Vector Boson Scattering at the LHC

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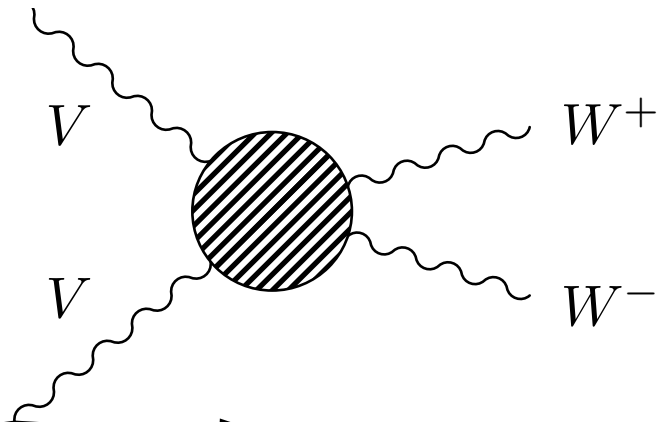
Outline

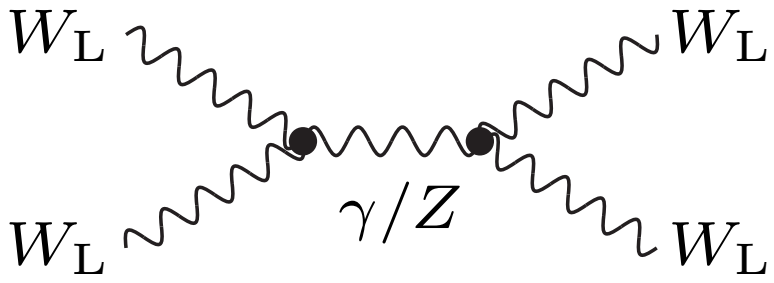
- What is Vector Boson Scattering?
- Why do we care about it?
- Vector Boson Scattering at the LHC
  - Searches for VBS performed on run I data
  - VBS in the ZZjj channel

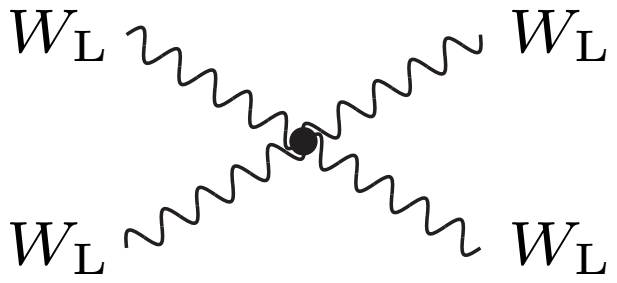
Vector Boson Scattering

- Vector Boson Scattering (VBS) is an interaction of the kind **VV'→VV'**, where V designates the electroweak bosons of the SM, i.e. **V = W, Z, & γ**



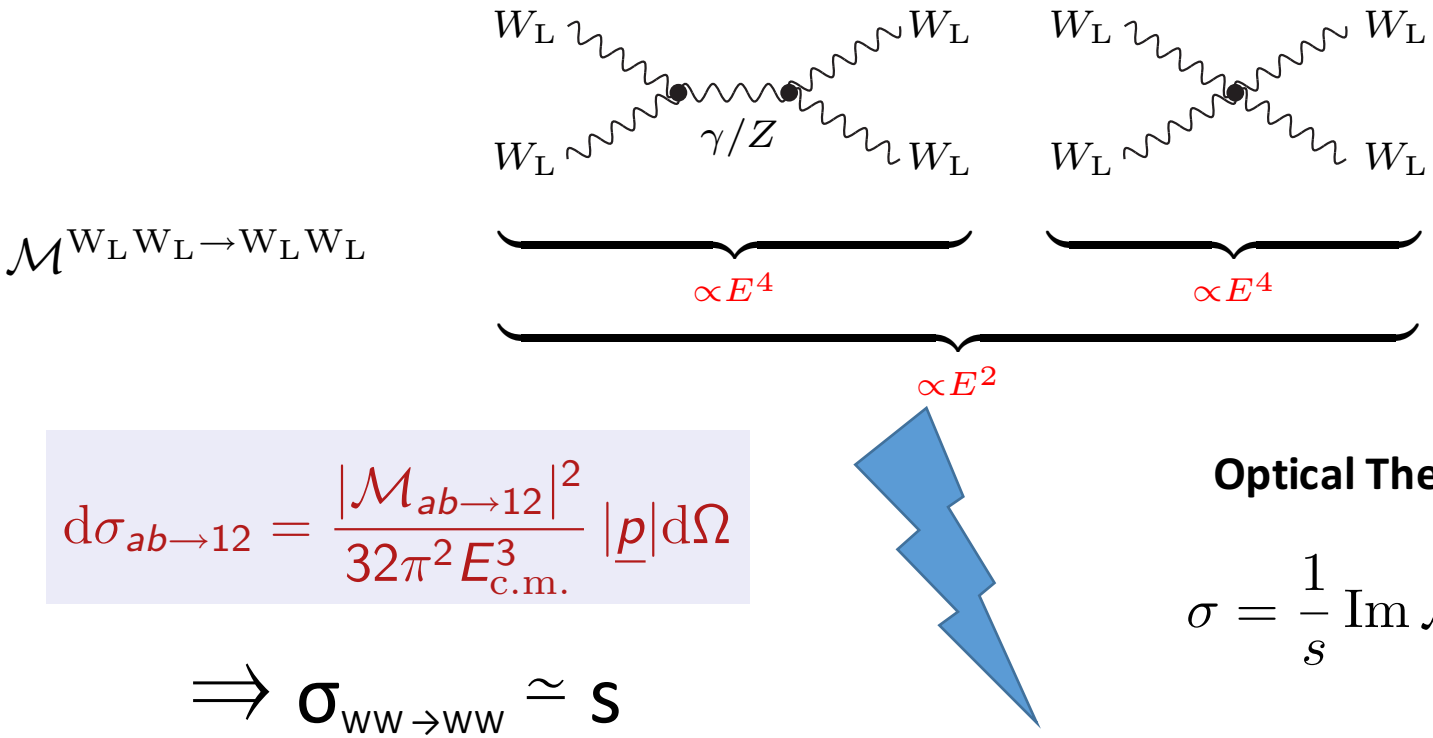
Example: WW →WW scattering





Why is VBS interesting?

CAUTION: Experimentalist talking about theory



$$d\sigma_{ab\to 12} = \frac{|\mathcal{M}_{ab\to 12}|^2}{32\pi^2 E_{c.m.}^3} |\underline{p}| d\Omega$$

$$\Rightarrow \sigma_{WW\to WW} \simeq s$$

Optical Theorem:

$$\sigma = \frac{1}{s} \mathrm{Im}\, \mathcal{M}_{\mathrm{forward}}$$

The scattering of longitidinal gauge bosons violates unitarity at the TeV scale!
(Unitarity violation = loss of conservation of probability)

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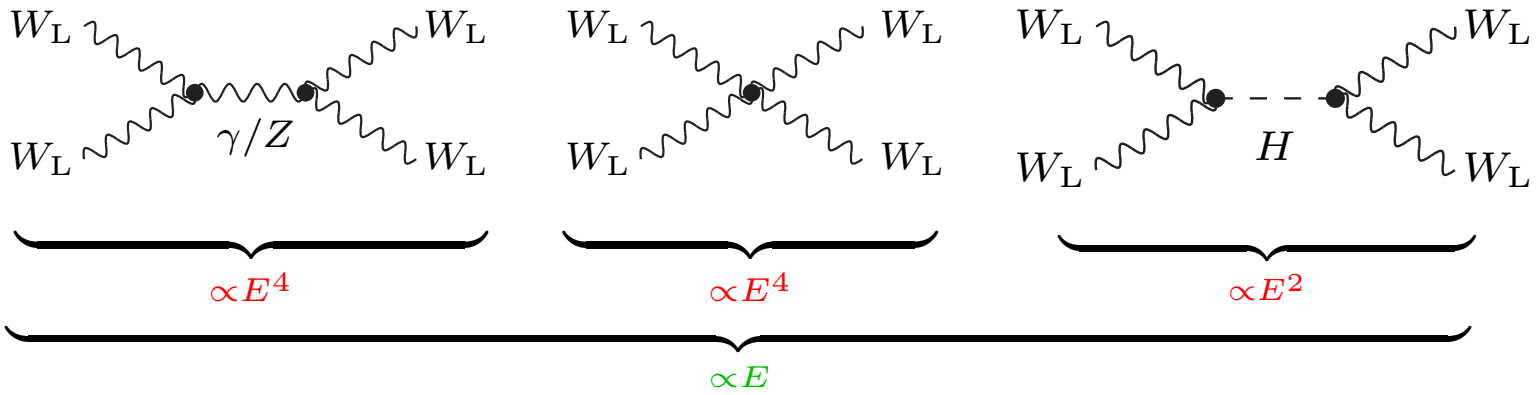


$$d\sigma_{ab\to 12} = \frac{|\mathcal{M}_{ab\to 12}|^2}{32\pi^2 E_{\text{c.m.}}^3} |\underline{p}| d\Omega$$

$$\Rightarrow \sigma_{WW\to WW} \simeq \frac{1}{s}$$

Optical Theorem:

$$\sigma = \frac{1}{s} \operatorname{Im} \mathcal{M}_{\text{forward}}$$

The Higgs of the Standard Model unitarizes the VBS cross section

Physics Case for VBS Studies

- In the SM Model without the Higgs, VBS processes violate unitarity in the longitudinal polarization mode at the TeV scale:
  - The minimal SM unitary is ensured by the destructive interference between VBS amplitudes and diagrams involving the Higgs
  - A consistent theory requires a Higgs boson with $m_H < 1$TeV or new Physics at the TeV scale

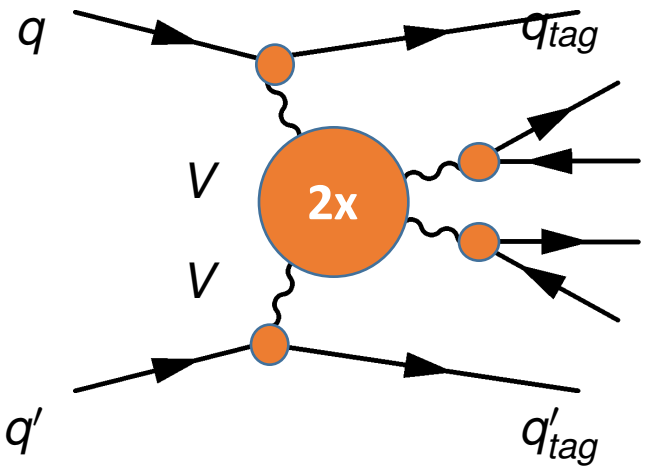
1 VBS allows to study the delicate **unitarization of the SM** and the role of H_{125} in the electroweak sector

- If New Physics (BSM) is present in the electroweak sector, VBS offers a promising approach by studying its impact on gauge boson couplings

2 VBS is a promising avenue for BSM physics searches via the probing of **anomalous triple & quartic gauge couplings (aTGC & aQGC)**

Vector Boson Scattering at the LHC

- At the LHC, VBS is initiated by the incoming quarks in the proton: each radiates off a vector boson which then undergo VBS
- As a purely electroweak process the cross-section is of order α^6_{EWK}
- Multiple production mechanisms:
  - Double Triple Gauge Coupling (TGC)
  - Quartic Gauge Coupling (QGC)
  - Higgs exchange in s- and t-channel



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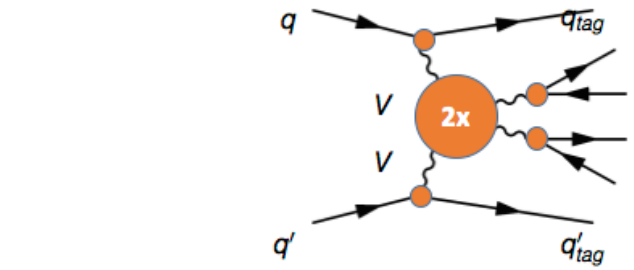
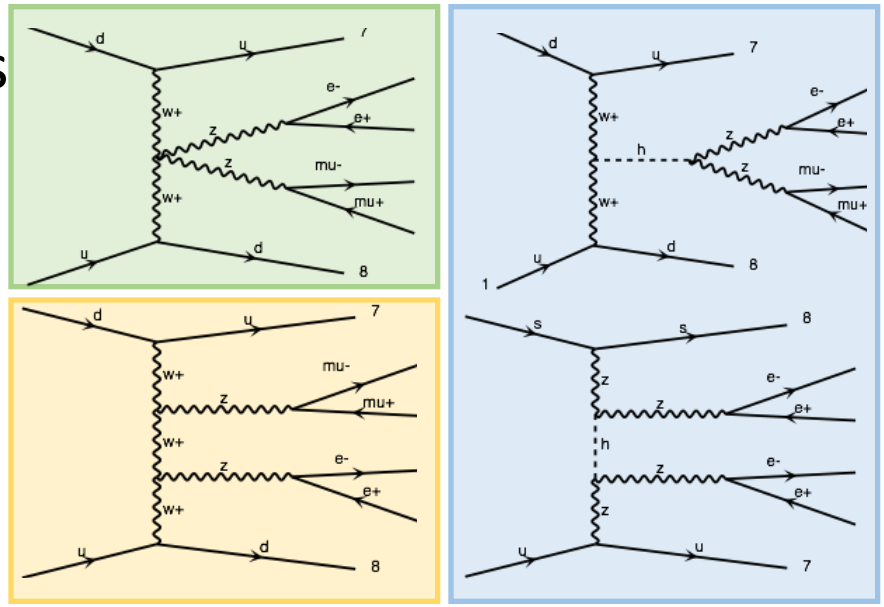


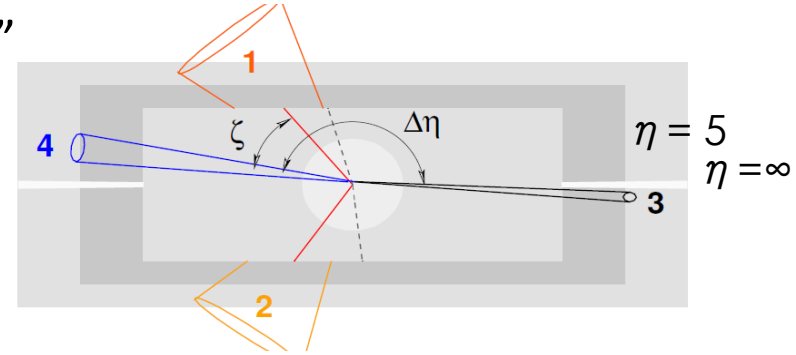


+ …

Signature of Vector Boson Scattering

VBS event topology is characterized by:

- Two, forward/backward jets at **large |η|** with high energy resulting from from the deflected incoming quarks -"tagging jets"
  - **Large $\Delta\eta_{jj}$ and m_{jj}**
  - Zeppenfeld variable used to capture centrality:
    - $z = \frac{1}{\Delta\eta_{jj}}(\eta - \frac{\eta_1+\eta_2}{2})$
    - Region between jets (z < 0.5) is referred to as central
- The **vector bosons** and their decay products **are central**
- **Central hadronic activity is suppressed** due to color decoherence

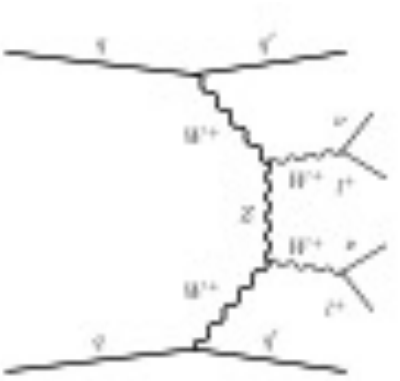


The sensitivity to VBS and aQGCs is at large center of mass energies, i.e. m_{VV} and related variables like m_T^{VV} or p_T^V.

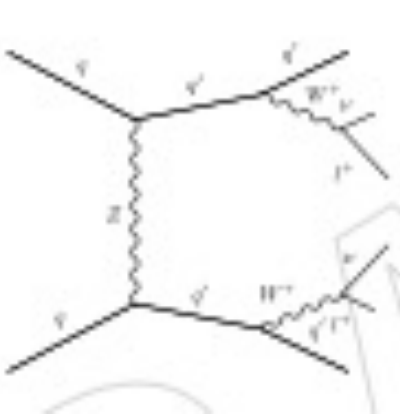
Status of VBS searches with run I data

- Both **ATLAS** and **CMS** performed searches for VBS in run I data:
  - Evidence for electroweak production of **same-sign WW plus 2 jets** with an observed (expected) significance of **3.6** (2.8)σ by ATLAS [1] and of 2.0 (3.1)σ by CMS [2]

VBS Signal



EWK production



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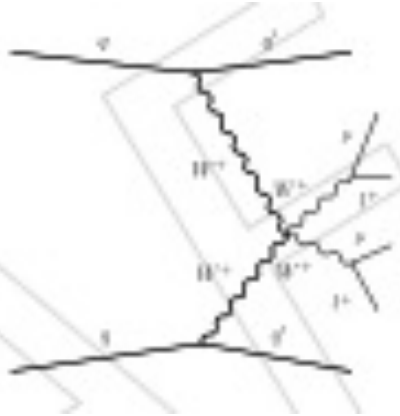
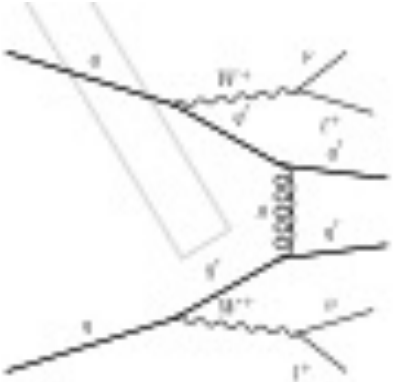


QCD production



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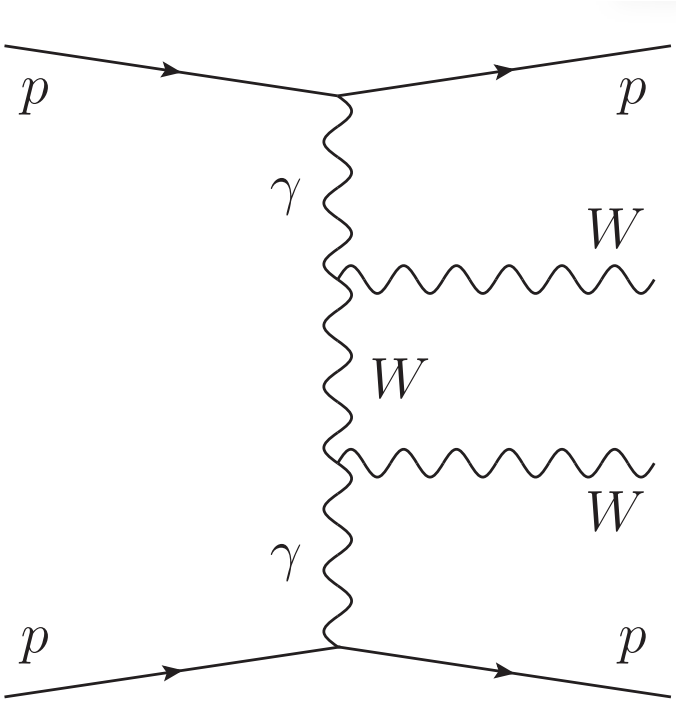

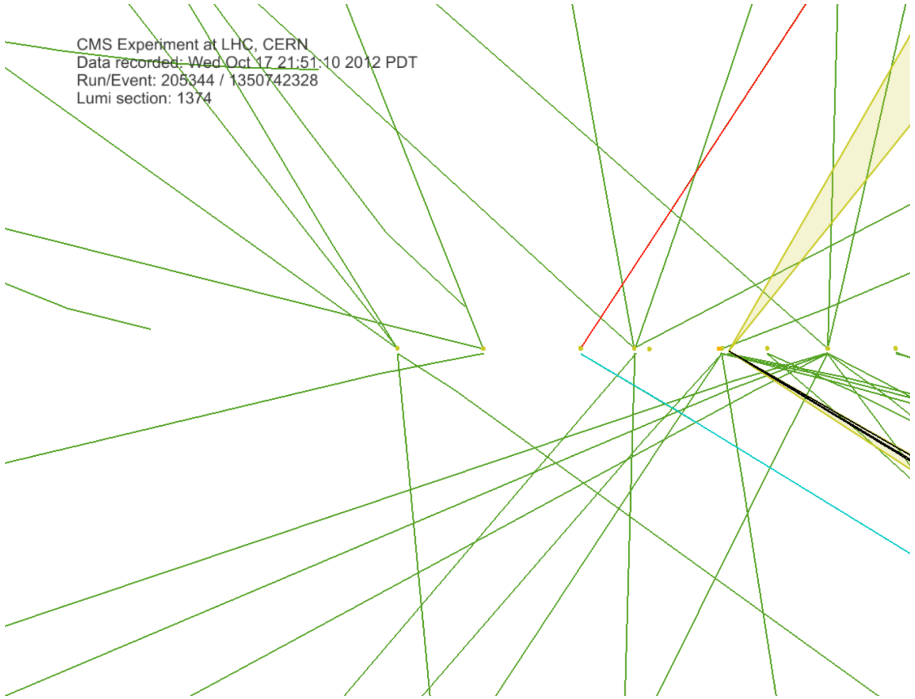

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  - Searches for electroweak production of Xγ plus 2 jets by CMS
    - **Zγjj** with **3.0** (2.1)σ evidence [3]
    - Wγjj with 2.5 (1.5)σ evidence [4]
  - Search for **γγ → WW** with 7 & 8 TeV data by CMS [5, 6] with evidence at **3.6** (2.5)σ

- Selected studies probing aQGCs:
  - Search for WWγ and WZγ production by CMS [7]
  - **Evidence for Wγγ** production by ATLAS [8] and [9]

Bibliography in backup

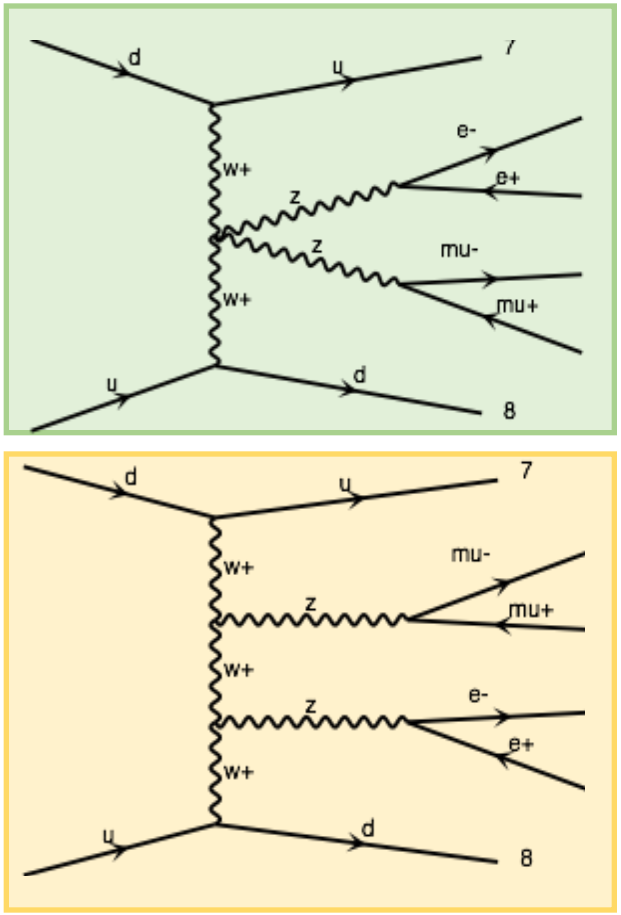
VBS in the 4l final state

Search for ZZ scattering in the 4l final state:

- Require two on-shell Z bosons reconstructed from isolated, prompt leptons (l = e or μ)

⇒ **Clean signature with small reducible backgrounds**

- Ratio of EWK signal to irreducible background from QCD not as favorable as same-sign WW, i.e. $\sigma_{QCD} \sim 10 \times \sigma_{EWK}$ <u>without VBS cuts</u>



Preliminary study of ZZjj event selection

- Goal was to explore a potential event selection for ZZjj using fast detector simulation, event counts for 100 fb^{-1}:

@ 100fb^{-1}	QCD (B)	EWK (S)	S/√[B]
Total # generated events	442.200	42.280	2.01
Lepton acceptance [$p_T > 7$ GeV, $\eta_\mu < 2.4$, $\eta_e < 2.5$]	214.644	23.246	1.59
Two on-shell Z bosons [60 GeV < m_Z < 120 GeV]	161.668	16.713	1.31
Tagging Jets [pT > 30 GeV, $\eta < 5.2$]	124.789	15.115	1.35
Tagging jet rapididty gap [$\Delta y > 3.0$]	15.831	9.154	2.30
Tagging jet invariant mass [m_{jj} >700 GeV]	3.272	7.162	3.96
Leptons are central	1.901	6.338	4.60
Jet veto [no >25 GeV pT jet between tagging jets]	**0,840**	**5.826**	**6.36**

- This crude estimate suggests that **VBS of Z bosons will be observable with the run II data**
- Search strategy will be similar to that employed for H → ZZ → 4l: Maximize the signal event acceptance and exploit the kinematics of the signal and background processes to extract signal

Summary

- Vector Boson Scattering allows to test the gauge structure of the electroweak sector by probing TGC and QGC
- Studying the unitarization of VBS is a test of electroweak symmetry breaking in the Standard Model
- Evidence for VBS for several channels has been found using LHC run I data
- The luminosities of the run II of the LHC will permit first observation of VBS in many channels and final states

Backup

Bibliography

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