VECTOR-BOSON FUSION AND SCATTERING MEASUREMENTS

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FOREWORD

• This is a VBS/VBF summary talk

• Only recent LHC Run2 results are included

• For those interested in more details, please refer to presentations (and watch recordings!) of the topical Monday session:
  • https://indico.cern.ch/event/905399/sessions/384934/#20210607
GAUGE SELF-COUPPLINGS

• Heavy gauge-bosons discovered decades before the Higgs boson
• Nevertheless, cubic and quartic gauge self-couplings yet among the least known SM structures
  • Theoretically very clean strengths determined by non-abelian SU(2)
  • Experimentally hard to investigate
  At the LHC final states:
   • with small cross-sections
   • and/or subdominant w.r.t. competing processes
VBF AND VBS AT THE LHC

- EW process:
  - Experimental signature: $V$ or $VV$ and 2 jets from scattered quarks

- TGC and/or QGC diagrams at the LO (direct access to self-couplings)

- $O(\%)$ NLO QCD corrections on the EW component, unlike most LHC processes

  - Theory uncertainties very small
  - EW corrections become as important

- May have large SM backgrounds

  - $Vjj$ or $VVjj$ with $jj$ from strong vertices
  - Top-quark production, for final states with many jets and/or $W$
OBSERVABLES / BSM MODELS (1)

- **Observables**
  - Cross-sections in detector-fiducial regions
    - EW only and/or total QCD+EW (theoretically cleaner, although interference terms are typically \( o(\%) \) of the signal)
    - Usually requiring large di-jet rapidity separation (\( \Delta y_{jj} \)) and/or mass (\( m_{jj} \))
      \( \Rightarrow \) enhances EW-only component
    - Differential, if data allows
  - Polarization
    - In the VBS case may be measured for both VV or be inclusive in one

- **Constraints on concrete BSM models**
  - A prominent example: alternative/additional sources of EWSB other than the Higgs boson modify significantly double-longitudinal component in VBS (\( qq \rightarrow V_L V_L qq \))

Ballestrero, Maina, Pelliccioli, JHEP 03, 170 (2018)
BSM MODELS (2): EFT

- **VBF** processes setting competitive limits on \( d=6 \) operator coefficients
  - Usually given using SILH or Warsaw bases
- **VBS** case more complex, as it receives similar-size BSM contributions from both \( d=6 \) and \( d=8 \). Two alternative approaches:
  - Neglect \( d=6 \), as constrained by many other LHC data (Higgs, dibosons...) \( \rightarrow \) set limits on \( d=8 \) coefficients using gauge-boson-specific basis by Eboli et al.
  - Include \( d=6 \) VBS constraints (although weaker) in combinations
    - arXiv:2101.03180
MEASUREMENT CHALLENGES

- **Experimental:**
  - **Large QCD backgrounds:** matrix-element techniques or machine-learning
  - **Missing neutrinos** in $W \to l\nu$ final states: $p_T^{l\nu}$ reconstruction ($1\nu$) or use approximations ($2\nu$)
  - **Jet systematic uncertainties** in forward regions

- **Physics modeling:**
  - **EW signals**
    - Large theory-experimental efforts to cross-validate MC generators
    - Parton-shower schemes very important
  - **VVjj QCD**
    - Very expensive computations at NLO and/or matched+merged (MG5_aMC@NLO/Sherpa)
    - Need careful validation in data control regions
  - **EFT QGCs**
    - Avoid unitarity violation by setting energy cut-offs

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VBF $W \rightarrow \ell \nu$

- **CMS:**
  - BDT-based analysis for EW extraction
    - Input variables: $p_{T,\text{miss}}$, $m_T(W)$, $m_{jj}$, $\Delta y_{jj}$, W Zeppenfeld variables…
    - Include quark-gluon discrimination for jets
  - Results:
    - Fiducial cross-section
    - EFT $d=6$ constraints (also combined with VBF Z, next slide)
    - Dedicated studies of extra jet activity with different PS programs

\[ \sigma(\text{EW } \ell vjj) = 6.07 \pm 0.12\,\text{(stat)} \pm 0.57\,\text{(syst)}\,\text{pb} \]

\[ \sigma_{\text{NLO}}(\text{EW } \ell vjj) = 6.74^{+0.02}_{-0.04}\,\text{(scale)} \pm 0.26\,\text{(PDF)}\,\text{pb} \]
**ATLAS:**
- Binned analysis in $m_{jj}$, in 1 signal and 3 control regions defined by $\xi_Z$ and $N_{jets}$ in $\Delta y_{jj}$ gap
- Focus on fiducial and differential cross-sections (EW and EW+QCD)

**CMS:**
- Similar to VBF W: BDT-based analysis for EW extraction
- Cross-section in fiducial (but looser) region
- Both: constraints on $d=6$ EFT

$\sigma_{\text{EW}} = 37.4 \pm 3.5 \text{ (stat)} \pm 5.5 \text{ (syst)} \text{ fb}$

HERWIG7+VBFNLO $39.5 \pm 3.4 \text{ (scale)} \pm 1.2 \text{ (PDF)} \text{ fb.}$
VBS $W^\pm W^\pm \to 2\ell^\pm 2\nu$

- «Golden channel» ($\sigma_{EW}/\sigma_{QCD} \sim 10$)
- Non-prompt background estimates from data
- ATLAS (SM observation)
  - Signal-region data in four $m_{jj}$ bins fit together with 3$\ell$ and low-$m_{jj}$ regions
- CMS (SM observation + EFT)
  - Fits of 2-dimensional distributions in bins of $m_{jj}$ and $m_{ll}$ in signal and control regions (also differentially in $m_{jj}$, $m_{ll}$, and leading-lepton $p_T$)
  - Stringent limits on $d=8$ EFT from $m_T(WW)$ distribution

VBS $W^\pm W^\pm \rightarrow 2\ell^\pm 2\nu$ POLARIZATION


- Challenging measurement
  - Dedicated MC simulation (MG5_aMC@NLO)
  - Very low expected yields for $W_L W_L$
  - $W$ four-momenta unknown (no direct access to helicity angles)

- CMS:
  - 2-dimensional fits of 2 BDT output scores
    - **Inclusive**: optimized to select EW $WW jj$ over backgrounds
    - **Signal**: optimized to select $W_L W_L$ or $W_L W_X$ over other polarization states
  - $2.6\sigma$ observed significance for $W_L W_X$
VBS $WZ \rightarrow 3\ell 1\nu$

- QCD $WZ \leftrightarrow$ largest background
  - Use of BDT-based analyses: inputs from lepton/jet kinematic variables and relative separation
  - $W$ four-momentum by constraining $m(W)$ to derive $p_L$\nu
- ATLAS (SM observation)
- CMS (SM observation + EFT)
  - Analysis methods shared with same-sign WW
  - Constraints on $d=8$ EFT from $m_T(WZ)$ distribution

\[ \sigma_{WZ_{ij}-EW}^{\text{fid.}} = 0.57^{+0.14}_{-0.13} \text{(stat.)}^{+0.05}_{-0.04} \text{(exp. syst.)}^{+0.05}_{-0.04} \text{(mod. syst.)}^{+0.01}_{-0.01} \text{(lumi.)} \text{ fb} \]

\[ \sigma_{WZ_{ij}-EW}^{\text{fid., Sherpa}} = 0.321 \pm 0.002 \text{(stat.)} \pm 0.005 \text{(PDF)}^{+0.027}_{-0.023} \text{(scale.)} \text{ fb} \]
VBS ZZ → 4ℓ

- QCD ZZ \rightarrow largest\ background
- ATLAS (5.5\σ\ significance)
  - BDT analysis
  - Combination with 2\ell 2ν\ channel
  - Focus on SM EW and EW+QCD cross-section
- CMS (4.0\σ\ signif. + EFT)
  - Using advanced MC simulation for loop-induced QCD ZZ
  - Matrix-element analyses (MEs from MCFM program, at LO)
  - Fiducial cross-sections in different EW-purity regions
  - Constraints on d=8 EFT operators (T8, T9) from m(4\ell)\ distribution


SEMILEPTONIC VBS VV

- $WVjj \rightarrow \ell \nu 4j$ or $\ell \nu 2j 1J$
- $ZVjj \rightarrow \ell \ell / \nu \nu 4j$
  or $\ell \ell / \nu \nu 2j 1J$

**ATLAS:**
- SM-targeted
- BDT-based in a total of 9 event categories (number of charged leptons, low/high purity merged-jet reconstruction, resolved-jet reconstruction)
- $2.7\sigma$ SM-VBS significance

**CMS:**
- cut-based analysis, optimized for VV high-invariant-mass regions
- 2 categories: $\ell \nu$ or $\ell \ell$ plus a merged jet
- Best limits on a large set of $d=8$ EFT operators
VBS WITH PHOTONS

- $W_{\gamma j j}$ (CMS) and $Z_{\gamma j j}$ analyses (CMS/ATLAS)
  - Leptonic heavy-boson decays combined with isolated photons (in ATLAS also converted $\gamma$ considered)
  - ATLAS: BDT-based analysis
  - CMS: two dimensional fits using $(m_{jj}, \Delta \eta_{jj})$ for $Z_{\gamma j j}$ and $(m_{jj}, m_{\gamma})$ for $W_{\gamma j j}$

- Significances:
  - $4.1\sigma$ ($Z_{\gamma j j}$ ATLAS)
  - $5.3\sigma$ ($W_{\gamma j j}$ CMS)
  - $Z_{\gamma j j}$ CMS: obervation + differential cross-sections

- For $W_{\gamma j j}$, best limits for certain $d=8$ operators ($M/T5, 6, 7$)

CMS-PAS-SMP-20-016
exclusive production processes are mediated through $\gamma\gamma$ fusion

- Use $e\mu$ final state
- Large QCD WW background removed by requiring 0 extra tracks in the detector → implies control on:
  - QCD WW underlying event
  - Pile-up description
  - Proton rescattering effects achieved through control samples + transfer factors

First observation of the process

$\sigma_{\text{meas}} = 3.13 \pm 0.31 \text{ (stat.)} \pm 0.28 \text{ (syst.) fb}$
«Scalar» operators (4 Higgs-field derivatives)
EFT D=8 SUMMARY

«Transverse» operators (4 gauge tensors)

aQGC Limits @95% C.L. [TeV^4]
«Mixed» (2 and 2)

• In general excellent agreement with expectations

EFT D=8 SUMMARY
• Good agreement with SM
  • VBS VV exhibits a (not yet significant) \( \sigma > \sigma_{SM} \) trend, but not specifically at high energy \( \leftrightarrow \) EFT limits
  • Importance of modeling of all di-boson+2 jet QCD contributions at the best possible accuracy \( \rightarrow \) very challenging task, large amount of theory literature in recent years
CONCLUSIONS

- **VBF and VBS challenges**
  - Low yields and in most cases large irreducible backgrounds, multivariate analyses are a must
  - Needs modeling of QCD with 2 extra jets with best possible accuracy

- **VBS and VBS measurements**
  - Among the rarest processes ever measured
  - Evidence/observation and first cross-section measurements only possible thanks to partial or full LHC 13-TeV data
  - Access to elusive gauge self-couplings and NP limits from EFTs
  - VBS VV investigating EWSB at scales different from Higgs mass
    - Polarization measurements crucial, we have just started

**Full set of Run 2 results + LHC Run3 data essential to clarify global picture**