}} > 20 \text{ GeV}, \qquad |y_\mathrm{j}| < 4.5,$$
$$M_\mathrm{jj} > 600 \text{ GeV}, \qquad y_{\mathrm{j}_1} \times y_{\mathrm{j}_2} < 0,$$
$$\Delta y_\mathrm{jj} > 4.$$

- Cuts on leptons:

$$p_{\mathrm{T,l}} > 20 \text{ GeV}, \qquad |y_\mathrm{l}| < 2.5,$$
$$\Delta R_\mathrm{jl} > 0.4, \qquad y_{\mathrm{j}_\mathrm{min}} < y_\mathrm{l} < y_{\mathrm{j}_\mathrm{max}},$$
$$\Delta R_\mathrm{ll} > 0.1.$$

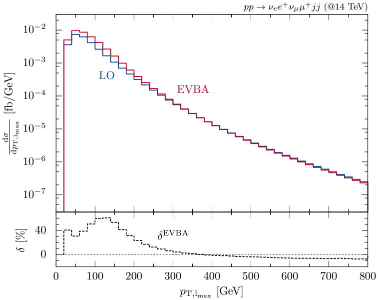
Numerical Results - Upper $p_{\mathrm{T,j}}$ Cut

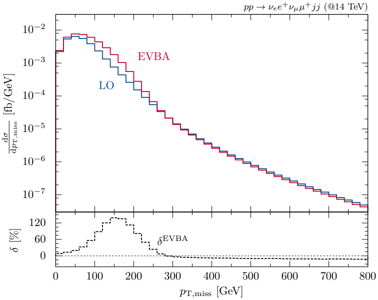
We now require $p_{\mathrm{T,j}} < 150\,\mathrm{GeV}$.

$\sqrt{s}$ [TeV]	σ_{LO} [fb]	σ_{EVBA} [fb]	δ^{EVBA}
14	$0.579(1)$	$0.817(2)$	41.1 %
100	$4.81(2)$	$6.38(3)$	32.6 %

Numerical Results - Upper $p_{T,j}$ Cut

We now require $p_{T,j} < 150\,\text{GeV}$.

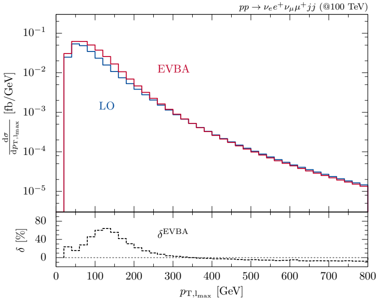


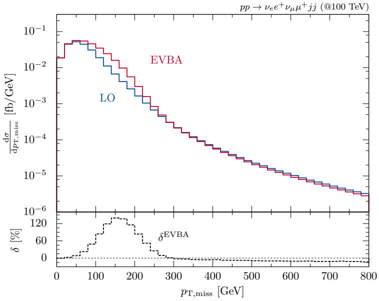


$\sqrt{s}$ [TeV]	σ_{LO} [fb]	σ_{EVBA} [fb]	δ^{EVBA}
14	$0.579(1)$	$0.817(2)$	41.1 %
100	$4.81(2)$	$6.38(3)$	32.6 %

Numerical Results - Upper $p_{\mathrm{T,j}}$ Cut

We now require $p_{\mathrm{T,j}} < 150\,\mathrm{GeV}$.

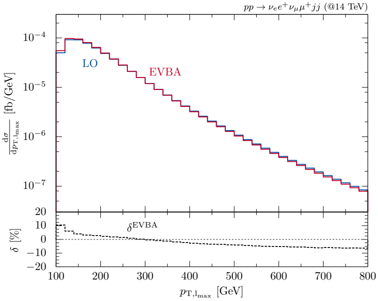


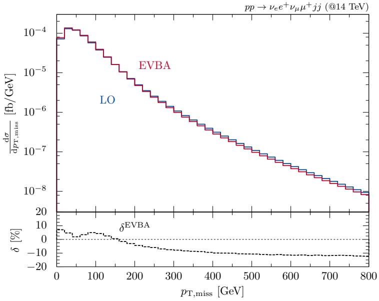


$\sqrt{s}$ [TeV]	σ_{LO} [fb]	σ_{EVBA} [fb]	δ^{EVBA}
14	$0.579(1)$	$0.817(2)$	41.1 %
100	$4.81(2)$	$6.38(3)$	32.6 %

Numerical Results - Upper $p_{T,j}$ Cut

We now require $p_{T,j} < 100\,\mathrm{GeV}$ and $p_{T,l} > 100\,\mathrm{GeV}$.

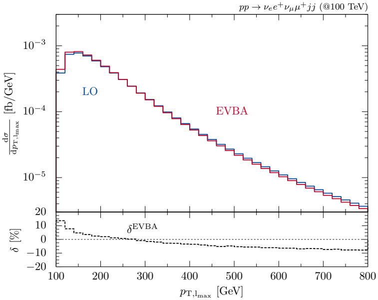


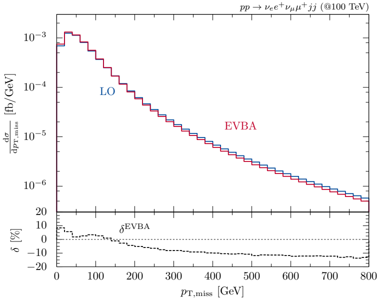


$\sqrt{s}$ [TeV]	σ_{LO} [fb]	σ_{EVBA} [fb]	δ^{EVBA}
14	0.011584(4)	0.011985(3)	3.5 %
100	0.11433(6)	0.11772(5)	3.0 %

Numerical Results - Upper $p_{\mathrm{T,j}}$ Cut

We now require $p_{\mathrm{T,j}} < 100\,\mathrm{GeV}$ and $p_{\mathrm{T,l}} > 100\,\mathrm{GeV}$.





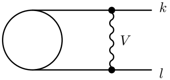
$\sqrt{s}$ [TeV]	σ_{LO} [fb]	σ_{EVBA} [fb]	δ^{EVBA}
14	0.011584(4)	0.011985(3)	3.5 %
100	0.11433(6)	0.11772(5)	3.0 %

Content

Logarithmic Electroweak Corrections

Typical one-loop Feynman diagrams that lead to Sudakov logarithms:

$$\sum_{k=1}^{n} \sum_{l<k} \sum_{V_a=A,Z,W^\pm}$$



For high energies, i.e. $s \gg M_{\mathrm{W}}^2$, logarithms become dominant and are of significant size

$$\frac{\alpha}{4\pi s_{\mathrm{w}}^2} \log^2 \frac{s}{M_{\mathrm{W}}^2} \simeq 6.6\%, \qquad \frac{\alpha}{4\pi s_{\mathrm{w}}^2} \log \frac{s}{M_{\mathrm{W}}^2} \simeq 1.3\%,$$

at $\sqrt{s} = 1$ TeV. $\rightarrow$ for VBS at the LHC we can approximate the EW corrections by considering only these logarithms!

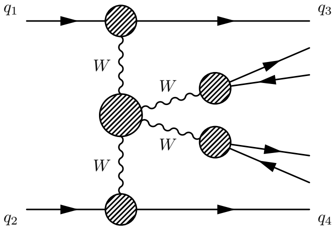
In LA the correction factorizes

$$\delta \mathcal{M}^{i_1 \ldots i_n} = \mathcal{M}_0^{i'_1 \ldots i'_n} \, \delta_{i'_1 i_1 \ldots i'_n i_n},$$

and the correction factor can be decomposed

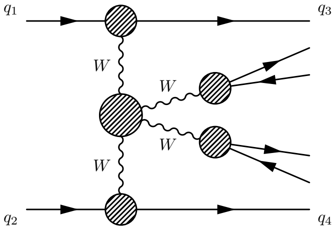
$$\delta = \underbrace{\delta^{\mathrm{LSC}} + \delta^{\mathrm{C}} + \delta^{\mathrm{PR}}}_{=\delta^{\mathrm{LL}}} + \underbrace{\delta^{\mathrm{SSC}}}_{=\delta^{\mathrm{NLL}}},$$

Radiative Corrections to VBS



- We neglect non-factorizable corrections.
- We neglect corrections to the emission and decay process.

Radiative Corrections to VBS



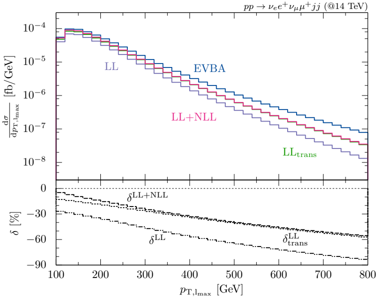
- We neglect non-factorizable corrections.
- We neglect corrections to the emission and decay process.

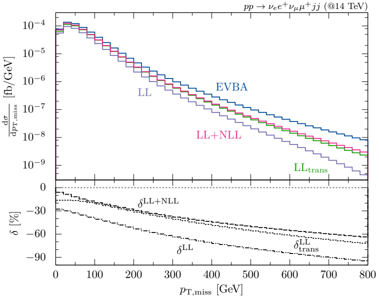
$\rightarrow$ We consider only corrections to the $W^+W^+ \rightarrow W^+W^+$ subprocess.

Hence, using the EVBA the correction can be written as

$$\delta\mathcal{M}_{qq}^{\text{EVBA}} = \sum_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} \frac{(-1)^{\lambda_1+\lambda_2}}{K_1K_2K_3K_4} \mathcal{M}_{\lambda_1}^{\text{prod}} \mathcal{M}_{\lambda_2}^{\text{prod}} \times \delta\widetilde{\mathcal{M}}_{\lambda_1\lambda_2\lambda_3\lambda_4}^{\text{VBS}} \times \widetilde{\mathcal{M}}_{\lambda_3}^{\text{decay}} \widetilde{\mathcal{M}}_{\lambda_4}^{\text{decay}}.$$

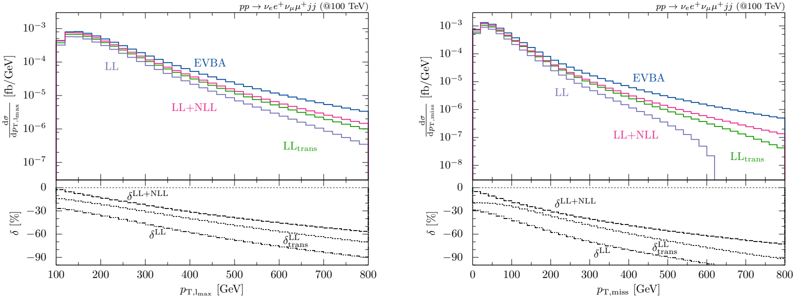
Numerical Results - EW Logarithms





$\sqrt{s}$ [TeV]	δ^{LL}_{trans}	δ^{LL}	δ^{LL+NLL}
14	-18.9 %	-35.1 %	-13.6 %
100	-23.8 %	-37.5 %	-13.8 %

Numerical Results - EW Logarithms



$\sqrt{s}$ [TeV]	$\delta^{\mathrm{LL}}_{\mathrm{trans}}$	δ^{LL}	$\delta^{\mathrm{LL+NLL}}$
14	-18.9 %	-35.1 %	-13.6 %
100	-23.8 %	-37.5 %	-13.8 %

Content

Conclusion

VBS in general

- Vector Boson Scattering is a key tool in probing the mechanism of EWSB.
- At the LHC all contributing processes need to be fully understood
  $\rightarrow$ kinematical cuts are required to suppress background contributions
- The EVBA may quantify the dominant region of VBS

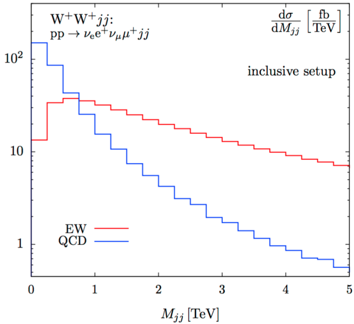
EVBA

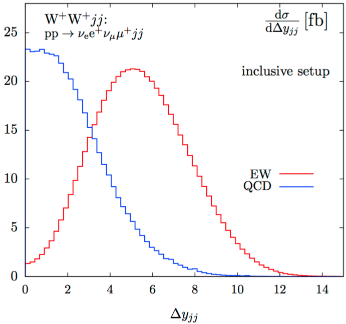
- The photon pole only appears as an artefact in a bad on-shell projection.
- For standard VBS cuts the approximation is not applicable as the collinearity of the W bosons is not ensured.
- If the collinearity is ensured the relative difference only amounts to $\sim 3.5\,\%$.
  $\rightarrow$ the EVBA yields an appropriate approximation in certain kinematic regions!

Logarithmic EW Corrections

- Both LL and NLL need to be taken into account.
- The NLO EW correction amounts to -13.6%, which is compatible with the literature.
  Biedermann, Denner, Pellen 2017 [arXiv:1708.00268]

QCD Background Suppression Cuts





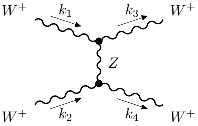
The SU(2) model

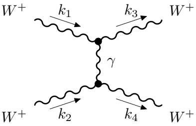
We consider a non-Abelian $SU(2)$ model in which no photon field appears.

$$SU(2)_{\mathsf{W}} \times U(1)_{\mathsf{Y}}: \quad D_\mu = \partial_\mu - \mathrm{i} g I^i_{\mathsf{W}} W^i_\mu + \mathrm{i} g' \frac{Y}{2} B_\mu,$$

$$\downarrow \qquad g' \to 0 \qquad (g = g_{\mathsf{SM}} = g_{SU(2)} = e/s_{\mathsf{w}})$$

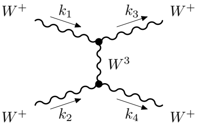
$$SU(2)_{\mathsf{W}}: \quad D_\mu = \partial_\mu - \mathrm{i} g I^i_{\mathsf{W}} W^i_\mu .$$





$$\mathcal{M}^{Z,t} \propto \frac{c^2_{\mathsf{w}}}{s^2_{\mathsf{w}}} \frac{1}{t - M^2_{\mathsf{Z}}} \qquad \mathcal{M}^{\gamma,t} \propto \frac{1}{t}$$

$\downarrow$

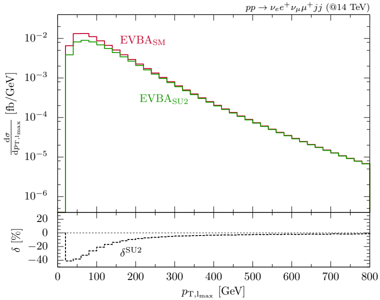


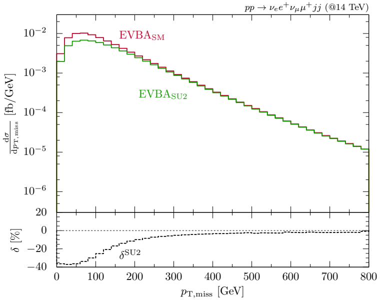
$$\downarrow$$

$$\mathcal{M}^{W^3,t} \propto \frac{1}{s^2_{\mathsf{w}}} \frac{1}{t - M^2_{\mathsf{W}}}$$

$\rightarrow$ no photon diagrams $\rightarrow$ no photon pole!

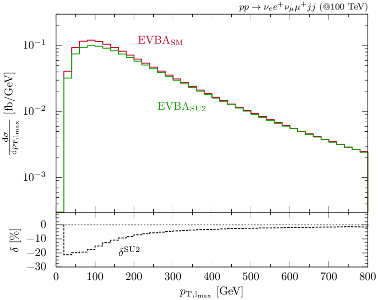
Numerical Results - $SU(2)$ model

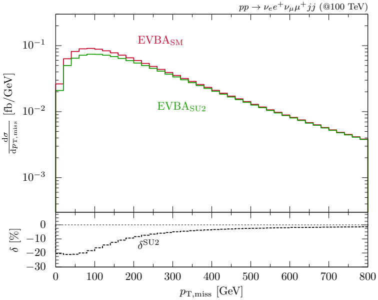




$\sqrt{s}$ [TeV]	$\sigma_{\rm EVBA}$ [fb]	$\sigma^{\rm SU2}_{\rm EVBA}$ [fb]	$\delta^{\rm SU2}$
14	1.6396(2)	1.2389(2)	-24.4 %
100	27.689(5)	24.713(5)	-10.7 %

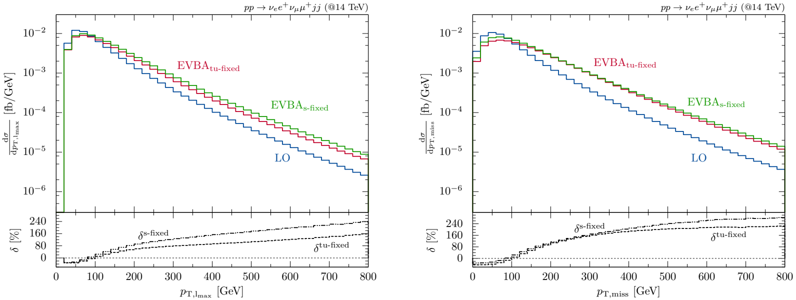
Numerical Results - $SU(2)$ model





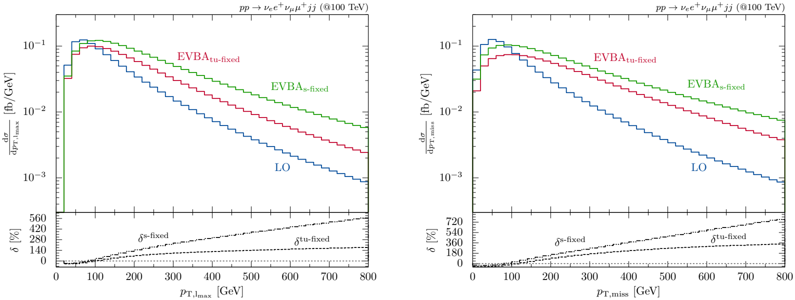
$\sqrt{s}$ [TeV]	σ_{EVBA} [fb]	$\sigma^{\text{SU2}}_{\text{EVBA}}$ [fb]	δ^{SU2}
14	1.6396(2)	1.2389(2)	-24.4 %
100	27.689(5)	24.713(5)	-10.7 %

Numerical Results - s fixed



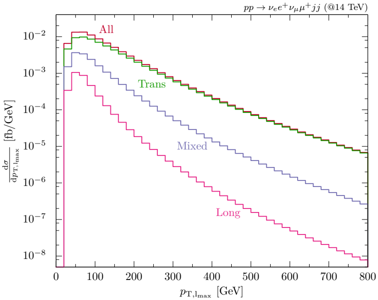
$\sqrt{s}$ [TeV]	σ_{LO} [fb]	$\sigma^{\text{s-fixed}}_{\text{EVBA}}$ [fb]	$\sigma^{\text{tu-fixed}}_{\text{EVBA}}$ [fb]	$\delta^{\text{s-fixed}}$	$\delta^{\text{tu-fixed}}$
14	1.2240(2)	1.4042(2)	1.2389(2)	14.7 %	1.2 %
100	19.289(3)	36.247(5)	24.713(5)	87.9 %	28.2 %

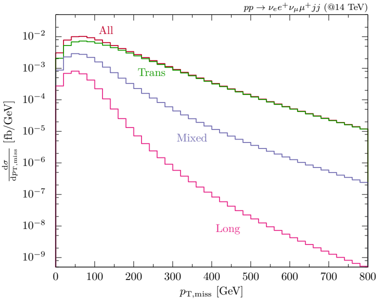
Numerical Results - s fixed



$\sqrt{s}$ [TeV]	σ_{LO} [fb]	$\sigma_{\text{EVBA}}^{\text{s-fixed}}$ [fb]	$\sigma_{\text{EVBA}}^{\text{tu-fixed}}$ [fb]	$\delta^{\text{s-fixed}}$	$\delta^{\text{tu-fixed}}$
14	1.2240(2)	1.4042(2)	1.2389(2)	14.7 %	1.2 %
100	19.289(3)	36.247(5)	24.713(5)	87.9 %	28.2 %

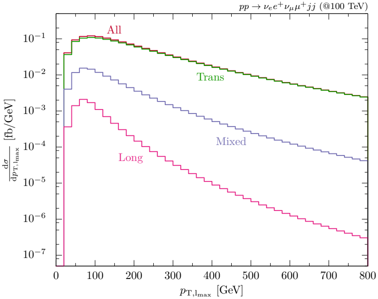
Numerical Results - Helicity Configurations

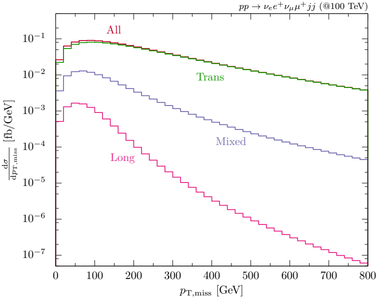




$\sqrt{s}$ [TeV]	σ_{EVBA} [fb]	$\sigma_{\text{EVBA}}^{\text{trans}}$ [fb]	$\sigma_{\text{EVBA}}^{\text{mixed}}$ [fb]	$\sigma_{\text{EVBA}}^{\text{long}}$ [fb]
14	1.6396(2)	1.2932(2)	0.32179(8)	0.06605(3)
100	27.689(5)	25.858(5)	2.0833(9)	0.1779(2)

Numerical Results - Helicity Configurations





$\sqrt{s}$ [TeV]	σ_{EVBA} [fb]	$\sigma^{\text{trans}}_{\text{EVBA}}$ [fb]	$\sigma^{\text{mixed}}_{\text{EVBA}}$ [fb]	$\sigma^{\text{long}}_{\text{EVBA}}$ [fb]
14	1.6396(2)	1.2932(2)	0.32179(8)	0.06605(3)
100	27.689(5)	25.858(5)	2.0833(9)	0.1779(2)

Complex-Shift Procedure

We set the W bosons on-shell by consistently shifting external momenta into the complex plane.

$$\tilde{p}_i^{\dot{A}B} = p_i^{\dot{A}}\,\tilde{p}_i^B\,, \qquad \tilde{p}_i^B = p_i^B + \sum_{f=3}^{4} z_{if}\,p_f^B\,, \qquad i = 1,2,$$

$$\tilde{p}_f^{\dot{A}B} = \tilde{p}_f^{\dot{A}}\,p_f^B\,, \qquad \tilde{p}_f^{\dot{A}} = p_f^{\dot{A}} + \sum_{i=1}^{2} z_{if}\,p_i^{\dot{A}}\,, \qquad f = 3,4,$$

Which is fixed by 4 on-shell conditions

$$\begin{aligned} M_{\mathsf{W}}^2 &= \tilde{k}_i^2 = (\tilde{p}_i - p_i')^2 = -2\tilde{p}_i \cdot p_i' \\ &= -2p_i \cdot p_i' - \sum_{f=3}^{4} z_{if}\,\langle p_i p_i' \rangle^* \langle p_f p_i' \rangle, \qquad i = 1,2, \\ M_{\mathsf{W}}^2 &= \tilde{k}_f^2 = (\tilde{p}_f + p_f')^2 = 2\tilde{p}_f \cdot p_f' \\ &= 2p_f \cdot p_f' + \sum_{i=1}^{2} z_{if}\,\langle p_i p_f' \rangle^* \langle p_f p_f' \rangle, \qquad f = 3,4. \end{aligned}$$

$\Rightarrow$ leads to inconsistent results which are off by several magnitudes or do not even converge.