Vector Boson Scattering at the LHC

Ulrike Schnoor
Michael Kobel, Anja Vest & Philipp Anger

IKTP TU Dresden
Blockkurs Graduiertenkolleg

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1. Vector Boson Scattering
   - Unitarity violation in VBS
   - Case 1: Light Higgs is found at the LHC
   - Case 2: No Higgs / Heavy Higgs
2. Measurement of VBS at ATLAS
   - Contributing Feynman Diagrams
   - Experimental Signature
3. Monte Carlo Predictions
   - Comparison between Whizard and Sherpa
   - Kinematics
4. Outlook

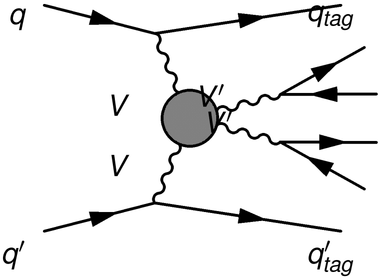
Why study Vector Boson Scattering at the LHC?

- Important channel to study **electroweak symmetry breaking** in case of
  - light (non-SM?) Higgs
  - heavy Higgs
  - other EWSB mechanism

  due to unitarity violation in this channel above $\sqrt{s_{VV}} \sim 1.2$ TeV
- Scattering of weak bosons in SM (including **triple and quartic gauge vertices**) not measured yet

What is Vector Boson Scattering?

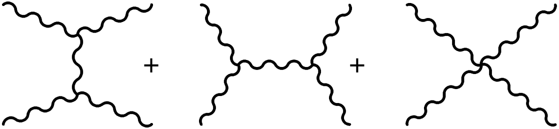
- Signal $qq' \rightarrow q_{tag}q'_{tag}VV$ (V = W or Z)



- "blobb" contains all VV scattering diagrams
- background:
  - irreducible electroweak background due to gauge dependence
  - reducible QCD background with the same final state

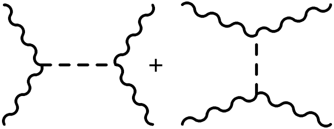
Unitarity violation in the VBS channel

Scattering of longitudinally polarized weak gauge bosons $W_L^+ W_L^-$



$$\mathcal{M}^{gauge} = -\frac{g^2}{4m_W^2} u + \mathcal{O}((E/m_W)^0)$$

Add s- and t-channel Higgs exchange amplitude:

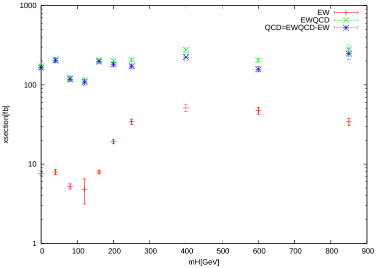


$$\mathcal{M}^{Higgs} = \frac{g^2}{4m_W^2}$$

in the limit
$s >> m_H^2, m_W^2$

$$\Rightarrow \mathcal{M}^{tot} = \mathcal{O}((\frac{E}{m_W})^0)$$

Case 1: Light Higgs is found at the LHC



VBS cross section is Higgs mass dependent
essentially $\sigma(m_{VV} < m_W)$
and $\sigma(m_{VV} > m_W)$

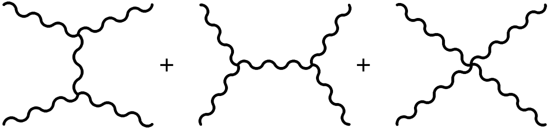
- channel is also sensitive to the **coupling strenghts** of Higgs to vector bosons
- probe SM or non-SM Higgs
- observe or exclude **strong WW scattering**

Case 2: No Higgs/ heavy Higgs

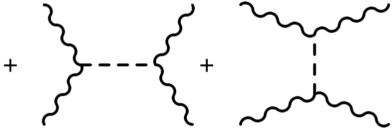
- no Higgs ($m_H \to \infty$) or heavy Higgs ($m_H \gtrsim 870\ GeV$): unitarity violated in VBS above $\sqrt{s_{VV}} \sim 1.2$ TeV $\to$ strong gauge sector
- $\Rightarrow$ **Higgs** or **new physics** will be visible at higher energies in this channel (possibly through VV resonances)
- new physics for EWSB e.g.
  - QCD-like technicolor models with chiral symmetry breaking
  - Higgsless extra-dimension models
  - models with additional vector bosons, etc.
- VBS allows to probe alternative EWSB mechanism
- model-independent approach: **effective Lagrangian with k-matrix unitarization** at higher energies, e.g. electroweak chiral Lagrangian with k-matrix unitarization (WHIZARD)

Contributions to WW+2j Final State: **EW**

SIGNAL: $\mathcal{O}(\alpha_w^4)$ WW, WZ, ZZ scattering graphs:

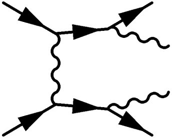


(triple/quartic gauge boson vertices)



(Higgs channels)

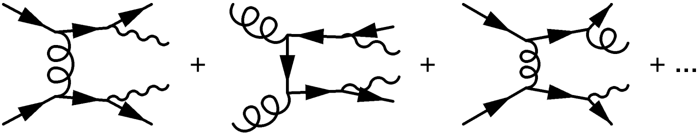
IRREDUCIBLE BACKGROUND: additional diagrams $\mathcal{O}(\alpha_w^4)$



+ ... (other EW processes)

Contributions to WW+2j Final State: **non-EW**

REDUCIBLE BACKGROUND: Diagrams $\mathcal{O}(\alpha_w^n), n \neq 4$

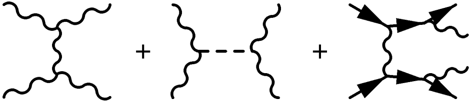


"QCD" + $t\bar{t}$ + W/Z+jets + ...

- Diagrams $\mathcal{O}(\alpha_w^4)$ can be separated gauge invariantly from diagrams with different order of α_w
- Backgrounds $\sim \alpha_w^n, n \neq 4$ to be reduced by kinematical/ topological cuts

Measurement of VV scattering

Compare all VBS contributions to data



$+ \ldots \} \, \mathcal{O}(\alpha_w^4)$

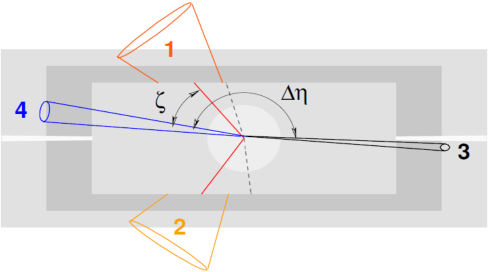
$$\stackrel{?}{=} \text{DATA - reducible background } (\sim \alpha_w^n, n \neq 4)$$

Event generation

EW	$\alpha_s = 0$	$\mathcal{O}(\alpha_w^4)$
EWQCD	$\alpha_s = \alpha_s(m_Z)$	$\mathcal{O}(\alpha_w^4)$ and $\mathcal{O}(\alpha_w^2)\mathcal{O}(\alpha_s^2)$

Experimental Signature

Tagging jets



1, 2 central leptons
3, 4 forward/backward tagging jets

Soft jet veto in central region

lack of color exchange between initial-state quarks ⇒ suppressed hadron production in central region

Monte Carlo Generation: WHIZARD and SHERPA

Production of $\boldsymbol{qq \rightarrow q_{\mathrm{tag}} q_{\mathrm{tag}} l \nu l \nu}$ at parton level

- q, q_{tag}: $u, \bar{u}, d, \bar{d}, s, \bar{s}$; $p_T^{jets} > 15\ GeV$; ΔR (j,j) > 1.0
- Leptons l: e^-, e^+, μ^-, μ^+, τ^-, τ^+; $p_T^{\mathrm{leptons}} > 15\ GeV$, $M_{ll} > 20\ GeV$
- Neutrinos ν: ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$
- $\sqrt{s} = 7\ TeV$
- $m_H = 120\ GeV$
- pdfset: cteq6l
- $\alpha_{QED} = 1/132.5$ (G_F scheme for electroweak coupling)

Configuration as similar as possible to get comparable results

Monte Carlo Predictions for VBS Cross Sections

Cross sections for VBS processes

Generator	σ_{EW}[fb]	σ_{EWQCD}[fb]
SHERPA	44.35	1262.13
WHIZARD	29.42	790.180

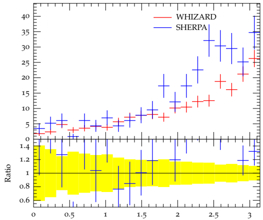
Differences between the generators: $\sim$ 35%
$\rightarrow$ WHIZARD and SHERPA authors

EW	$\alpha_s = 0$	$\mathcal{O}(\alpha_w^4)$
EWQCD	$\alpha_s = \alpha_s(m_Z)$	$\mathcal{O}(\alpha_w^4)$ and $\mathcal{O}(\alpha_w^2)\mathcal{O}(\alpha_s^2)$

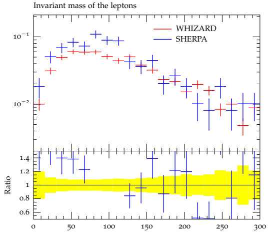
- cross sections correspond to few events in 2011/2012 ($\mathcal{L} \sim 10\ \mathrm{fb}^{-1}$)
- compare to H$\rightarrow$WW + 2j: not published yet (in ATLAS)

Comparison between WHIZARD and SHERPA

WHIZARD vs. SHERPA (normalized to their respective cross sections)



ϕ of leading tagging jet (EW)



invariant mass of charged leptons (EW)

- generate more exclusive samples (e.g. purely WZ: FS $e^+e^-\mu^+\nu_\mu$) to find origin of the differences
- for VBS analysis apply stronger VBS cuts, e.g. on $\Delta\eta$(jets) $\rightarrow$ reduce differences between generators

Kinematic distributions with WHIZARD

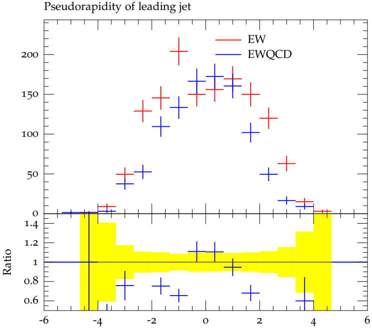
Kinematic distributions on the following slides from private RIVET Analysis: $jj \to jjW^+W^- \to jjl^+l^-\nu_l\bar{\nu}_l$

- 2 W's reconstructed from leptons (e or μ) and MET
- jet reconstruction with anti-k_T (R = 0.4)
- **tagging jets**: opposite hemispheres $\to \eta_{j1} \cdot \eta_{j2} < 0$ required

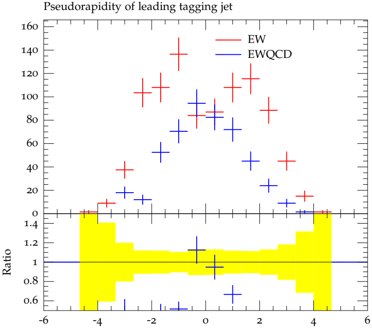
Both EW and EWQCD are normalized to 1.0 for better comparability (normally EWQCD $\sim$ 25 times EW)

Pseudorapidity distributions of jets

η of leading jet

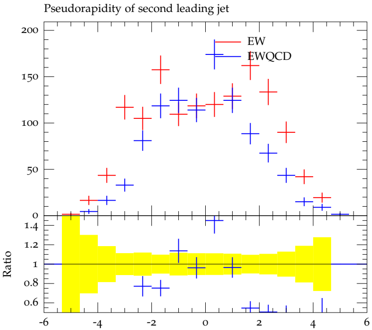


η of leading tagging jet

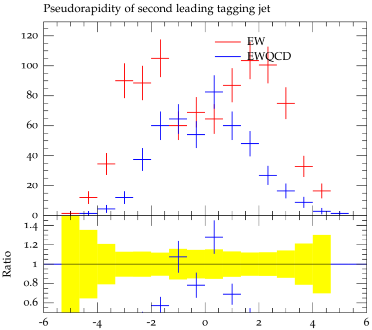


Pseudorapidity distributions of jets (WHIZARD)

η of second leading jet

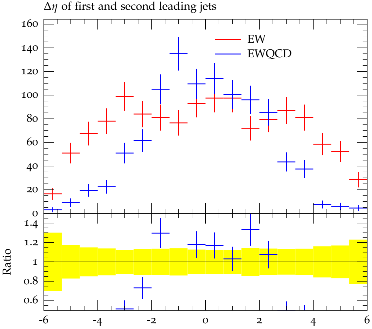


η of second leading tagging jet

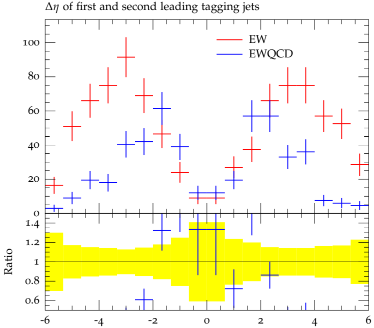


Difference in pseudorapidity

$\Delta\eta$ of first and second leading jet

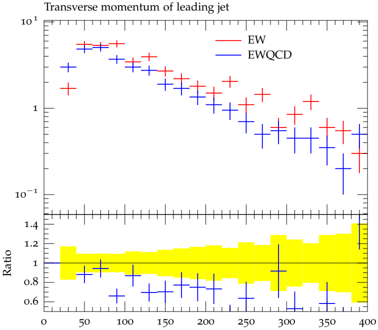


$\Delta\eta$ of first and second leading tagging jet

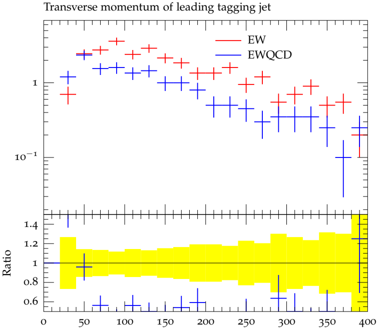


Transverse momentum of jets

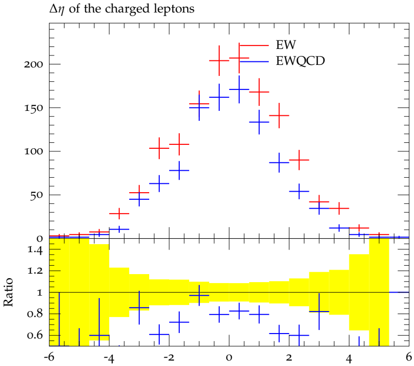
p_T of leading jet

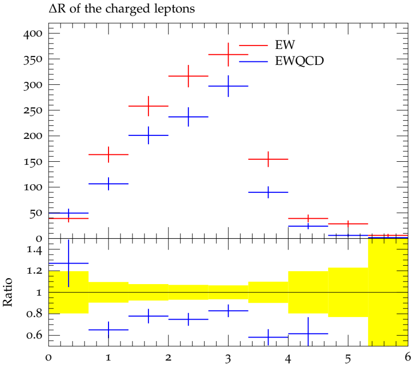


p_T of leading tagging jet



Lepton pseudorapidity and Δ R



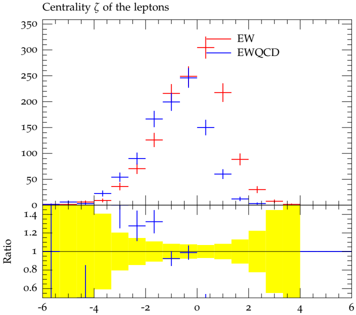


both after applying tagging jet cut

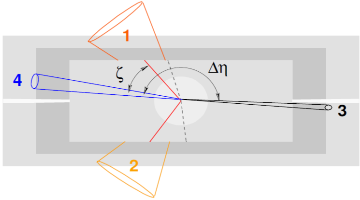
Lepton centrality (VBS feature)

Lepton centrality ζ

ζ := min$\{$min$\{\eta_{l1}, \eta_{l2}\}$ - min$\{\eta_{j1}, \eta_{j2}\}$, max$\{\eta_{j1}, \eta_{j2}\}$ - max$\{\eta_{l1}, \eta_{l2}\}\}$



- both leptons within tagging jets (in η): $\zeta > 0$
- one or both leptons larger η than closest jet: $\zeta < 0$
- for VBS, ζ tends to be rather positive



Outlook and Plans

- Analysis plans
  - Analyze ATLAS data 2011/12
  - Find reason for discrepancies between WHIZARD and SHERPA
- Establish SM vector boson scattering incl. triple and quartic gauge vertices (not experimentally measured up to now)
- Probe EWSB mechanism in this channel, i/a with model-independent Lagrangian
- Set limits on anomalous contributions to this process (alternatives to Higgs mechanism, non-SM weak boson quartic vertex)

BACKUP

Scattering of longitudinally polarized vector bosons

Unitarity violation only for longitudinal gauge-boson scattering:

- $\mathcal{A}(V_T V_T \to V_T V_T) \sim \mathcal{O}(1)$:
  $\to$ no violation of unitarity
- $\mathcal{A}(V_L V_L \to V_L V_L) \sim \frac{s}{m_V^2}$:
  $\to$ violates unitarity above $\sqrt{s_{VV}} \approx 1.2$ TeV

V_L scattering associated to scattering of "Goldstone" scalars (w, z) via equivalence theorem:

$$\mathcal{A}(W_L W_L \to W_L W_L) = \mathcal{A}(ww \to ww)$$
$$\mathcal{A}(W_L Z_L \to W_L Z_L) = \mathcal{A}(wz \to wz)\ etc.$$

Branching ratios of various decay channels

VBS contributions from different final states of W decays

Final states:

$qq \rightarrow q_{\mathrm{tag}} q_{\mathrm{tag}} WW$:	$WW \rightarrow \ell\nu\ell\nu$	BR 0.046
	$WW \rightarrow qq\ell\nu$	BR 0.292
$qq \rightarrow q_{\mathrm{tag}} q_{\mathrm{tag}} WZ$:	$WZ \rightarrow \ell\nu\ell\ell$	BR 0.015
	$WZ \rightarrow qq\ell\ell$	BR 0.045
	$WZ \rightarrow qq\ell\nu$	BR 0.151
$qq \rightarrow q_{\mathrm{tag}} q_{\mathrm{tag}} ZZ$:	$ZZ \rightarrow \ell\ell\ell\ell$	BR 0.005
	$ZZ \rightarrow qq\ell\ell$	BR 0.094
	$ZZ \rightarrow \ell\ell\nu\nu$	BR 0.027

(with $l = e, \mu$)