VBSCan@Snowmass: An outlook for VBS

MBI 2021 – Milano - Bicocca University

Richard Ruiz

Institute of Nuclear Physics – Polish Academy of Science (IFJ PAN)

23 August 2021

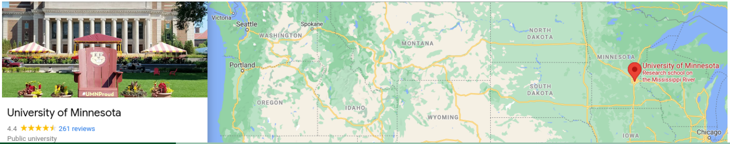
Thank you to organizers and fellow participants!

(hardships continue but the outlook is encouraging!)

What exactly is Snowmass?

"Snowmass Mountain should not be confused with the Snowmass ski area, located outside Snowmass Village; nor … Snowmass Peak, … that towers over Snowmass Lake." [Wikpedia]

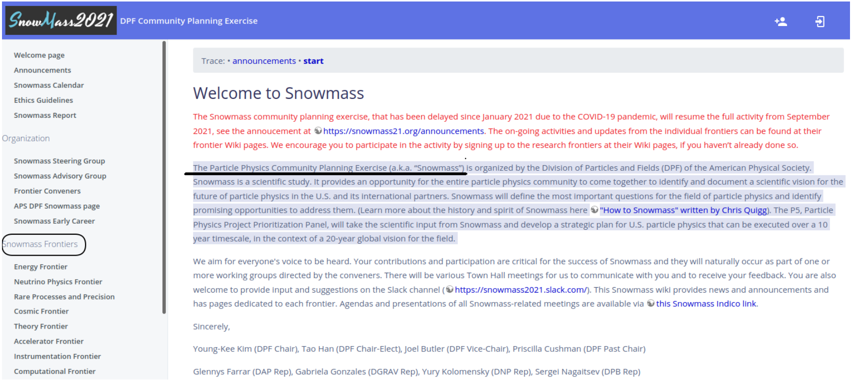
… nor be confused with the University of Minnesota



Snowmass is an ongoing, decadal community effort to (re)assess and (re)align physics priorities in North America

- Builds on output of the European Strategy Update(s)
- In practice, a ***global*** effort like the ESU!

https://snowmass21.org

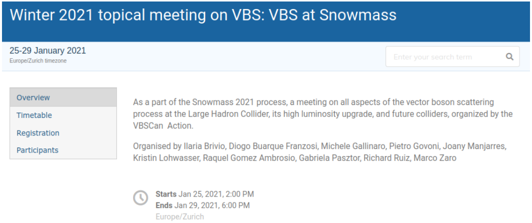


Vector boson scattering / fusion (VBS/F) relevant to several "frontiers"

- Energy (← click to explore the frontier's page)
- Theory
- Computation
- and others!

To support effort, **VBSCan** + **LHC EW WG on multi-bosons** organized

VBSCan@Snowmass Workshop (indico.cern.ch/event/980773)



Success: 22 invited and submited talks, from Run II SM measurements and BSM searches to projections for HL-LHC and future colliders!

Success: completion of the VBSCan@Snowmass review and whitepaper

Editors: D. Buarque Franzosi, M. Gallinaro, RR [2106.01393]

Builds on and extends VBSCan proceedings from:

- Split (2017) [1801.04203]
- Thessaloniki (2018) [1906.11332]
- Istanbul Midterm Meeting (2019) [2004.00726]
- Lisbon (2019) [2005.09889]

Complementary to milestone VBSCan studies

e.g., Ballestrero, et al [1803.07943], and Covarelli, et al [2102.10991]

Vector Boson Scattering Processes: Status and Prospects

Diogo Buarque Franzosi (ed.)[g,d], Michele Gallinaro (ed.)[h], Richard Ruiz (ed.)[i], Thea K. Aarrestad[c], Mauro Chiesa[o], Antonio Costantini[k], Ansgar Denner[t], Stefan Dittmaier[f], Flavia Cetorelli[l], Robert Franken[t], Pietro Govoni[l], Tao Han[p], Ashutosh V. Kotwal[a], Jinmian Li[r], Kristin Lohwasser[q], Kenneth Long[c], Yang Ma[p], Luca Mantani[k], Matteo Marchegiani[e], Mathieu Pellen[f], Giovanni Pelliccioli[t], Karolos Potamianos[n], Jürgen Reuter[b], Timo Schmidt[t], Christopher Schwan[m], Michał Szleper[s], Rob Verheyen[j], Keping Xie[p], Rao Zhang[r]

[a]Department of Physics, Duke University, Durham, NC 27708, USA
[b]Deutsches Elektronen-Synchrotron (DESY) Theory Group, Notkestr. 85, D-22607 Hamburg, Germany
[c]European Organization for Nuclear Research (CERN) CH-1211 Geneva 23, Switzerland
[d]Department of Physics, Chalmers University of Technology, Fysikgården 1, 41296 Göteborg, Sweden
[e]Swiss Federal Institute of Technology (ETH) Zürich, Otto-Stern-Weg 5, 8093 Zürich, Switzerland
[f]Universität Freiburg, Physikalisches Institut, Hermann-Herder-Straße 3, 79104 Freiburg, Germany
[g]Physics Department, University of Gothenburg, 41296 Göteborg, Sweden
[h]Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Lisbon, Av. Prof. Gama Pinto, 2 - 1649-003, Lisboa, Portugal
[i]Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego, Cracow 31-342, Poland
[j]University College London, Gower St, Bloomsbury, London WC1E 6BT, United Kingdom
[k]Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université Catholique de Louvain, Chemin du Cyclotron, B-1348 Louvain la Neuve, Belgium
[l]Milano - Bicocca University and INFN, Piazza della Scienza 3, Milano, Italy
[m]Tif Lab, Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano, Via Celoria 16, 20133 Milano, Italy
[n]Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
[o]Dipartimento di Fisica, Università di Pavia, Via A. Bassi 6, 27100 Pavia, Italy
[p]Pittsburgh Particle Physics, Astrophysics, and Cosmology Center, Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
[q]Department of Physics, Sheffield University, UK
[r]College of Physics, Sichuan University, Chengdu 610065, China
[s]National Center for Nuclear Research, ul. Pasteura 7, 02-093 Warszawa, Poland
[t]Universität Würzburg, Institut für Theoretische Physik und Astrophysik, Emil-Hilb-Weg 22, 97074 Würzburg, Germany

What did we learn?

Chapter II. VBS at the LHC

- Current results on vector boson scattering ← See talks by Sun, Mecca, Duda, Yap, others
- Polarization and τ lepton studies in VBS ← See talks Pellicciolli, Roloff, others
- Precise theoretical predictions for VBS

Precise theoretical predictions for VBS[1]

[1] **Please forgive me:** refs in this talk are cherry-picked for clarity/plot usage; they do not reflect full community effort. Please see review for fuller, more complete (correct) referencing.

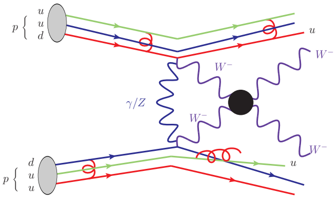
Major advancements in computational techniques for VBF/VBS last few years

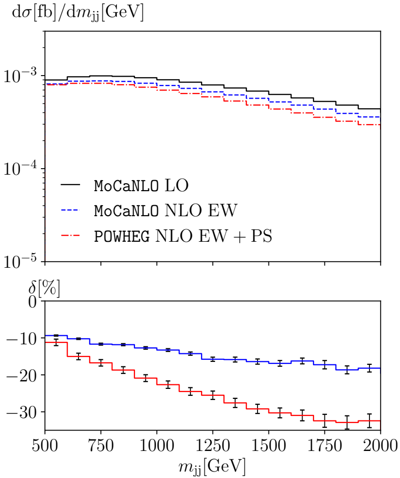
- **NLO in EW**, **NLO in EW+QCD**, and **PS** beyond LL/N_c see talks by Lindert, Plätzer, others

- "EW@NLO" in event generators

E.g., POWHEG [1611.02951], Recola+Sherpa [1704.05783],

MadGraph5_aMC@NLO [1804.10017],





Biedermann, Denner, and Pellen [1611.02951, others]

$$\underbrace{\delta_{\rm LL}}_{\approx -12\%} = \underbrace{\frac{\alpha}{4\pi}}_{\approx (13/2.)\times 10^{-4}} \left\{ \underbrace{-4 C_W^{\rm EW}}_{\approx -35} \underbrace{\log^2\left(\frac{Q^2}{M_W^2}\right)}_{\sim 20ish} + \underbrace{2 b_W^{\rm EW}}_{\approx 26} \log\left(\frac{Q^2}{M_W^2}\right) \right\}$$

Significant progress also in computing helicity-polarized cross sections

- Diboson at **NLO in EW+QCD**

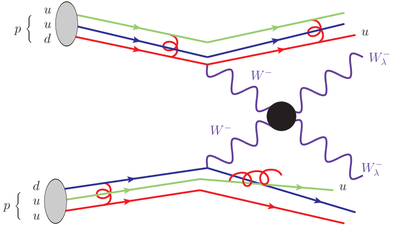
e.g,Baglio, et al [1910.13746], Denner & Pelliccioli [2107.06579]

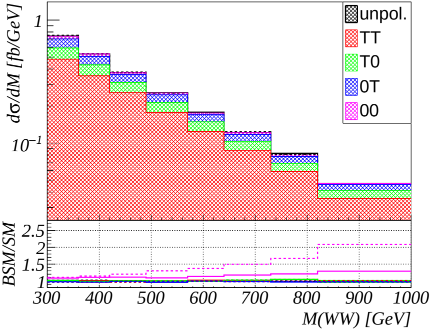
- Diboson at **NNLO in QCD**

(see talks by Popescu and Koole!)

- Automation in MadGraph5@LO →

(see tutorial by DBF at the VBFCan training school)





Buarque Franzosi, Mattelaer, RR, Shil, [1912.01725]

Just add {X} to simulate, e.g., $pp \to W^\pm(\lambda = 0)\gamma(\lambda = +)jj$ at $\mathcal{O}(\alpha_s^0\alpha^4)$

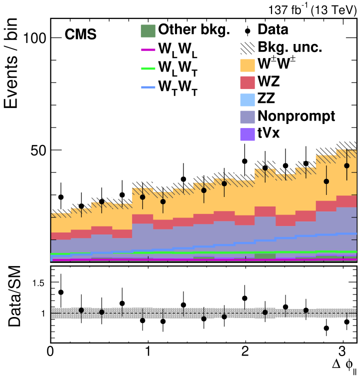
```
MG5_aMC>define vv = w+ w-
Defined multiparticle vv = w+ w-
MG5_aMC>generate p p > vv{0} a{+} j j QCD^2=0 QED^2=8
Interpreting 'QED^2=8' as 'QED^2<=8'
Interpreting 'QCD^2=0' as 'QCD^2<=0'
INFO: Trying process: g g > w+{0} a{R} d u~ QCD^2<=0 QED^2<=8 @1
INFO: Trying process: g g > w+{0} a{R} d c~ QCD^2<=0 QED^2<=8 @1
```

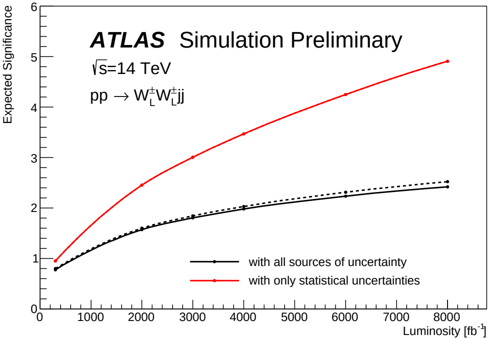
- **bosons**: X = 0,+,-,A
- **fermions**: X = R,L

LO decay synatx and MadSpin both work!

Outlook on measuring polarized VBS cross sections is encouraging

(L) CMS [2009.09429] (R) ATLAS [ATL-PHYS-PUB-2017-023]





Chapter III. VBS prospects for the HL-LHC

- Experimental projections for the HL-LHC ← See talks by half the speakers
- SMEFT in VBS at the HL-LHC ← See talks by the other half

Trott, Homiller, Chaudhary, Magni, Boldrini, Ricci, Bhattacharya, Durieux, Zeppenfeld, others

- Neutrino BSM with VBS signatures
- Anomaly detection with machine learning ← BSM/theory perspective
- Machine learning for VBS ← PID/experimental perspective
- Detector and performance upgrades for the HL-LHC

Neutrino BSM with VBS signatures[2]

[2] Not a review, just some results!

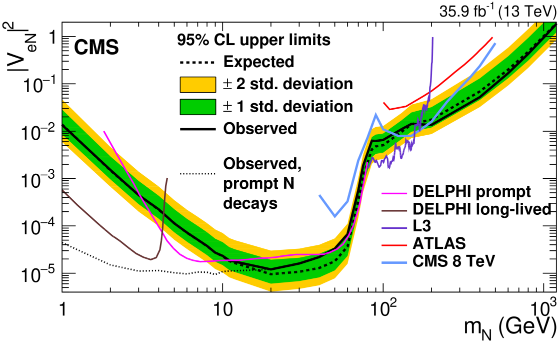
For reviews on LNV/LFV at colliders, see Cai, Li, Han, RR [1711.02180], and Pascoli, RR, Weiland [1812.08750]

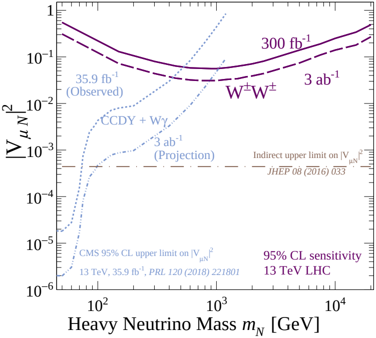
Type I Seesaws hypothesize a new scalar SM singlet ν_R

- **Depending** on assumptions, $m_\nu \sim \Lambda_{LNV}$ or $\langle\Phi\rangle^2/\Lambda_{LNV}$

For specifics, see, e.g., Pascoli, et al [1712.07611]

- Sterile neutrino N and mixing $|V_{\ell N}|^2$ accessibly with VBF/VBS





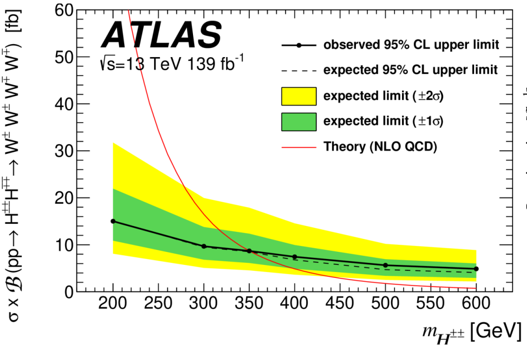
High-mass sensitivity at ATLAS and CMS driven by $W\gamma$ and $W^\pm W^\pm$

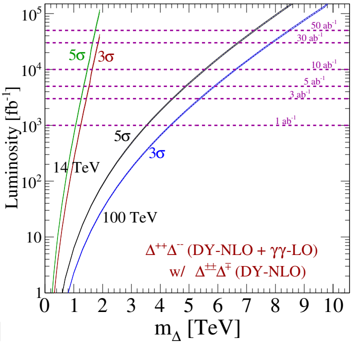
Alva, Han, RR [1411.7305]; Pascoli, RR, Weiland [1812.08750]; Fuks, Neundorf, Peters, RR, Saimpert [2011.02547];

- See backup for connections between $W^\pm W^\pm$ with muon $g_\mu - 2$

Type II Seesaws hypothesize a new scalar $SU(2)_L$ triplet Δ

- Small $\langle\Delta\rangle$ generates LH Majorana masses for ν
- $H^0, H^\pm,\ H^{\pm\pm}, \xi^0$ carry $SU(2)_L$ charges; accessibly in VBS/F





At LHC with $\mathcal{L} = 5$ ab^{-1}, 3σ sensitivity up to $m_\Delta \sim 1.5$ TeV

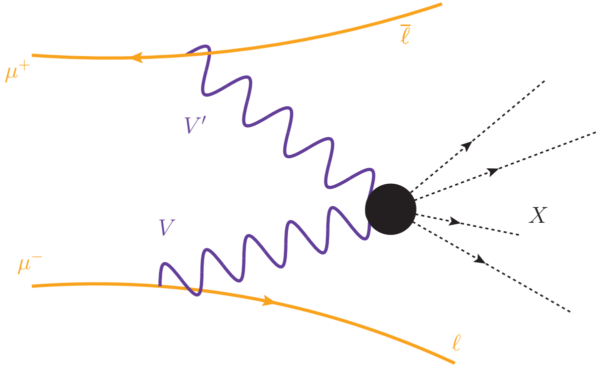
Fuks, Nemevšek, and RR [1912.08975] + new FeynRules NLO UFO TypeIISeesaw

- **Note**: can be improved for specialized final state / parameter space

IV VBS at future colliders

- EW parton distribution functions ← See talk by T. Han
- EW parton showers ← This is super cool (no time!)
- SMEFT with VBS at $\mu^+\mu^-$ colliders
- BSM with VBS at $\mu^+\mu^-$ colliders ← See talk by T. Han
- VBS at e^+e^- colliders ← EFT physics here, too!
- production from new resonances ← 100 TeV pp collider

(SM)EFT with VBS at future e^+e^- $\mu^+\mu^-$ colliders



The 2020 Update for the European Strategy of Particle Physics has designated an e^+e^- Higgs factory as one of the **highest priorities**, particularly as a staging platform to an even higher energy pp collider

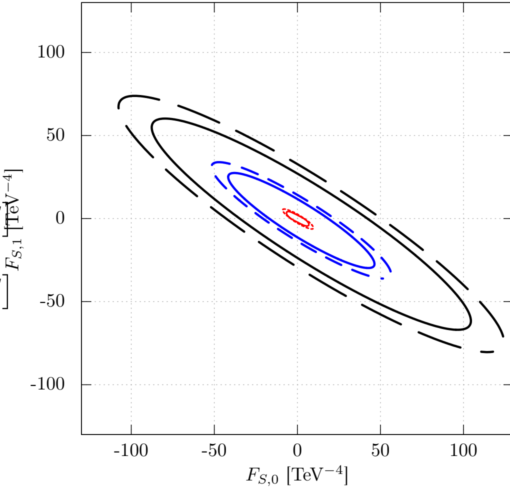
Briefing book [1910.11775], 2020 "Update" [CERN-ESU-013]

$W^+W^- \to W^+W^-/ZZ$ at $\sqrt{s} = 1$ (1.4) [3] TeV with $\mathcal{L} = 5$ (1.5) [2] ab^{-1} data can probe $d = 8$ operators

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

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

solide (dashed) = (un)polarized e^+e^- beams



Fleper, Kilian, Reuter, Sekulla [1607.03030]

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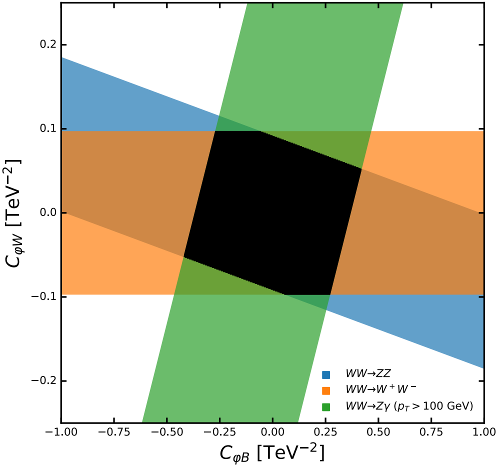
Briefing book [1910.11775], 2020 "Update" [CERN-ESU-013]

Modulo $m_e \leftrightarrow m_\mu$, physics at e^+e^- and $\mu^+\mu^-$ colliders are the same

$W^+W^- \rightarrow W^+W^-/ZZ/Z\gamma$ at $\sqrt{s} = 3$ TeV with $\mathcal{L} = 6$ ab^{-1} data can probe (many) $d = 6$ operators

$$\mathcal{L}_{\phi B} = C_{\phi B}\left[H^\dagger H\right] B^{\mu\nu} B_{\mu\nu}$$
$$\mathcal{L}_{\phi W} = C_{\phi B}\left[H^\dagger H\right] W_I^{\mu\nu} W^I_{\mu\nu}$$

Costantini, Maltoni, Mantani, et al [2005.10289]



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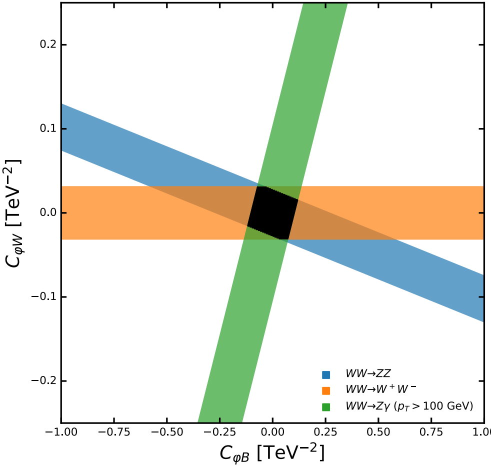
Briefing book [1910.11775], 2020 "Update" [CERN-ESU-013]

Modulo $m_e \leftrightarrow m_\mu$, physics at e^+e^- and $\mu^+\mu^-$ colliders are the same

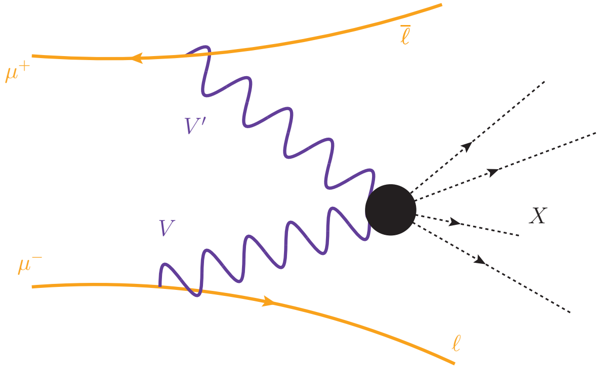
$W^+W^- \to W^+W^-/ZZ/Z\gamma$ at $\sqrt{s} = 14$ TeV with $\mathcal{L} = 20$ ab^{-1} data can probe (better) $d = 6$ operators

$$\mathcal{L}_{\phi B} = C_{\phi B} \left[H^\dagger H\right] B^{\mu\nu} B_{\mu\nu}$$
$$\mathcal{L}_{\phi W} = C_{\phi B} \left[H^\dagger H\right] W_I^{\mu\nu} W^I_{\mu\nu}$$

Costantini, Maltoni, Mantani, et al [2005.10289]

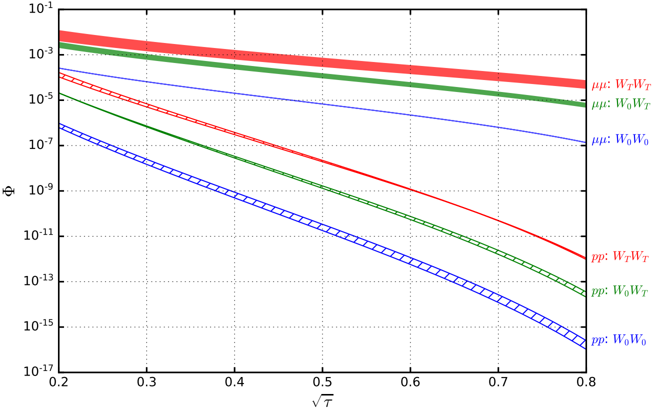


VBS at future muon colliders



Noteworthy that $W^+_\lambda W^-_{\lambda'}$ parton luminosites (Φ) in $\mu^+\mu^-$ collisions can exceed those at a *pp* collider (holds for other VV', too!)

$$\Phi_i j(\tau, Q) = \int_\tau^1 \frac{d\xi}{\xi} f_{i/\mu}(\xi, Q) f_{j/\mu}\left(\frac{\tau}{\xi}, Q\right), \quad \tau = \frac{Q^2}{s}$$



Costantini, RR, et al [2005.10289]

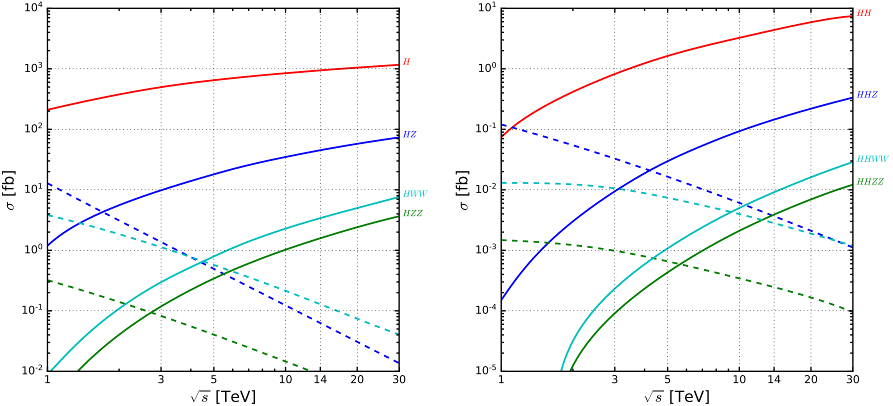
Running the numbers for a $\mu^+\mu^-$ scattering[3][4]

[3] Out-of-the-box MadGraph5_aMC@NLO, except we upgraded the box to better handle (throw more die) phase space integration over t-channel momentum exchange

[4] For vector boson fusion/scattering (VBF/S) processes, we selected for VBF/VBS diagrams in a gauge-invariant manner

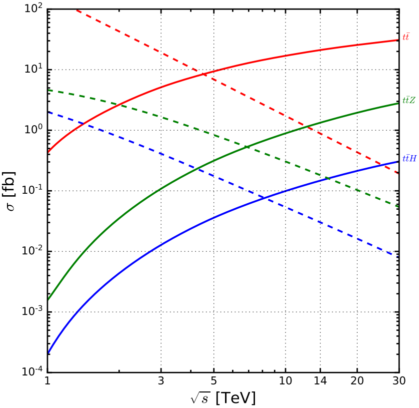
Higgs production

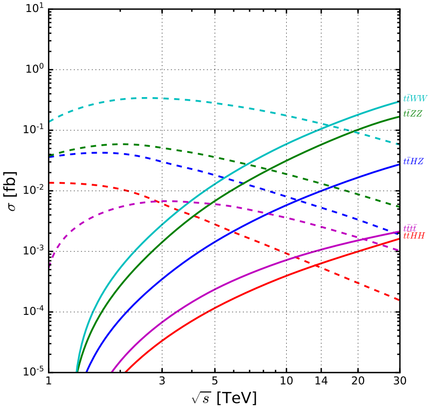
cross sections (σ) vs $\sqrt{s}$ for s-channel annihilation (dash) vs VBF (solid)



- $\sigma^{VBF} > \sigma^{s-channel}$ since
  - $\sigma^{s-channel} \sim 1/s$
  - $\sigma^{VBF} \sim \log^2(M_{VV}^2/M_V^2)/M_{VV}^2$ due to forward emission of $V = W/Z$

Top production

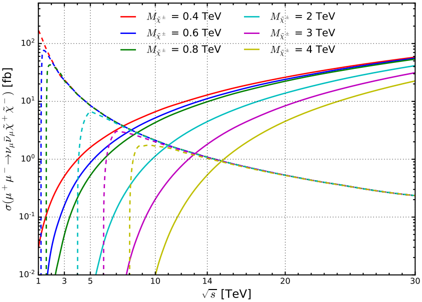


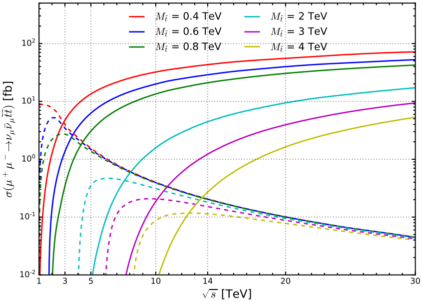


- Do you notice a pattern?

SUSY

(L) chargino pairs (R) stop pairs

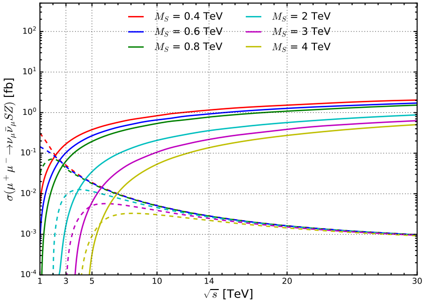


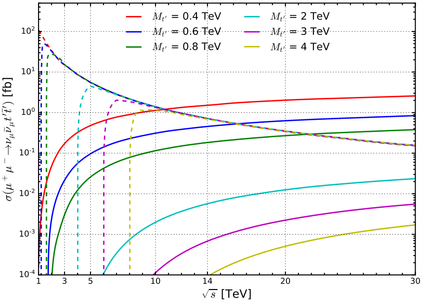


- And now?

Simple Extensions

(L) *S*inglet + *Z* production (R) vector-like top pair production

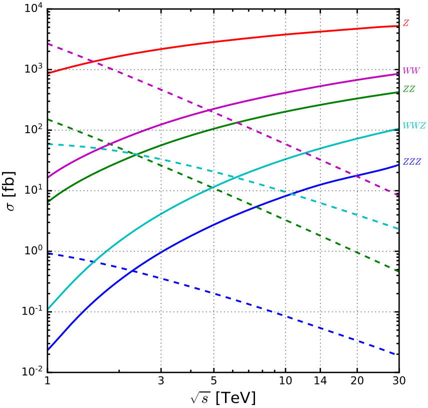


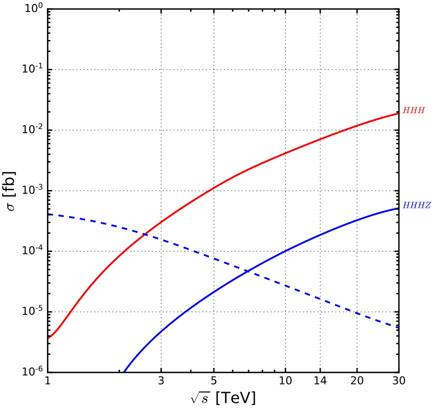


- . . . a little different but a lot of the same

Many-boson production[5]

[5] My favorite! I find these processes really neat!





- Eventually, **VBF becomes the dominant** production vehicle of many types of processes

When annihilation and VBS channels are driven by same physics, evidence that **dominance of VBS is universal** and occurs at $\sqrt{s}$ for

w/ A. Costantini, et al [2005.10289]

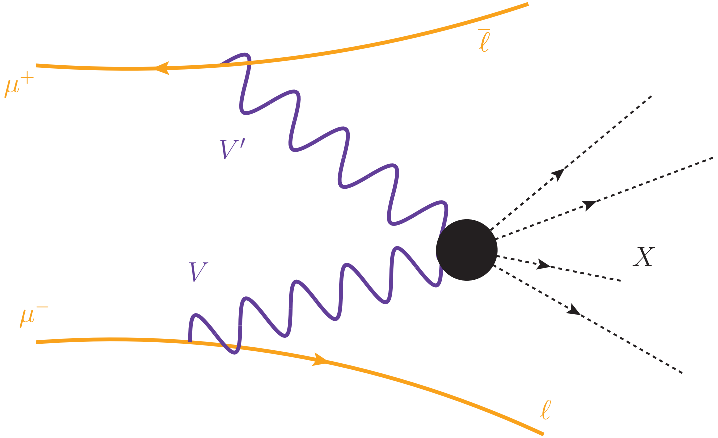
$$\frac{\sigma^{\rm VBF}}{\sigma^{s-ch.}} \sim \mathcal{S}\left(\frac{g_W^2}{4\pi}\right)^2 \left(\frac{s}{M_X^2}\right) \log^2 \frac{s}{M_V^2} \log \frac{s}{M_X^2} > 1$$

Scaling estimate not so bad if $M_X \gg M_V$. Difference is about $\mathcal{O}(10\%)$

mass (M_X) [TeV]	SZ (Singlet)	H_2Z (2HDM)	$t'\overline{t'}$ (VLQ)	$\tilde{t}\bar{\tilde{t}}$ (MSSM)	$\tilde{\chi}^0\tilde{\chi}^0$ (MSSM)	$\tilde{\chi}^+\tilde{\chi}^-$ (MSSM)	Scaling (Eq. 7.7)
400 GeV	2.1 TeV	2.1 TeV	11 TeV	2.9 TeV	3.2 TeV	7.5 TeV	1.0 (1.7) TeV
600 GeV	2.5 TeV	2.5 TeV	16 TeV	3.8 TeV	3.8 TeV	8.1 TeV	1.3 (2.4) TeV
800 GeV	2.8 TeV	2.8 TeV	22 TeV	4.3 TeV	4.3 TeV	8.5 TeV	1.7 (3.1) TeV
2.0 TeV	4.0 TeV	4.0 TeV	>30 TeV	7.8 TeV	6.9 TeV	11 TeV	3.7 (6.8) TeV
3.0 TeV	4.8 TeV	4.8 TeV	>30 TeV	10 TeV	9.0 TeV	13 TeV	5.3 (9.8) TeV
4.0 TeV	5.5 TeV	5.5 TeV	>30 TeV	13 TeV	11 TeV	15 TeV	6.8 (13) TeV

Table 9. For representative processes and inputs, the required muon collider energy $\sqrt{s}$ [TeV] at which the VBF production cross section surpasses the s-channel, annihilation cross section, as shown in figure 17. Also shown are the cross over energies as estimated from the scaling relationship in equation (7.7) assuming a mass scale M_X ($2M_X$).

Question: For large enough $\sqrt{s}$, a $\mu^+\mu^-$ collider is effectively an "*EW boson collider*." When do EW bosons become partons?



Many *fascinating* ways to explore this, e.g., EW parton showers and PDFs

Letter of Interest: EW effects in very high-energy phenomena

C. Arina, G. Cuomo, T. Han, Y.Ma, F. Maltoni, A. Manohar, S. Prestel, R. Ruiz, L. Vecchi, R. Verheyen, B. Webber, W. Waalewijn, A. Wulzer, K. Xie

to be submitted to the Theory Frontier (TF07) and Energy Frontier (EF04)

1 Introduction

Phenomena that take place at multi-TeV scales — high-energy elementary particle scattering or the annihilation/decay of ultra heavy states such as dark matter particles — can give rise to relativistic, final states that are naturally accompanied by additional radiation, that in turn leads to particle showers and final states with large particle multiplicities. In the the Standard Model, the effects of QCD and QED radiation are well understood and treated at various level of sophistication. These range from fixed-order computations at an increasing accuracy to resummed computations via parton showering algorithms and semi-analytic approaches. Even matching/merging between the two while keeping their respective accuracies is available.

In such multi-TeV scales processes typical momentum transfers Q are much larger than the electroweak (EW) scale $m \sim m_Z$, and intial- and final-state EW radiation becomes important. In particular, EW boson emission gives rise to transition rates that grow with logarithms of the type $\log Q/m$. For sufficiently large Q, these logarithms must be resummed in order to recover physically meaningful results. Despite recent progress, a fully exclusive approach that can take care of fixed-order EW corrections, resum large EW logarithms in both inital and final states, systematically account for power corrections, and is implemented in ready-to-use Monte Carlo

Snowmass 21 LoI: SNOWMASS21-TF7_TF0-EF4_EF0-026

Stay tuned! Lots of effort in parallel and a coherent picture is forming!

Thank you!

[6] sterile neutrinos and Δa_μ

[6] V. Cirigliano, W. Dekens, J. de Vries, K. Fuyuto, E. Mereghetti [2105.11462]

ν**SMEFT** is the Standard Model Effective Field Theory extended by ν_R

$\psi^2 H^3$		$\psi^2 H^2 D$		$\psi^2 HX$(+H.c.)	
$\mathcal{O}_{L\nu H}$(+H.c.)	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{H\nu}$	$(\bar{\nu}_R\gamma^\mu\nu_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{\nu B}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$
		$\mathcal{O}_{H\nu e}$(+H.c.)	$(\bar{\nu}_R\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$
$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R)$(+H.c.)	
$\mathcal{O}_{\nu\nu}$	$(\bar{\nu}_R\gamma^\mu\nu_R)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu}$	$(\bar{L}\gamma^\mu L)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Le}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e)$
$\mathcal{O}_{e\nu}$	$(\bar{e}\gamma^\mu e)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{Q\nu}$	$(\bar{Q}\gamma^\mu Q)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Qd}$	$(\bar{L}\nu_R)\epsilon(\bar{Q}d)$
$\mathcal{O}_{u\nu}$	$(\bar{u}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu\nu_R)$			$\mathcal{O}_{LdQ\nu}$	$(\bar{L}d)\epsilon(\bar{Q}\nu_R)$
$\mathcal{O}_{d\nu}$	$(\bar{d}\gamma^\mu d)(\bar{\nu}_R\gamma_\mu\nu_R)$				
$\mathcal{O}_{du\nu e}$(+H.c.)	$(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$				
$(\bar{L}R)(\bar{R}L)$		$(\not{L}\cap B)$(+H.c.)		$(\not{L}\cap \not{B})$(+H.c.)	
$\mathcal{O}_{Qu\nu L}$(+H.c.)	$(\bar{Q}u)(\bar{\nu}_R L)$	$\mathcal{O}_{\nu\nu\nu\nu}$	$(\bar{\nu}_R^c\nu_R)(\bar{\nu}_R^c\nu_R)$	$\mathcal{O}_{QQd\nu}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(Q_\alpha^i C Q_\beta^j)(d_\sigma C\nu_R)$
				$\mathcal{O}_{udd\nu}$	$\epsilon_{\alpha\beta\sigma}(u_\alpha C d_\beta)(d_\sigma C\nu_R)$

Table 1: The complete basis of dimension-six operators involving ν_R taken from Ref. [24]. The operators are expressed in terms of a column vector of n gauge singlet fields, ν_R, and of SM fields, the lepton and Higgs doublets, L and H, the quark left-handed doublet $Q = (u_L, d_L)^T$, and the right-handed fields e, u, and d.

Unexpectedly, only one νSMEFT can generate the right Δa_μ

$$\mathcal{L}_{H\nu e} \approx \frac{gv^2}{2\sqrt{2}\Lambda^2}\sum_{k=1}^{3}\left[\bar{C}_{H\nu e}\right]_{k\ell}\left(\overline{N_k}\gamma^\mu P_R\,\ell_R\right)W_\mu^+\left(1+\frac{h}{v}\right)^2 + \text{H.c.}$$

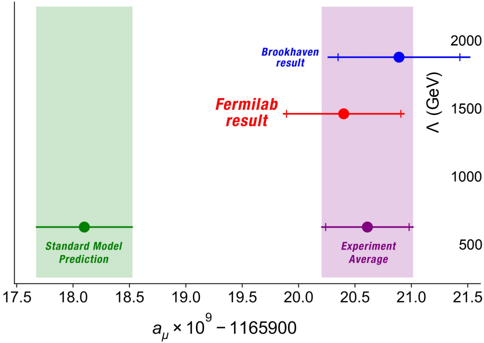
This generates Δa_μ of the form

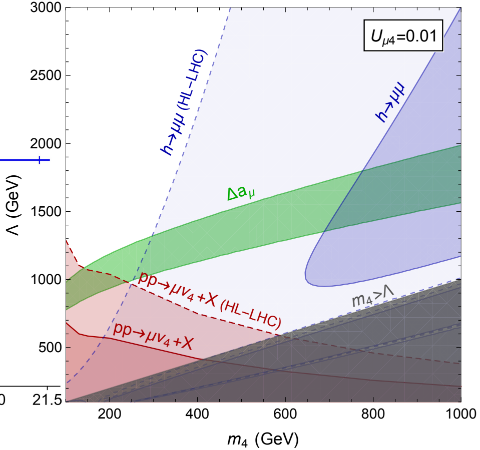
$$\Delta a_\mu \sim -\frac{2m_\mu m_N}{(4\pi)^2\Lambda^2}\text{Re}\left(V_{\mu N}\left[\bar{C}_{H\nu e}\right]_{N\mu}\right)$$

(see [2105.11462] for exact formula!)

Anomalous magnetic moment of the μ at the LHC

Fermilab's Muon g-2 expt. has *confirmed* that $a_\mu = (g_\mu - 2)/2$ is *a bit* large [2104.03281]





Interesting finding: If N are involved in Δa_μ, then expect something in

$$pp \to N\mu^\pm + X \text{ and } H \to \mu^+\mu^-$$

in Run III data and at the HL-LHC (see paper for details! Cirigliano, RR, de Vries, et al (2105.11462))