Vector Boson Scattering: Status and Prospects

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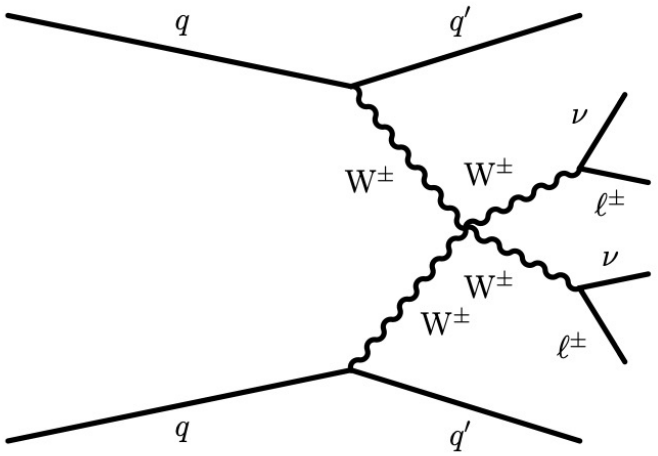
- ✓ Introduction
- ✓ VBS at the LHC
- ✓ Cross section and polarization
- ✓ VBS and BSM at Run3-5
- ✓ Future prospects beyond LHC

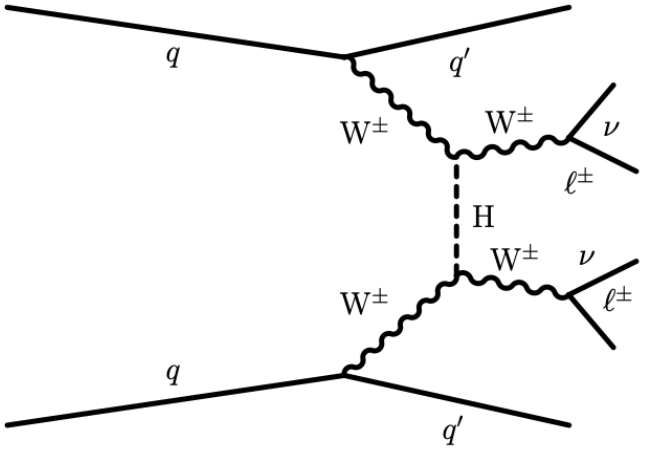
Planet Earth
Year 2022

= only

VBS and VBF

- VBF and VBS processes provide key measurements to probe the mechanism of EWK symmetry breaking and test effect of BSM models
- $V_L V_L \rightarrow V_L V_L$ scattering is unitarized by the interference with the H exchange





WW & WZ & ZZ

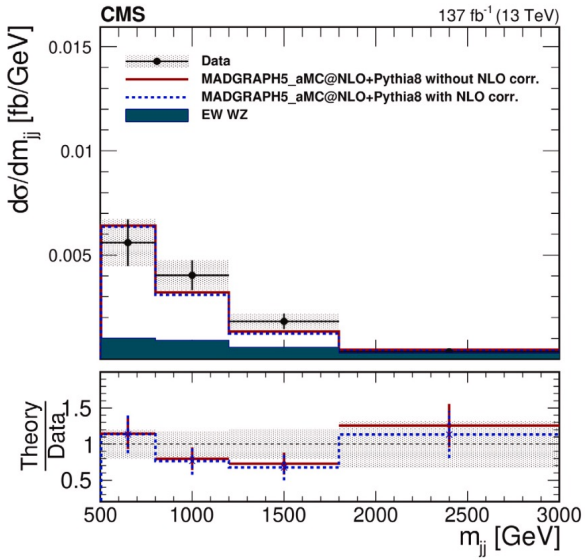
PLB 809(2020)135710, arXiv:2004.10612

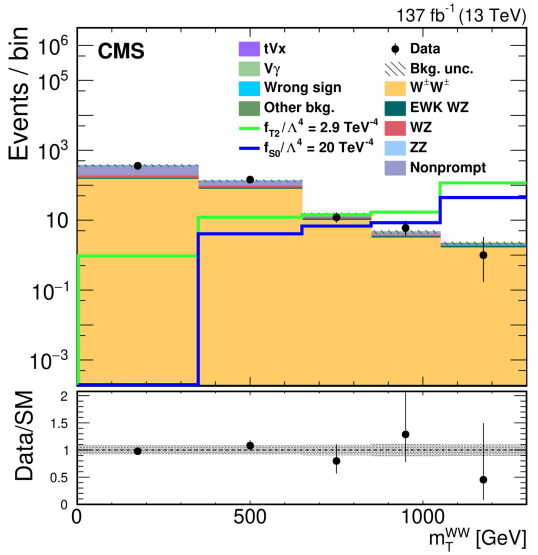
Study VVjj processes

- WWjj:
  - EW production dominant over QCD
  - Distinct same-sign (SS) lepton final state with low bkg (“golden channel”)
- WZjj:
  - Sensitive to charged resonances or couplings
  - Clean signature, larger bkg
- ZZjj:
  - Fully reconstructed final state provides maximal information

Absolute and normalized differential cross section measurements

EW WZ: 6.8(5.3)σ
EW WW: far above 5σ
EW ZZ: far above 5.5(3.9)σ





Polarization: VBS WW

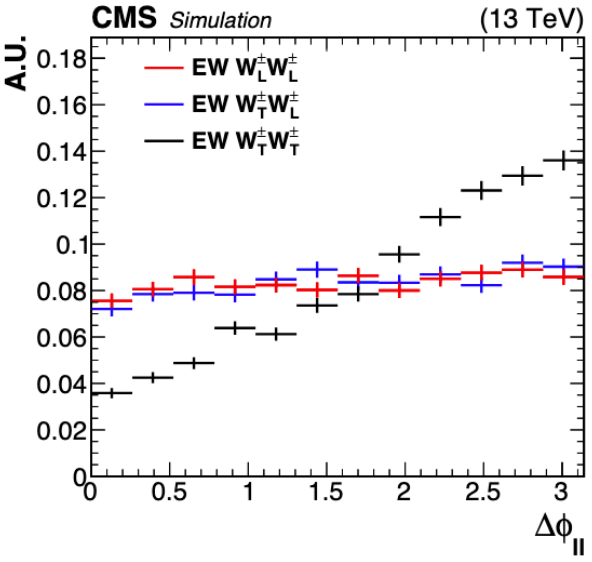
PLB 812(2020)136018

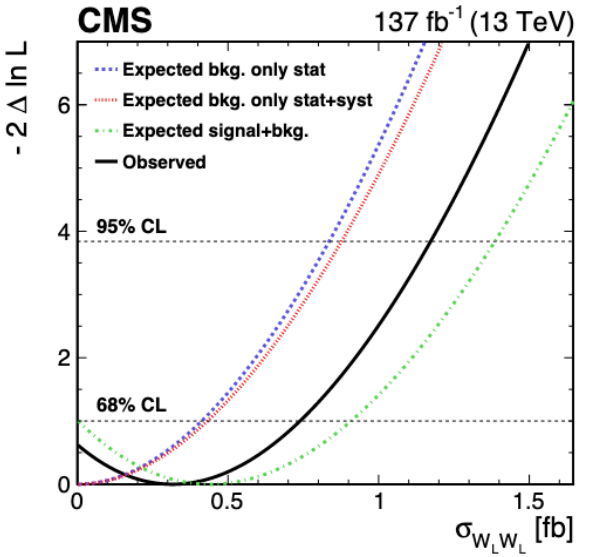
- Polarization measurements allow important tests of EWSB mechanism
  - Challenging since low expected yields for W_LW_L
  - four-momentum of W boson unknown
- EW production cross section of polarized WW
  - W and Z bosons have a spin 1 and can be longitudinally polarized as they are massive
- Polarization: simultaneous production of W/Z allows study fundamental interactions btw them

obs (exp) significance (W_LW_X): 2.3(3.1)σ

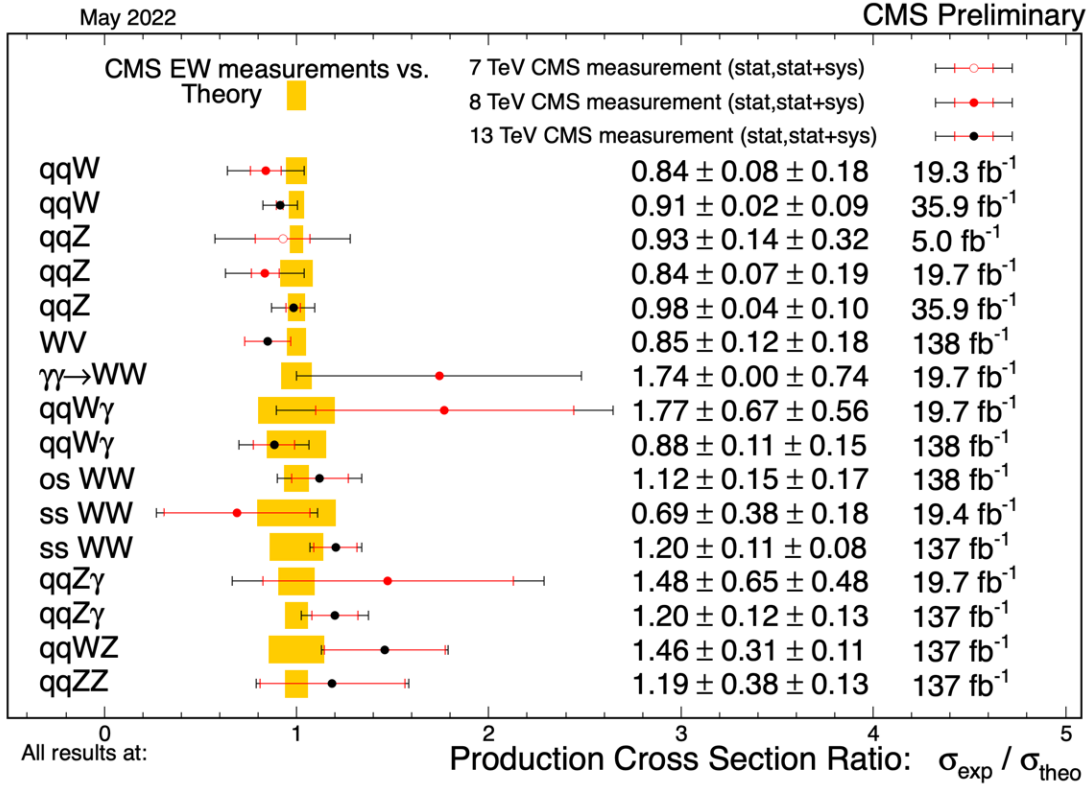
Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^\pm W_L^\pm$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^\pm W_T^\pm$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^\pm W_X^\pm$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^\pm W_T^\pm$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

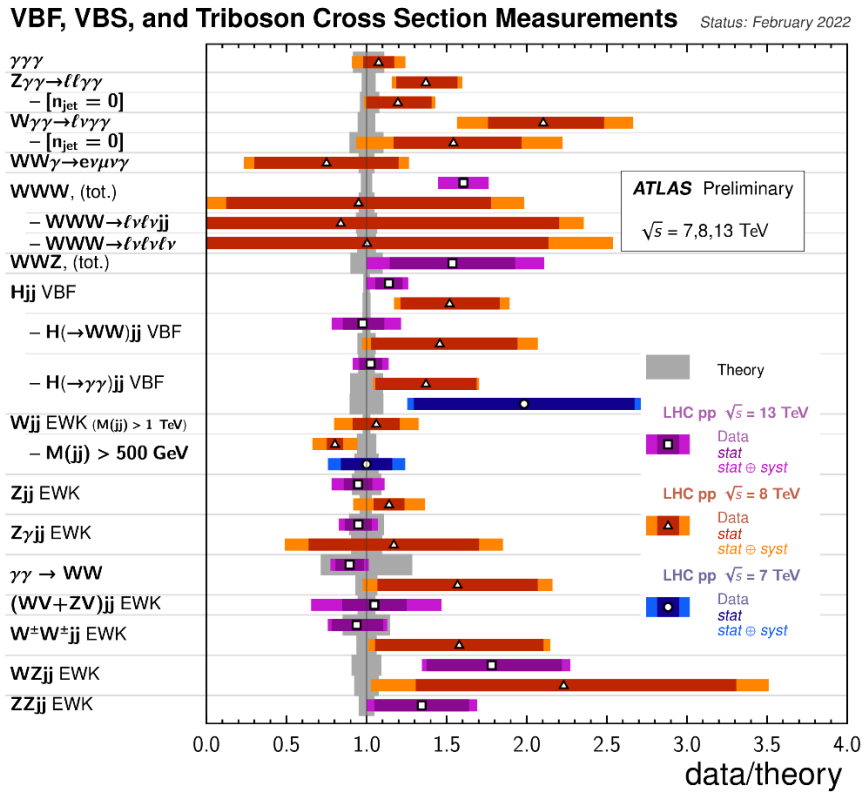
In the WW CoM frame





Cross section summary



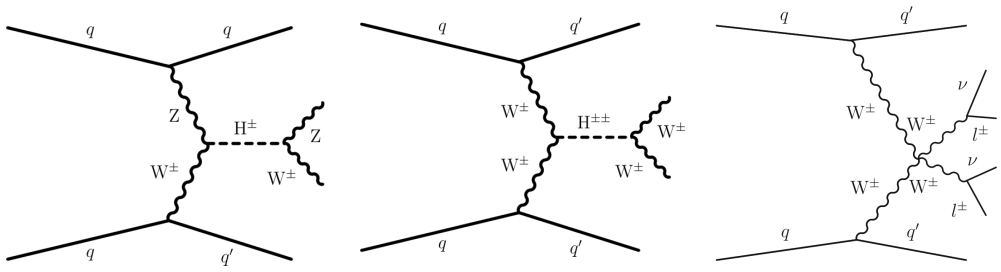


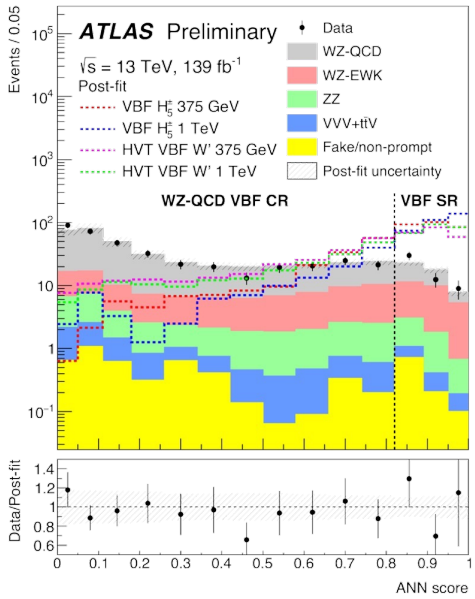
- Good agreement with SM
- Important to model QCD contribution: a challenging task

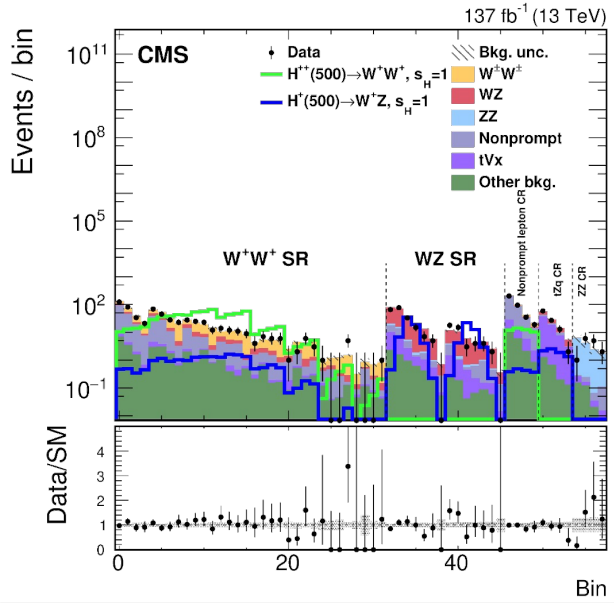
Charged Higgs etc.

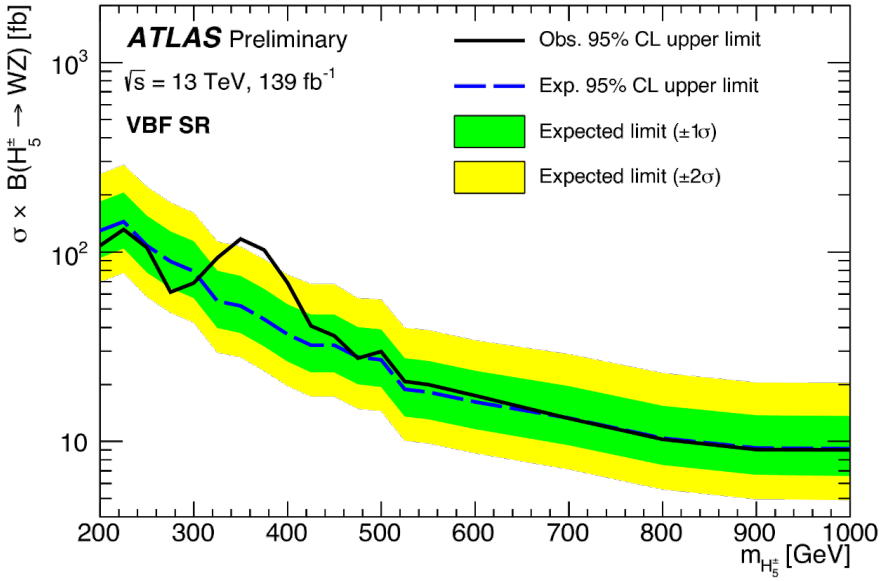
EPJC 81(2021)723, arXiv:2207.03925

- Search for charged Higgs in GM model: H^+ and H^{++}
- Search for resonant production
  - Only fermiophobic H^+ considered
  - Require 2/3 leptons
  - Good bkg description of data in SR









Anomalous couplings

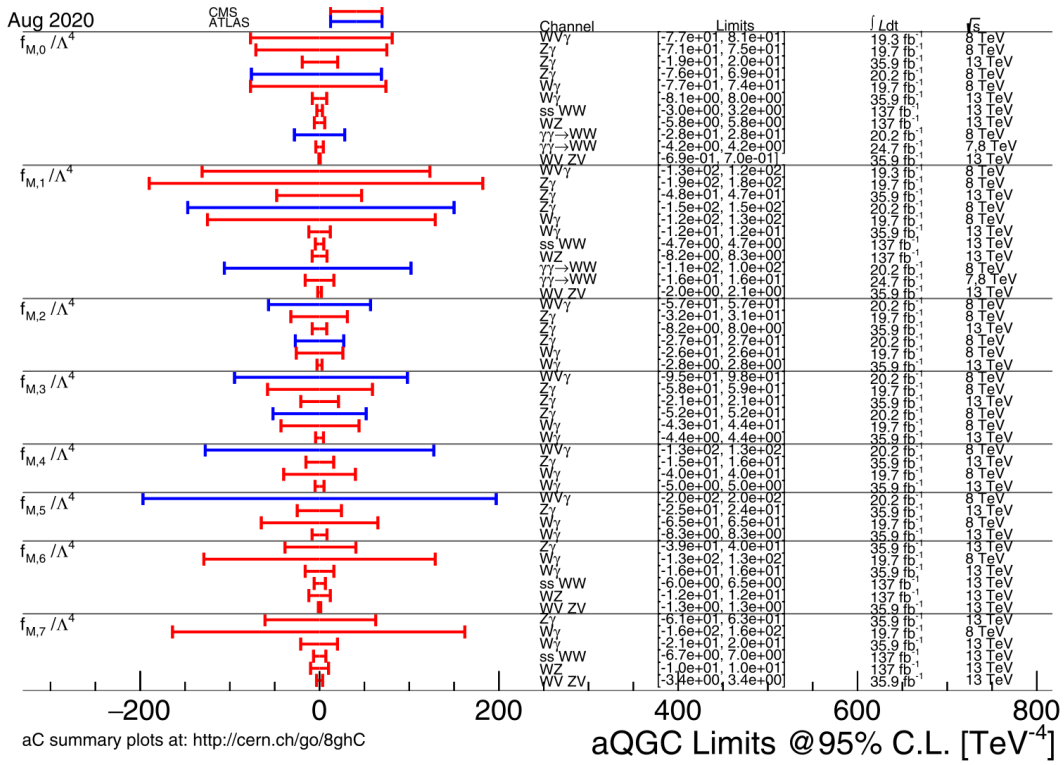
- Searches for BSM may be parametrized in the Effective Field Theory (EFT) approach
- Limits on aQGCs set using EFT. Dim-6 and dim-8 operators may modify VVjj production
  - Dim-5 operator may probe $0\nu\beta\beta$ and Lepton Number Violation (see prev. slide)

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \Sigma_i \frac{C_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots$$

- EFT amplitudes grow with M_{VV} and the growth is non-physical above a scale Λ. Sets limits on validity of EFT approach
- Replace EFT amplitudes with SM in $>\Lambda$ region ("clipping")

Gauge boson self-interactions

- SM precisely predicts strength of EWK gauge boson interactions
- Studied several processes sensitive to TGCs/QGCs
  - Charged TGCs/QGCs consistent with SM predictions
  - Neutral TGCs/QGCs forbidden
  - Processes may occur through higher-order diagrams at very low rates
- LHC provides the most sensitive limits

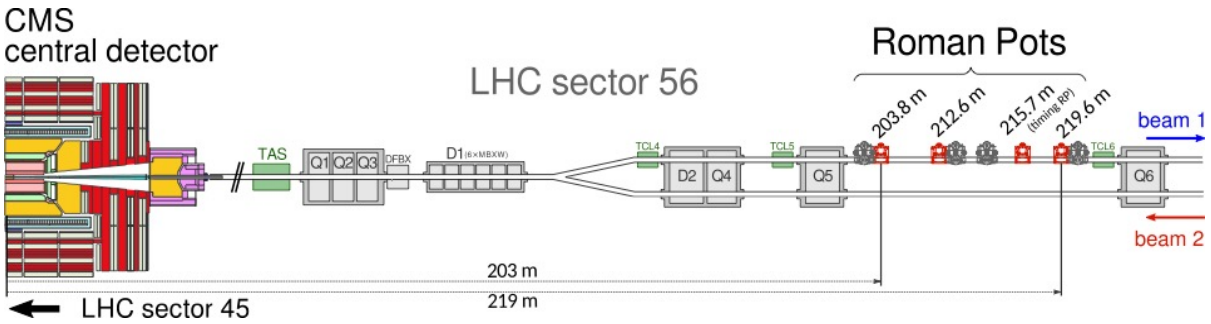


Physics w/ forward protons

JHEP 07(2018)153, CMS-EXO-21-007, CMS-TOP-21-007, CMS-EXO-19-009, CMS-SMP-21-004

Study photon-mediated processes

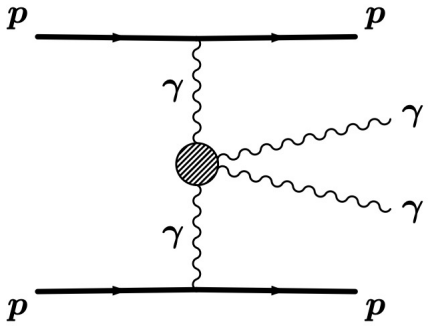
- Tag leading protons w/forward det.
- Small expected SM production
- Search for (non-)resonant excess in high-mass tails (AQGC/EFT)



Exclusive diphotons

CMS-EXO-21-007

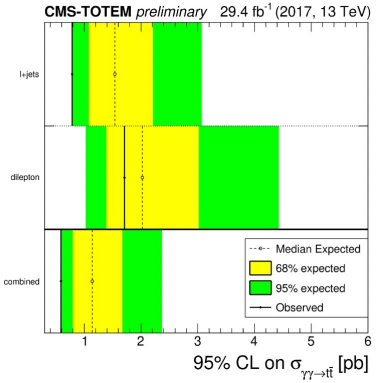
Light-by-light scattering: $\gamma\gamma \longrightarrow \gamma\gamma$, sensitive to ALPs, probe neutral QGC



Exclusive top quark pairs

CMS-TOP-21-007

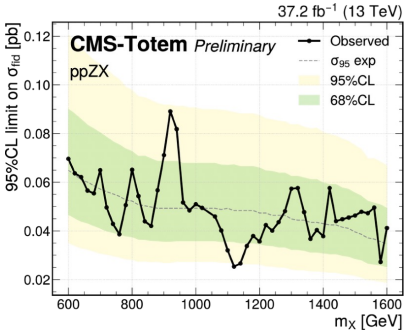
Search for central exclusive production of ttbar pairs in pp interactions with tagged protons



Zγ+X production

CMS-PAS-EXO-19-009

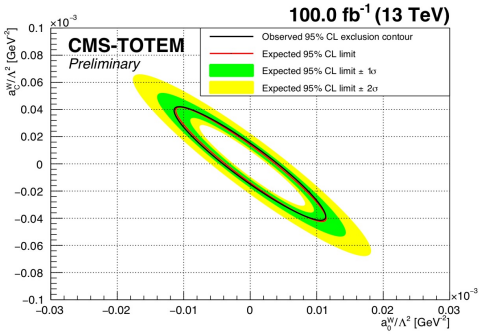
Search for anomalous Z/γ* central production



Exclusive WW/ZZ

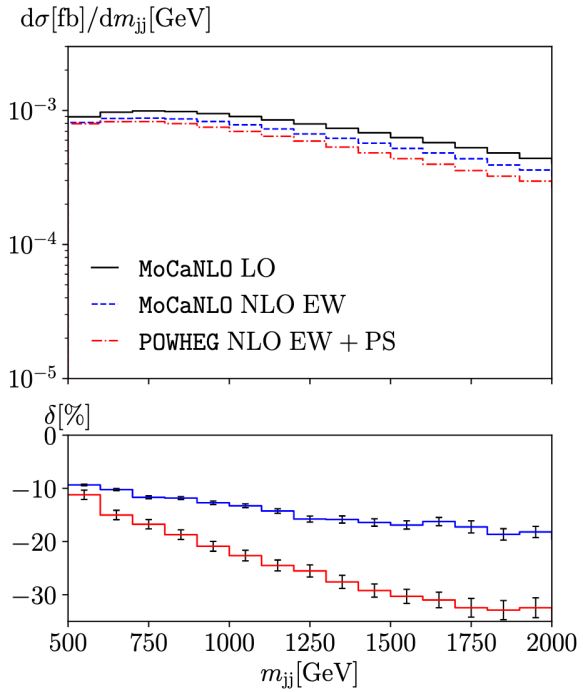
CMS-SMP-21-004

Search for $\gamma\gamma \longrightarrow$ WW/ZZ with forward protons

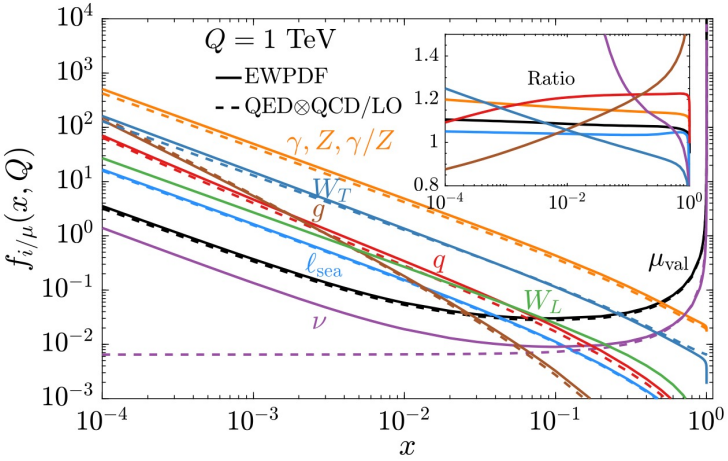


Theoretical predictions

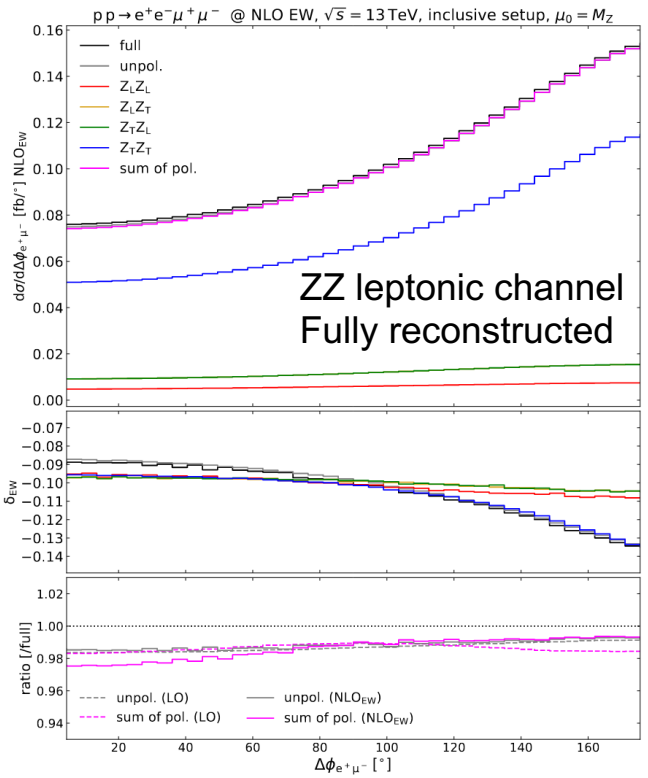
- Steady progress in computational techniques for VBS/VBF
  - NLO in EW, NLO in EW+QCD, PS beyond LL/N_C
  - EW@NLO in event generators
  - Include EW corrections in PS



- EW PDFs and their extrapolation to high-energy lepton colliders
  - Estimate PDFs for a high-energy muon beam
  - At Q=1 TeV, overall size of EW corrections is ~10-20% (much larger for specific final states)



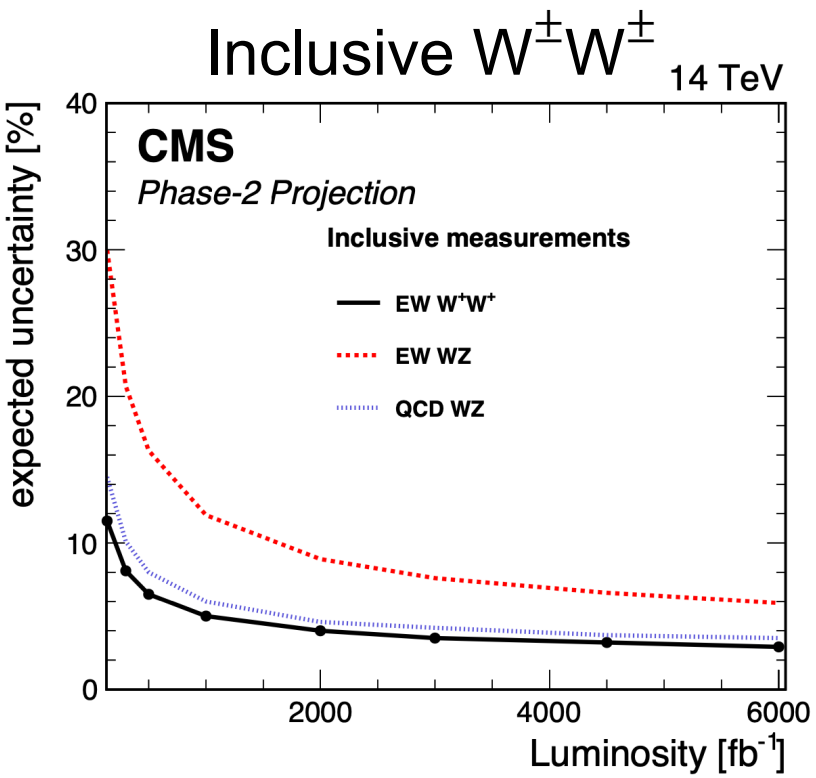
- Significant progress in computing helicity-polarized cross sections
  - Diboson at NLO in EW+QCD
  - Diboson at NNLO in QCD

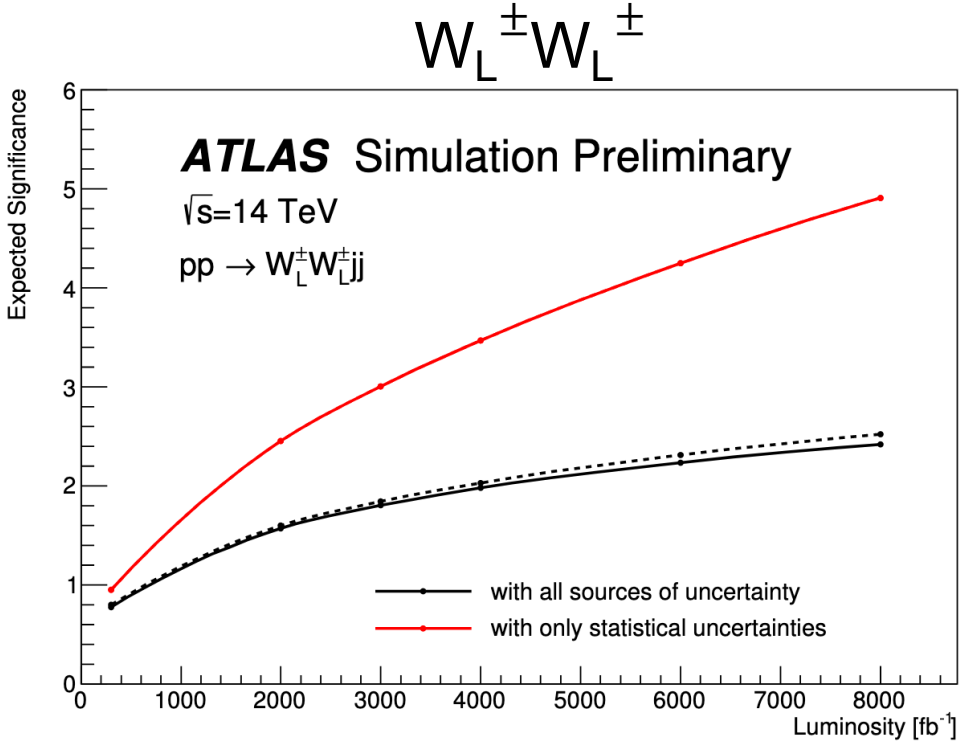


Prospects for HL-LHC

CMS-PAS-FTR-21-001, ATL-PHYS-PUB-2018-052

- Prospects for the study of VBS WW/WZ channels
  - Inclusive and polarized EW WW production





Based on existing 13 TeV results extrapolated to 14 TeV at HL-LHC

Detector upgrades @ HL-LHC

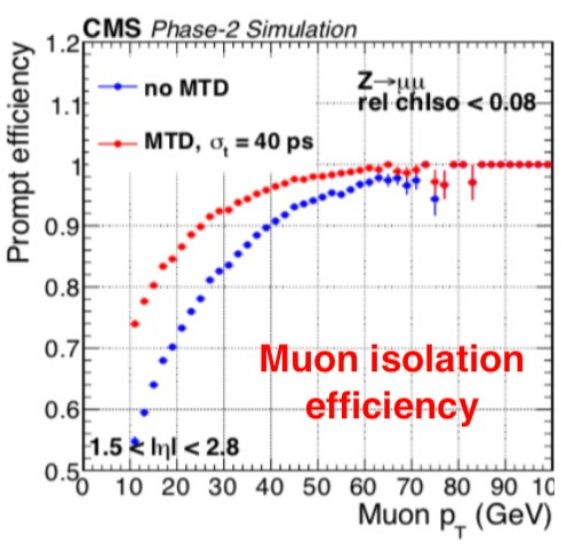
CERN-CMS-TDR-020

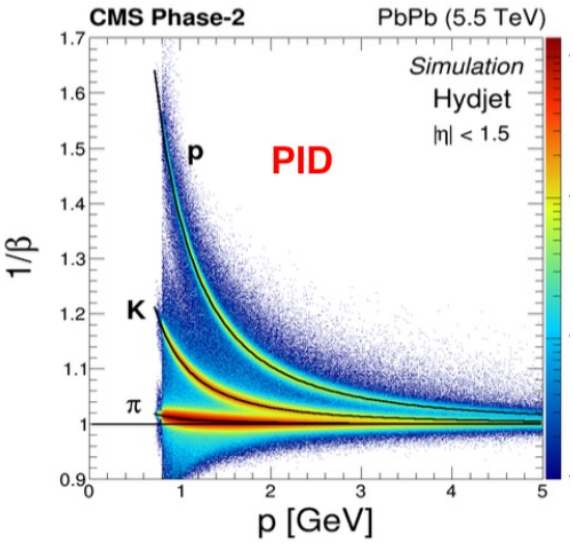
- Timing detectors: a new paradigm in HEP for PU rejection
- Improve particle reconstruction/ID
  - Increase object-ID efficiency and isolation
  - Improve missing transverse momentum resolution
  - Reduce fake jet reconstruction
  - Will help forward jet reconstruction in high PU
- 10%-20% gain in S/B in many Higgs decay channels

HH production sensitivity (sigmas) at 3 ab^{-1}

Channel	No MTD	$\langle\sigma_t\rangle$ 35 ps	$\langle\sigma_t\rangle$ 50 ps
bbbb	0.89	0.95	0.94
bbττ	1.3	1.58	1.48
bbγγ	1.7	1.85	1.83
bbWW	0.53	0.579	0.576
bbZZ	0.38	0.423	0.418
Combined	2.4	2.71	2.63
Luminosity gain	-	+26%	+20%

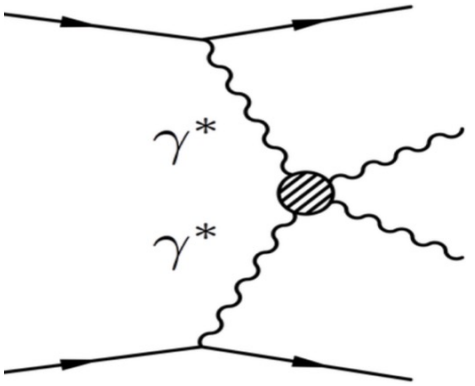
HL-LHC@140PU

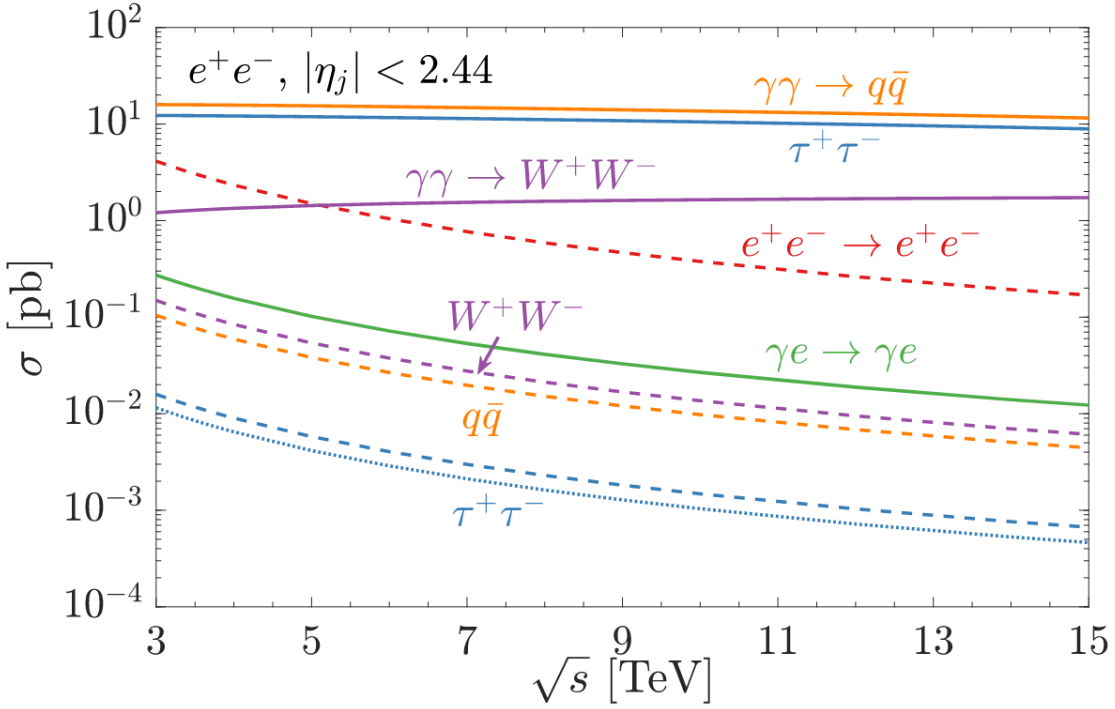




VBS @ Lepton Colliders

- Lepton colliders with $\sqrt{s}$~few TeVs have advantages to measure VBS processes
  - well defined initial state, separate spin, polarization, quantum numbers, etc.
- An e^+e^- collider (ILC or CLIC) can cover energies up to a few TeVs
- Photon-induced EW production of VBF/VBS becomes dominant at high $\sqrt{s}$

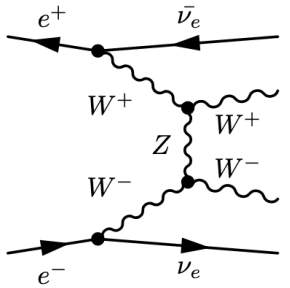


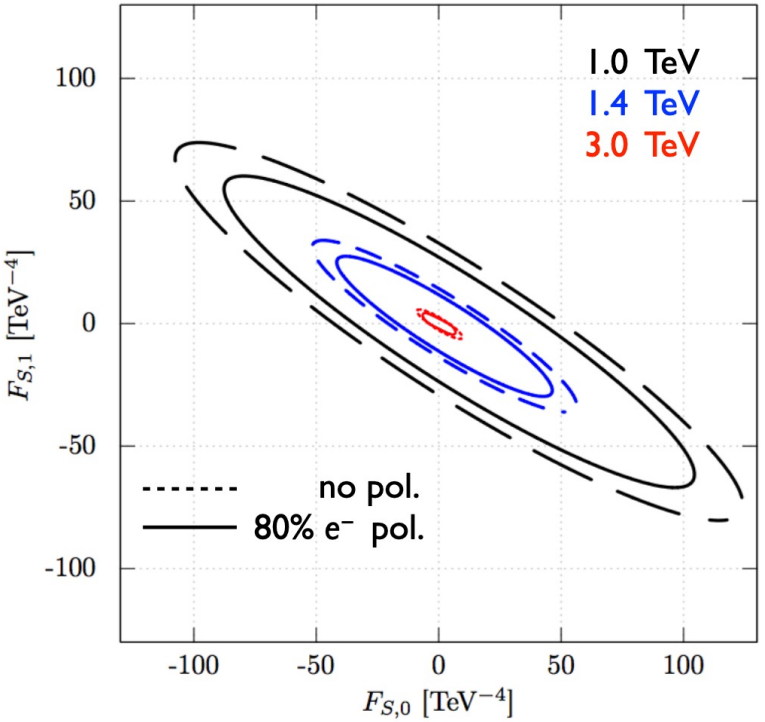


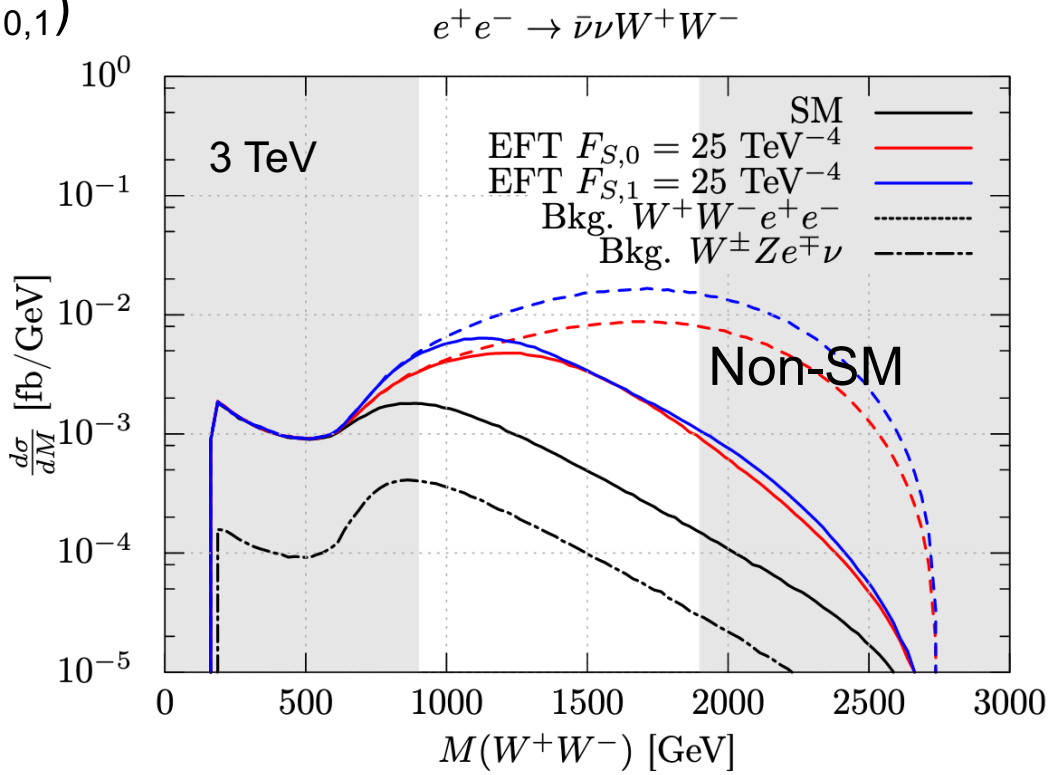
VBS at e^+e^- colliders: sensitivity

arXiv:1607.03030

- Polarized beams offer enhancement in sensitivity
  - Well defined initial state, clean final state
  - vs. EFT expansion parameters
- Differential cross sections with SM and non-SM values
  - Can probe dim-8 operators (ex. $F_{S,0,1}$)







Precision Higgs physics

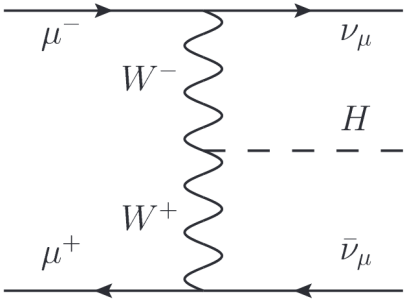
arXiv:2008.12204

- Higgs boson couplings to EW gauge bosons
- At high energy, H and HH production rely on VBF topology

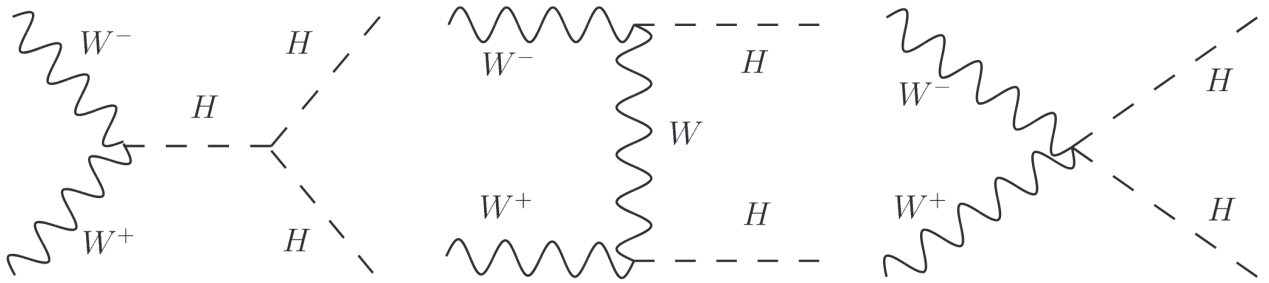
$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu\, H \qquad (WW \text{ fusion})$$
$$\mu^+\mu^- \to \mu^+\mu^-\, H \qquad (ZZ \text{ fusion}).$$

Muon collider vs other

$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)



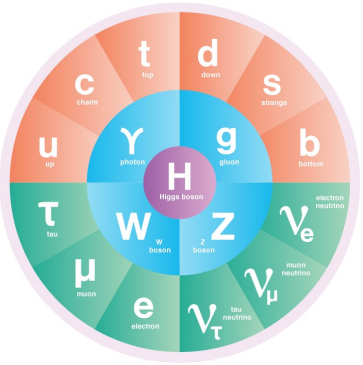
WWH/ZZHH couplings



HHH/WWHH couplings

Summary

- VBS to investigate SM and probe NP effects
  - Direct scrutiny of EWSB
  - Extensions to SM offer alternative EWSB mechanisms
- Several processes and final states investigated
  - Rare process, limited statistics
  - Indirect BSM studies with the EFT approach
  - Current and future studies at LHC and beyond
- VBS processes observed but need to be studied



⇒ Clean environment of lepton collider at highest energies is a fantastic opportunity for searches for NP in the EW sector

Introduction

arXiv:2106.01393

- Observation of the Higgs boson
  - Consistent with SM, within current uncertainties
  - W and Z acquire longitudinal polarization via the Brout-Englert-Higgs mechanism
- Is the Higgs the only player for the EWSB mechanism?
  - VBS is key process to test EWSB
  - Complementary to direct Higgs measurements
- LHC as a gauge boson collider to study VBS/VBF processes

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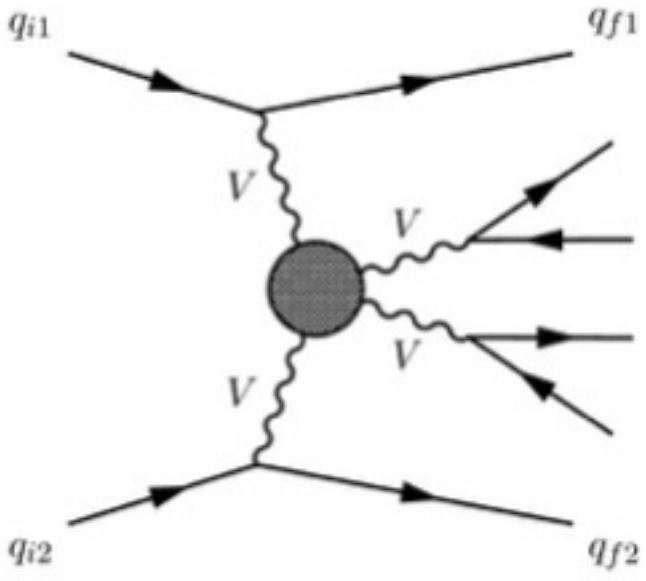
Motivation

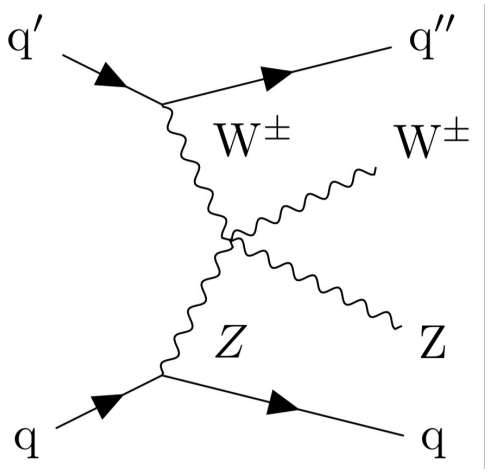
- Electroweak process characterized by VVjj (V=γ,W,Z) final state
- The physics potential
  - Precision test of EWSB at high energies
  - Probe the Higgs mechanism
  - Non-standard Higgs couplings
  - Higgs portal: New Higgs sector physics
- Probes nature of SM:
  - Direct access to triple/quartic gauge couplings
  - Sensitive to couplings btw Higgs and gauge bosons
  - Complementary to Higgs measurements at scales >m_H
- Portal to BSM:
  - Model-independent via EFTs (dim-6 and dim-8)
  - Constraints on aQGCs



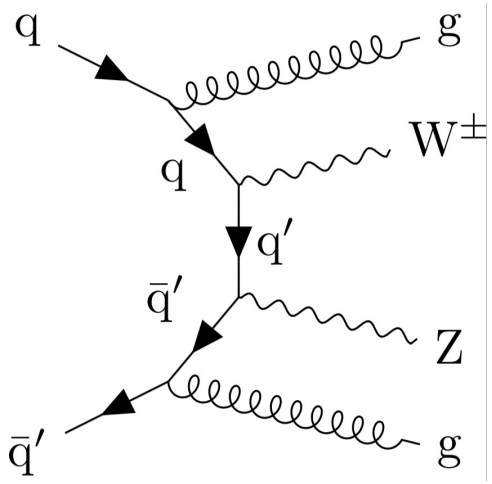
Signal and background

arXiv:2005.09889

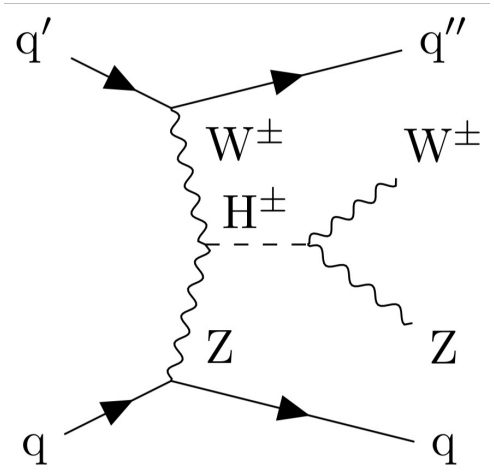
- VV production via vector boson scattering (V=W,Z,γ)
  - Purely EW process
  - QCD induced diagrams are treated as background
- V self-interactions (and with H) precisely predicted
- Deviations from predictions may signal new physics in EW sector
- Experimental challenges: rare process, precision?



VBS WZjj



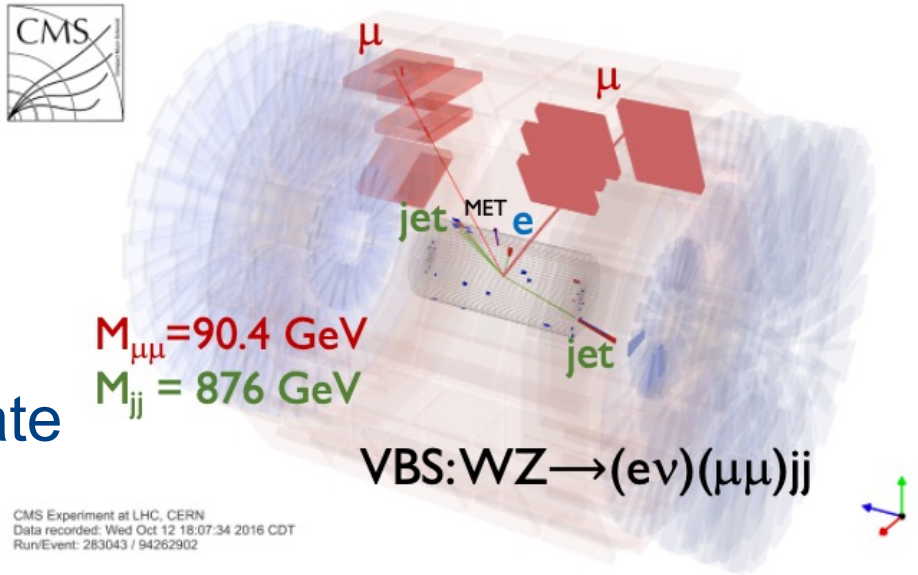
Non-VBS WZjj



BSM $H^{\pm}$

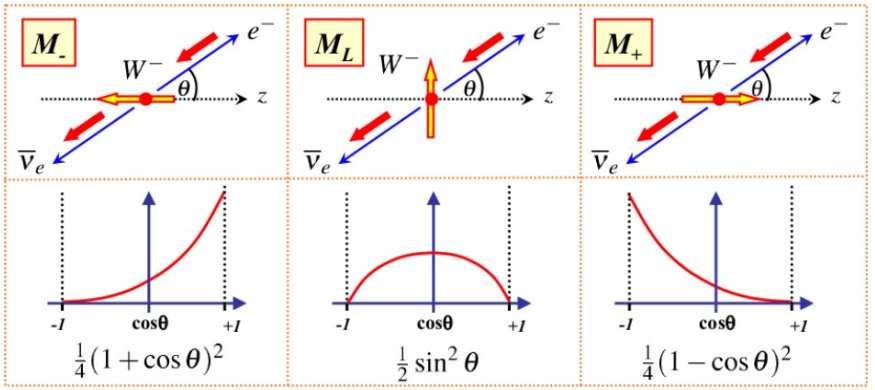
Experimental signature

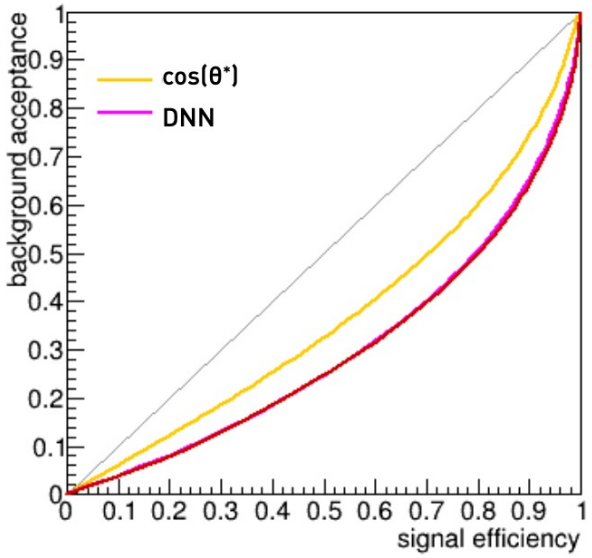
- Event topology
  - 2 vector bosons produced centrally
  - 2 energetic forward jets in opposite hemispheres
  - Large m_{jj} and $\Delta\eta_{jj}$
- Signature defined on diboson final state
  - Fully leptonic: 4 e/μ + 2 jets
  - Semi-leptonic/hadronic: 1(2) e/μ + jets
  - Fully hadronic: 4 or 6 jets
- Tree-level contributions to final state
  - EWK: signal component $O(\alpha_{EW}^4)$
  - QCD: background,$O(\alpha_{EW}^2\ \alpha_S^2)$, suppressed at high m_{jj}, high $|\Delta\eta_{jj}|$ region
  - Interference: O(%) of signal

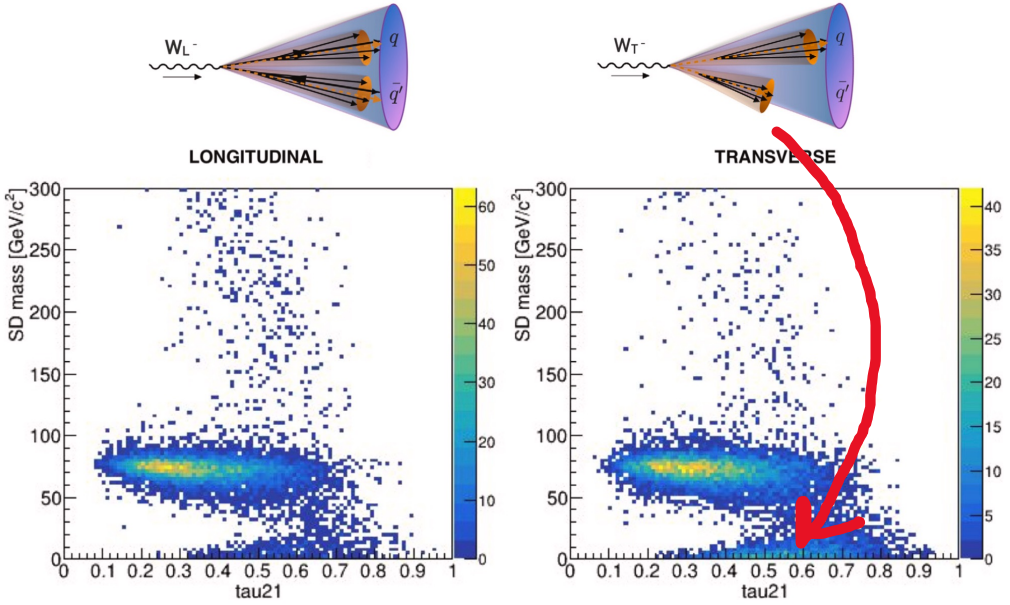


Advanced analysis methods

- Polarization in VBS
- discriminating power of W_T vs W_L in jet substructure
  - W_T decay products preferentially anti-parallel to W momentum
    →*asymmetry in p_T btw sub-jets*





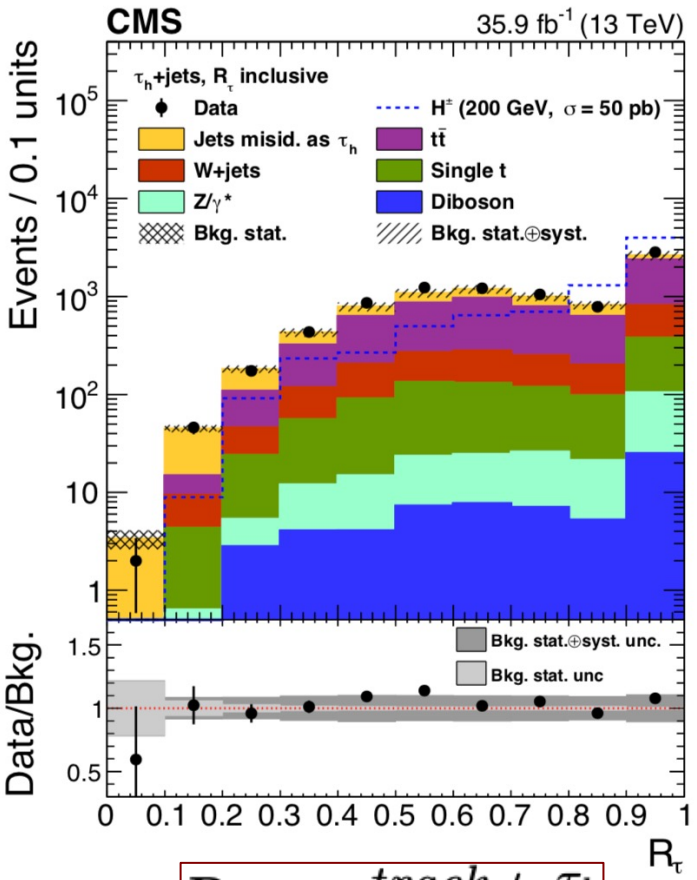


Tau leptons

arXiv:1903.04560

Final processes with taus in the final state

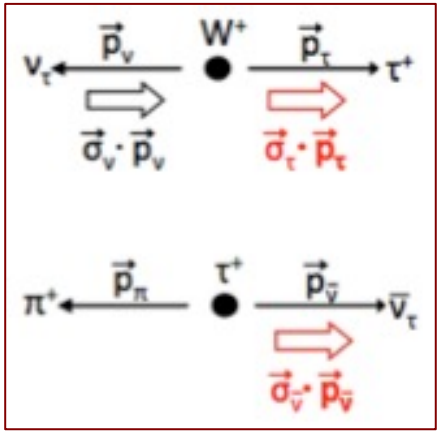
- Not yet studied in VBS processes
- cross section measurements including τs
- Includes only 3rd generation quarks/leptons
- Syst unc: tauId, fakes
- If special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W



$$R_\tau = p_T^{track}/p_T^{\tau_h}$$

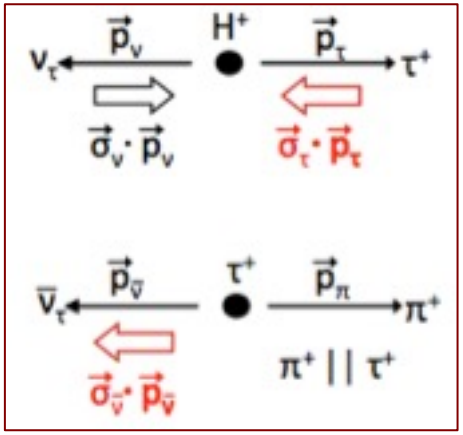
Use R for signal extraction: binned maximum likelihood fit

SM



vs

BSM

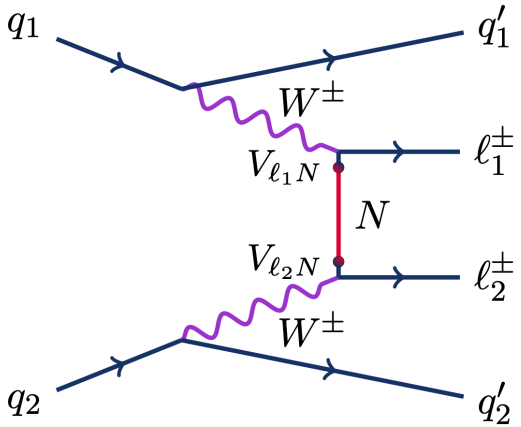


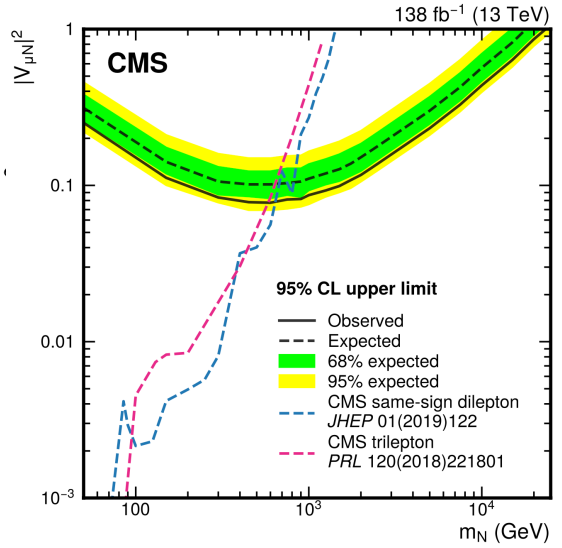
Exotic searches

arXiv:2011.02547, arXiv:2206.08956

High mass sensitivity at LHC driven by $W\gamma$ and $W^{\pm}W^{\pm}$

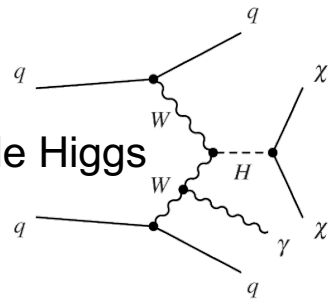
- Type I seesaws hypothesize a new scalar singlet ν_R
  - Sterile neutrino N and mixing $|V_{\ell N}|^2$ accessible with VBF/VBS
  - Probe heavy neutrinos
  - Test dim-5 Weinberg operators



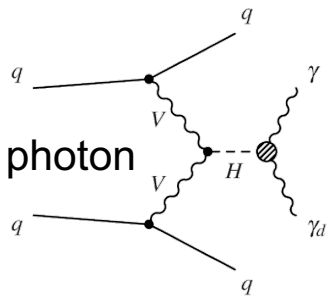


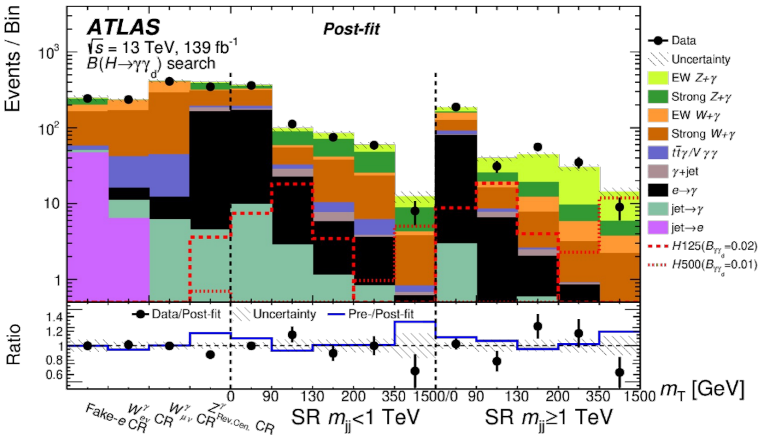
- Isolated photon + invisible
- SM: $Z(\rightarrow\nu\nu)\gamma jj$
  - $O(\alpha_{EW}^5)$ process
- BSM
  - $H\rightarrow\gamma+\gamma_D$
  - $H\rightarrow$*invisible* $+\gamma$

Invisible Higgs



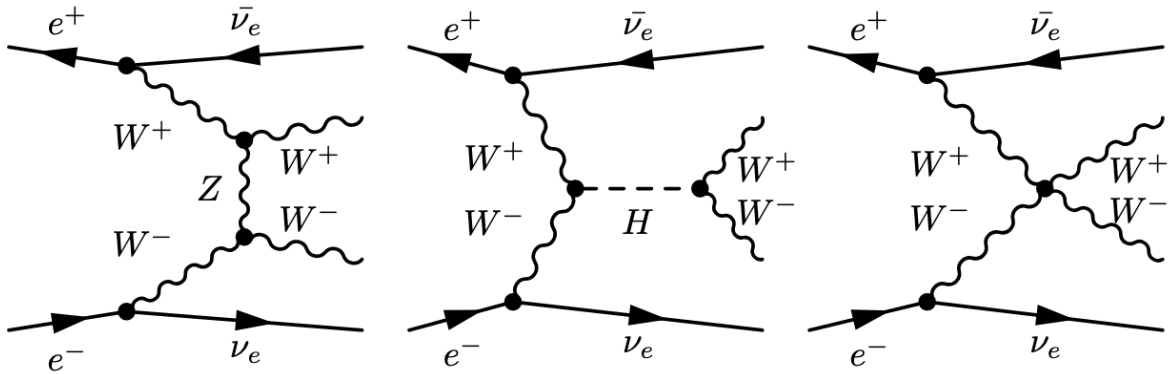
Dark photon



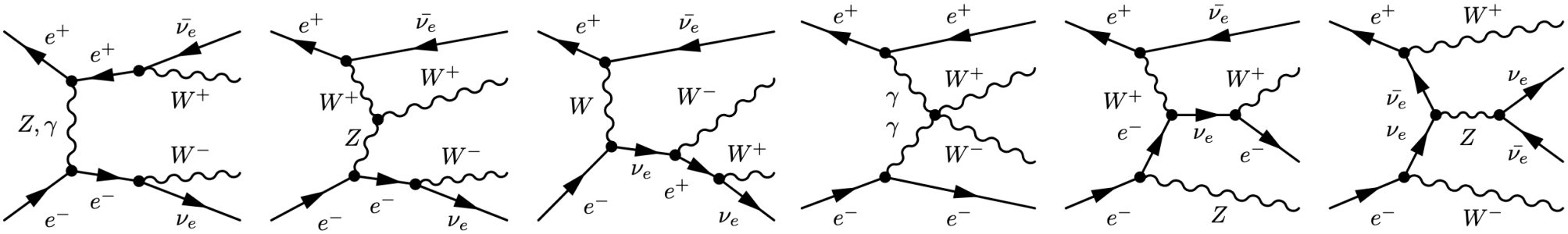


VBS at e^+e^- colliders

- Signal: triple gauge couplings, Higgs VV couplings, quartic gauge couplings



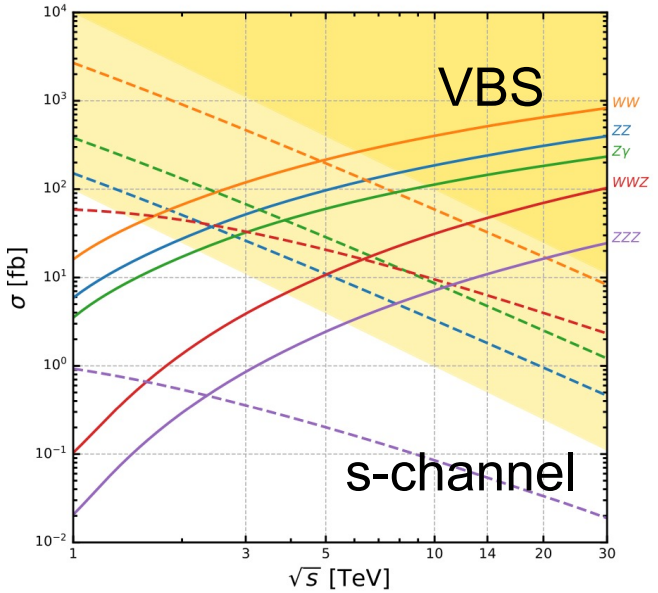
- Backgrounds

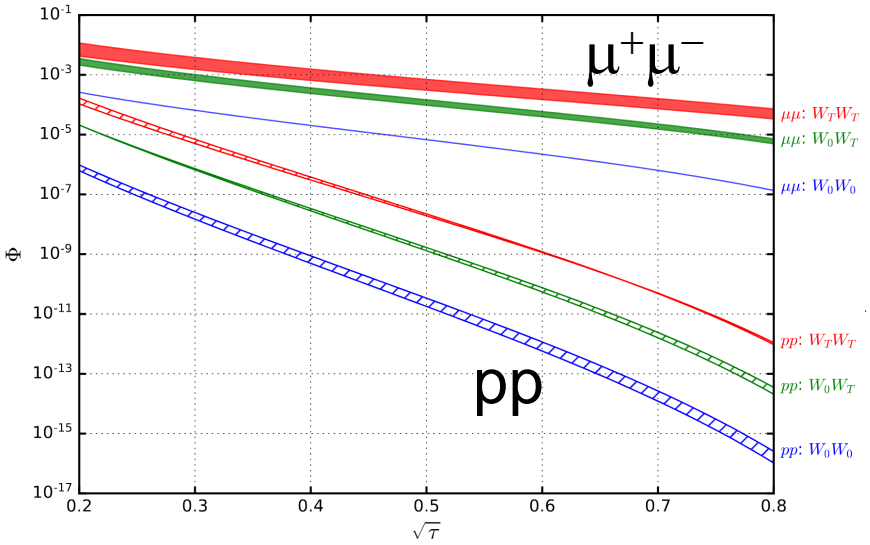


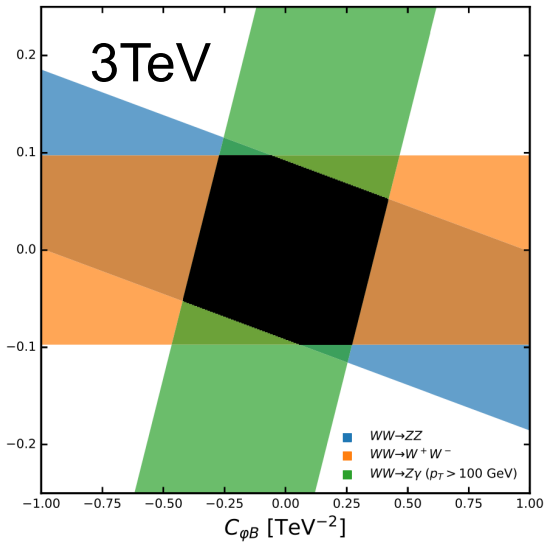
VBS @ muon collider

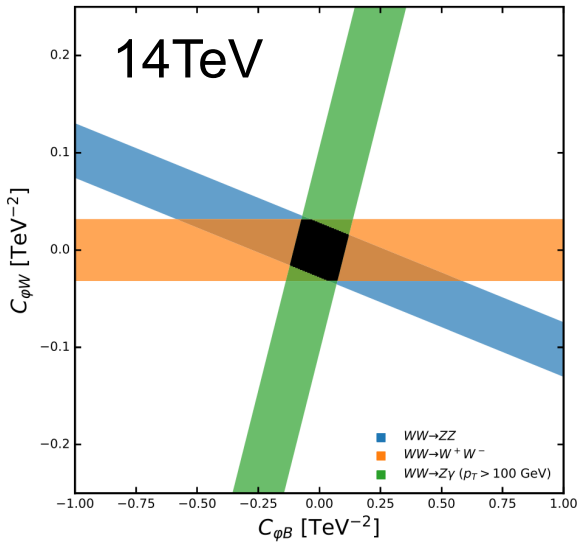
Multi-boson production WW/ZH production

- same physics at e^+e^- & $\mu^+\mu^-$ colliders (except m_e vs m_μ)
- VBS takes over at $\sqrt{s}$~2-3TeV
- WW parton luminosities exceed those at pp collider
- WW at 14 TeV with 20ab^{-1} can probe dim-6 operators



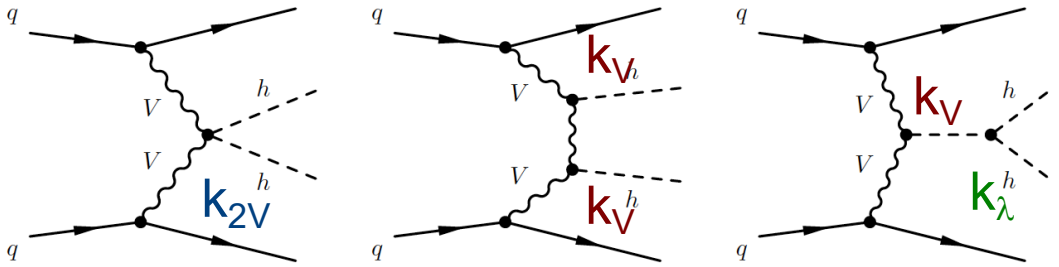


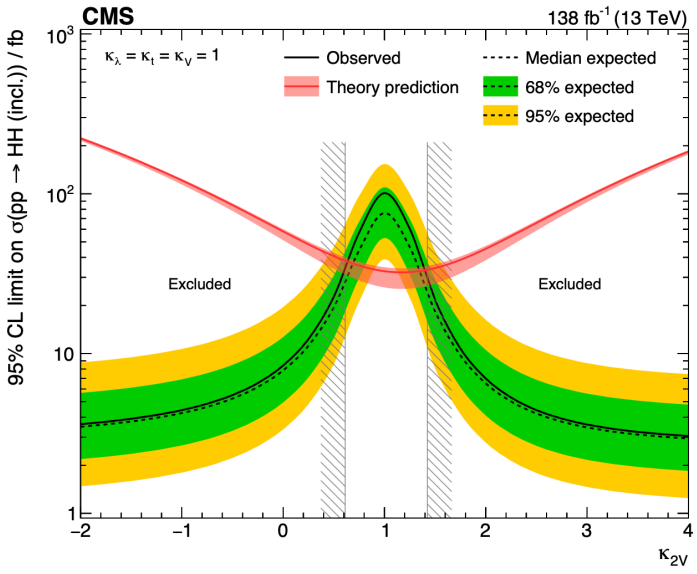


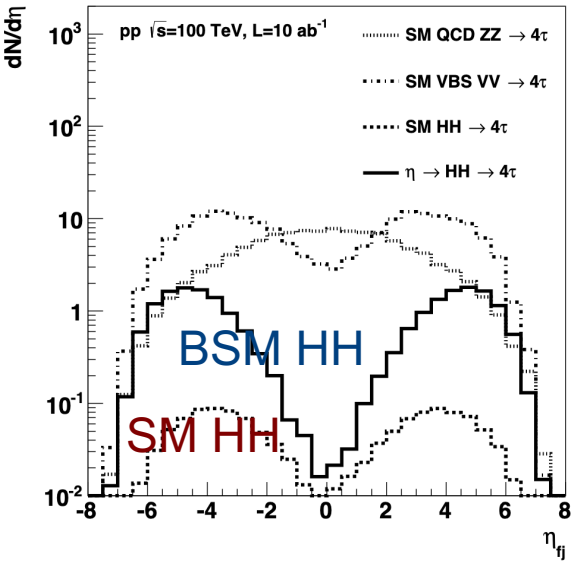


Higgs pair production: VBF

- Higgs pair production gives access to Higgs self-coupling
- HH is one of the main goals @LHC and beyond
  - ggF and VBF production
  - Rare process
  - Both non-resonant (SM) and resonant (BSM) production
- 4-5σ sensitivity can be reached at HL-LHC
- 1% (?) precision can be achieved at 100TeV

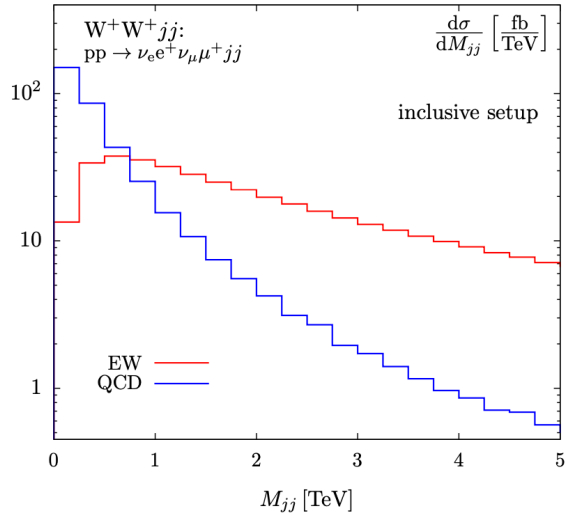


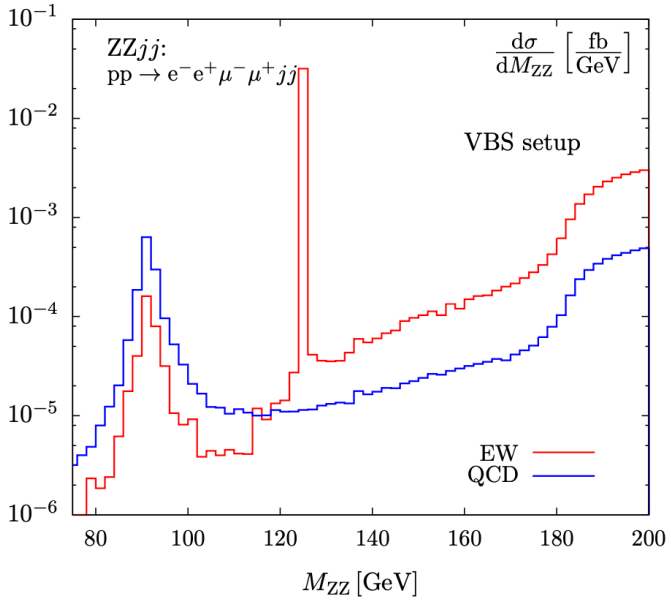


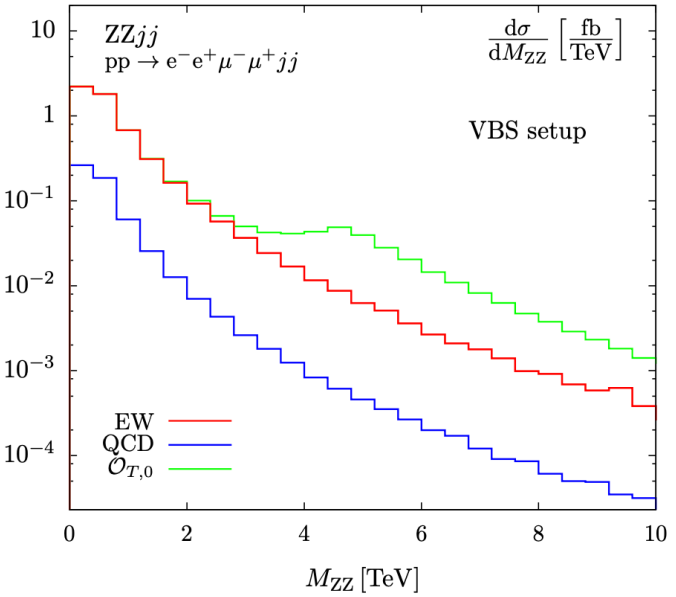


VBS @ 100 TeV

- VV leptonic final states
  - Final state fully reconstructed
  - Consider EFT dim-8 operators
- pp→ ZZjj
  - Sensitive to scalar resonances, background to VBF H production







$W_L W_L$ @ 100 TeV

- $W_L W_L$ scattering relevant for VVH coupling
- Longitudinal component extracted from angular distribution of the two leptons
- Extract HWW coupling mod. constraints k_W