

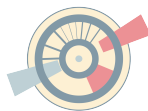
VBSCan@Snowmass: An outlook for VBS

MBI 2021 – Milano - Bicocca University

Richard Ruiz

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

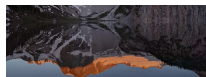
23 August 2021



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.” [Wikipedia]



Snowmass Mountain

5.0 ★★★★★ 7 reviews
Mountain peak

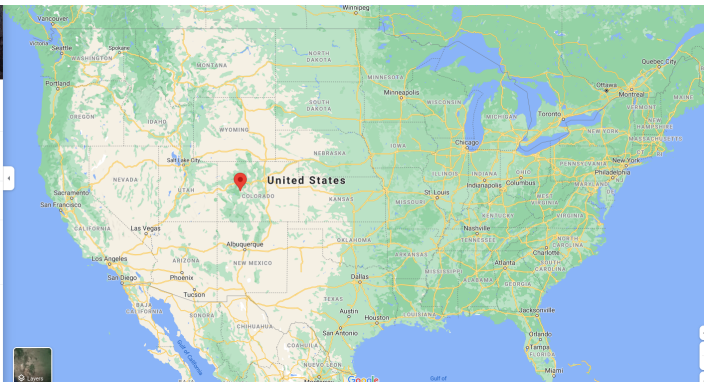


14,099-ft. tall mountain named for its expansive snowfield, offering challenging hiking trails.

Colorado 81623, United States

4WSM+HC Snowmass Village, Colorado, United States

Photos

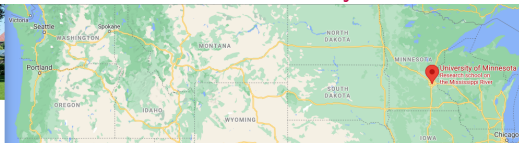


... nor be confused with the University of Minnesota



University of Minnesota

4.4 ★★★★★ 261 reviews
Public university



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>

The screenshot shows the Snowmass2021 website. The header is blue with the 'Snowmass2021' logo and the text 'DPF Community Planning Exercise'. Below the header is a navigation menu with links: 'Welcome page', 'Announcements', 'Snowmass Calendar', 'Ethics Guidelines', and 'Snowmass Report'. The 'Snowmass Frontiers' link is circled. The main content area has a breadcrumb trail 'Trace: • announcements • start' and a 'Welcome to Snowmass' heading. The text below the heading states that the Snowmass community planning exercise, delayed since January 2021 due to the COVID-19 pandemic, will resume full activity from September 2021. It also mentions that on-going activities and updates from individual frontiers can be found at their frontier Wiki pages. A paragraph describes the Particle Physics Community Planning Exercise (a.k.a. "Snowmass") organized by the Division of Particles and Fields (DPF) of the American Physical Society. It states that Snowmass is a scientific study providing an opportunity for the entire particle physics community to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. It will define the most important questions for the field of particle physics and identify promising opportunities to address them. A link is provided to learn more about the history and spirit of Snowmass, and another link points to a "How to Snowmass" document written by Chris Quigg. The text also mentions the PS, Particle Physics Project Prioritization Panel, which will take the scientific input from Snowmass and develop a strategic plan for U.S. particle physics that can be executed over a 10-year timescale. The text concludes by stating that the aim is for everyone's voice to be heard and that contributions and participation are critical for the success of Snowmass. It mentions that there will be various Town Hall meetings for communication and feedback, and that the Snowmass wiki provides news and announcements and has pages dedicated to each frontier. Agendas and presentations of all Snowmass-related meetings are available via a link to the Snowmass Indico link. The footer of the page lists the names of the steering group members: Young-Kee Kim (DPF Chair), Tao Han (DPF Chair-Elect), Joel Butler (DPF Vice-Chair), Priscilla Cushman (DPF Past Chair), Glennys Farrar (DAP Rep), Gabriela Gonzales (DGRAV Rep), Yury Kolomensky (DNP Rep), and Sergei Nagaitsev (DPB Rep).

Snowmass2021 DPF Community Planning Exercise

Welcome page
Announcements
Snowmass Calendar
Ethics Guidelines
Snowmass Report

Organization

Snowmass Steering Group
Snowmass Advisory Group
Frontier Conveners
APS DPF Snowmass page
Snowmass Early Career
Snowmass Frontiers

Energy Frontier
Neutrino Physics Frontier
Rare Processes and Precision
Cosmic Frontier
Theory Frontier
Accelerator Frontier
Instrumentation Frontier
Computational Frontier

Trace: • announcements • **start**

Welcome to Snowmass

The Snowmass community planning exercise, that has been delayed since January 2021 due to the COVID-19 pandemic, will resume the full activity from September 2021, see the announcement at <https://snowmass21.org/announcements>. The on-going activities and updates from the individual frontiers can be found at their frontier Wiki pages. We encourage you to participate in the activity by signing up to the research frontiers at their Wiki pages, if you haven't already done so.

The Particle Physics Community Planning Exercise (a.k.a. "Snowmass") is organized by the Division of Particles and Fields (DPF) of the American Physical Society. Snowmass is a scientific study. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. Snowmass will define the most important questions for the field of particle physics and identify promising opportunities to address them. (Learn more about the history and spirit of Snowmass here ["How to Snowmass" written by Chris Quigg](#)). The PS, Particle Physics Project Prioritization Panel, will take the scientific input from Snowmass and develop a strategic plan for U.S. particle physics that can be executed over a 10-year timescale, in the context of a 20-year global vision for the field.

We aim for everyone's voice to be heard. Your contributions and participation are critical for the success of Snowmass and they will naturally occur as part of one or more working groups directed by the conveners. There will be various Town Hall meetings for us to communicate with you and to receive your feedback. You are also welcome to provide input and suggestions on the Slack channel (<https://snowmass2021.slack.com/>). This Snowmass wiki provides news and announcements and has pages dedicated to each frontier. Agendas and presentations of all Snowmass-related meetings are available via [this Snowmass Indico link](#).

Sincerely,

Young-Kee Kim (DPF Chair), Tao Han (DPF Chair-Elect), Joel Butler (DPF Vice-Chair), Priscilla Cushman (DPF Past Chair)
Glennys Farrar (DAP Rep), Gabriela Gonzales (DGRAV Rep), Yury Kolomensky (DNP Rep), Sergei Nagaitsev (DPB Rep)

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)

Winter 2021 topical meeting on VBS: VBS at Snowmass

25-29 January 2021
Europe/Zurich timezone

Overview


Timetable

Registration

Participants

As a part of the Snowmass 2021 process, a meeting on all aspects of the vector boson scattering process at the Large Hadron Collider, its high luminosity upgrade, and future colliders, organized by the VBSCan Action.

Organised by Ilaria Brivio, Diogo Buarque Franzosi, Michele Gallinaro, Pietro Govoni, Joany Manjarres, Kristin Lohwasser, Raquel Gomez Ambrosio, Gabriela Pasztor, Richard Ruiz, Marco Zaro

 **Starts** Jan 25, 2021, 2:00 PM
Ends Jan 29, 2021, 6:00 PM
Europe/Zurich

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

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.)^{a,d}, Michele Gallinaro (ed.)^b, Richard Ruiz (ed.)^c, Thea K. Aarstad^e, Mauro Chiesa^o, Antonio Constantini^h, Ansgar Dennerⁱ, Stefan Dittmaier^j, Flavia Cetorelli^k, Robert Franken^l, Pietro Govoni^m, Tao Hanⁿ, Ashutosh V. Kotwal^p, Jinmian Li^q, Kristin Lohwasser^r, Kenneth Long^s, Yang Ma^t, Luca Mantani^u, Matteo Marchegiani^v, Mathieu Pellen^w, Giovanni Pelliccioli^x, Karolos Potamianos^y, Jürgen Reuter^z, Timo Schmidt¹, Christopher Schwan², Michal Szeleper³, Rob Verheyen⁴, Keping Xie⁵, Rao Zhang⁶

^aDepartment of Physics, Duke University, Durham, NC 27708, USA

^bDeutsches Elektronen-Synchrotron (DESY) Theory Group, Notkestr. 85, D-22607 Hamburg, Germany

^cEuropean Organization for Nuclear Research (CERN) CH-1211 Geneva 23, Switzerland

^dDepartment of Physics, Chalmers University of Technology, Fysikgården 1, 41296 Göteborg, Sweden

^eSwiss Federal Institute of Technology (ETH) Zürich, Otto-Stern-Weg 5, 8093 Zürich, Switzerland

^fUniversität Freiburg, Physikalisches Institut, Hermann-Herder-Straße 3, 79104 Freiburg, Germany

^gPhysics Department, University of Gothenburg, 41296 Göteborg, Sweden

^hLaboratório de Instrumentação e Física Experimental de Partículas (LIP), Lisbon, Av. Prof. Gama Pinto, 2 - 1649-003, Lisbon, Portugal

ⁱInstitute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego, Cracow 31-342, Poland

^jUniversity College London, Gower St, Bloomsbury, London WC1E 6BT, United Kingdom

^kCentre for Cosmology, Particle Physics and Phenomenology (CP3),

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^lMilano - Bicocca University and INFN, Piazza della Scienza 3, Milano, Italy

^mTif Lab, Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano, Via Celoria 16, 20133 Milano, Italy

ⁿDepartment of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK

^oDipartimento di Fisica, Università di Pavia, Via A. Bassi 6, 27100 Pavia, Italy

^pPittsburgh Particle Physics, Astrophysics, and Cosmology Center, Department of Physics and Astronomy,

University of Pittsburgh, Pittsburgh, PA 15260, USA

^qDepartment of Physics, Sheffield University, UK

^rCollege of Physics, Sichuan University, Chengdu 610065, China

^sNational Center for Nuclear Research, ul. Pasteura 7, 02-093 Warszawa, Poland

^tUniversität Würzburg, Institut für Theoretische Physik und Astrophysik, Emil-Hilb-Weg 22, 97074 Würzburg, Germany

p-ph] 2 Jun 2021

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 Pelliccioli, Roloff, others
- Precise theoretical predictions for VBS

Precise theoretical predictions for VBS¹

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.

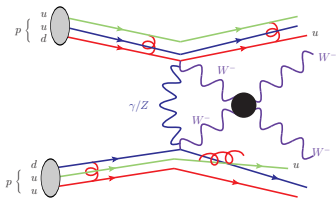
Major advancements in computational techniques for VBF/VBS last few years

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

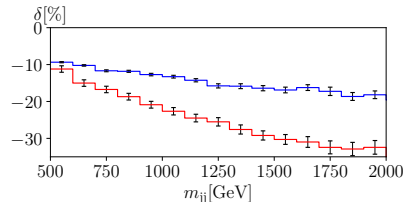
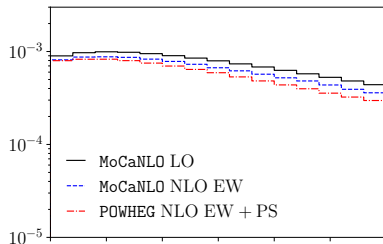
- “EW@NLO” in event generators

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

MadGraph5_aMC@NLO [[1804.10017](#)],



$d\sigma[\text{fb}]/dm_{ij}[\text{GeV}]$



Biedermann, Denner, and Pellen [[1611.02951](#), others]

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

Significant progress also in computing helicity-polarized cross sections

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

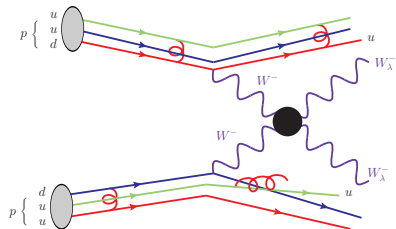
e.g., Baglio, et al [1910.13746], Denner & Pelliccioli [2107.06579]

- Diboson at **NNLO in QCD**

(see talks by Popescu and Koole!)

- Automation in MadGraph5@LO →

(see tutorial by DBF at the VBFCan training school)

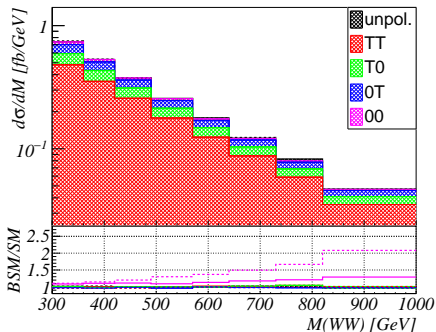


Just add {X} to simulate, e.g., $pp \rightarrow W^\pm(\lambda=0)\gamma(\lambda=+)jj$ at $\mathcal{O}(\alpha_s^0\alpha^4)$

- **bosons**: $X = 0, +, -, A$

- **fermions**: $X = R, L$

LO decay syntax and MadSpin both work!



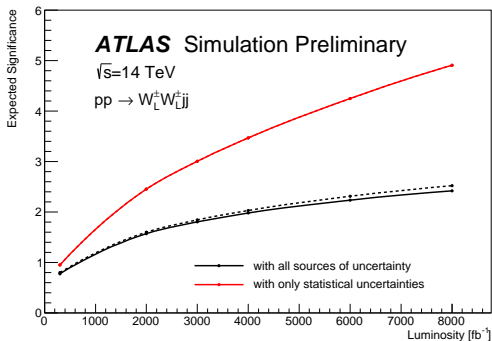
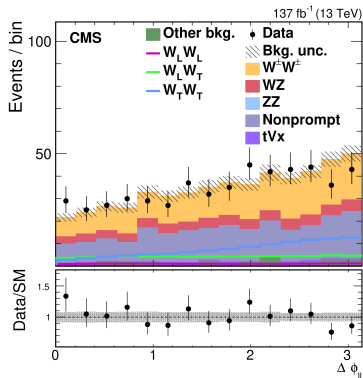
Buarque Franzosi, Mattelaer, RR, Shil, [1912.01725]

```
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
```

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 signatures²

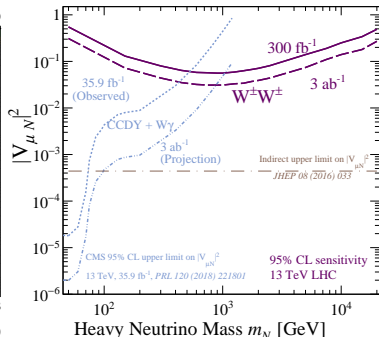
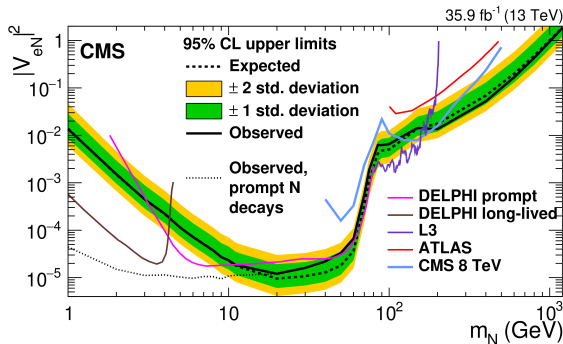
² Not a review, just some results!

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



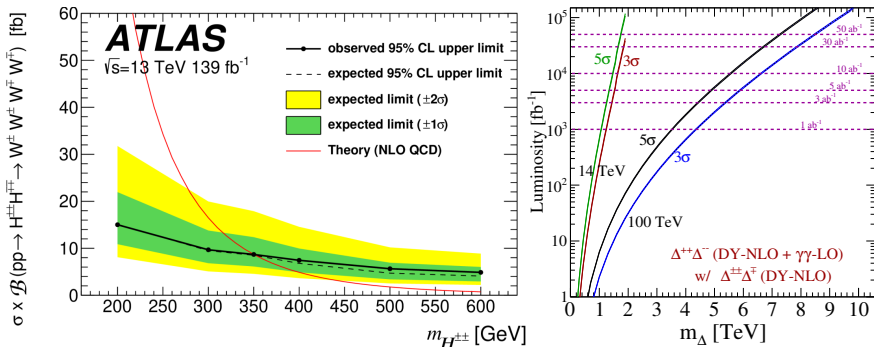
High-mass sensitivity at ATLAS and CMS driven by $W\gamma$ and $W^\pm W^\pm$

Alva, Han, RR [1411.7305]; Pascoli, RR, Weiland [1812.08750]; Fuks, Neundorff, 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 $\mathcal{L} = 5 \text{ ab}^{-1}$, 3σ sensitivity up to $m_{\Delta} \sim 1.5 \text{ TeV}$

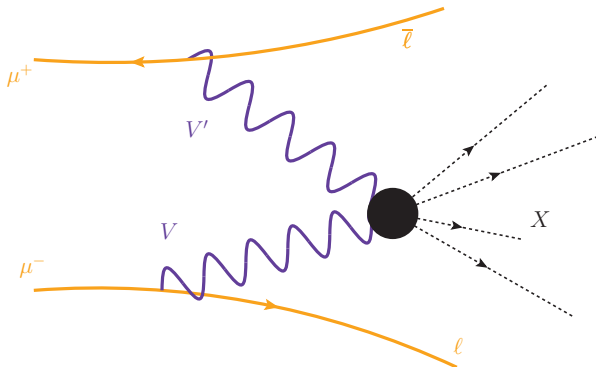
Fuks, Nemevšek, and RR [1912.08975] + new FeynRules NLO UFO TypeIISeesaw

- **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

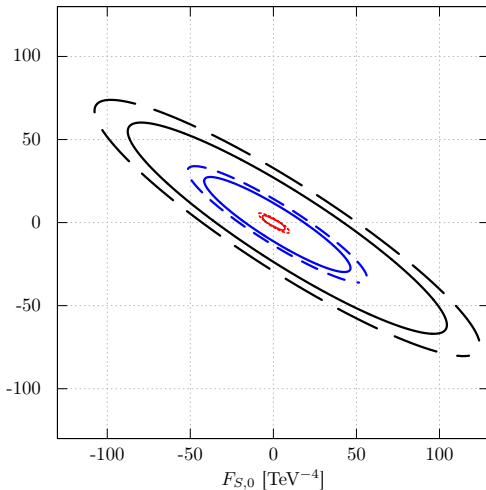
Briefing book [1910.11775], 2020 "Update" [CERN-ESU-013]

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

$$\begin{aligned}\mathcal{L}_{S,0} &= F_{S,0} \text{Tr} [(D_\mu H)^\dagger D_\nu H] \text{Tr} [(D^\mu H)^\dagger D^\nu H] \\ \mathcal{L}_{S,1} &= F_{S,1} \text{Tr} [(D_\mu H)^\dagger D^\mu H] \text{Tr} [(D_\nu H)^\dagger D^\nu H]\end{aligned}$$

$F_{S,i} [\text{TeV}^{-4}]$

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



Fleper, Kilian, Reuter, Sekulla [1607.03030]

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

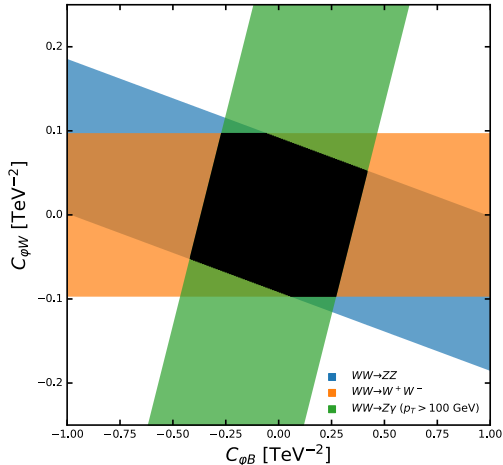
Briefing book [1910.11775], 2020 “Update” [CERN-ESU-013]

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 $\mathcal{L} = 6 \text{ ab}^{-1}$ data can probe (many) $d = 6$ operators

$$\begin{aligned}\mathcal{L}_{\phi B} &= C_{\phi B} [H^\dagger H] B^{\mu\nu} B_{\mu\nu} \\ \mathcal{L}_{\phi W} &= C_{\phi B} [H^\dagger H] W_I^{\mu\nu} W_{\mu\nu}^I\end{aligned}$$

Costantini, Maltoni, Mantani, et al [2005.10289]



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

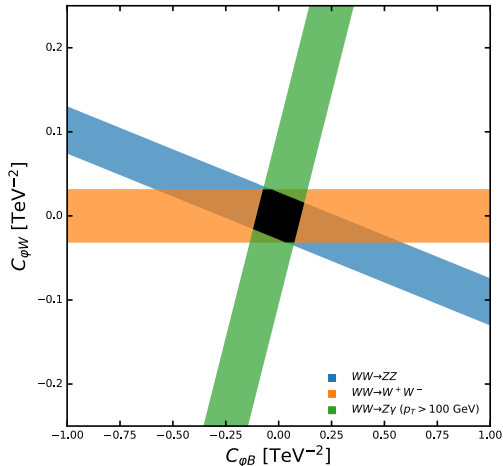
Briefing book [1910.11775], 2020 "Update" [CERN-ESU-013]

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

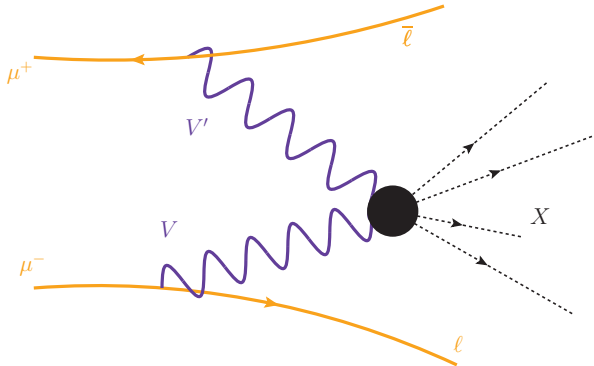
$W^+W^- \rightarrow W^+W^-/ZZ/Z\gamma$ at $\sqrt{s} = 14$ TeV with $\mathcal{L} = 20 \text{ ab}^{-1}$ data can probe (better) $d = 6$ operators

$$\begin{aligned}\mathcal{L}_{\phi B} &= C_{\phi B} [H^\dagger H] B^{\mu\nu} B_{\mu\nu} \\ \mathcal{L}_{\phi W} &= C_{\phi W} [H^\dagger H] W_I^{\mu\nu} W_{\mu\nu}^I\end{aligned}$$

Costantini, Maltoni, Mantani, et al [2005.10289]

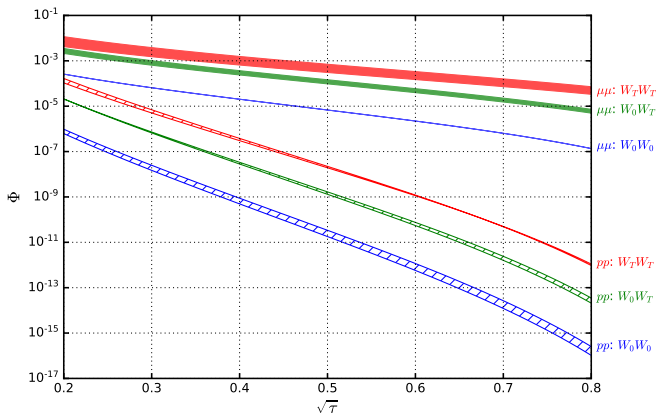


VBS at future muon colliders



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

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



Costantini, RR, et al [2005.10289]

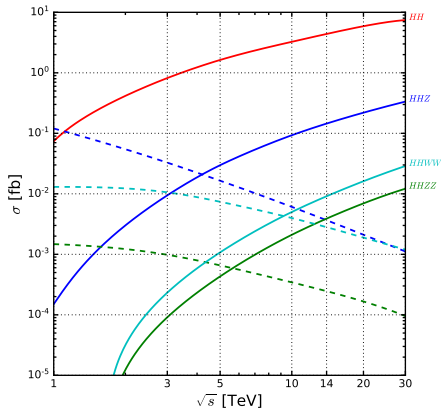
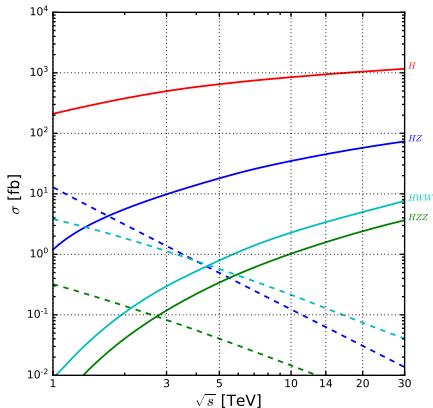
Running the numbers for a $\mu^+\mu^-$ scattering³⁴

³Out-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

⁴For 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)

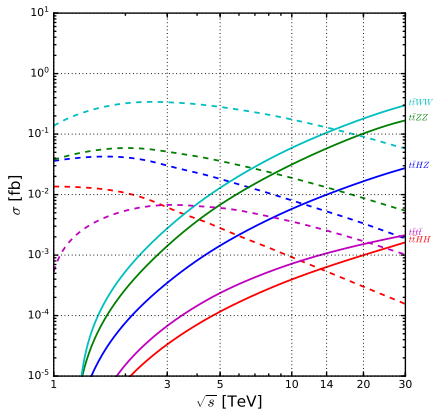
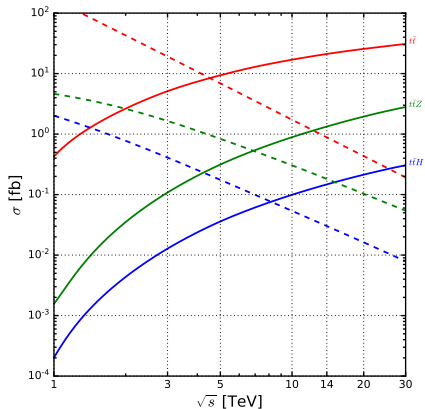


• $\sigma^{VBF} > \sigma^{s\text{-channel}}$ since

▶ $\sigma^{s\text{-channel}} \sim 1/s$

▶ $\sigma^{VBF} \sim \log^2(M_{VV}^2/M_V^2)/M_{VV}^2$ due to forward emission of $V = W/Z$

Top production

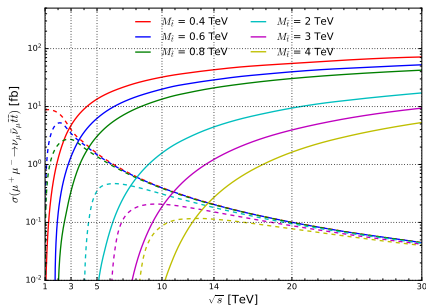
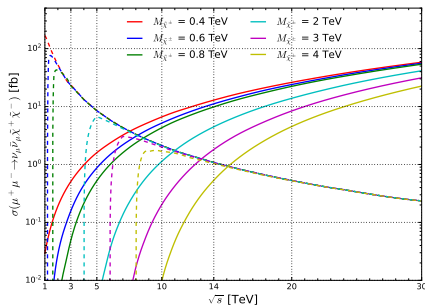


• Do you notice a pattern?

SUSY

(L) chargino pairs

(R) stop pairs

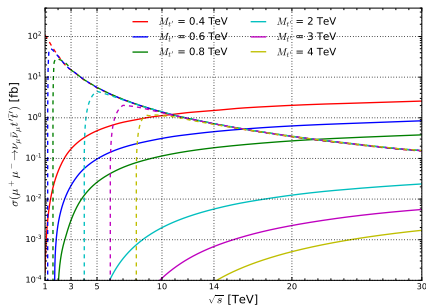
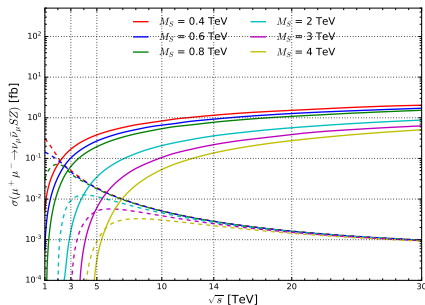


• And now?

Simple Extensions

(L) Singlet + Z production

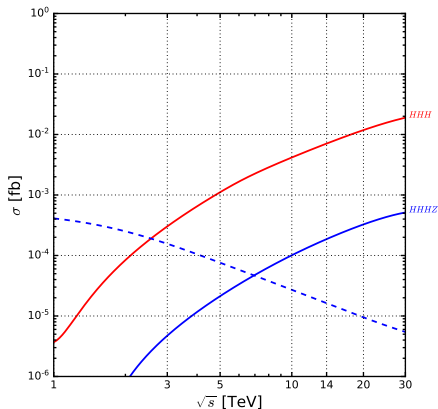
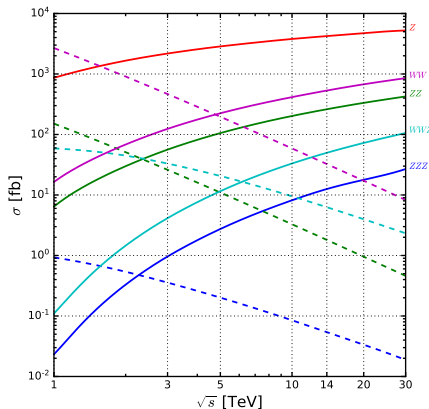
(R) vector-like top pair production



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

Many-boson production⁵

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]

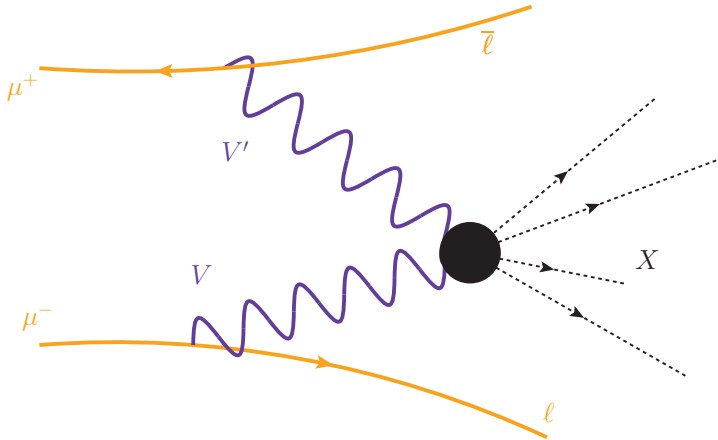
$$\frac{\sigma^{\text{VBF}}}{\sigma^{s\text{-}ch.}} \sim \mathcal{S} \left(\frac{g_W^2}{4\pi} \right)^2 \left(\frac{s}{M_X^2} \right) \log^2 \frac{s}{M_V^2} \log \frac{s}{M_X^2} > 1$$

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)	$t'\bar{t}'$ (VLQ)	$\tilde{t}\bar{\tilde{t}}$ (MSSM)	$\tilde{\chi}^0\bar{\tilde{\chi}}^0$ (MSSM)	$\tilde{\chi}^+\bar{\tilde{\chi}}^-$ (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 initial- 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 initial 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

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

$\psi^2 H^3$		$\psi^2 H^2 D$		$\psi^2 HX(+\text{H.c.})$	
$\mathcal{O}_{L\nu H}(+\text{H.c.})$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{H\nu}$	$(\bar{\nu}_R\gamma^\mu\nu_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{\nu B}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$
		$\mathcal{O}_{H\nu e}(+\text{H.c.})$	$(\bar{\nu}_R\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$
$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R)(+\text{H.c.})$	
$\mathcal{O}_{\nu\nu}$	$(\bar{\nu}_R\gamma^\mu\nu_R)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu}$	$(\bar{L}\gamma^\mu L)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Le}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e)$
$\mathcal{O}_{e\nu}$	$(\bar{e}\gamma^\mu e)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{Q\nu}$	$(\bar{Q}\gamma^\mu Q)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Qd}$	$(\bar{L}\nu_R)\epsilon(\bar{Q}d)$
\mathcal{O}_w	$(\bar{u}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu\nu_R)$			$\mathcal{O}_{LdQ\nu}$	$(\bar{L}d)\epsilon(\bar{Q}\nu_R)$
$\mathcal{O}_{d\nu}$	$(\bar{d}\gamma^\mu d)(\bar{\nu}_R\gamma_\mu\nu_R)$				
$\mathcal{O}_{d\nu e}(+\text{H.c.})$	$(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$				
$(\bar{L}R)(\bar{R}L)$		$(\bar{L}\cap B)(+\text{H.c.})$		$(\bar{L}\cap\bar{B})(+\text{H.c.})$	
$\mathcal{O}_{Q\nu L}(+\text{H.c.})$	$(\bar{Q}u)(\bar{\nu}_R L)$	$\mathcal{O}_{\nu\nu\nu}$	$(\bar{\nu}_R^c\nu_R)(\bar{\nu}_R^c\nu_R)$	$\mathcal{O}_{QQd\nu}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(Q_\alpha^i C Q_\beta^j)(d_\sigma C\nu_R)$
				$\mathcal{O}_{udd\nu}$	$\epsilon_{\alpha\beta\sigma}(u_\alpha C d_\beta)(d_\sigma C\nu_R)$

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 ν SMEFT can generate the right Δa_μ

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

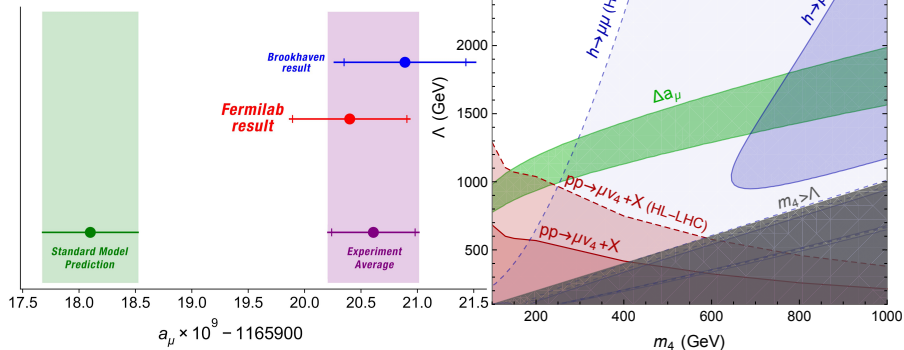
This generates Δa_μ of the form

$$\Delta a_\mu \sim -\frac{2m_\mu m_N}{(4\pi)^2 \Lambda^2} \text{Re} \left(V_{\mu N} [\bar{C}_{H\nu e}]_{N\mu} \right) \quad (\text{see [2105.11462] for exact formula!})$$

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

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

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