Vector Boson Scattering: Status and Prospects for the Large Hadron Collider and Beyond

Vrije Universiteit Brussel – Seminar

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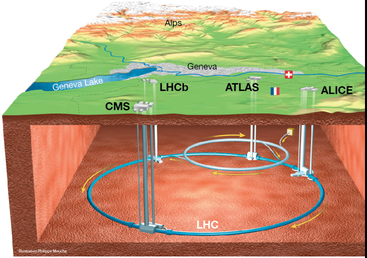
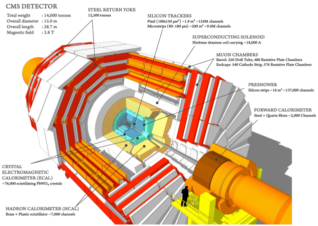
NARODOWE CENTRUM NAUKI

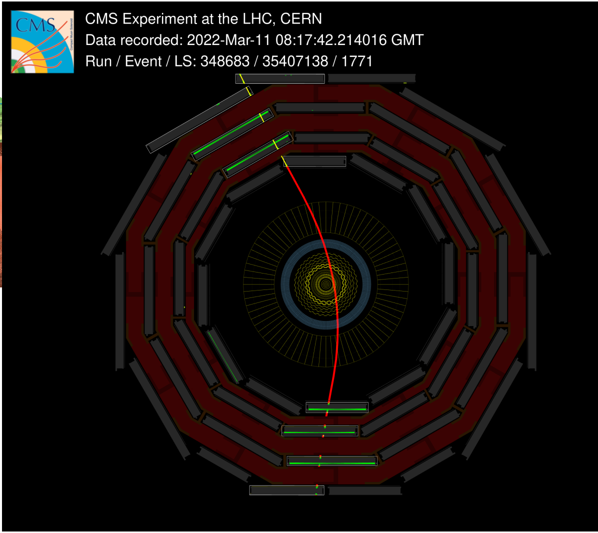
COMETA

Thank you for the invitation!

A real **cosmic muon** (μ) passing through the **CMS** detector at the **LHC**







Since $|\vec{B}| = 4$ T and radius $\neq 0, \infty$ $\Longrightarrow$ μ **is massive and charged!**

Particle Physics: Then and Now

Since the late 20th, a chief goal of particle physics has been to establish the **spectrum of particles**, their **structures**, and their **properties**

possible with many tools, e.g., production at colliders, tabletop measurements of fundamental symm., and rare decays

Particle Physics: Then and Now

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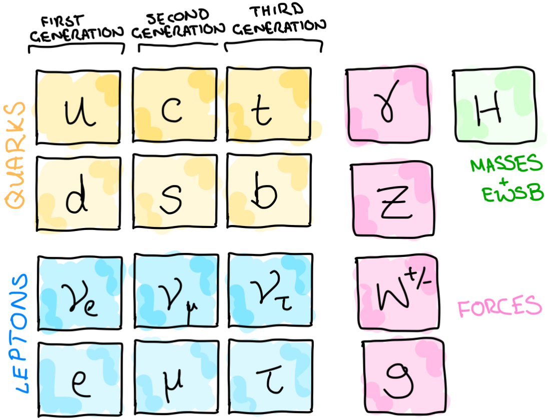
The Standard Model (SM) of particle physics

– position indicates quantum numbers/ charges

(just like in chemistry!)

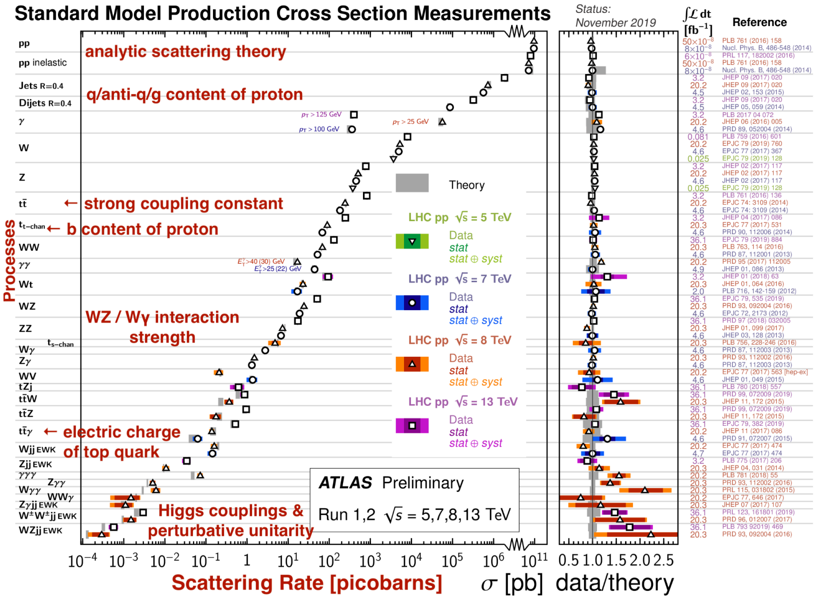
– e.g., spin, weak isospin, color, electromagnetic, weak hyper charge



credit: I. Bigaran

Today's goals include understanding the origin of the SM itself

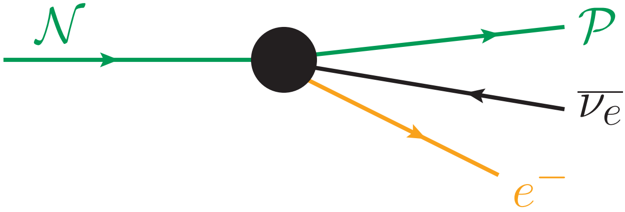
Undoubtedly, the SM is incredibly successful...



incredible TH & EX agreement ... but not perfect (we will return to this point!)

first a few ingredients

Nuclear β decay[1]

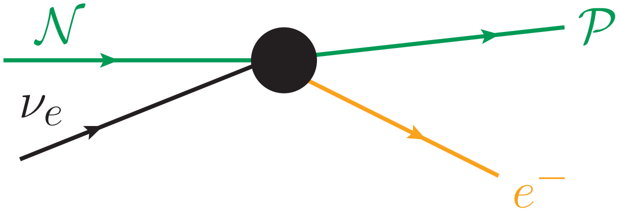


$$\mathcal{L}_{\rm Fermi} = G_F \left[\overline{\mathcal{N}}\gamma^\mu P_L \mathcal{P}\right] \cdot \left[\overline{\nu_e}\gamma_\mu P_L e\right]$$

Fermi('31)

[1] For non-experts: Action $= \mathcal{S} = \int dt\ L = \int d^4x\ \mathcal{L}$. ← HEP uses Lagrangian density with four-vectors x^μ, k^μ

Inverting ν_e leg $\implies$ inverse β decay (ν-nucleus scattering!)



$$-i\mathcal{M}(\nu_e\mathcal{N} \to e^-\mathcal{P}) \sim G_F\ [\overline{u}(k_{\mathcal{P}})\gamma^\mu P_L u(k_{\mathcal{N}})]\cdot[\overline{u}(k_e)\gamma_\mu P_L u(k_{\nu_e})] \sim G_F\ E^2$$

$$\implies \sigma(\nu_e\mathcal{N} \to e^-\mathcal{P}) \sim \frac{1}{\text{(flux)}}\ \sum\!\!\!\!\!\!\int_{\text{dof}}\ \text{(phase space)} \times |\mathcal{M}|^2 \sim G_F^2\frac{E^4}{\pi E^2}$$

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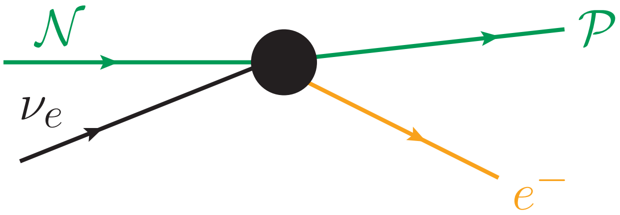

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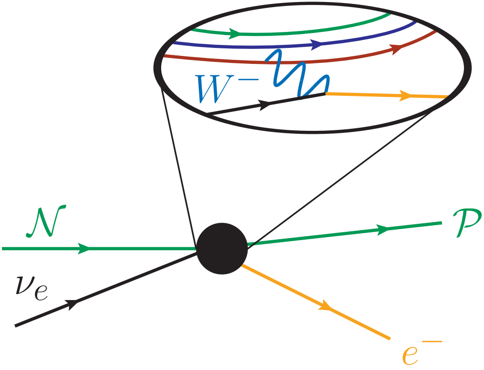
$\implies$ **scatt. rate (σ) grows with scatt. energy but without limit**

$\implies$ **violation of unitarity in scattering theory, i.e., $\sum$(prob)≤ 1**

Inverse β decay is a charged-current interaction!



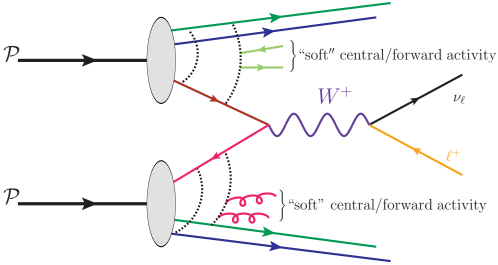
Fermi thry is the low-energy manifestation of the electroweak thry

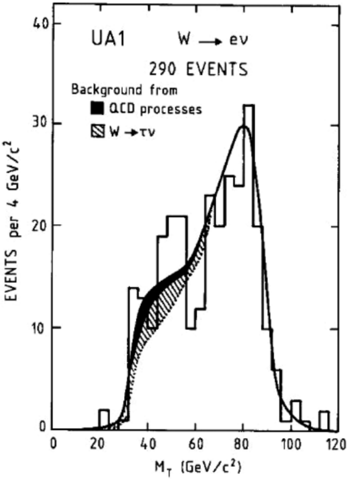
$$\left(\frac{g_W}{\sqrt{2}}\right)^2 \times \left(\frac{g_{\mu\nu} - \frac{q_\mu q_\nu}{M_W^2}}{q^2 - M_W^2 + i\Gamma_W M_W}\right) \xrightarrow{|q^2| \ll M_W^2} \frac{-g_W^2}{2M_W^2} = -2\sqrt{2}G_F$$

$$\implies \sigma(\nu_e \mathcal{N} \to e^- \mathcal{P}) \sim \frac{g_W^4}{\pi} \frac{E^2}{(E^2 - M_W^2)^2}$$ ← high-E behavior is regulated (finite)

Rotating graph $\Longrightarrow$ $W^{\pm}$ boson production

predicted by Glashow, Weinberg, Salam ('68); + (’79); discovered by UA1,UA2('83); ('84)





Transverse mass distribution for all W → eν events recorded by UA1

Electroweak sector of Standard Model is powerful:

– explains β decay

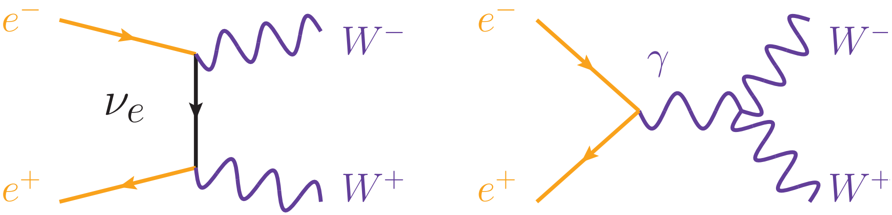
– explains inverse β decay

– predicts $W^{\pm}$ production in pp collisions

– some inputs needed, e.g., G_F, M_W

A little surgery with diagrams $\Longrightarrow$ W^+W^- pair production

(why make one $W^\pm$ when you can make W^+W^- pairs?)



$$-i\mathcal{M}(e^-e^+ \xrightarrow{\nu} W^+W^-) \sim g_W^2 \times E \times \left(\frac{-E}{E^2}\right) \times \left(\frac{E}{M_W}\right)^2 \sim -g_W^2 \frac{E^4}{E^2 M_W^2}$$

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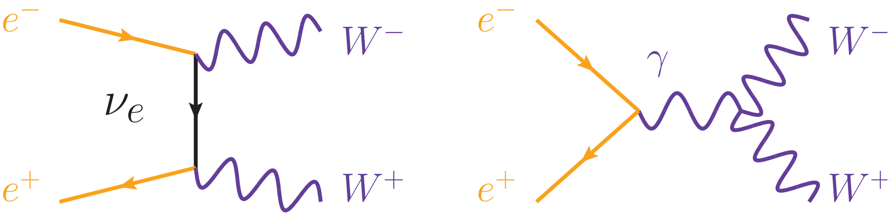

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$\Longrightarrow$ **scattering amplitude ($\mathcal{M}$) grows with scattering energy!**

$\Longrightarrow$ **violation of unitarity in scattering theory!**

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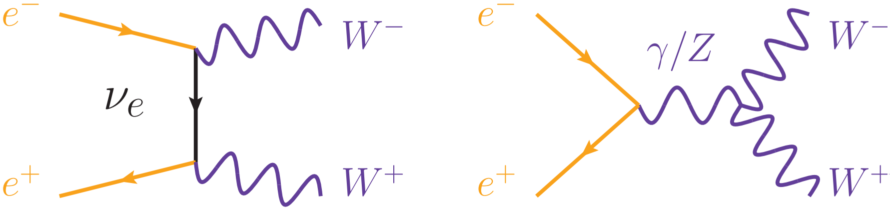

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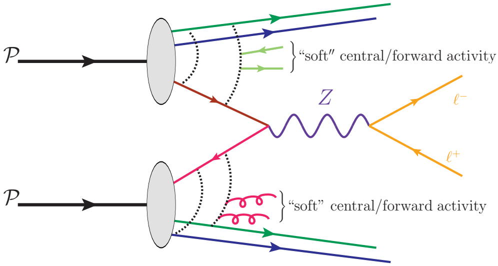
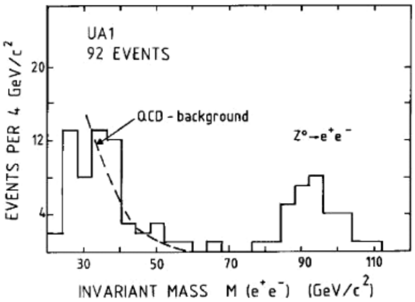
$$-i\mathcal{M}(e^-e^+ \overset{Z}{\to} W^+W^-) \sim \left(\frac{g_W}{\cos\theta_W}\right)(g_W \cos\theta_W) \times (+E) \times \cdots \sim +g_W^2 \frac{E^4}{E^2 M_W^2}$$

Delicate (structural) cancellations when all particles are included!

Diagram fun $\Longrightarrow$ Z boson production

predicted by Glashow, Weinberg, Salam ('68); + ('79); discovered by UA1,UA2('83); ('84)





Invariant mass distribution of all e^+e^- pairs recorded by UA1

Electroweak sector of Standard Model is powerful:

– explains β decay

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– some inputs needed, eg, G_F, M_W, M_Z

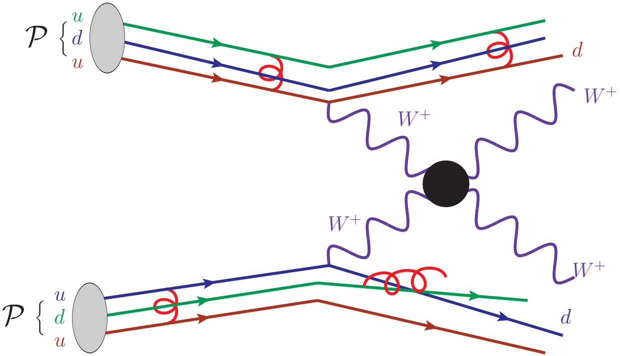
The Standard Model toolbox

- $W^{\pm}$, Z, γ all exist!
- **effective field theories break down at high energies ☺**
- **unitarity violation = bad ☹**
- **breakdown of theory $\implies$ unitarity violation ☹**
- **missing contributions $\implies$ unitarity violation ☹**
- **small mis-cancellations from new contributions $\implies$ E-enhanced scattering rates ☺**

vector boson scattering (VBS) / fusion (VBF)

Cut, rotate, glue, etc. sub-graphs $\Longrightarrow$ $W^+W^+ \to W^+W^+$ scattering

(why make W^+W^- pairs when you can *scatter* them?)



Just one of many examples:

– W^+W^-, $W^\pm Z$, $W^\pm\gamma$, $\gamma\gamma$, ZZ, $Z\gamma$ scattering are all possible

– $W^+W^- \to ZZ$, $W^\pm\gamma \to W^\pm Z$, etc, are also possible

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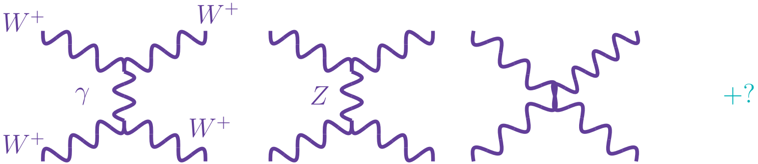

$$-i\mathcal{M}(W^+W^+ \to W^+W^+) \sim \left(\frac{E}{M_W}\right)^4 \times \left(\frac{-M_W^2}{E^2}\right) \times g_W^2(s_\theta^2 + c_\theta^2) \sim \frac{-g_W^2 E^2}{M_W^2}$$

$\implies$ scattering amplitude $(\mathcal{M})$ grows with scattering energy!

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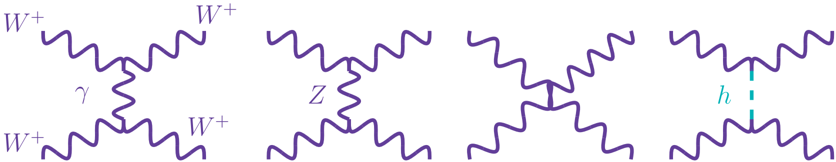

Higgs  ('13)

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$$-i\mathcal{M}(W^+W^+ \xrightarrow{h} W^+W^+) \sim \left(\frac{E}{M_W}\right)^4 \times \left(\frac{1}{E^2}\right) \times (g_W M_W)^2 \sim \frac{+g_W^2 E^2}{M_W^2}$$

Delicate (structural) cancellations when all particles are included!

Lee, Quigg, and Thacker ('77x2); Chanowitz and Gaillard ('84,'85)

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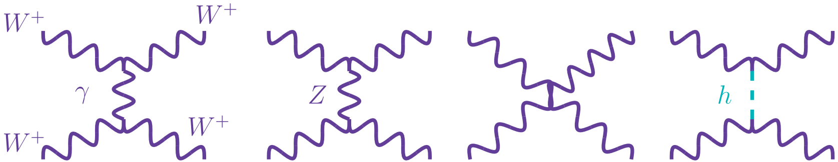

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Lee, Quigg, and Thacker ('77x2); Chanowitz and Gaillard ('84,'85)

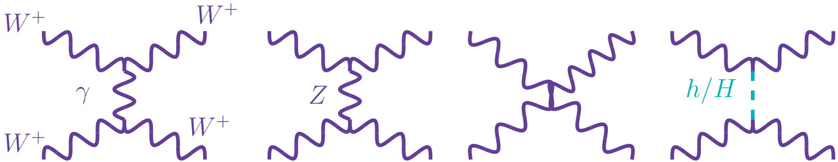
$\Longrightarrow$ modified $h - V - V$ couplings can disrupt cancellations

Too many contributions?

It is possible that Higgs with $m_h = 125$ GeV is one of several in nature

add'l scalars appears in Two Higgs Doublet Models, Supersymmetry, scalar-singlet dark matter, composite Higgs

$$\underbrace{|h_{\rm SM}\rangle}_{\rm interaction\ eigenstate} = \underbrace{\cos\psi\ |h_{\rm 125\ GeV}\rangle}_{\rm mass\ eigenstate} + \underbrace{\sin\psi\ |H_{\rm several\ TeV}\rangle}_{\rm mass\ eigenstate}$$

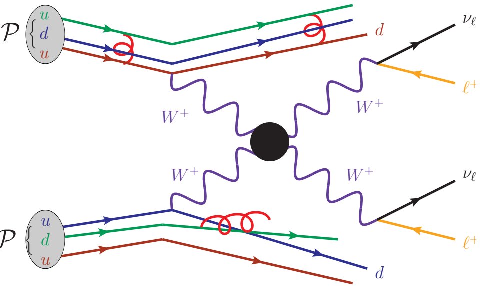


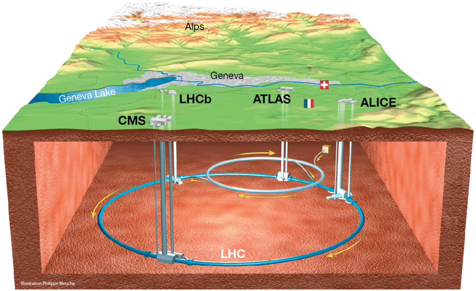
$$-i\mathcal{M}(W^+W^+ \xrightarrow{h/H} W^+W^+) \sim \frac{g_W^2 E^4}{M_W^2(E^2 - \cancel{m_h^2})}\underbrace{\cos^2\psi}_{\mathcal{O}(1)} + \frac{g_W^2 E^4}{M_W^2(\cancel{E^2} - m_H^2)}\underbrace{\sin^2\psi}_{\ll 1}$$

$\implies$ **$\mathcal{M}$ grows with scattering energy for $E_{(\sim 1\ \rm TeV)} \ll m_{H(\rm several\ TeV)}$!**

big idea: studying VBS = studying Higgs sector

The **LHC** is the **largest, etc.** hadron collider (pp, pA, AA) at $\sqrt{s} = 13.6$ TeV, with a **broad particle and nuclear physics program**





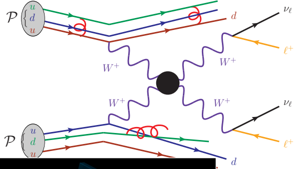
The **ATLAS** and **CMS** detectors at the **LHC** were designed to study VBS

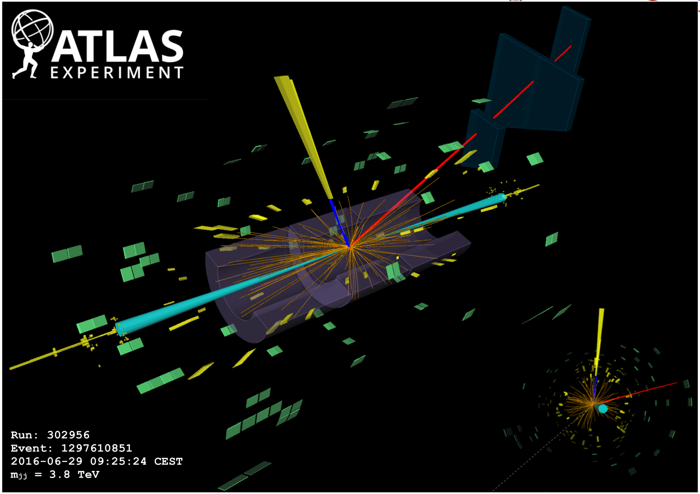
LHC's long-term plan includes using VBS to measure SM physics with high precision and search for new phenomena

Buarque (ed.), Gallinaro (ed.), RR (ed.), et al, Rev. Physics ('22) [arXiv:2106.01393]

ATLAS $W^+W^+ \to W^+W^+$ candidate event

$(pp \to e^+\nu_e\mu^+\nu_\mu jj)$





[PRL('19)]

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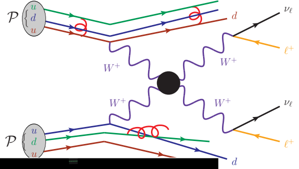
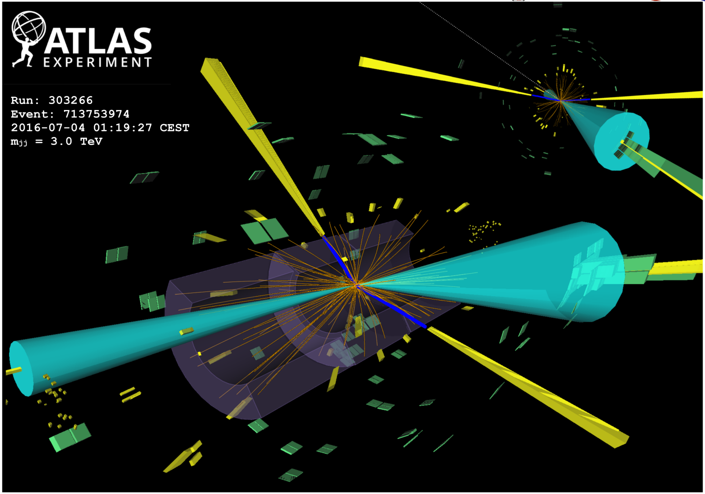
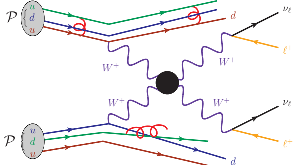
$(pp \to e^+e^+\nu_e\nu_e jj)$

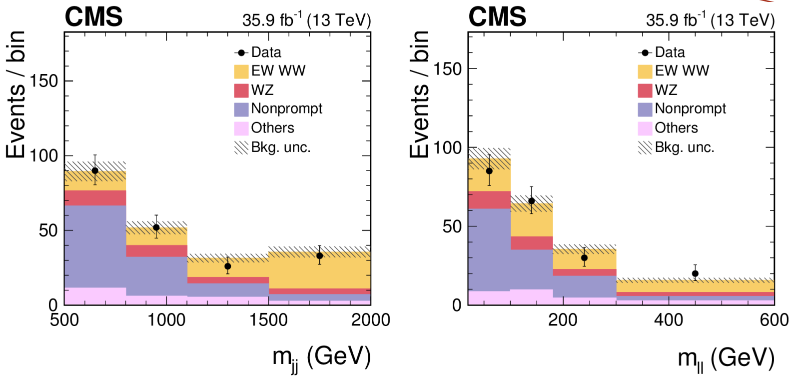




[PRL('19)]

Plotted: in $pp \to \ell_1^\pm \ell_2^\pm \nu\nu jj$, invariant mass of (L) (jj)-system, (R) ($\ell_1 \ell_2$)-system





[PRL('18)]

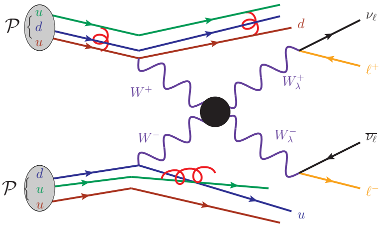
VBS observed for first time during LHC's Run II [CMS('18),ATLAS('19)]

- VBS at the LHC probes multi-TeV energy scales
- First measurements of VBS within 20% of SM predictions

polarization

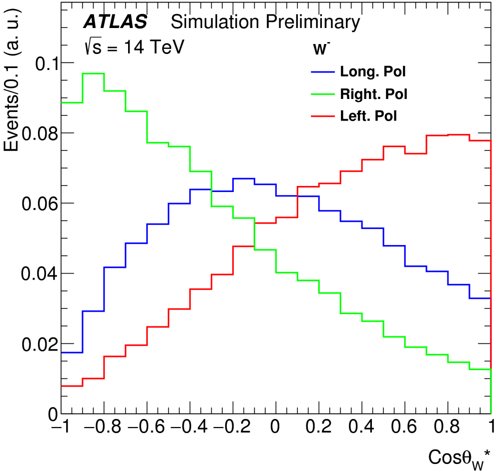
The $W^\pm_\lambda, Z_\lambda$ bosons are massive, spin-1 objects

– 2 transverse polarizations (L,R)
– 1 longitudinal polarization (0)



polarizations of vector bosons imprint on kinematics!

Plotted: angle of outgoing W^- in $pp \to W^+ W^-_\lambda jj$ via VBS



ATLAS [ATL-PHYS-PUB-2018-023]

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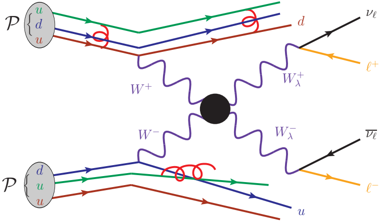
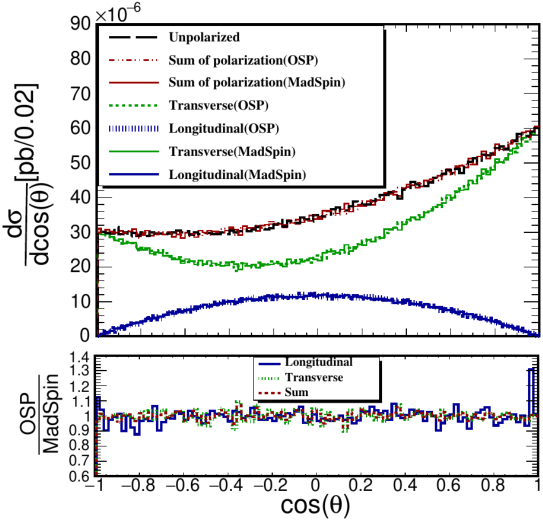


polarizations also imprint on kinematics of decay products!

Plotted: angle of outgoing ℓ^- in $pp \to W^+ W^-_\lambda jj \to W^+ \ell^- \overline{\nu_\ell} jj$ via VBS



Buarque Franzosi, RR, et al [(JHEP'20)]

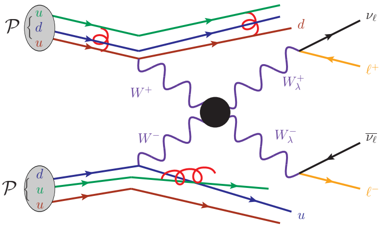
First measurement of polarization in $W^\pm W^\pm$ scattering

CMS (PLB'20)

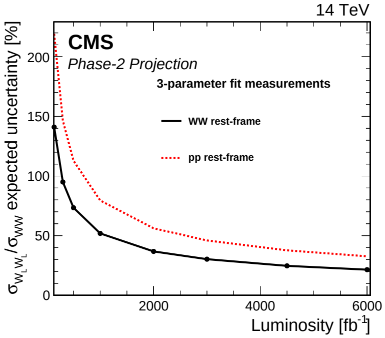
The $W^\pm_\lambda, Z_\lambda$ bosons are massive, spin-1 objects

– 2 transverse polarizations (L,R)
– 1 longitudinal polarization (0)

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



uncertainties sizable but will improve with time



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CMS [CMS-PAS-FTR-21-001]

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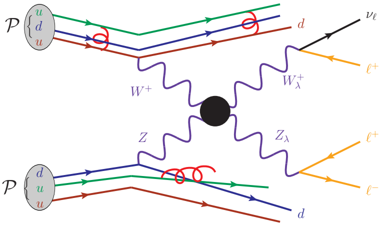
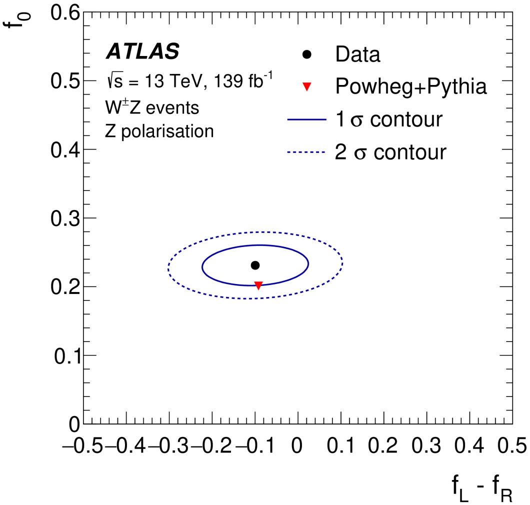


polarization also imprints on kinematics of decay products!

First measurement of polarization fractions (f_λ) in $W^{\pm}Z$ scattering

ATLAS [PLB('23)]



calculating scattering rates for helicity-polarized particles

Calculating helicity-polarized cross sections is delicate business

loss of Lorentz invariance, etc!

$$\Pi^{V}_{\mu\nu}(q) = \frac{-i\left(g_{\mu\nu} - q_\mu q_\nu / M_V^2\right)}{q^2 - M_V^2 + iM_V\Gamma_V} = \sum_{\lambda\in\{0,\pm1,A\}} \eta_\lambda \left(\frac{-i\varepsilon_\mu(q,\lambda)\ \varepsilon^*_\nu(q,\lambda)}{q^2 - M_V^2 + iM_V\Gamma_V}\right)$$

Different treatments of weak boson propagators

- **double-pole approximation/on-shell projection**

  Aeppli, et al ('93,'94); Denner, et al ('00); others

- **spin-truncated propagator [MadGraph]**

  w/ Buarque Franzosi, Mattelaer, Shil [1912.01725]

- **full NLO in QCD+EW for VV' production and decay [PowHEG]**

  Denner, Pellicciioli [2107.06579]; Pellicciioli, et al [2311.16031], others

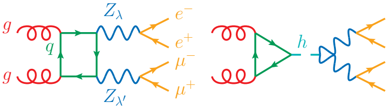
- **partial NLO in QCD for arbitrary processes [Sherpa]**

  Hoppe, et al [2310.14803]

Calculating helicity-polarized cross sections is delicate business

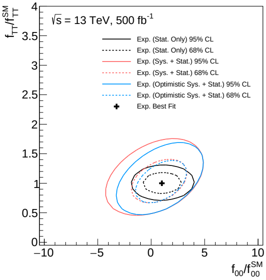
$$\frac{-i\ \varepsilon_\mu(q,\lambda)\ \varepsilon^*_\nu(q,\lambda)}{q^2-M_V^2} =$$

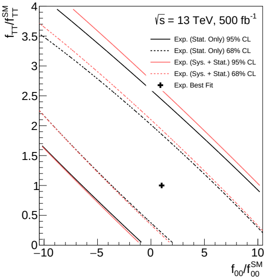
$V_\lambda(q)$



- **NEW! helicity polarization as a Feynman rule** w/ Javurkova, et al [2401.17365]

Projected sensitivity to pol. for (L) $gg \to Z_\lambda Z_{\lambda'}$ and (R) $VV \to Z_\lambda Z_{\lambda'}$





singly and doubly charged scalars

New Higgs bosons?

It is possible that Higgs with $m_h = 125$ GeV is one of several in nature

add'l scalars appears in Two Higgs Doublet Models, Supersymmetry, scalar-singlet dark matter, composite Higgs

$$\underbrace{|h_{\rm SM}\rangle}_{\rm interaction\ eigenstate} = \underbrace{\cos\psi\ |h_{\rm 125\ GeV}\rangle}_{\rm mass\ eigenstate} + \underbrace{\sin\psi\ |H_{\rm several\ TeV}\rangle}_{\rm mass\ eigenstate}$$

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It is also possible new Higgses are not arbitrary but belong to a group

e.g., Type II Seesaw model for neutrino masses: $\Delta\mathcal{L} = y\overline{L}\cdot\Delta L^c \to (yv_2)\ \overline{\nu_L}\nu_L^c$

$$\Phi_{\rm SM} = \frac{1}{\sqrt{2}}\begin{pmatrix} i\sqrt{2}G^+ \\ v_1 + h^0_{\rm SM} + iG^0 \end{pmatrix}$$

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$$\Phi_{\rm SM} = \frac{1}{\sqrt{2}}\begin{pmatrix} i\sqrt{2}G^+ \\ v_1 + h^0_{\rm SM} + iG^0 \end{pmatrix} \qquad \Delta_{\rm Type\ II} = \frac{1}{\sqrt{2}}\begin{pmatrix} H^+ & \sqrt{2}H^{++} \\ v_2 + H^0 + i\xi^0 & -H^+ \end{pmatrix}$$

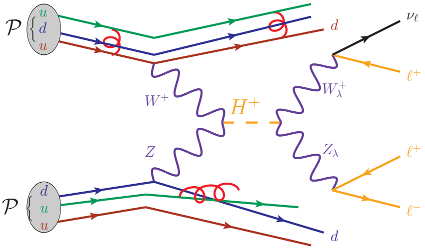
$\Longrightarrow$ **if h^0 and H^0 are accessible with VBS, then also $H^\pm$ and $H^{\pm\pm}$**

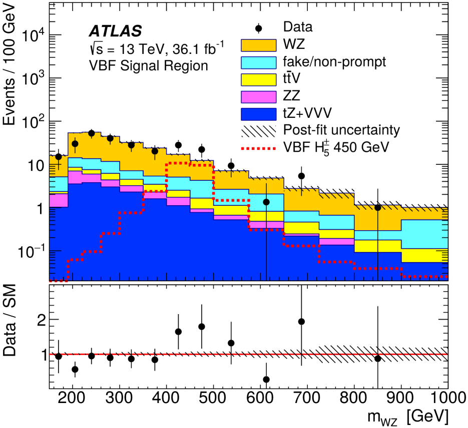
Singly ($H^{\pm}$) and doubly ($H^{\pm\pm}$) charged scalars are predicted in several popular models

Two Higgs Doublet Models, Supersymmetry, Type II Seesaw, Georgi-Machacek model

Plotted: invariant mass of (WZ)-system in $pp \to W^{\pm}(\to jj)Z(\to \ell^{+}\ell^{-})jj$

ATLAS [PRL('15)]





Searches for $H^{\pm}$ in $W^{\pm}Z$ scattering with early Run II data gave *suggestive hints of something new* ☺!

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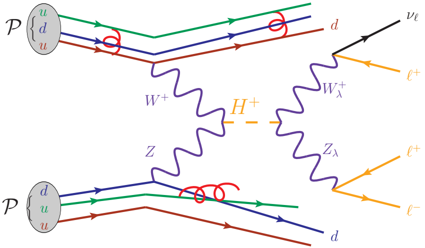
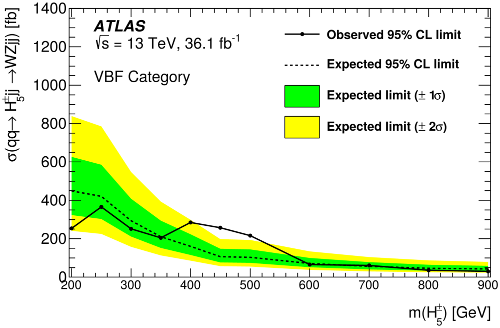
Two Higgs Doublet Models, Supersymmetry, Type II Seesaw, Georgi-Machacek model



Plotted: excluded upperlimit on scattering rate of $pp \to W^\pm Zjj$ via $H^\pm$ as a function of $m_H^\pm$

ATLAS [PRL('15)]



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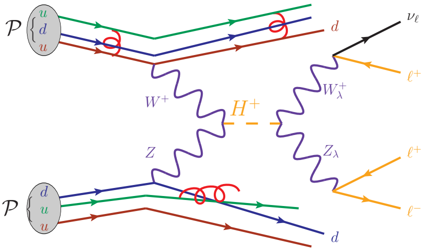
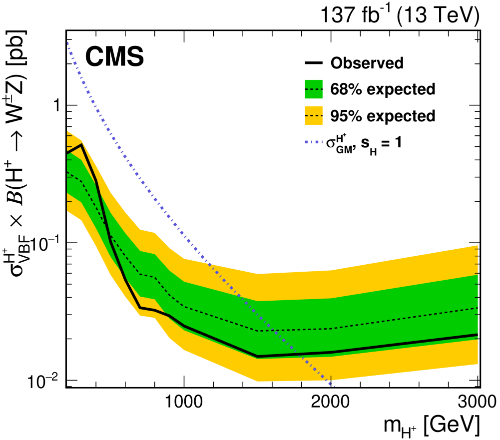


Searches for $H^{\pm}$ in $W^{\pm}Z$ scattering with all Run II data shows "bump"

just a statistical fluctuation ☹

Plotted: excluded upperlimit on scattering rate of $pp \to W^{\pm}Zjj$ via $H^{\pm}$ as a function of $m_H^{\pm}$ CMS [EPJC('21)]



heavy (Majorana) fermions[2]

[2] For reviews at colliders, see Cai, Han, Li, RR [1711.02180] and Pascoli, RR, Weiland [1812.08750]

for non-experts: adding ν_R to the SM (1 slide)

To generate Dirac masses for ν like other SM fermions, we need ν_R

$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\nu \overline{L}\tilde{\Phi}\nu_R + H.c. = -y_\nu \left(\overline{\nu_L} \quad \overline{\ell_L}\right)\begin{pmatrix}\langle\Phi\rangle + h \\ 0\end{pmatrix}\nu_R + H.c.$$

$$= \underbrace{-y_\nu\langle\Phi\rangle}_{=m_D}\overline{\nu_L}\nu_R + H.c. + \ldots$$

ν_R do not exist in the SM, so pretend that they do and $\nu_R = \nu_R^c$:

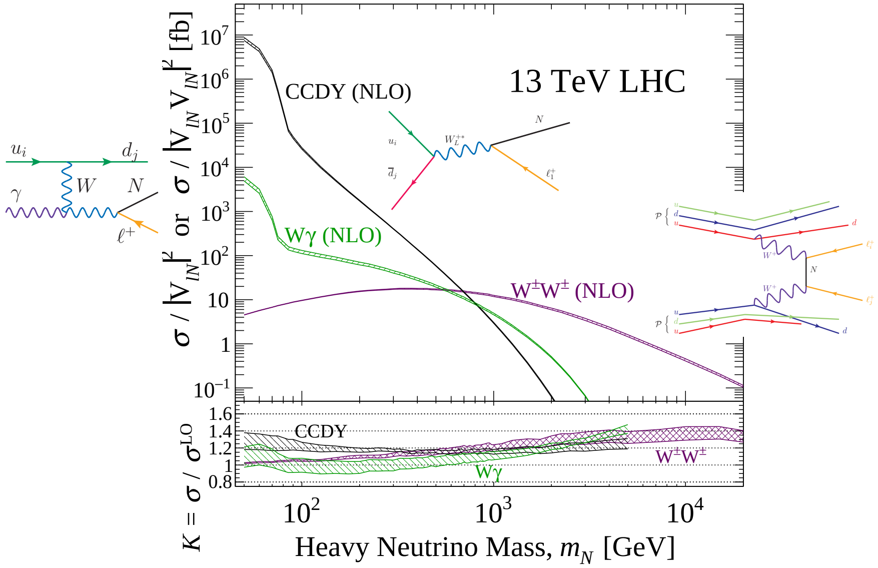
$$\Longrightarrow \mathcal{L}_{\text{mass}} = \frac{-1}{2}\underbrace{\left(\overline{\nu_L} \quad \overline{\nu_R^c}\right)}_{\text{chiral state}} \underbrace{\begin{pmatrix} 0 & m_D \\ m_D & \mu_{\not{L}}\end{pmatrix}}_{\text{mass matrix (chiral basis)}} \begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix}$$

(sizes of m_D & $\mu_{\not{L}}$ have major impact on pheno; see Pascoli, et al [1712.07611])

After diagonalizing the mass matrix, identify ν_L (chiral eigenstate) in the SM as a linear combination of mass eigenstates:

$$\underbrace{|\nu_L\rangle}_{\text{chiral state}} = \cos\theta \underbrace{|\nu\rangle}_{\text{light mass state}} + \sin\theta \underbrace{|N\rangle}_{\text{heavy mass state}} \text{ (this is a prediction!)}$$

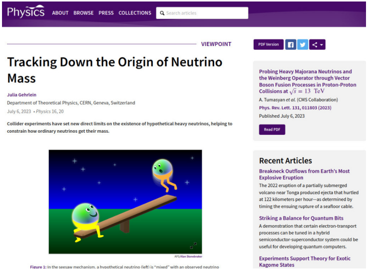
Plotted: Normalized production rate ($\sigma/|V|^{2\ (4)}$) vs m_N



$\gamma W^{\pm}$ and $W^{\pm}W^{\pm}$ scattering drive high-mass scattering rates!

w/ Fuks, Neundorf, Peters, Saimpert [PRD('21)]

Search for $W^\pm W^\pm \to \ell^\pm \ell'^\pm$ quickly adopted by LHC groups!


Physics ABOUT BROWSE PRESS COLLECTIONS

VIEWPOINT

Tracking Down the Origin of Neutrino Mass

Julia Gehrlein
Department of Theoretical Physics, CERN, Geneva, Switzerland

July 6, 2023 • Physics 16, 20

Collider experiments have set new direct limits on the existence of hypothetical heavy neutrinos, helping to constrain how ordinary neutrinos get their mass.

Figure 1: In the seesaw mechanism, a hypothetical neutrino (left) is "mixed" with an observed neutrino

Probing Heavy Majorana Neutrinos and the Weinberg Operator through Vector Boson Fusion Processes in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV
A. Tumasyan et al. (CMS Collaboration)
Phys. Rev. Lett. 131, 011803 (2023)
Published July 6, 2023

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The 2022 eruption of a partially submerged volcano near Tonga produced ejecta that hurtled at 122 kilometers per hour—as determined by timing the ensuing rupture of a seafloor cable.

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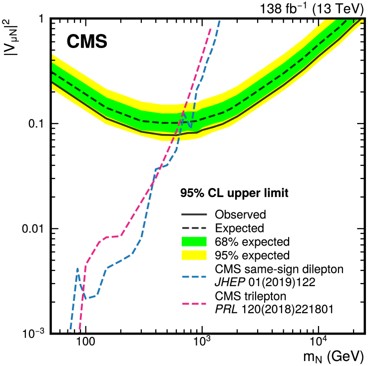
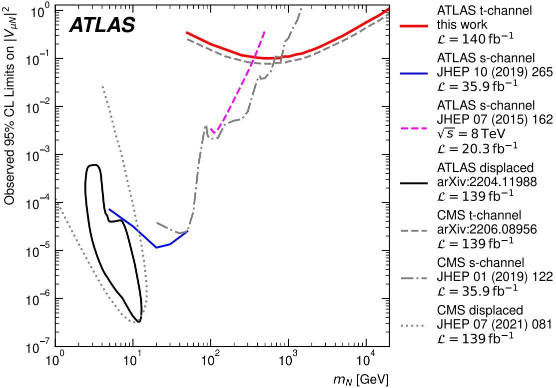
A demonstration that certain electron-transport processes can be tuned in a hybrid semiconductor-superconductor system could be useful for developing quantum computers.

Experiments Support Theory for Exotic Kagome States





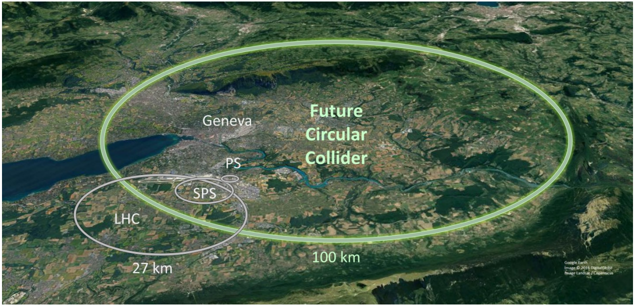
ATLAS ('23) [2305.14931]

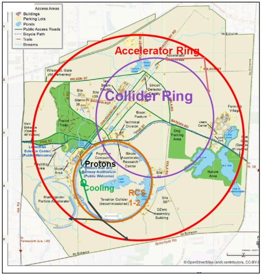
$ee/e\mu$ **channels at Moriond**

← **CMS ('22) [2206.08956]**

a future beyond the LHC

Many physics and technical discussions are taking place over the successor of the **LHC** (beyond '30s-'40s)



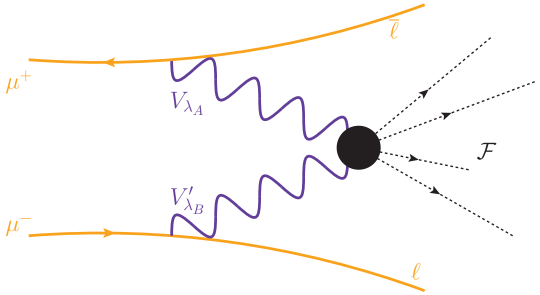


Multi-stage 100 TeV e^+e^-pp collider at CERN (FCC program)
and 14-30 TeV $\mu^+\mu^-$ at Fermilab are most supported

European Strategy for Particle Physics [1910.11775,CERN-ESU-013, Mid-term review ('24)];

Black (ed.), Jindariani (ed.), Li (ed.), F. Maltoni (ed.), et al, [2209.01318]

Why?[3] Situation where scattering formalism is **theoretically interesting**



Partonic collisions at $Q \sim \mathcal{O}(10)$ TeV explore when **electroweak (EW)** symmetry is nearly restored, i.e., $(M^2_{W/Z/H}/Q^2) \to 0$

See C. Bauer, et al ('16,'17,'18); T. Han, et al ('16,'20,'21); A. Manohar, et al ('14,'18) + others

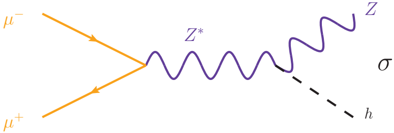
When momentum transfers reach $Q \sim \mathcal{O}(10)$ TeV, vector boson scattering (**VBS/VBF**) **acts a bit... funny**

w/ A. Costantini, et al [JHEP('20)]

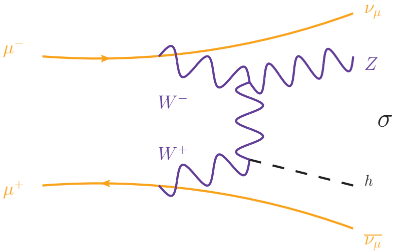
[3] Many motivations, e.g., Al Ali, et al. [2103.14043]; R&D progress as reported in the European Strategy Update (Delahaye, et al) [1901.06150], muoncollider.web.cern.ch; Snowmass (on-going this week)

some examples of VBS at higher energies

Quick interlude: *s*-channel annihilation vs VBS



$$\sigma^{s-channel} \sim \frac{g^4}{s}$$

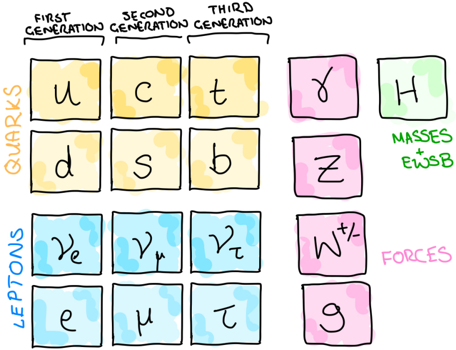


$$\sigma^{VBF} \sim \frac{g^8}{M_{WW}^2} \log^2\left(\frac{M_{WW}^2}{M_W^2}\right)$$

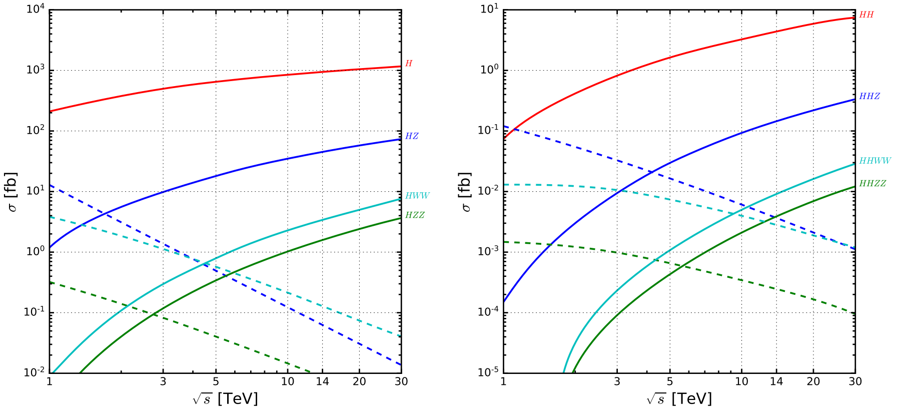
More legs $\Longrightarrow$ more propagators $\Longrightarrow$ $\int dk^2/(k^2 - M_W^2) \sim \log(\Lambda^2/M_W^2)$

Larger s $\Longrightarrow$ larger (M_{WW}^2/M_W^2) $\Longrightarrow$ collinear V compensate for g

Higgs production

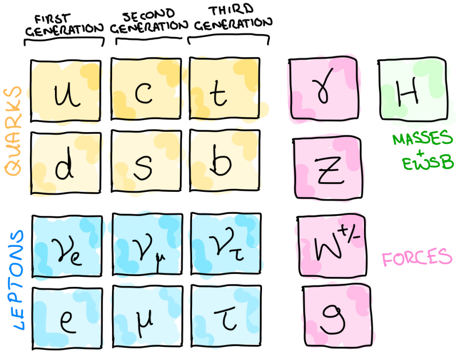


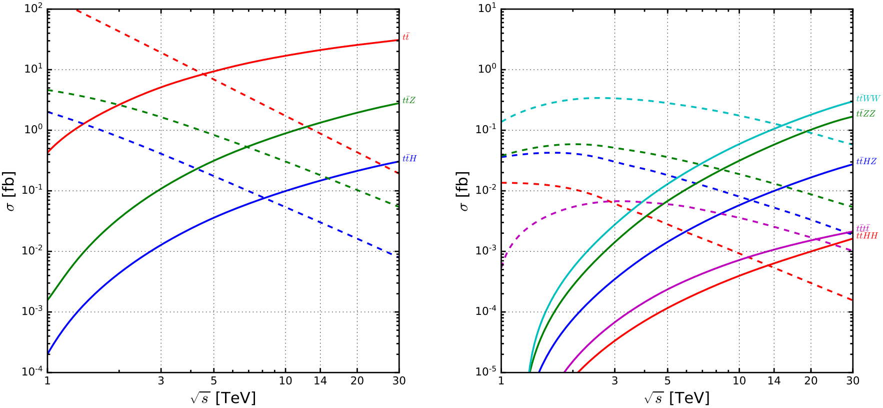
cross sections (σ) vs $\sqrt{s}$ for s-channel annihilation (dash) vs VBS (solid)



- Eventually, $\sigma^{VBF} > \sigma^{s-channel}$ 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 $V = W/Z$

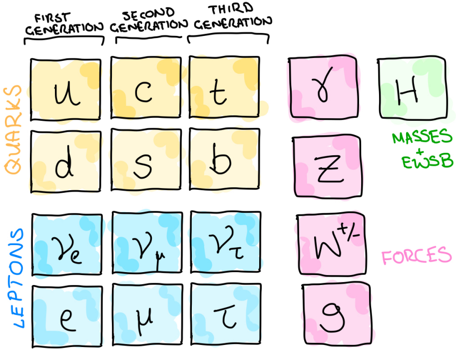
Top production



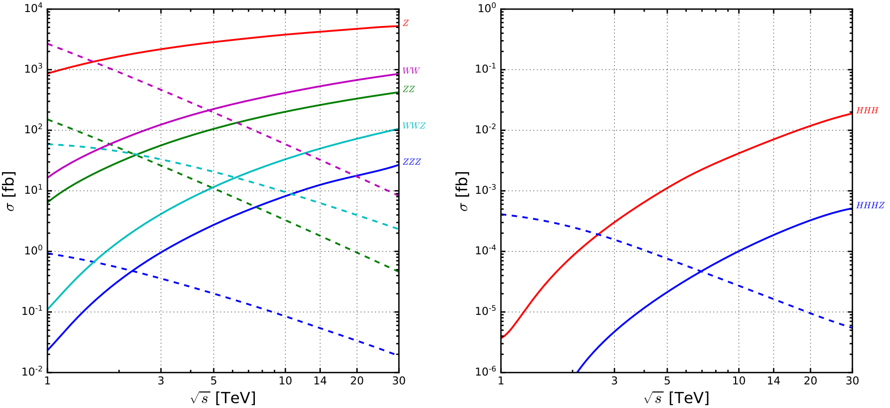


- Do you notice a pattern?

Many-boson production[4]



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



- **VBF is the dominant production vehicle for many processes**

Evidence for trend that VBS rates will always exceed s-ch. rates

Is this obvious? (not to me at first!) **Is there intuition for this?** (yes!)

w/ A. Costantini, et al [JHEP('20,'21)]

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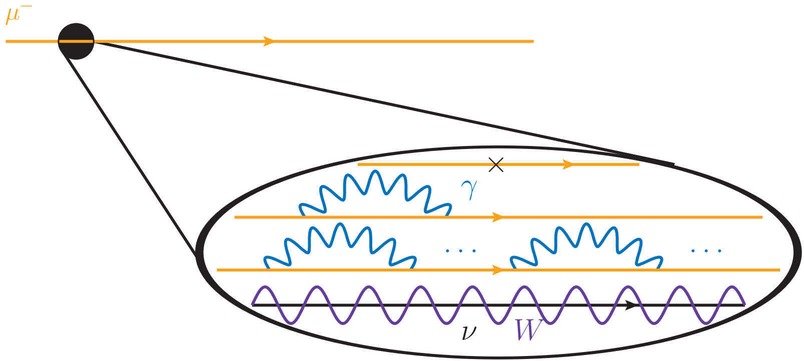

idea: increasing σ^{VBS} is manifestation of growing partonic content

Evidence for trend that VBS rates will always exceed s-ch. rates

Is this obvious? (not to me at first!) **Is there intuition for this?** (yes!)

w/ A. Costantini, et al [JHEP('20,'21)]

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w/ A. Costantini, et al [JHEP('20,'21)]

Idea: crudely compare the production of X by writing generically

$$\sigma^{s-ch.} \sim \frac{(s-M_X^2)}{(s-M_V^2)^2} \sim \frac{(s-M_X^2)}{s^2} \quad \leftarrow \text{assumes } s \gg M_V^2$$

$$\frac{d\sigma^{VBF}}{dz_1 dz_2} \sim \underbrace{f_V(z_1) f_{V'}(z_2)}_{\text{"}\mu\text{PDFs"}} \underbrace{\frac{(M_{VV'}^2 - M_X^2)}{(M_{VV'}^2 - M_V^2)^2}}_{M_{VV'}^2 = z_1 z_2 s \gg M_V^2} \sim f_V(z_1) f_{V'}(z_2) \frac{(z_1 z_2 s - M_X^2)}{(z_1 z_2)^2} \frac{\sigma^{s-ch.}}{(s - M_X^2)}$$

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PDFs are largest when $z = E_V/E_\mu \ll 1$ but $E_V \sim \sqrt{s} \gg M_V$

$$\implies f_V(z_i) \sim \frac{g_W^2}{4\pi} \frac{1}{z_i} \log\left(\frac{s}{M_V^2}\right) \quad \leftarrow \text{crude approximation}$$

Evidence for trend that VBS rates will always exceed s-ch. rates

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w/ A. Costantini, et al [JHEP('20,'21)]

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$$\frac{d\sigma^{VBF}}{dz_1 dz_2} \sim \underbrace{f_V(z_1) f_{V'}(z_2)}_{\text{“}\mu\text{PDFs"}} \underbrace{\frac{(M_{VV'}^2 - M_X^2)}{(M_{VV'}^2 - M_V^2)^2}}_{M_{VV'}^2 = z_1 z_2 s \gg M_V^2} \sim f_V(z_1) f_{V'}(z_2) \frac{(z_1 z_2 s - M_X^2)}{(z_1 z_2)^2} \frac{\sigma^{s-ch.}}{(s - M_X^2)}$$

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Observation: $\sigma^{VBF} = \sigma^{s-ch.} \times \int dz_1 dz_2 \ldots$ is solvable for $M_{VV'} \gg M_X$!

Universal behavior: when production of X by VBS and annihilation are driven by same physics, VBS **dominates** when $\sqrt{s}$ satisfies

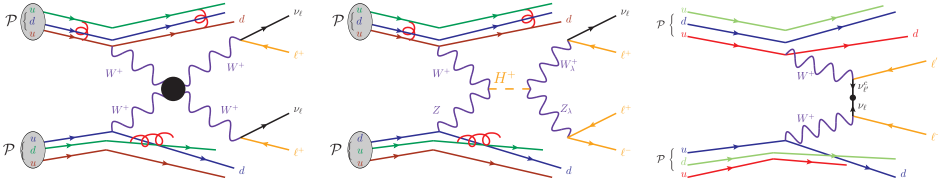
$$\frac{\sigma^{\mathrm{VBF}}}{\sigma^{s-ch.}} \sim \mathcal{S}\left(\frac{g_W^2}{4\pi}\right)^2 \left(\frac{s}{M_X^2}\right) \log^2 \frac{s}{M_V^2} \log \frac{s}{M_X^2} > 1$$

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 ($2M_X$).

summary and outlook



Vector boson scattering is a powerful probe of the **Standard Model** and **new phenomena**

Long-predicted but observed first during Run I/II of LHC!

– **With Run II data,** first measurements of VBS and key test of SM

– **Run III (now-'25):** VBS as new probe of new phenomena

– **Run IV ('30-'40)** legacy precision measurements + novel exploration of SM at high energies

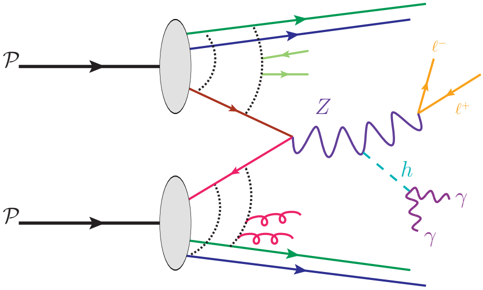
Buarque (ed.), Gallinaro (ed.), RR (ed.), et al, Rev. Physics ('22) [arXiv:2106.01393]

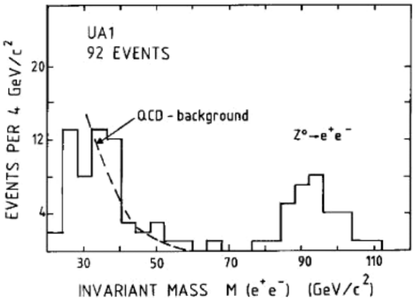
Thank you!

backup

Diagram games $\Longrightarrow$ h boson production

predicted by Brout, Engler ('64), Higgs ('64); + Nobel ('14); discovered by ATLAS and CMS ('12)





Invariant mass distribution of all e^+e^- pairs recorded by UA1

Electroweak sector of Standard Model is powerful:

– explains β decay

– explains inverse β decay

– explains masses of $W^\pm, Z$, e, others

– inputs needed, eg, G_F, M_W, M_Z, m_h

neutrino masses

For the experts (1 slide)

To generate m_ν via the Higgs mechanism, we need ν_R

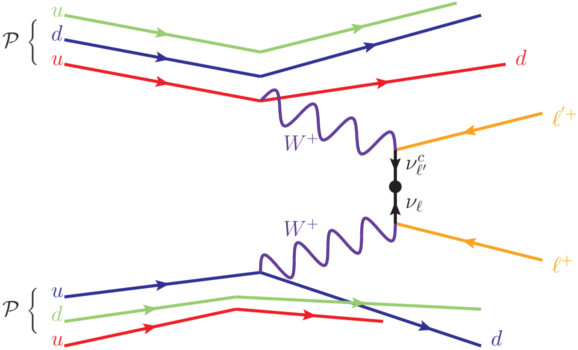
$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\nu \overline{L}\tilde{\Phi}\nu_R + \dots \quad = \quad -y_\nu \left(\overline{\nu_L} \quad \overline{\ell_L}\right) \begin{pmatrix} \langle \Phi \rangle + h \\ 0 \end{pmatrix} \nu_R + \dots$$
$$= \quad \underbrace{-y_\nu \langle \Phi \rangle}_{\equiv m_\nu} \overline{\nu_L} \nu_R + \dots$$

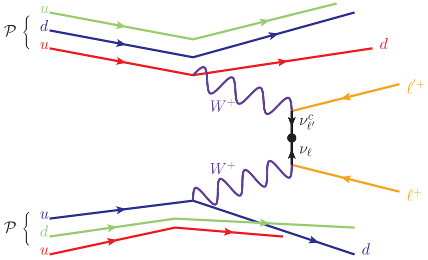
ν_R do not exist in the SM, so $m_\nu = 0$!

Dilemma: postulating ν_R requires either new conservation laws or violation of **lepton number** and/or **lepton flavor number** symmetries

(expected but no evidence! suggestive that there is more to the picture)

neutrinoless $\beta\beta$ decay (at $d = 5$) at the LHC



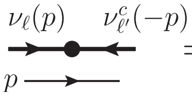


The helicity amplitude for the $0\nu\beta\beta$ process $q\overline{q'} \to \ell_1^+ \ell_2^+ \overline{f} f'$ is

$$\mathcal{M}_{LNV} = J^{\mu}_{f_1 f_1'} J^{\nu}_{f_2 f_2'} \Delta^{W}_{\mu\alpha} \Delta^{W}_{\nu\beta} \underbrace{T^{\alpha\beta}_{LNV} \mathcal{D}(p_\nu)}_{\text{lepton current}}$$

Difficult to simulate since Weinberg op. modifies propagator of ν_ℓ

modern Monte Carlo tools work in mass basis and do not like the idea of modifying $\langle 0|\overline{\nu_{\ell'}}\nu_\ell|0\rangle$



$$= \frac{i\not{p}}{p^2} \frac{-iC_5^{\ell\ell'} v^2}{\Lambda} \frac{i\not{p}}{p^2} = \frac{i m_{\ell\ell'}}{p^2}$$

Solution: Treat vertex as a particle! Invent unphysical Majorana fermion with (small) mass $m_{\ell\ell}$ that couples to all lepton flavors

recovers right behavior!

$$T^{\alpha\beta}_{LNV} \mathcal{D}(p_\nu) \propto \gamma^\alpha P_L \frac{i(\not{p} + m_{\ell\ell'})}{p^2 - m^2_{\ell\ell'}} \gamma^\beta P_R = \gamma^\alpha P_L \frac{i m_{\ell\ell'}}{p^2} P_L \gamma^\beta \times \left[1 + \mathcal{O}\left(\left|\frac{m^2_{\ell\ell'}}{p^2}\right|\right)\right]$$

Plotted: Normalized production rate $(C_5 = 1)$ vs scale (Λ)

w/ Fuks, Neundorf, Peters, Saimpert [2012.09882]

Full $2 \to 4$ calculation at NLO(+PS) in QCD is more involved

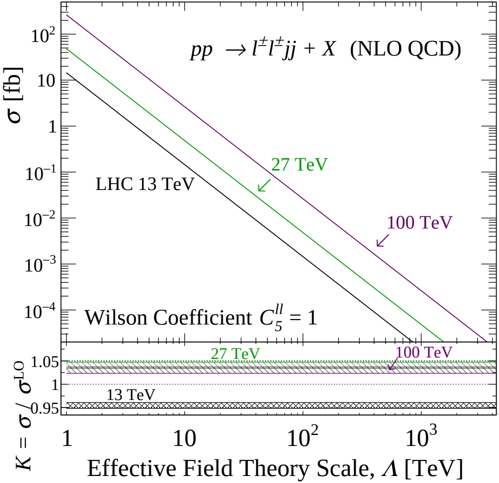
Used `mg5amc` + NEW `SMWeinberg` UFO libraries

Driven by $W_0^+ W_0^+$ scattering

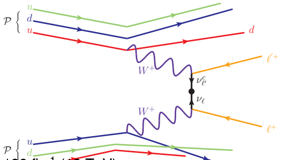
$\hat{\sigma}(W^+ W^+ \to \ell^+ \ell^+) \sim \frac{|C_5^{\ell\ell}|^2}{18\pi\Lambda^2}$

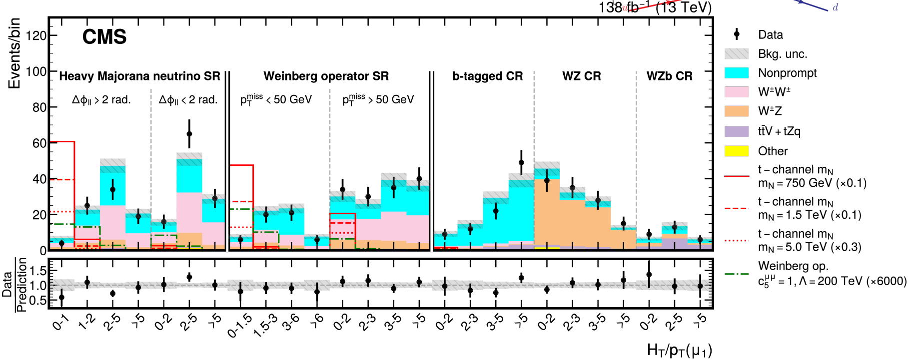
Once σ is obtained for a "high" scale, i.e., $C_5^{\ell\ell'} = 1, \Lambda = 200$ TeV, rescale for other Λ / C_5.

C_5^{ee}/Λ is heavily constrained. **What can the LHC say about $C_5^{\ell\ell'}$?**



Plotted: "hadronic energy / lepton energy"
for different signal categories
in $pp \to \mu^\pm \mu^\pm jj$ via $W^\pm W^\pm \to \mu^\pm \mu^\pm$





For the first time collider searches for Weinberg operator constrains

$$\Lambda / C_5^{\mu\mu} \gtrsim 5 \text{ TeV}$$

w/ Fuks, Neundorf, Peters, Saimpert [PRD('21, '21)] CMS [PRL('22)]