Studying Weak Boson Scattering at the LHC with WHIZARD

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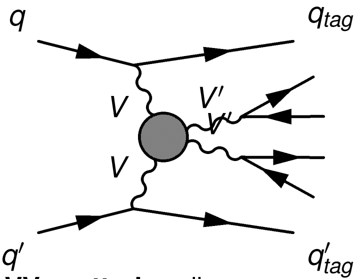
Studying Vector Boson Scattering at the LHC

- Important process to study **electroweak symmetry breaking** in case of
  - light (non-SM?) Higgs
  - heavy Higgs
  - other EWSB mechanism
- Promising channel: unitarity violation above $\sqrt{s_{VV}} \sim 1.2$ TeV
- Scattering of weak bosons in SM not measured yet

What is Vector Boson Scattering?

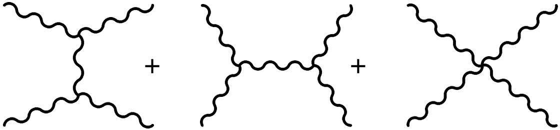
- Signal $qq' \to q_{tag}q'_{tag}VV$ (V = W or Z)



- "blobb" contains all **VV scattering** diagrams
- processes with the same final state:
  - non-VBS electroweak processes (irreducible due to gauge dependence)
  - QCD background at different order of couplings
  - other reducible backgrounds like $t\bar{t}$, W/Z + jets, etc.

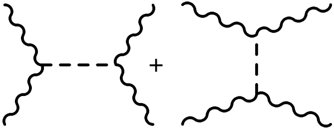
Unitarity violation in the VBS channel

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:

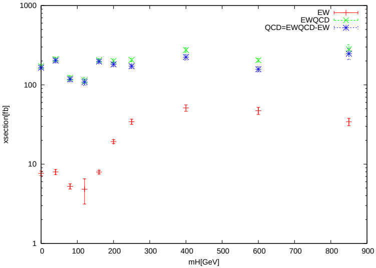


$$\mathcal{M}^{Higgs} = \frac{g^2}{4m_W^2} u$$

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 $\sigma(m_H < 2m_W)$
and $\sigma(m_H > 2m_W)$

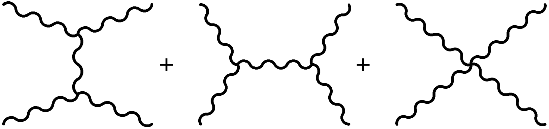
- channel is also sensitive to the **coupling strengths** of Higgs to vector bosons
- probe SM or non-SM Higgs
- observe or exclude **strong WZ scattering**

Case 2: No Higgs/ heavy Higgs

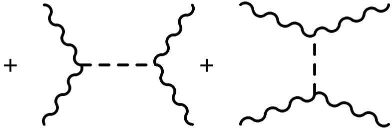
- no Higgs ($m_H \to \infty$) or heavy Higgs ($m_H \gtrsim 870\ GeV$): unitarity violated in VBS above $\sqrt{s_{VV}} \sim 1.2$ TeV $\to$ strong gauge sector
- $\Rightarrow$ **Higgs** or **new physics** will be visible at higher energies in this channel (possibly through VV resonances)
- VBS allows to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

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

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

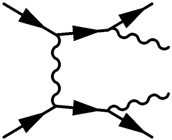


(triple/quartic gauge boson vertices)



(Higgs channels)

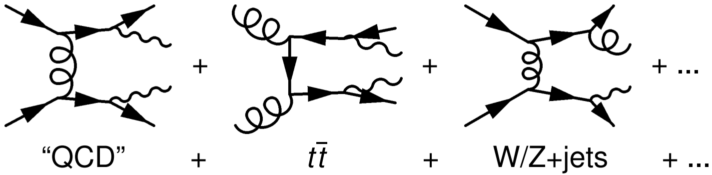
SIGNAL without VBS topology: additional diagrams $\mathcal{O}(\alpha_w^4)$



+ ... (other EW processes)

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

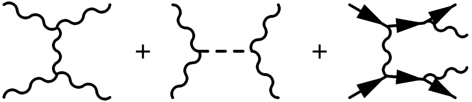
REDUCIBLE BACKGROUND: Diagrams $\mathcal{O}(\alpha_w^n), n \neq 4$



- 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



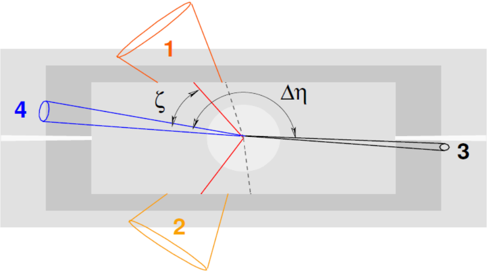
$+ \ldots \} \, \mathcal{O}(\alpha_w^4)$

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

Event generation

EW	$\alpha_s = 0$	$\mathcal{O}(\alpha_w^4)\mathcal{O}(\alpha_s^0)$
EWQCD	$\alpha_s = \alpha_s(m_Z)$	any $\mathcal{O}(\alpha_w^n)\mathcal{O}(\alpha_s^m)$ incl. $\mathcal{O}(\alpha_w^4)\mathcal{O}(\alpha_s^0)$ (=EW)

Experimental Signature



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

Tagging jets

initial quarks radiating off the vector bosons ⇒ highly energetic jets with large $|\Delta\eta|$

Soft jet veto in central region

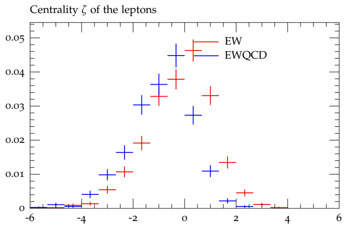
lack of color exchange between initial-state quarks ⇒ suppressed hadron production in central region

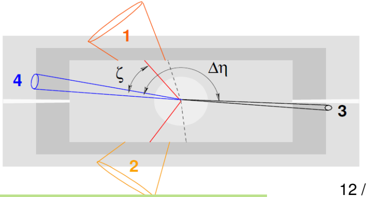
Lepton centrality (VBS feature)

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 in η between tagging jets: $\zeta > 0$ (VBS topology)
- one or both leptons at larger $|\eta|$ than closest jet: $\zeta < 0$
- EW tends to have more positive ζ than EWQCD



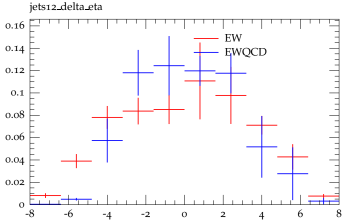


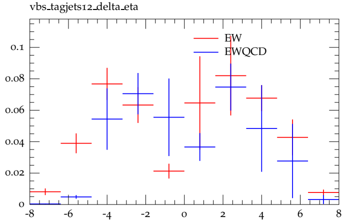
Tagging jets

Jet distributions with / without opposite hemisphere cut ($\eta_{j1} \cdot \eta_{j2} < 0$)

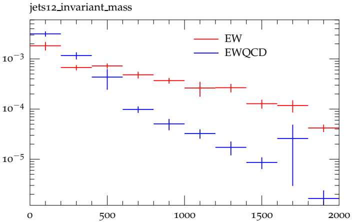
all events | only events with $\eta_{j1} \cdot \eta_{j2} < 0$

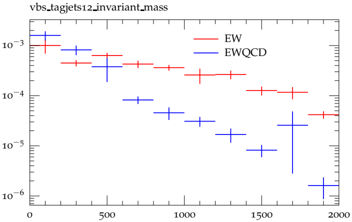
$\Delta\eta_{jj}$





M_{jj}





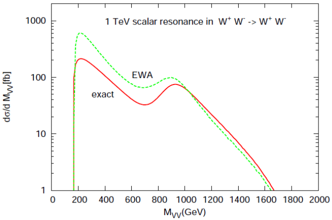
WHIZARD 2.0 for VBS

WHIZARD's specialty: SM_km

- model-independent implementation of BSM contributions to VBS
- low-energy effective theory (electroweak chiral Lagrangian)
- k-matrix unitarization
- additional resonances of different spin and isospin described by coupling, mass, and width

Advantages of WHIZARD's SM_km w.r.t. other methods

- no violation of unitarity
- full 6-fermion final state
- avoids Effective *W* Approximation (EWA) (inappropriate in some parts of phase space)
- angular correlations preserved



Validation: WHIZARD and SHERPA

Production of $jj \rightarrow j_{\text{tag}} j_{\text{tag}} l\nu l\nu$ at parton level

Flavors

- partons j: u, $\bar{u}$, d, $\bar{d}$, s, $\bar{s}$, c, $\bar{c}$ and gluons
- charged leptons: e, μ, τ
- neutrinos: ν_e, ν_μ, ν_τ

Parameters and kinematic cuts:

- $p_T(\text{l}) > 15$ GeV, $p_T(\text{j}) > 15$ GeV, $\Delta R(j,j) > 1.0$, $M_{ll} > 20$ GeV
- $\sqrt{s} = 7$ TeV, $m_H = 120$ GeV
- PDFset: CTEQ6l
- G_F scheme for electroweak coupling ($\alpha_{QED} = 1/132.5$)

Configuration as similar as possible to get comparable results

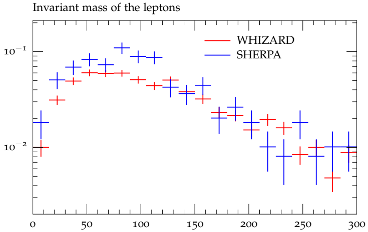
Monte Carlo Predictions for VBS Cross Sections

Cross sections for process as defined above

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

Differences between the generators: $\sim$ 35%

WHIZARD VS. SHERPA M_{ll}



invariant mass of charged leptons (EW)

$\rightarrow$ generate more exclusive samples to find origin of the differences

- Same Sign/ Opposite Sign
- WW/WZ/ZZ

Investigation of Exclusive Samples

Investigate cross section differences

Process	VV	SHERPA		WHIZARD	
		EW	EWQCD	EW	EWQCD
$uu \to dde^+\mu^+\nu_e\nu_\mu$	W^+W^+	**0.72**	**1.73**	**0.71**	**1.98**
$ud \to ude^+e^-\nu_e\bar{\nu}_e$	W^+W^-/ZZ	**1.03**	**4.67**	**0.74**	**4.44**
$ud \to ude^+\mu^-\nu_e\bar{\nu}_\mu$	W^+W^-	**1.00**	**4.31**	**0.67**	**3.93**
$ud \to ude^+e^-\nu_\mu\bar{\nu}_\mu$	ZZ	**0.081**	**0.30**	**0.067**	**0.26**

(cross-sections in fb)

Couplings in event Generation

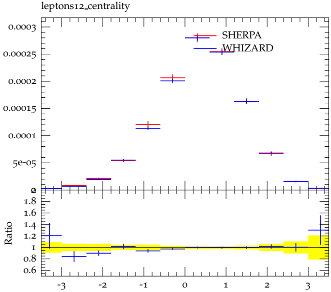
EW	$\alpha_s = 0$	$\mathcal{O}(\alpha_w^4)$
EWQCD	$\alpha_s = \alpha_s(m_Z)$	any $\mathcal{O}(\alpha_w^n)\mathcal{O}(\alpha_s^m)$ incl. $\mathcal{O}(\alpha_w^4)\mathcal{O}(\alpha_s^0)$ (=EW)

Following kinematic distributions to compare WHIZARD and SHERPA

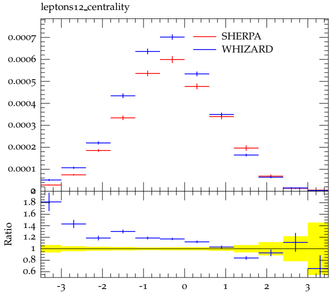
Same Sign $uu \to dde^+\mu^+\nu_e\nu_\mu$: W^+W^+

Centrality of leptons

EW



EWQCD



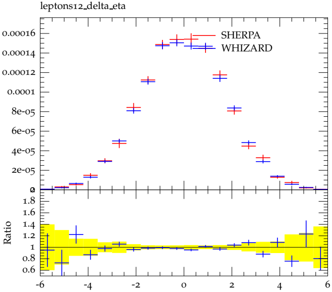
- EW: perfect agreement (cross section difference <1 %)
- EWQCD: WHIZARD produces more leptons with small centrality

→ Overview of *EW* and *EWQCD* plots for this channel

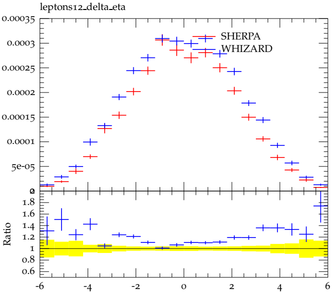
Same Sign $uu \to dde^+\mu^+\nu_e\nu_\mu$: W^+W^+

$\Delta\eta$ of leptons

EW



EWQCD



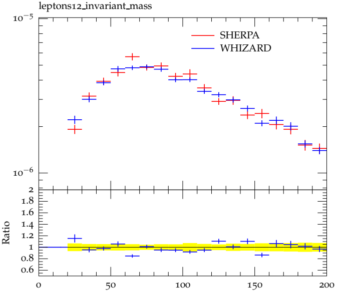
- EW: perfect agreement (cross section difference $<$1 %)
- EWQCD: WHIZARD produces excess of leptons with larger $\Delta\eta$

$\to$ Overview of *EW* and *EWQCD* plots for this channel

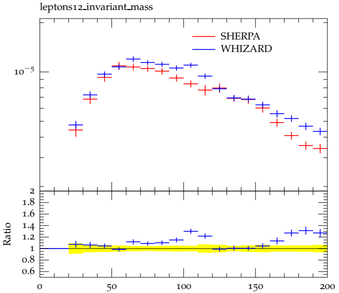
Same Sign $uu \to dde^+\mu^+\nu_e\nu_\mu$: W$^+W^+$

Invariant mass of leptons

EW



EWQCD



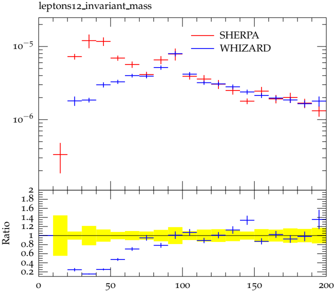
- EW: perfect agreement (cross section difference <1 %)
- EWQCD: WHIZARD excess around 100 GeV

→ Overview of *EW* and *EWQCD* plots for this channel

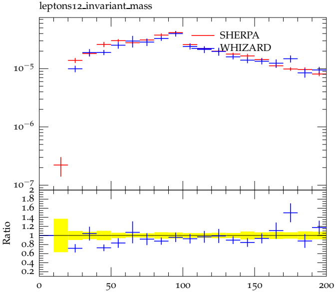
Opposite Sign $ud \to ude^+e^-\nu_e\bar{\nu}_e$: W$^+W^-$/ZZ

Invariant mass of leptons

EW



EWQCD



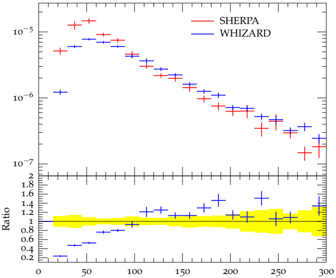
- EW: SHERPA excess at small invariant masses of leptons
- EWQCD: difference consistent with being fully due to EW contribution

$\to$ Overview of *EW* and *EWQCD* plots for this channel

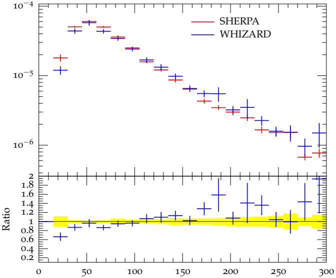
Opposite Sign $ud \rightarrow ude^+e^-\nu_e\bar{\nu}_e$: W$^+W^-$/ZZ

Transverse momentum of leading lepton

EW



EWQCD



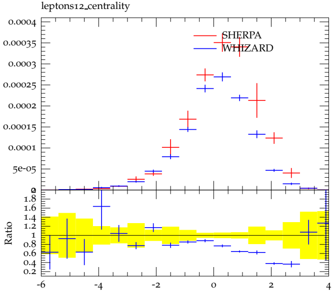
- EW: SHERPA excess at small transverse momentum
- EWQCD: difference consistent with being fully due to EW contribution

→ Overview of *EW* and *EWQCD* plots for this channel

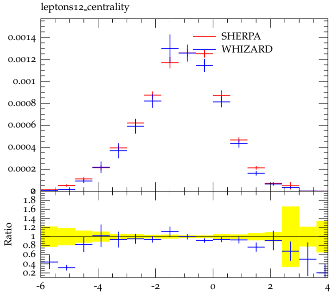
Opposite Sign $ud \to ude^+e^-\nu_e\bar{\nu}_e$: W$^+W^-$/ZZ

Lepton centrality

EW



EWQCD



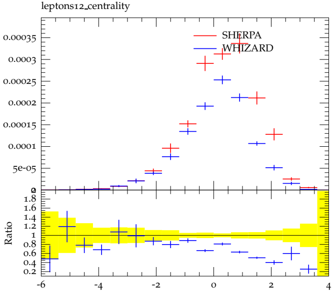
- EW: SHERPA excess at higher centrality
- EWQCD: difference consistent with being fully due to EW contribution

$\to$ Overview of *EW* and *EWQCD* plots for this channel

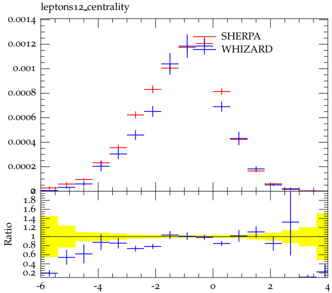
Opposite Sign $ud \to ude^+\mu^-\nu_e\bar{\nu}_\mu$: $\mathbf{W^+W^-}$ only

Lepton centrality

EW



EWQCD



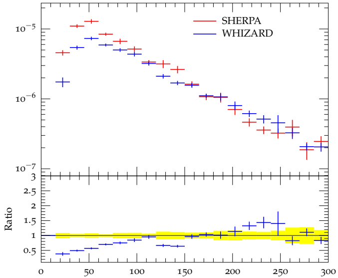
- EW: SHERPA excess at higher centrality
- EWQCD: difference consistent with being fully due to EW contribution

→ Overview of *EW* and *EWQCD* plots for this channel

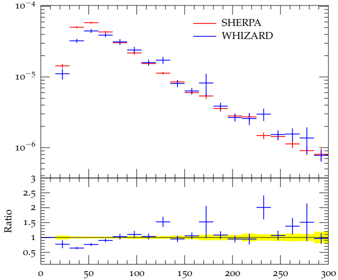
Opposite Sign $ud \to ude^+\mu^-\nu_e\bar{\nu}_\mu$: $\mathbf{W^+W^-}$ **only**

Transverse momentum of leading lepton

EW



EWQCD



- EW: SHERPA more at low p_T; WHIZARD more at high p_T
- EWQCD: difference consistent with being fully due to EW contribution

→ Overview of *EW* and *EWQCD* plots for this channel

Outlook and Plans

- Find reason for discrepancies between WHIZARD and SHERPA
- Validate signal samples in ATLAS
- Measure SM vector boson scattering with ATLAS data 2011/2012
- Probe EWSB mechanism in this channel with model-independent Lagrangian
- Set limits on anomalous contributions to this process

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:

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

(with $l = e, \mu$)