Vector boson Scattering

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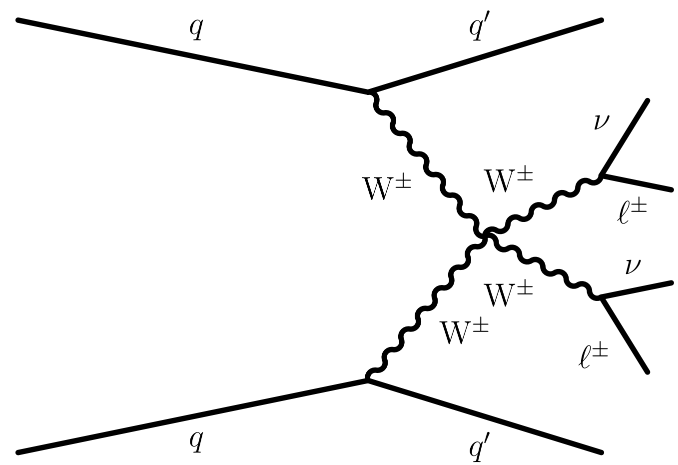
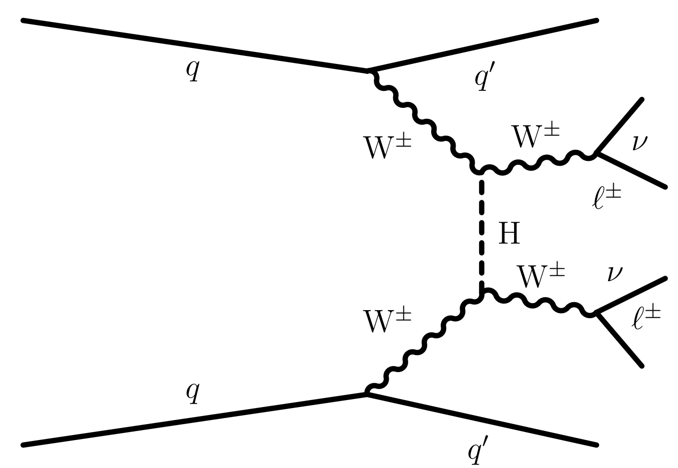
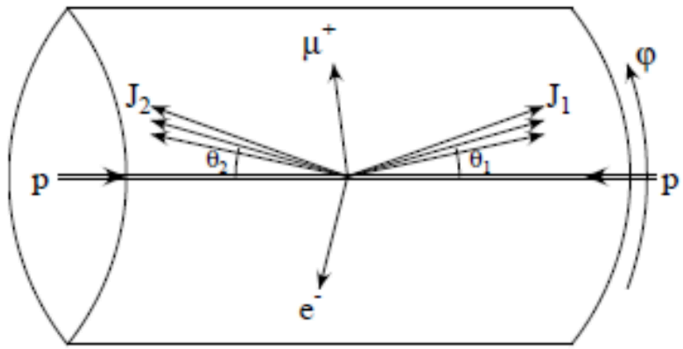
EF04 Topical Group Community Meeting

Vector boson scattering

- VBS VV->VV scattering
- Key measurements to fully explore EWSB and probe for BSM models
- $V_L V_L \rightarrow V_L V_L$ scattering unitarized by the interference with amplitudes involving Higgs bosons
    - Window for new physics
- Anomalous triple and quartic gauge boson couplings

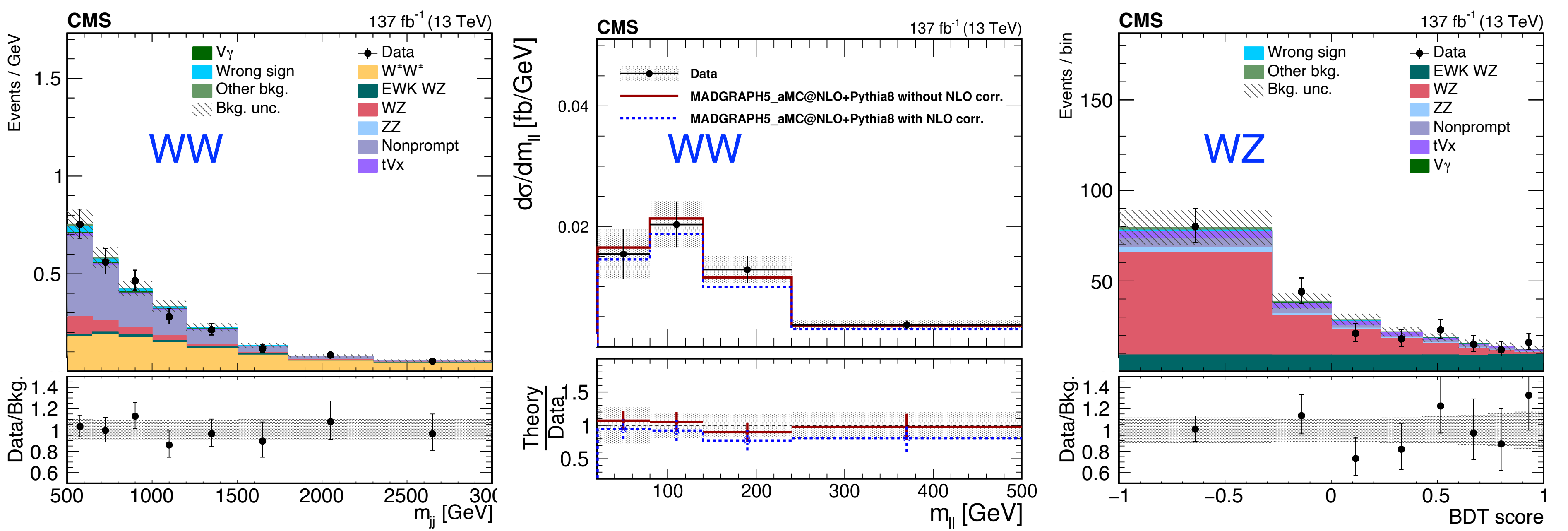






Latest LHC Run 2 measurements

- Measurements of WZjj and same-sign WWjj production cross sections in fully leptonic final states (arXiv: 2005.01173)
  - First differential cross section measurements of same-sign WWjj process
    - Fiducial cross section measurement with a precision of roughly ~10%
  - EW WZ measurement by CMS (6.8 sigma)



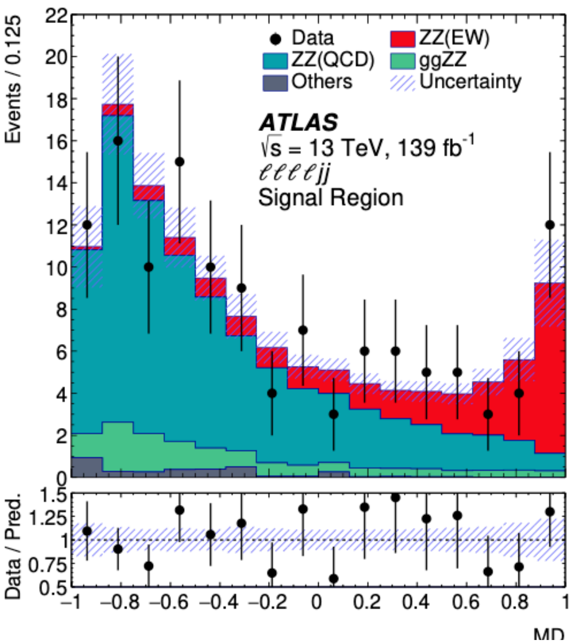
Latest LHC Run 2 measurements

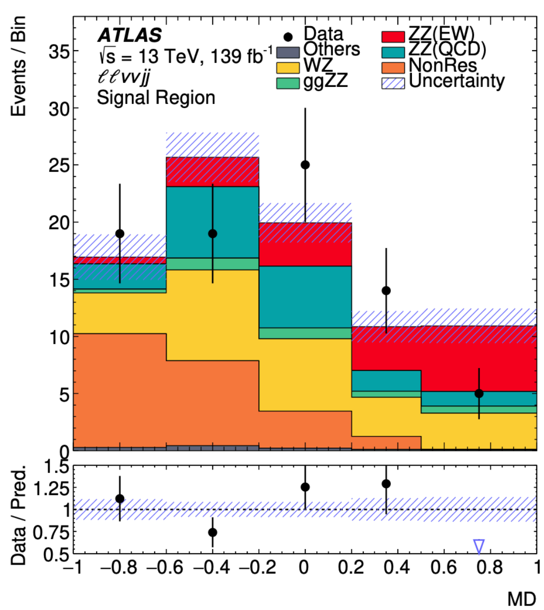
- Measurements of WZjj and same-sign WWjj production cross sections in fully leptonic final states (arXiv: 2005.01173)
  - First differential cross section measurements of same-sign WWjj process
    - Most accurate to date, with a precision of roughly 10%
  - EW WZ measurement by CMS (6.8 sigma)

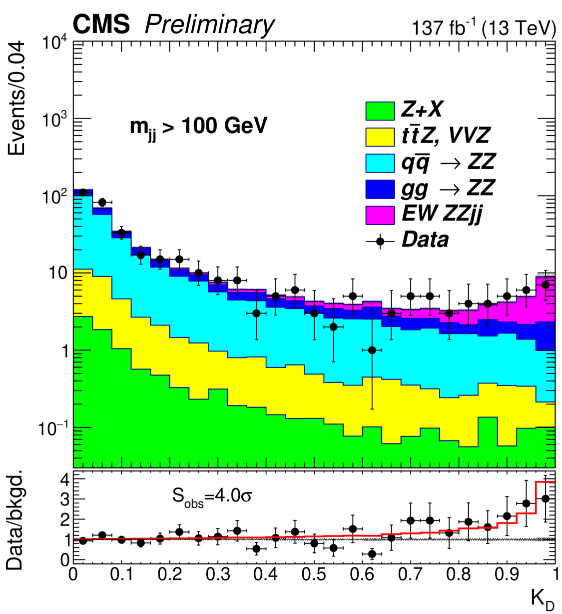
Process	$\sigma \mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 $0.39\,(\text{stat}) \pm 0.14\,(\text{syst})$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 $0.40\,(\text{stat}) \pm 0.23\,(\text{syst})$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 $0.45\,(\text{stat}) \pm 0.18\,(\text{syst})$	3.12 ± 0.70	3.12 ± 0.70

Latest LHC Run 2 measurements

- Observation of EW ZZjj production
  - ATLAS observation with 5.5 (4.3 expected) sigma (arXiv: 2004.10612)
    - 4lepton + 2l2nu final staes
  - CMS evidence with 4 (3.5 expected) sigma (CMS-SMP-20-001)
    - 4lepton final state





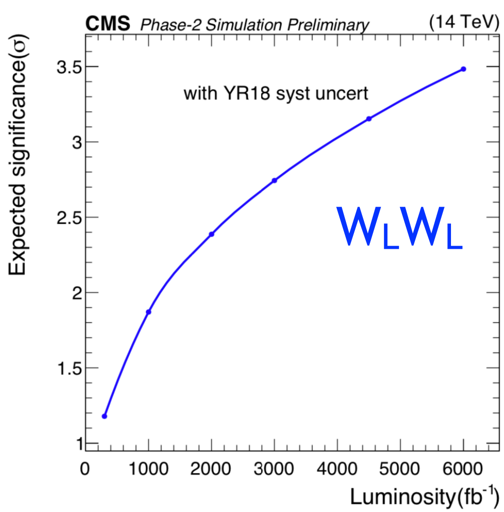


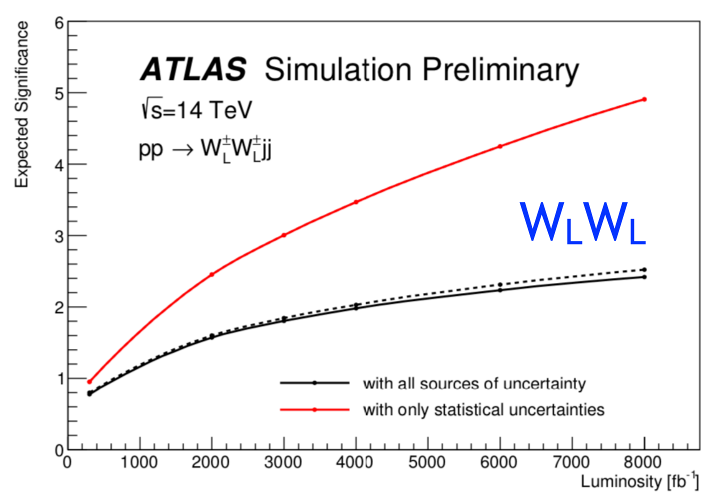
HL-LHC and HE-LHC

- Studies of same-sign WW, WZ, and ZZ processes at HL-LHC and HE-LHC
  - CERN-LPCC-2018-03
  - Access to longitudinal scattering

process	$\sqrt{S} = 14$ TeV	$\sqrt{S} = 27$ TeV
W^+W^+jj	2.33 fb	8.65 fb
W^+W^+jj ($\lvert\Delta y_{jj}\rvert$>2.4)	2.49 fb	9.11 fb
W^+Zjj	0.82 fb	3.16 fb
$ZZjj$	0.11 fb	0.44 fb

Z_LZ_L	significance	
	w/ syst. uncert.	w/o syst. uncert.
HL-LHC	1.4σ	1.4σ
HE-LHC	5.2σ	5.7σ





For discussion

- Which future collider option maximizes the BSM physics potential for the VBS processes?
  - Can we have a quantitative answer to this question as an outcome of these Snowmass studies?
- Collider options to consider:
  - e-collider (several to many TeV)
  - mu-collider (several to many TeV)
  - p-collider (FCC-hh, SPPC)
  - e-collider (Higgs factory, TerraZ, etc.)
    - Precision measurements of Higgs/EW sector, shorter timescale
- What benchmarks to use to compare different collider options?
    - EFT dim-6 operators?
    - EFT dim-8 operator?
    - New physics models (for example Georgi-Machacek?)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

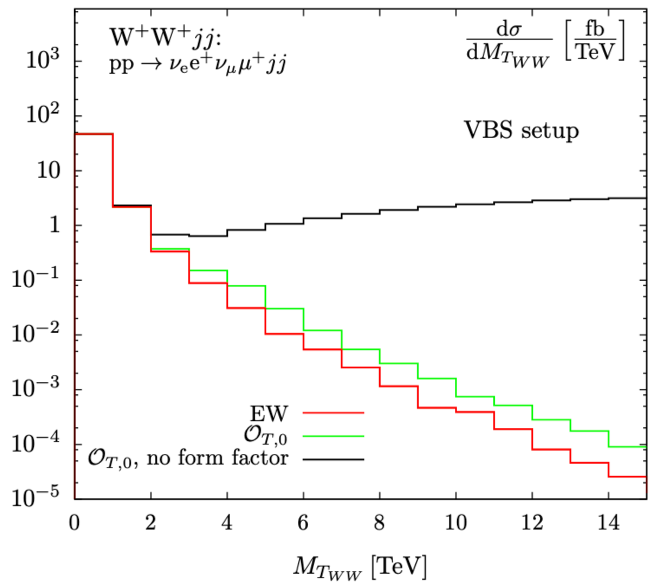
100 TeV hadron collider

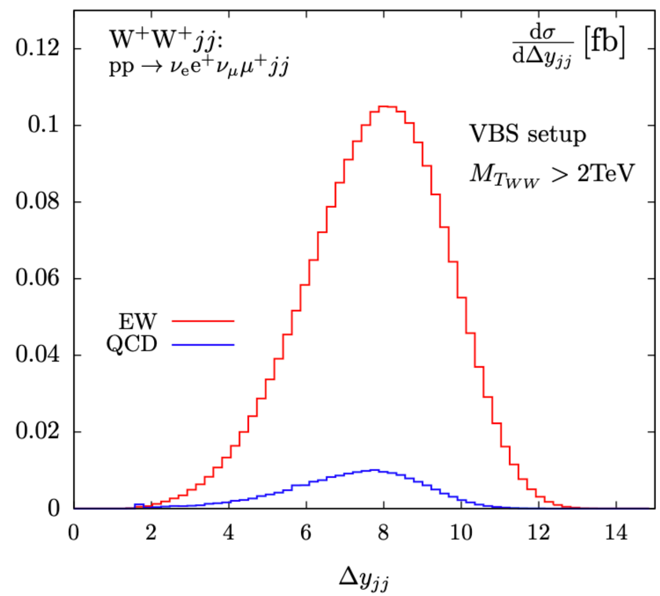
- Interesting studies for pp 100 TeV collider (arXiv:1704.04911)
  - Opportunity to study kinematic range not accessible to present colliders
    - Forward rapidity coverage is important

$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger(D^\mu\Phi)\right] \times \left[(D_\nu\Phi)^\dagger(D^\nu\Phi)\right] ,$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger(D^\mu\Phi)\right] ,$$
$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] ,$$

FT0=0.1/TeV^4, L=30ab^{-1}

VBS channel	σ_S [fb]	σ_B [fb]	S/B	$S/\sqrt{B}$	$S/\sqrt{S+B}$
W^+W^+jj	0.66	0.52	1.27	159	105
W^+Zjj	0.061	0.055	1.11	45	31
$ZZjj$	0.22	0.12	1.83	110	65
W^+W^-jj	4.8	8.2	0.58	290	231

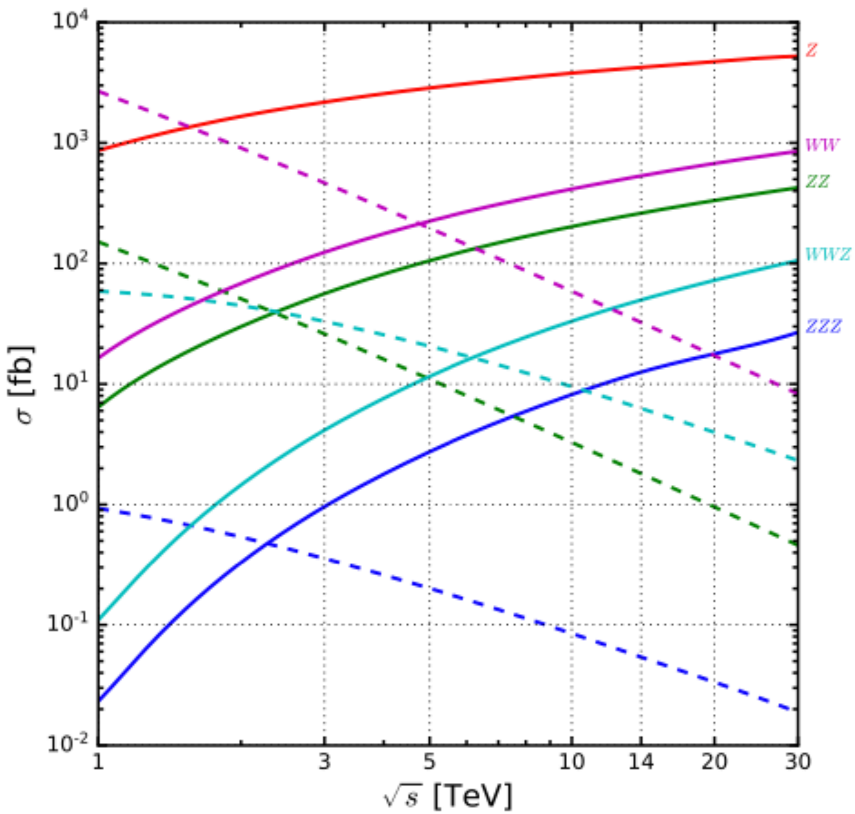




VBS example (mu-collider)

- Cross sections of VBS process in a recent paper (arXiv:2005.10289)
  - mu-collider at few ~TeV is a high luminosity boson collider!
  - Production cross sections grow as logs while the corresponding s-channel decrease as 1/s

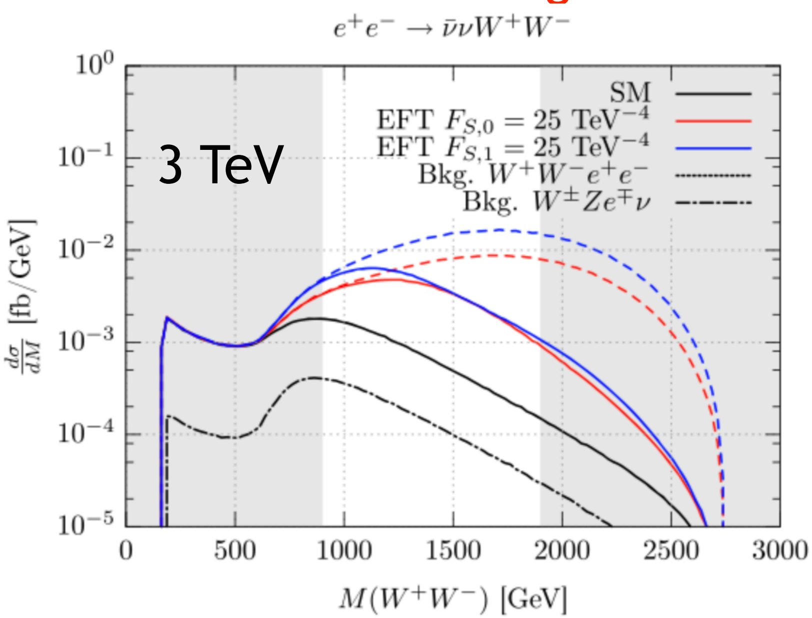
- These promising results motivate further detailed analysis of VBS in mu-colliders
  - Kinematic distributions
  - Background processes
  - “Clean environment" compared to harden colliders



dashed->s-channel

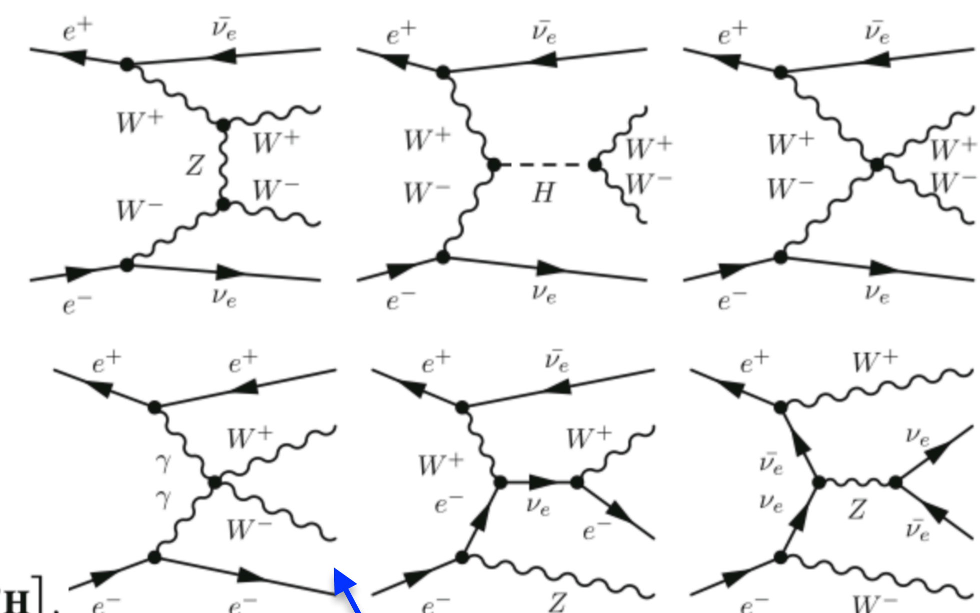
VBS example (TeV e-collider)

- Similar considerations as in previous slide apply to e-colliders
  - Recent studies of scattering of W/Z bosons at high-energy lepton colliders (arXiv:1607.03030)
    - More detailed comparisons of sensitives should be done to benchmark against mu- and hadron-colliders



$$\mathcal{L}_{S,0} = F_{S,0}\,\mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger\,\mathbf{D}_\nu\mathbf{H}\right]\mathrm{tr}\left[(\mathbf{D}^\mu\mathbf{H})^\dagger\,\mathbf{D}^\nu\mathbf{H}\right],$$

$$\mathcal{L}_{S,1} = F_{S,1}\,\mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger\,\mathbf{D}^\mu\mathbf{H}\right]\mathrm{tr}\left[(\mathbf{D}_\nu\mathbf{H})^\dagger\,\mathbf{D}^\nu\mathbf{H}\right].$$

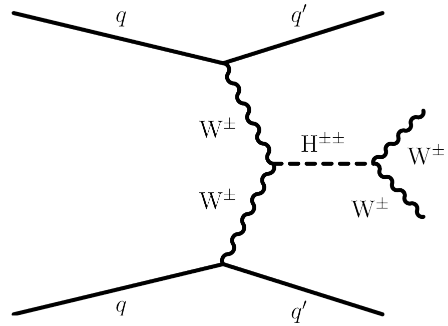


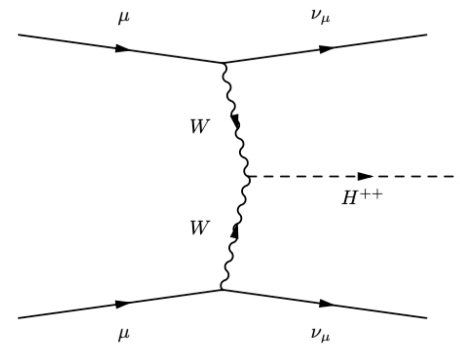
Partially reducible photon-induced

Georgi-Machacek model

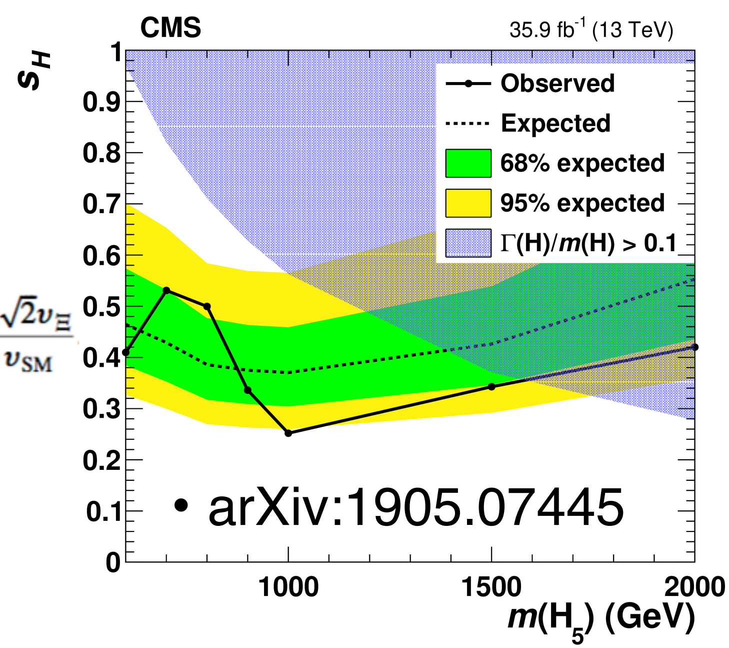
- An example of BSM model that can be used as a benchmark
  - Production of singly and doubly charged Higgs bosons

$$\Phi = \begin{pmatrix} \phi_2^* & \phi_1 \\ -\phi_1^* & \phi_2 \end{pmatrix}, \qquad \Xi = \begin{pmatrix} \chi_3^* & \xi_1 & \chi_1 \\ -\chi_2^* & \xi_2 & \chi_2 \\ \chi_1^* & -\xi_1^* & \chi_3 \end{pmatrix}.$$

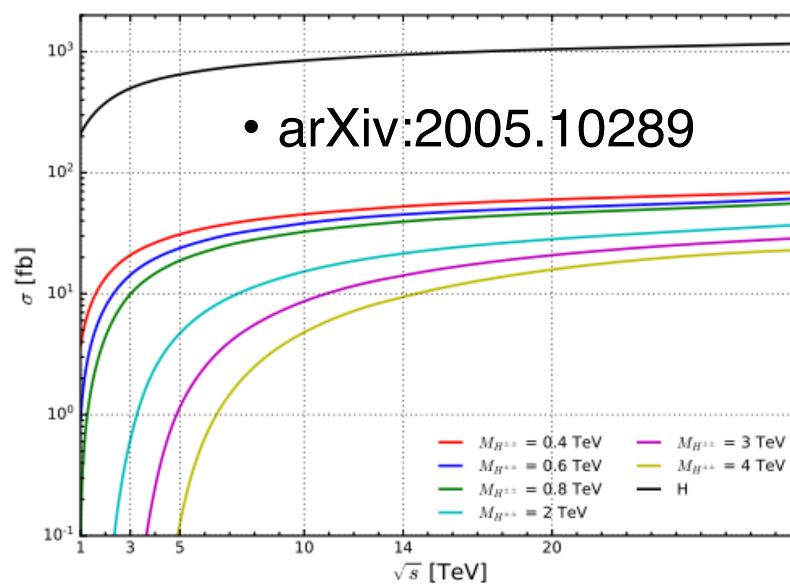




$$\sin\theta_H =: s_H = \frac{2\sqrt{2}v_\Xi}{v_{SM}}$$



- arXiv:1905.07445



- arXiv:2005.10289

Summary

- Preliminary considerations for the VBS studies for Snowmass
- Which future collider option maximizes the BSM physics potential for the VBS processes?
    - What benchmarks (EFT, BSM) should we include when comparing the physics reach of different collider options?
- Roadmap to a unified VBS study:
    1. adopt the collider/detector scenarios endorsed by snowmass community
    2. agree on some model parameter benchmarks (eft6/8,bsm)
    3. agree on some acceptable generator tools (Madgraph, Whizard, etc.)
    4. with these conventions, explore the generator/collider process space for model parameter sensitivity
    5. introduce increasing experimental realism
    6. introduce increasing theoretical realism
    7. provide comparative analysis for model parameter sensitivity