Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

UNIVERSITÀ
DEGLI STUDI
DI TORINO

Topics in the Standard Model of Fundamental Interactions

Second Year Seminar

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Curriculum: Theoretical Physics
PhD cycle: XXXII

Outline

Part 1 Vector bosons polarizations in VBS at the LHC

Part 2 Precise predictions for W^+W^+ scattering at the LHC

Part 3 Subtraction of infrared singularities at NNLO QCD

Part 1

Vector bosons polarizations in VBS at the LHC

based on [Ballestrero, Maina, GP, 1710.09339]

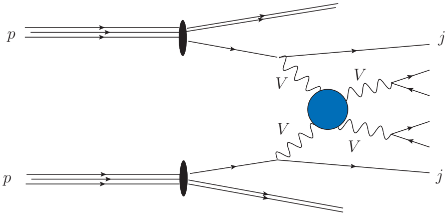
Vector bosons polarizations in VBS at the LHC

Introduction

In the Standard Model (SM) of elementary particles, the mediators of the electroweak interaction are γ (massless), Z and $W^{\pm}$ (massive) bosons with spin 1.

W, Z have 3 polarization states: longitudinal, left and right.

At the Large Hadron Collider (LHC), one of the most interesting processes for the study of $W^{\pm}, Z$ bosons is Vector Boson Scattering.



The **longitudinal scattering** is sensitive to the mechanism of electroweak spontaneous symmetry breaking: discriminating power between SM and new physics.

→ **importance of theoretical predictions for polarized VBS**
→ prescription for the separation of polarization modes needed

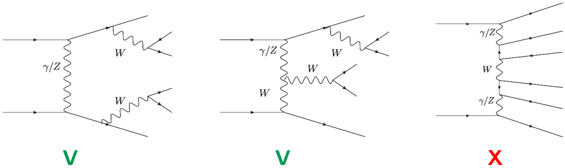
Vector bosons polarizations in VBS at the LHC

Polarized W^+W^- scattering

$pp \to jje^-\mu^+\nu\nu$. (fully leptonic channel).
Leading electroweak order $\mathcal{O}(\alpha^6)$ (LO EW). Signal region: $M_{jj} > 600$ GeV, $|\Delta\eta_{jj}| > 3.6$.

Main issues:

- select doubly resonant diagrams only and employ On-Shell projections (OSP) to make the calculation gauge invariant



- separate polarizations in W^- propagator (W^+ unpolarized, for simplicity)

$$|\mathcal{A}_{unpol}|^2 = \sum_{\lambda\lambda'} \mathcal{A}^*{}_{\lambda}\mathcal{A}_{\lambda'} = \underbrace{\sum_{\lambda} |\mathcal{A}_{\lambda}|^2}_{\text{incoherent sum}} + \underbrace{\sum_{\lambda\neq\lambda'} \mathcal{A}^*{}_{\lambda}\mathcal{A}_{\lambda'}}_{\text{interference}} \tag{1}$$

Polarized cross–section with definite polarization λ is $\propto |\mathcal{A}_{\lambda}|^2$.

Numerical implementation in `PHANTOM`: any VBS process, LO EW.

Vector bosons polarizations in VBS at the LHC

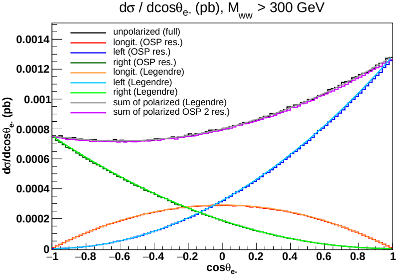
Polarized W^+W^- scattering: $W^+_{\text{unpol}}(\to \mu^+\nu_\mu)W^-_{\text{pol}}(\to e^-\bar{\nu}_e)$

Validation of the numerical predictions with the expected analytic result, without leptonic cuts: Legendre expansion.

Distribution in $\cos\theta^*_e$: $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_e}(W^- \to e^-\bar{\nu}_e) =$

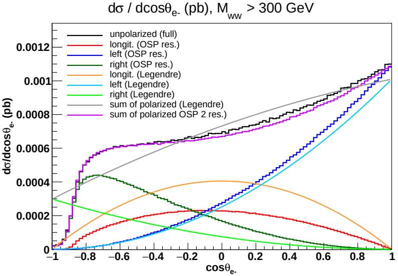
$$= \frac{3}{4}f_0(1-\cos\theta^{*\,2}_e) + \frac{3}{8}f_L(1+\cos\theta^*_e)^2 + \frac{3}{8}f_R(1-\cos\theta^*_e)^2$$

Perfect agreement ($< 1\%$ discrepancy) for shapes and polarization fractions (f_i).



In the presence of lepton cuts ($p_t^\ell > 20$ GeV, $|\eta_\ell| < 2.5$), Legendre analysis fails, no closed analytic form for $d\sigma/d\cos\theta^*_e$.

- **Interference among polarization modes amplitudes is small (% level).**
- **Incoherent sum of 3 polarized distributions approximates fairly well the full (exact) computation.**



Vector bosons polarizations in VBS at the LHC

Conclusions and outlook

We found a good prescription for the separation of polarization modes in VBS: already performed detailed studies for W^+W^- and $W^\pm W^\pm$.

Ongoing work:

(i) polarizations for VBS-ZZ ($pp \to jj\, e^+e^-\mu^+\mu^-$)

(ii) polarizations for VBS-WZ ($pp \to jj\, e^+e^-\mu^+\nu_\mu$), with ν reconstruction: **benchmark for semileptonic**

Organization of *VBS Polarization Workshop* in Paris, 10^{th}-12^{th} Oct. 2018: polarization studies are rapidly evolving and getting more and more interest!

Part 2

Precise predictions for W^+W^+ scattering at the LHC

based on [Ballestrero et al., GP, 1803.07943]

Precise predictions for W^+W^+ scattering at the LHC

Motivations

VBS is a process of great interest for the upcoming LHC runs:

- it is capable of probing both the electroweak sector of the Standard Model
- and hypothetical modifications of it, due to new physics

→ **precise theoretical predictions for W^+W^+ scattering ($pp \to jje^+\nu_e\mu^+\nu_\mu$).**

Goals of the work:

- predictions at LO and NLO QCD: comparison of Monte Carlo generators,
- evaluation of the goodness of commonly employed approximations,
- matching of LO/NLO predictions to Parton Shower (not detailed here).

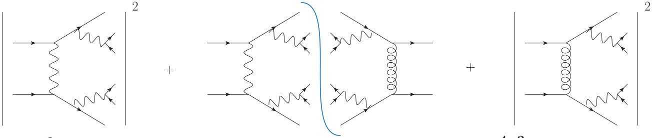
Project of the theory group of the VBSCan Collaboration.

Precise predictions for W^+W^+ scattering at the LHC

Fixed order contributions

Tree-level: $\mathcal{O}(\alpha^6)$ (EW, signal), $\mathcal{O}(\alpha_s^2\alpha^4)$ (QCD, bkg) and $\mathcal{O}(\alpha_s\alpha^5)$ (interf.)

LO



$\boldsymbol{\alpha^6}$: signal

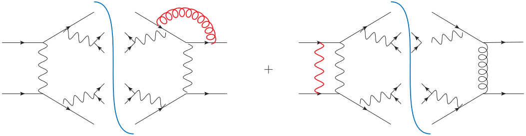
$\alpha^{\mathbf{5}}\alpha_{\mathbf{s}}$: interference

$\alpha^{\mathbf{4}}\alpha_{\mathbf{s}}^{\mathbf{2}}$: QCD background

In the "signal region" ($m_{j_1j_2} > 500$ GeV, $|\Delta\eta_{j_1j_2}| > 2.5$), EW contribution is dominant.

2 contributions at NLO $\mathcal{O}(\alpha_s\alpha^6)$

NLO



$\alpha^{\mathbf{6}}\alpha_{\mathbf{s}}$: QCD correction of the signal α^6
dominant

$\alpha^{\mathbf{6}}\alpha_{\mathbf{s}}$: EW correction of the interference $\alpha^5\alpha_s$
small

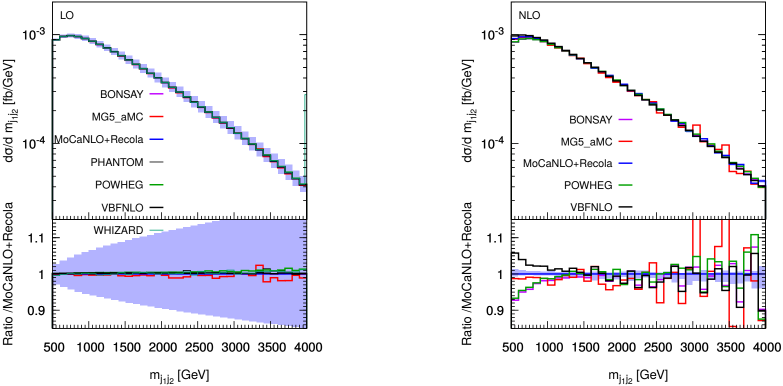
VBS approximations (both at LO and NLO QCD) neglect certain sets of diagrams and interfereces, because of kinematics or color suppression.

Precise predictions for W^+W^+ scattering at the LHC

Results at fixed order

Comparison at LO (α^6) and NLO ($\alpha_s\alpha^6$) in the “signal region”.

Fig.: differential cross-section in the invariant mass of the two leading jets $m_{j_1j_2}$.



Very good agreement at LO ($< 1\%$ accuracy) in almost all phase-space.

Fair agreement but larger discrepancies at NLO (few % accuracy, at most 10%).

Remark: include all contributions when possibile (no approx.), mainly at NLO QCD.

Part 3

Subtraction of infrared singularities at NNLO QCD

based on

- [Magnea, Maina, GP, Signorile-Signorile, Torrielli, Uccirati, 1806.09570]
- [Magnea, Maina, GP, Signorile-Signorile, Torrielli, Uccirati, 1809.05444]

Subtraction of infrared singularities at NNLO QCD

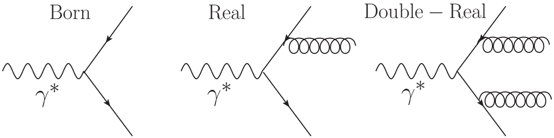
Motivations

- The Standard Model (SM) is not the end of the story: new physics under investigation at the LHC.
- Fundamental issues related to the infrared structure of Quantum Chromo-Dynamics (QCD) are still to be understood.

An answer is **precision physics**: theoretical predictions with the highest possible precision, in order to compare them with experimental data.

Any process at the LHC can be computed at LO and NLO (QCD, EW) with Monte Carlo generators (some of them fully automatic).

The cutting-edge is next-to-next-to-leading order in α_S (NNLO QCD).



Sample diagrams for Born, real and double-real contributions entering the LO, NLO and NNLO calculation for $\gamma^* \to jj$

Subtraction of infrared singularities at NNLO QCD

Anatomy of a NLO calculation (massless, partons in the final state only)

NLO contribution to the differential cross-section in the var. X

$$\frac{d\sigma_{\mathrm{NLO}}}{dX} \quad = \quad \int d\Phi_n \, V \, \delta(X - X_n) + \int d\Phi_{n+1} \, R \, \delta(X - X_{n+1}) \, . \tag{2}$$

where $R = \left| \mathcal{A}_{n+1}^{(0)} \right|^2$, $V = 2 \, \mathbf{Re} \left[\mathcal{A}_n^{(0)*} \, \mathcal{A}_n^{(1)} \right]$ (real and virtual contributions).

In $d = 4 - 2\epsilon$, phase-space integration of R results in explicit infrared (IR) poles in ϵ, which cancel those of V, if X infrared safe, ensuring the cross section is finite (KLN).

Subtraction procedure: avoiding analytic integration of the full R amplitudes by adding and subtracting to Eq. (2) a counterterm

$$\left. \frac{d\sigma_{\mathrm{NLO}}}{dX} \right|_{\mathrm{ct}} = \int d\Phi_{n+1} \, K \; \delta_n(X) \, , \qquad I = \int d\Phi_{\mathrm{rad}} \, K \, , \tag{3}$$

$d\Phi_{n+1} \, K$ has the same singular limits of $d\Phi_{n+1} \, R$ and must be simple to be analytically integrated in d dim.

$$\frac{d\sigma_{\mathrm{NLO}}}{dX} = \int d\Phi_n \left(V + I \right) \delta(X - X_n) \, + \int \left(d\Phi_{n+1} \, R \, \delta(X - X_{n+1}) - d\Phi_{n+1} \, K \, \delta(X - X_n) \right)$$

First and the second terms separately finite in $d = 4$: efficient numerical integration.

Subtraction of infrared singularities at NNLO QCD

A Local Analytic Sector Subtraction scheme

Key idea:

- Step 1 understand existing NLO schemes, their advantages and bottlenecks;
- Step 2 merge them, retaining only advantageous features, to find a simpler scheme;
- Step 3 extend such scheme to NNLO.

The aim is to build a subtraction scheme which is local (locality of IR counterterms), general (for any IR-safe variable), analytic (makes maximal usage of the analytic information) and efficient (numerical implementation).

Driving idea for local subtraction counterterms organization:

- Factorization of QCD virtual amplitudes

Subtraction of infrared singularities at NNLO QCD

A Local Analytic Sector Subtraction scheme (at NLO)

Our proposed scheme (at NLO) aims at being as “minimal” as possible:

- phase-space sector partition, to select the minimal set of IR divergencies in each sector: $\mathcal{W}_{ij}$ sector functions
- counterterms written as sums of terms, each $\propto$ universal IR kernels: soft eikonal $\mathcal{I}_{lm}^{(i)}$ / collinear Altarelli-Parisi $P_{ij}^{\mu\nu}$ × Born matrix-elements

$$\overline{\mathbf{S}}_i \, R \propto \sum_{l,m} \mathcal{I}_{lm}^{(i)} B_{lm} \,, \qquad \overline{\mathbf{C}}_{ij} \, R \propto \frac{P_{ij}^{\mu\nu}}{s_{ij}} B_{\mu\nu} \tag{4}$$

- different phase space remapping in each term → simple analytic integration

$$K = \sum_{i,j\neq i} \left(\overline{\mathbf{S}}_i + \overline{\mathbf{C}}_{ij} - \overline{\mathbf{S}}_i \, \overline{\mathbf{C}}_{ij} \right) R \, \mathcal{W}_{ij} = \sum_i \overline{\mathbf{S}}_i \, R + \sum_{i,\,j>i} \overline{\mathbf{C}}_{ij} \left(1 - \overline{\mathbf{S}}_i - \overline{\mathbf{S}}_j \right) R \,. \tag{5}$$

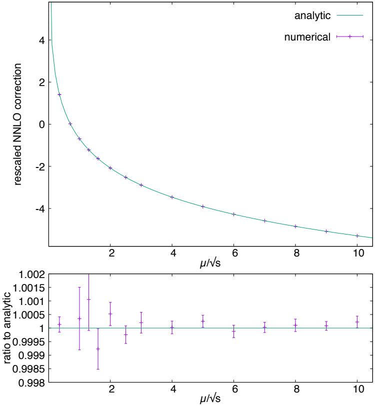
It works pretty well at NLO!

Differential cross-sections for $e^+e^- \to jj$, $h \to gg$ (comparison with `MadGraph`).

Subtraction of infrared singularities at NNLO QCD

A Local Analytic Sector Subtraction scheme: NNLO results

Proof-of-concept: $T_R\, C_F$ contributions to $e^+e^- \to jj$ @ NNLO



Inclusive cross-section (NNLO correction) obtained via numerical implementation of the subtraction scheme, compared with the analytic result,

$$\frac{\sigma_{\rm NNLO}}{\sigma_{\rm LO}\left(\frac{\alpha_S}{2\pi}\right)^2 T_R\, C_F} = \left(-\frac{11}{2} + 4\,\zeta_3 - \log\frac{\mu^2}{s}\right)$$

with the renormalization-scale dependence.

Great agreement ($\lesssim 0.1\%$):
the subtraction scheme works!

Ongoing work:

- full $e^+e^- \to jj$
- going differential: kinematic distributions

List of Publications

Papers:

1. A. Ballestrero, E. Maina and G. Pelliccioli, *W boson polarization in vector boson scattering at the LHC*, JHEP 1803 (2018) 170, arXiv:1710.09339 [hep-ph]
2. A. Ballestrero et al., *Precise predictions for same-sign W-boson scattering at the LHC*, Eur.Phys.J. C78 (2018) no.8, 671, arXiv:1803.07943 [hep-ph]
3. L. Magnea, E. Maina, G. Pelliccioli, C. Signorile-Signorile, P. Torrielli and S. Uccirati, *Local Analytic Sector Subtraction at NNLO*, arXiv:1806.09570 [hep-ph], accepted by JHEP
4. L. Magnea, E. Maina, G. Pelliccioli, C. Signorile-Signorile, P. Torrielli and S. Uccirati, *Factorisation and Subtraction beyond NLO*, arXiv:1809.05444 [hep-ph], submitted to JHEP

Proceedings:

1. E. Maina, A. Ballestrero and G. Pelliccioli, *W boson polarization in vector boson scattering at the LHC*, PoS EPS-HEP2017 (2017) 451
2. C. F. Anders et al., *VBSCan Split 2017 Workshop Summary*, arXiv:1801.04203 [hep-ph]
3. L. Magnea, E. Maina, G. Pelliccioli, C. Signorile-Signorile, P. Torrielli and S. Uccirati, *Analytic tools for IR subtraction beyond NLO*, to appear on PoS LL2018 (2018)
4. VBSCan collaboration, *VBSCan Thessalonoki 2018 Workshop Summary*, in preparation