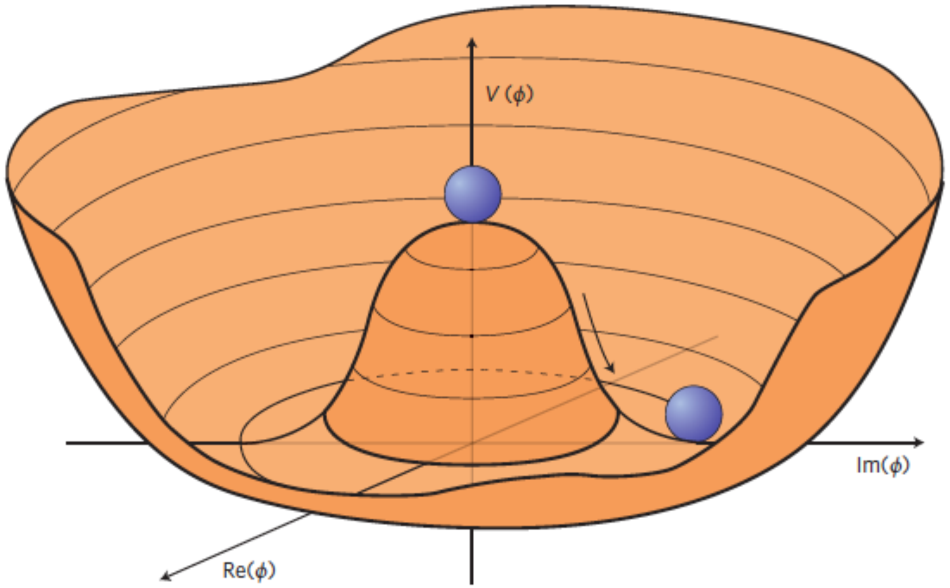
Probing Electroweak Symmetry Breaking at the LHC



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Nikhef PhD Topical Lectures
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The Need for Electroweak Symmetry-Breaking

Theory ref: [Logan]

Starting point: The SM Lagrangian and invariance under $SU(3)_C \times SU(2)_L \times U(1)_Y$.

$$\underbrace{\mathcal{L}_{\text{SM}}}_{} = \underline{\mathcal{L}_{\text{gauge}}} + \underline{\mathcal{L}_{\text{Higgs}}} + \underline{\mathcal{L}_{\text{fermion}}}$$

- Introduced to ensure gauge invariance under $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Encodes gauge boson dynamics
- Mass term $\frac{1}{2}m^2 B_\mu B^\mu$ not gauge invariant → forbidden.

- Encodes fermion kinetics, boson-fermion interactions
- Mass term $m\bar{\psi}\psi = m(\overline{\psi_R}\psi_L + \overline{\psi_L}\psi_R)$ not gauge invariant → forbidden.

- Mass terms for bosons and fermions are forbidden by gauge invariance!
  - ➢ Time for the Higgs piece...

The Higgs Piece

Theory ref: [Logan]

How to save this picture? → Add a complex scalar field:

Four degrees of freedom

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

Relevant term in the Lagrangian:

$$\mathcal{L}_{\text{Higgs}} = \left|\mathcal{D}_\mu \Phi\right|^2 - V(\Phi) + \mathcal{L}_{\text{Yukawa}}$$

Interaction between Higgs and gauge bosons

$$\mathcal{D}_\mu = \left(\partial_\mu - i g_s G^a_\mu t^a_c - i g W^p_\mu T^p_L - i g' B_\mu Y\right)$$

Higgs potential → leads to Electroweak Symmetry Breaking (EWSB)

Interaction between Higgs and fermions

The Higgs Potential

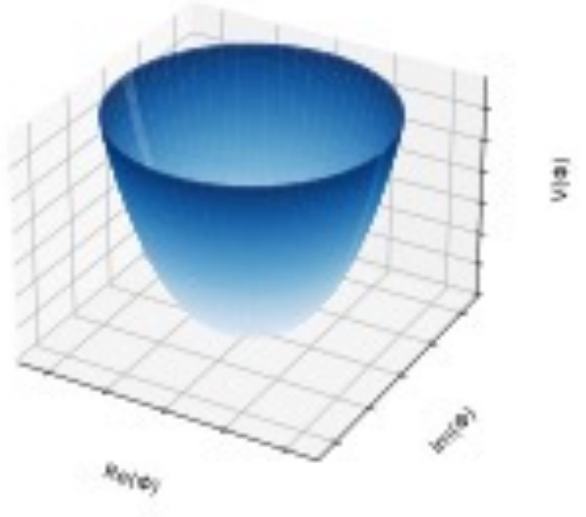
Theory ref: [Logan]

$$\boxed{V(\Phi) = \left(-\mu^2\,|\Phi|^2 + \lambda\,|\Phi|^4\right)}$$

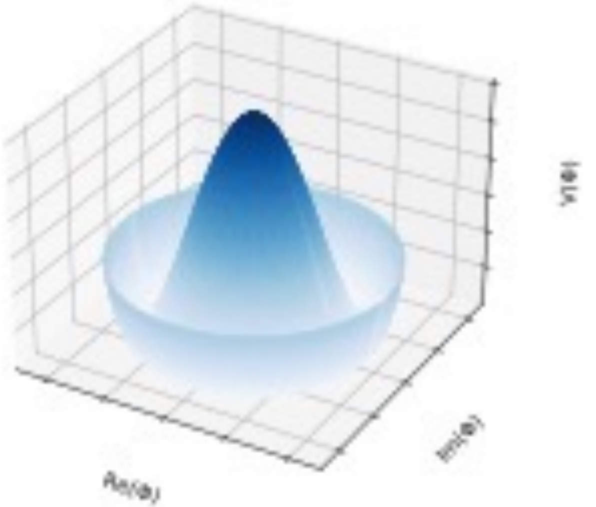
Shape depends on the signs of μ and λ:

- $\lambda < 0$: Potential is unbounded from below, no stable state of lowest energy
- $\lambda > 0$: Depends on sign of μ

$-\mu^2 > 0$



$-\mu^2 < 0$



Projection onto one field of the Φ doublet:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

Symmetry Breaking

Theory ref: [Logan]

Let's examine the $-\mu^2 < 0$ case more closely:

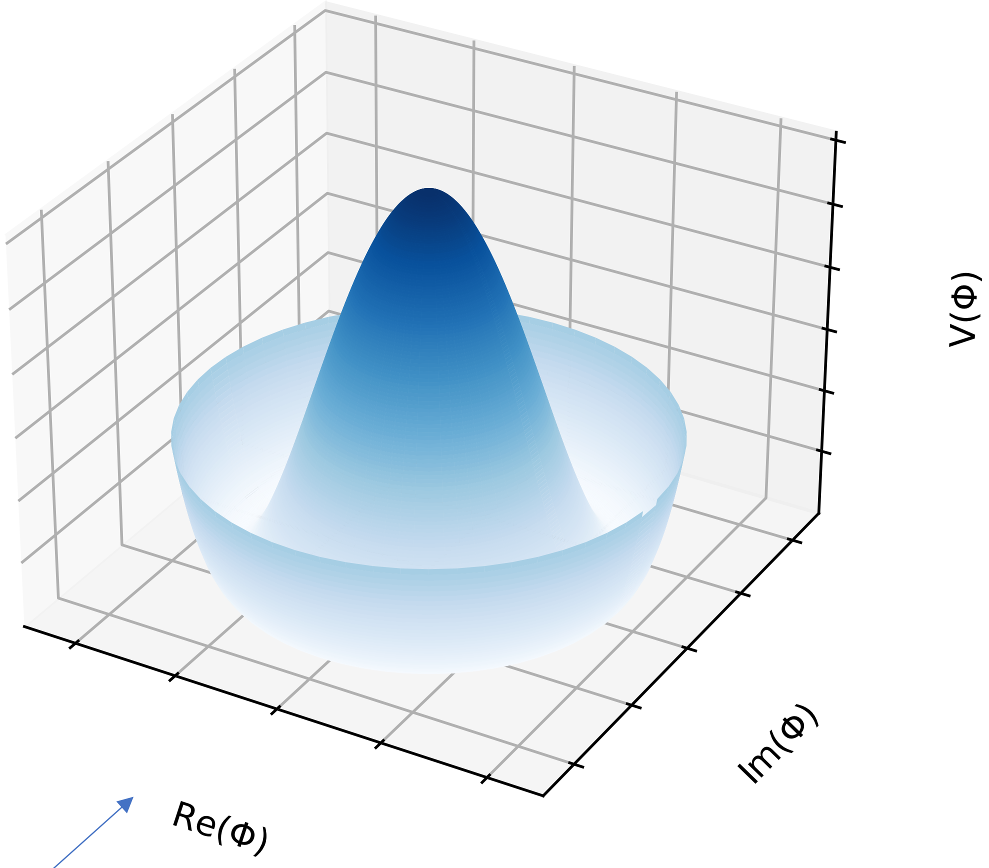
- Minimum (vacuum state) at $|\phi| = \sqrt{\frac{\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$

  In 2D: Ring of degenerate minima
  In 4D: Hypersphere of degenerate minima

- Under $SU(2)_L \times U(1)_Y$ gauge transformations: vacuum state rotates into a vector of the same length but pointing in a different direction → not invariant!

→ Choosing one minimum energy state *spontaneously breaks* electroweak symmetry.

$-\mu^2 < 0$



Projection onto one field of the Φ doublet:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

Consequences of EWSB

Theory ref: [Logan]

Expand the Φ field around the minimum: $$\Phi = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ h+v \end{bmatrix}$$

(Usual form in the "unitary gauge" → minimizes scalar degrees of freedom)

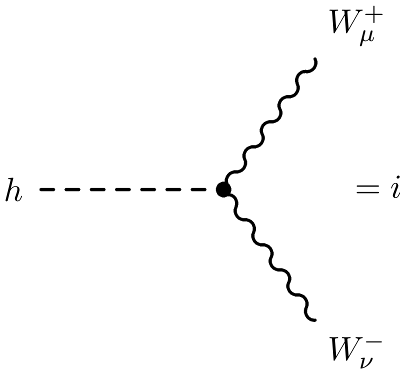
Insert back into the Lagrangian: $$\mathcal{L}_{\text{Higgs}} = \left|\mathcal{D}_\mu \Phi\right|^2 - V(\Phi) + \mathcal{L}_{\text{Yukawa}}$$

Consequences:

1. Physical gauge bosons with masses and couplings to *h*

$$L \supset \frac{g^2 v^2}{4} W_\mu^+ W^{-\mu} + \frac{g^2 v}{2} h W_\mu^+ W^{-\mu} + \frac{g^2}{4} hh W_\mu^+ W^{-\mu}.$$

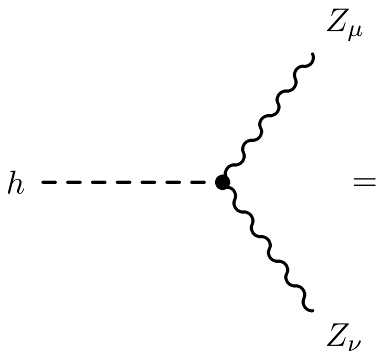
$$M_W^2 = \frac{g^2 v^2}{4}$$



$$= i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}$$

$$L \supset \frac{(g^2 + g'^2)v^2}{8} Z_\mu Z^\mu + \frac{(g^2 + g'^2)v}{4} h Z_\mu Z^\mu + \frac{(g^2 + g'^2)}{8} hh Z_\mu Z^\mu.$$

$$M_Z^2 = \frac{(g^2 + g'^2)v^2}{4}$$



$$= i\frac{(g^2 + g'^2)v}{4} \cdot 2 g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}$$

Consequences of EWSB

Theory ref: [Logan]

Expand the Φ field around the minimum: $$\Phi = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ h + v \end{bmatrix}$$

(Usual form in the "unitary gauge" → minimizes scalar degrees of freedom)

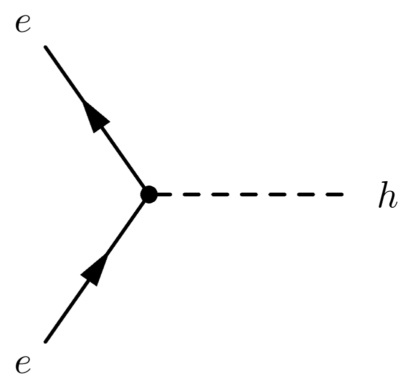
Insert back into the Lagrangian: $$\mathcal{L}_{\text{Higgs}} = \left|\mathcal{D}_\mu \Phi\right|^2 - V(\Phi) + \mathcal{L}_{\text{Yukawa}}$$

Consequences:

2. Fermion masses and couplings to *h*

$$L \supset -y_u \frac{v+h}{\sqrt{2}} \bar{u}_L u_R - y_d \frac{v+h}{\sqrt{2}} \bar{d}_L d_R - y_e \frac{v+h}{\sqrt{2}} \bar{e}_L e_R + (h.c.)$$

$$m_i = \frac{y_i v}{\sqrt{2}}$$



$$= -i \frac{y_e}{\sqrt{2}} = -i \frac{m_e}{v}$$

Consequences of EWSB

Theory ref: [Logan]

Expand the Φ field around the minimum: $$\Phi = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ h+v \end{bmatrix}$$

(Usual form in the "unitary gauge" → minimizes scalar degrees of freedom)

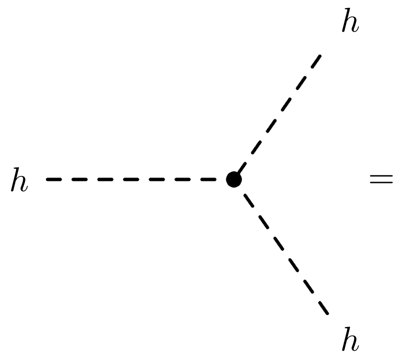
Insert back into the Lagrangian: $$\mathcal{L}_{\text{Higgs}} = \left|\mathcal{D}_\mu \Phi\right|^2 - V(\Phi) + \mathcal{L}_{\text{Yukawa}}$$

Consequences:

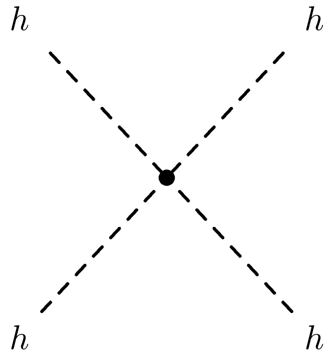
3. Higgs boson (h) mass and self-couplings

$$L \supset -\lambda v^2 h^2 - \lambda v h^3 - \frac{\lambda}{4} h^4 + \text{const.}$$

$$m_H = \sqrt{2\lambda v^2}$$



$$= -i\lambda v \cdot 3! = -6i\lambda v = -3i\frac{m_h^2}{v}$$



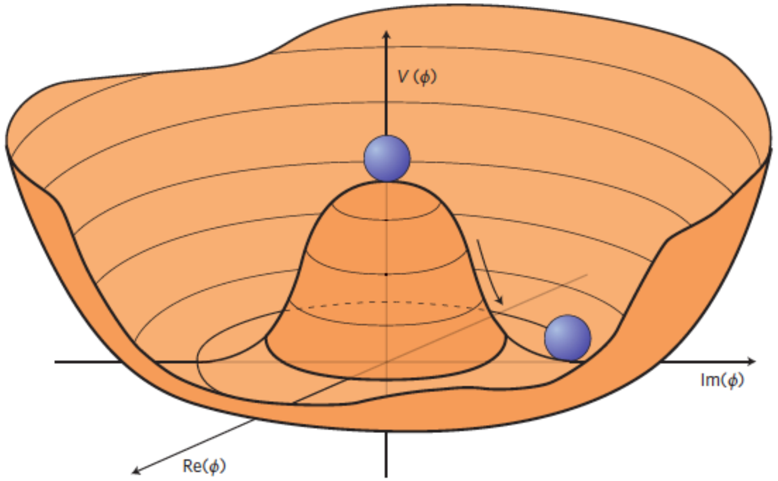
$$= -i\frac{\lambda}{4} \cdot 4! = -6i\lambda = -3i\frac{m_h^2}{v^2}$$

The End!

... Or is it?

EWSB is a crucial piece of the SM....
but is it the right piece?

The rest of this lecture: How we can try to answer that question at the Large Hadron Collider (LHC).



1. The Higgs boson's couplings

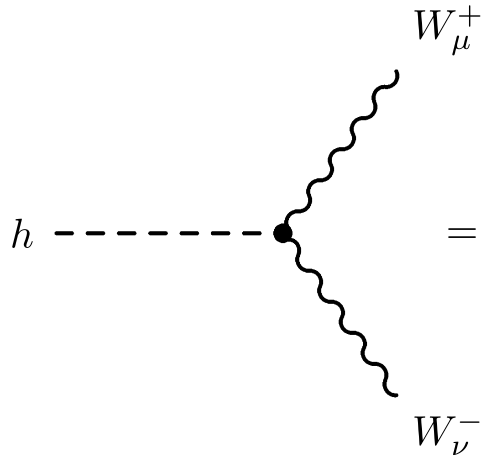
2. The shape of the Higgs potential

3. Diboson processes

1. Higgs Boson Couplings

Higgs Boson Couplings

- The couplings of the Higgs boson to other particles after EWSB are uniquely predicted:



measured

$$= i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}$$

measured

- How can we confirm that the prediction lines up with the reality?

- **At the LHC:** Can't directly access the couplings. Instead use them to calculate production cross-sections times branching ratios of the Higgs boson:

Zero-width approximation: production and decay factorize.

Coupling of particle f to H

$$\sigma(i \to H \to f) = \sigma(i \to H) \cdot \frac{\Gamma(H \to f)}{\Gamma_H} = \sigma(i \to H) \cdot \mathrm{BR}(H \to f)$$

Coupling of particle i to H

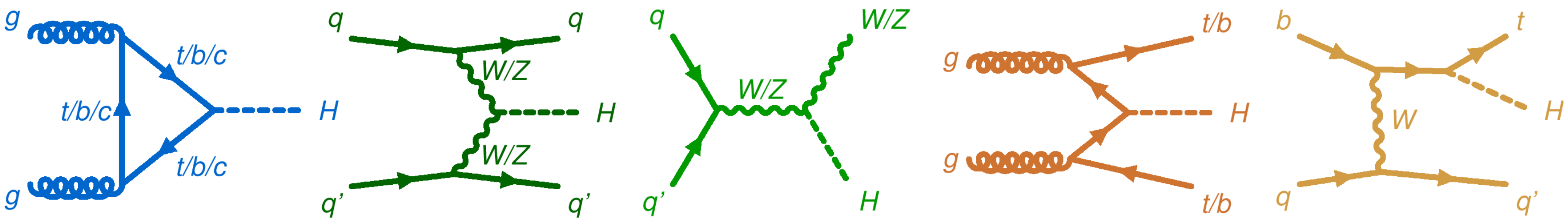
Couplings of H to all particles

Masses of each particle also enter the calculation.

Higgs Boson Production and Decay at the LHC

Figures from here

Production modes at the LHC:



Gluon fusion (ggF) (87%)
- Higgs coupling to heavy quarks

Vector boson fusion (VBF) (7%)
- Higgs coupling to W and Z bosons

Vector boson associated production (VH) (4%)
- Higgs coupling to W and Z bosons

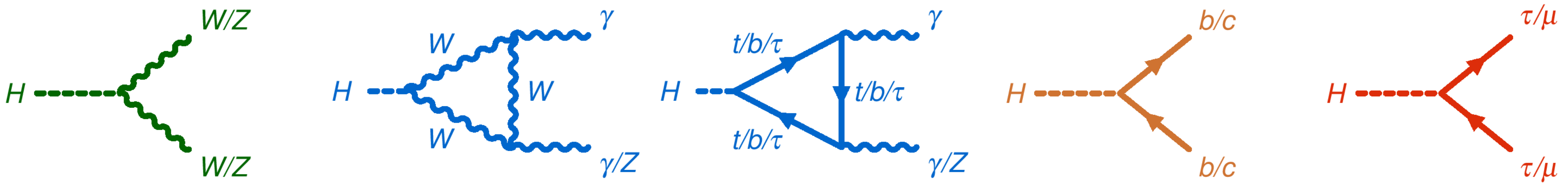
Top- and bottom-associated production, single-top production (2%)
- Higgs coupling to *t* and *b* quarks

- **Experimentally:** some trade-off between statistics (ggF) and "clean" signatures (VBF, VH).

Higgs Boson Production and Decay at the LHC

Figures from [here]

Decay modes at the LHC:



WW **(22%), *ZZ* (3%)**
- Usually use leptonic decays for clean signature and mass reconstruction

$\gamma\gamma$ (0.2%), $Z\gamma$ (0.2%)
- Extremely clean at the expense of tiny BR

$b\bar{b}$ (58%), $c\bar{c}$ (3%)
- Large backgrounds, rely on *b*- and *c*-tagging.

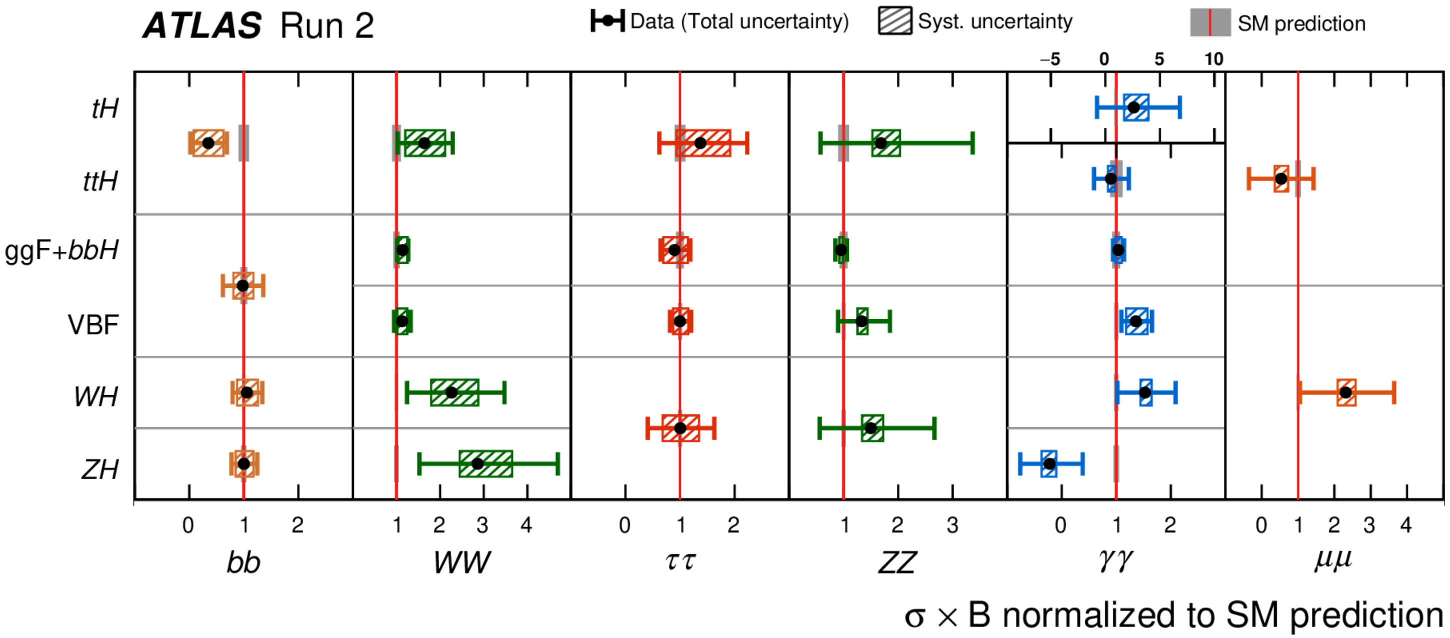
$\tau\tau$ (6%), $\mu\mu$ (0.02%)
- Only leptonic decays currently accessible.

- **Experimentally:** Same trade-off as with production: largest decay mode ($b\bar{b}$) has substantial hadronic background, smaller ones ($\gamma\gamma$, *VV* with leptonic decays) have smaller backgrounds and better mass resolution.

Measuring Higgs Production

- In practice, at the LHC: count number of events, since $n(i \to H \to f) = \sigma(i \to H) \cdot \mathrm{BR}(H \to f) \cdot \mathcal{L}^{int}$
    - Apply selections designed to target a specific Higgs boson production and decay process
    - Subtract background (non-Higgs events)
    - Count number of remaining events and compare to prediction.

- Results: Measurements made in multiple production modes and decay channels in LHC Run 2.



[ATLAS Run 2 Higgs combination](#)

p-value (compatibility with SM): 72%

Getting Closer to Couplings

Limitation: Measurements of cross-sections times branching ratio can't disentangle deviations in production from deviations in decay.

$$n(i \to H \to f) = \sigma(i \to H) \cdot \mathrm{BR}(H \to f) \cdot \mathcal{L}^{int} \longrightarrow$$ *Affected by i-H and f-H couplings.*

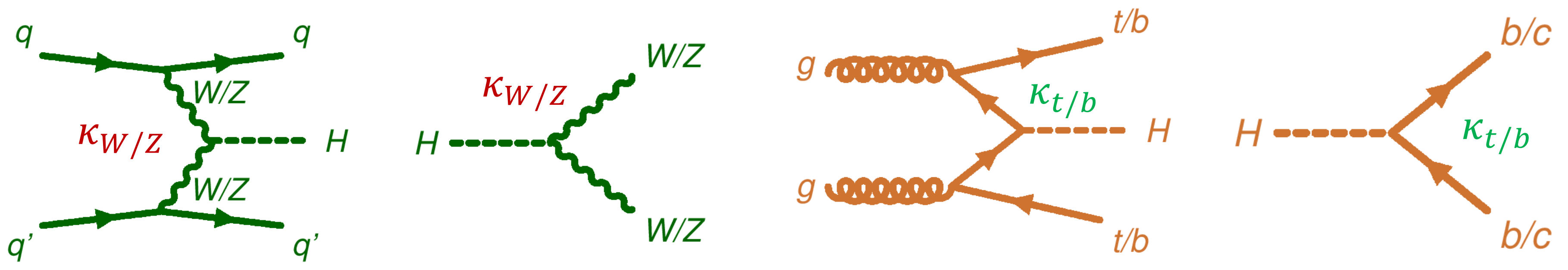
Access couplings more directly with the **Kappa framework:**

$$\sigma(i \to H) \cdot \mathrm{BR}(H \to f) = \sigma(i \to H) \cdot \frac{\Gamma(H \to f)}{\Gamma_H} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2(\vec{\kappa})} \cdot \sigma^{SM}(i \to H) \cdot \frac{\Gamma^{SM}(H \to f)}{\Gamma_H^{SM}}$$

κ_j parametrizes deviations in coupling of Higgs to particle j:

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$$

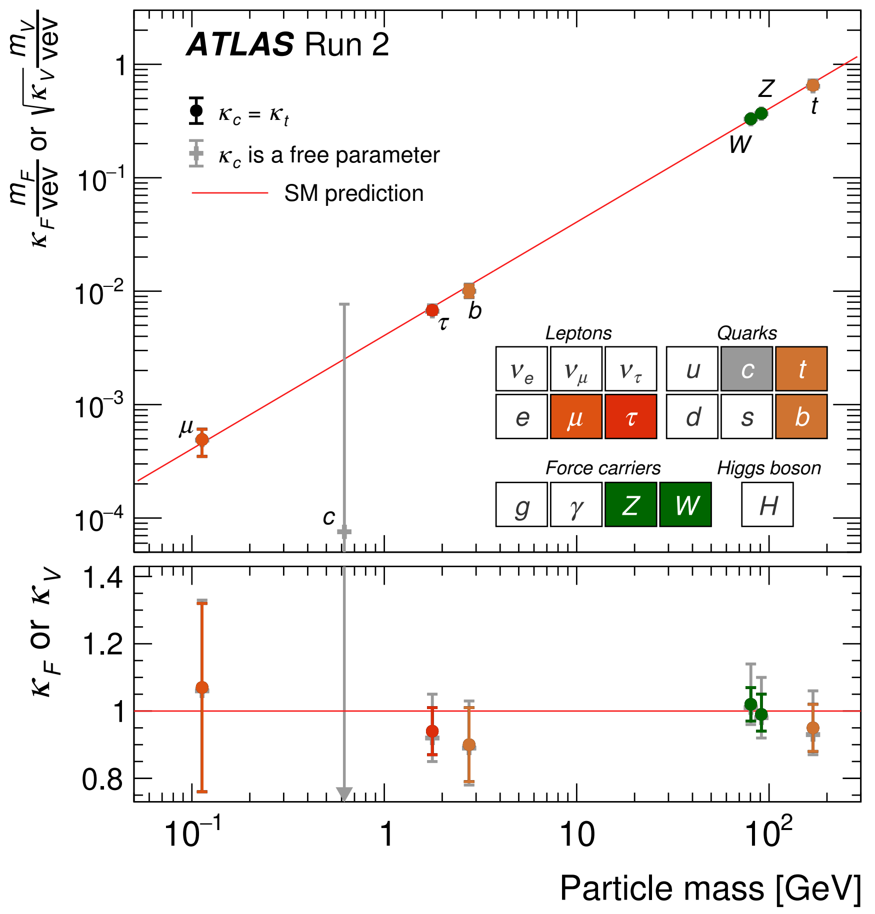
Exploit multiple decay/production combinations to constrain kappas:



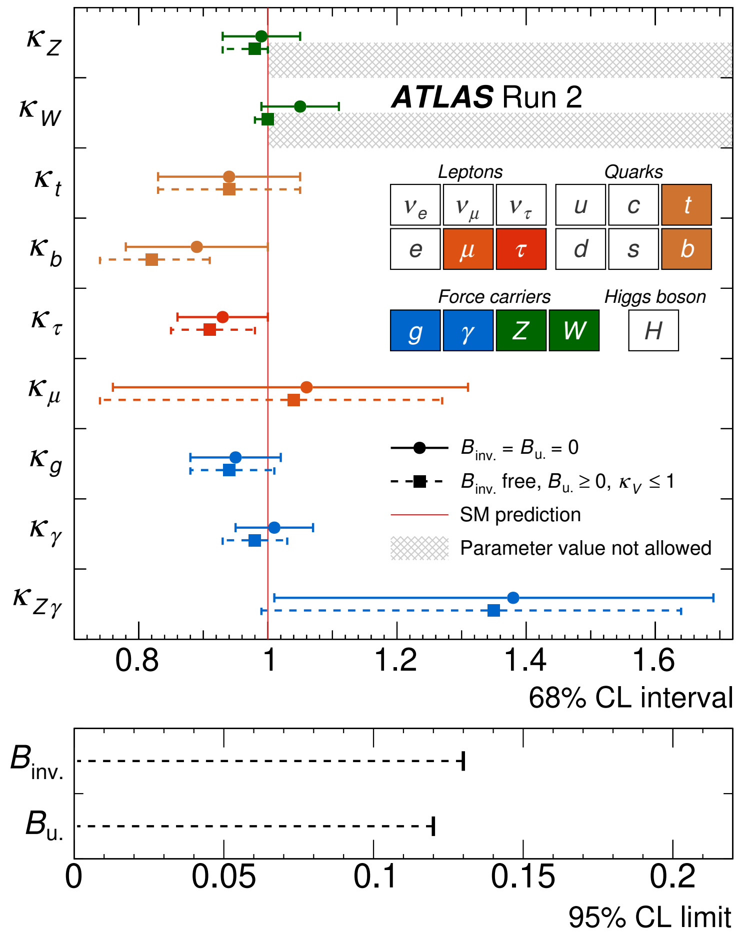
Measurements of Couplings

Results:

Predicted scaling of couplings with mass holds well:



Couplings consistent with SM, but decays to invisible particles still poorly-constrained (SM: 0.1%):



ATLAS Run 2 Higgs combination

Resolving an Ambiguity

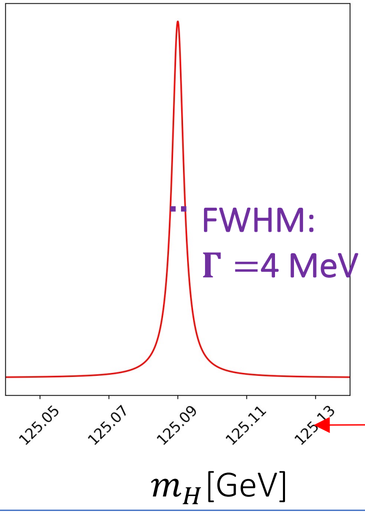
There is an **ambiguity** that affects couplings measurements:

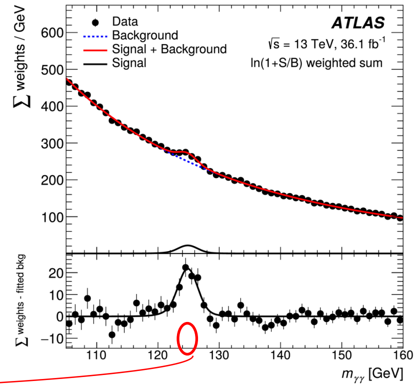
$$\frac{\sigma_{i\to H\to f}}{\sigma^{SM}_{i\to H\to f}} = \frac{\kappa_i^2 \kappa_f^2}{\Gamma_H(\vec{\kappa})/\Gamma_H^{SM}} \qquad \kappa_i^2 = \frac{\sigma_{i\to H}}{\sigma^{SM}_{i\to H}}, \quad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}}$$

→ Deviations in the Higgs width and **couplings** could cancel!

Requires assumptions in kappa framework, or a direct measurement of the Higgs width.

Tricky: SM prediction of Higgs width is only 4 MeV!





arXiv:1806.00242

ϑ(GeV) resolution from mass measurements due to detector resolution.
→ Not sufficient.

Measuring the Higgs Width

Solution 1: Exploit $H \to VV$ decays:

1. Large enhancement of the offshell $H^* \to VV$ cross-section for $m_{VV} \sim 2m_V$ → Offshell cross-section should be measurable.

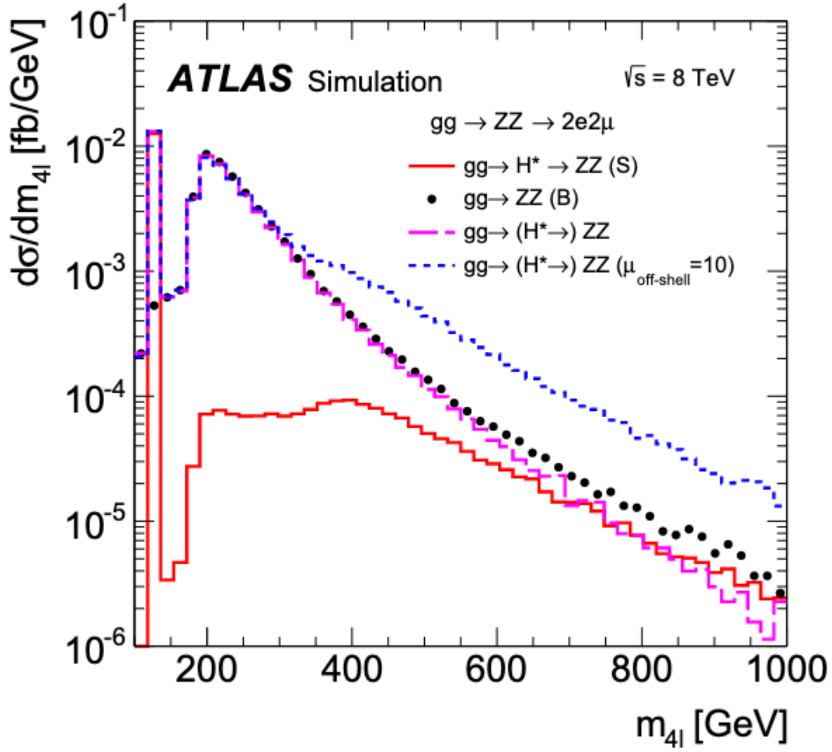
2. For $m_{VV} \gg 2m_V$, the Higgs cross-section is independent of the width:

$$\frac{\sigma^{\text{offshell}}_{i\to H\to f}}{\sigma^{\text{offshell, SM}}_{i\to H\to f}} = \kappa_i^2\kappa_f^2 \qquad \frac{\sigma^{\text{onshell}}_{i\to H\to f}}{\sigma^{\text{onshell, SM}}_{i\to H\to f}} = \frac{\kappa_i^2\kappa_f^2}{\Gamma_H/\Gamma_H^{SM}}$$

Combining offshell and onshell measurements constrains the width!

$$\frac{\sigma^{\text{offshell}}_{i\to H\to f}}{\sigma^{\text{onshell}}_{i\to H\to f}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

arXiv:1503.01060



m_{ZZ} distribution for $gg \to (H^*) \to ZZ$, showing enhancement near $m_{ZZ} = 2m_V$.

Measuring the Higgs Width

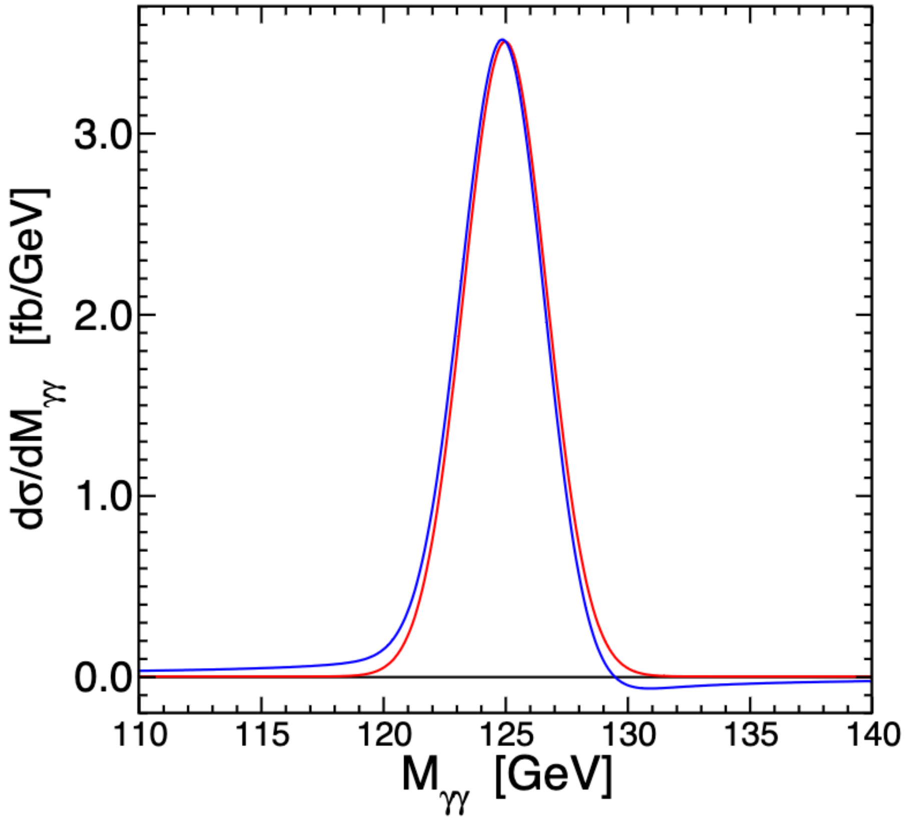
arXiv:1208.1533

Solution 2: Exploit $H \to \gamma\gamma$ interference:

1. The $gg \to H \to \gamma\gamma$ and $gg \to \gamma\gamma$ processes interfere, which has the effect of shifting the mass distribution slightly.

2. The size of the shift can be measured using its p_T^H dependence or comparison with $H \to ZZ$ mass measurement.

3. The shift depends on the Hgg and $H\gamma\gamma$ effective couplings → can measure those.



Higgs mass peak without (red) and with (blue) the interference contribution.

Width can be extracted from this independent measurement of the couplings:

$$\kappa_g^2 \kappa_\gamma^2 \frac{\sigma_{gg\to H\to\gamma\gamma}}{\sigma^{SM}_{gg\to H\to\gamma\gamma}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

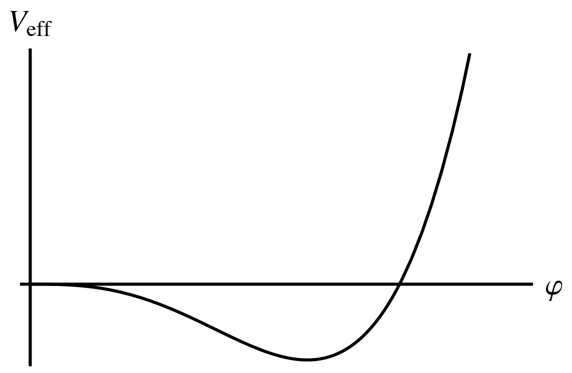
2. Shape of the Higgs Potential

Back to the Higgs Potential

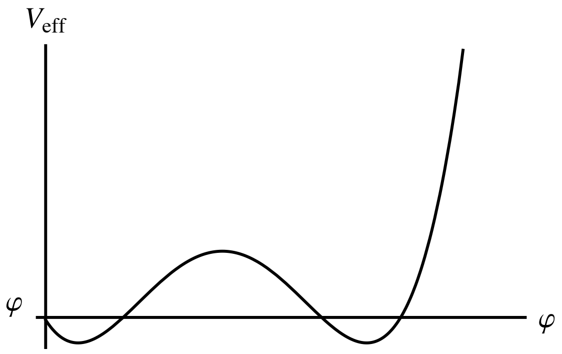
$$V(\Phi) = \left(-\mu^2 |\Phi|^2 + \lambda |\Phi|^4\right)$$

The parameter λ is important in determining whether EWSB can occur:

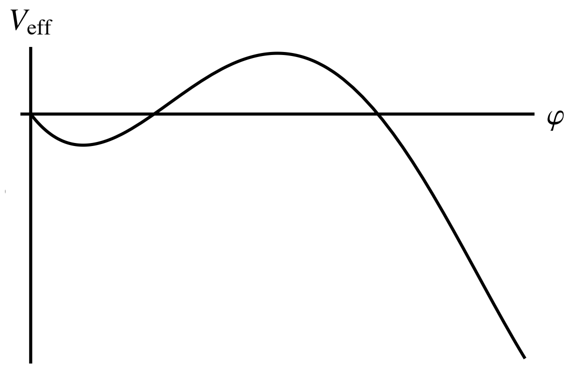
- $\lambda < 0$: Potential is unbounded from below, no stable state of lowest energy
- $\lambda > 0$: Depending on sign of μ, can get EWSB.



Stable: no other minimum



Metastable: can tunnel to other minimum



Unstable: potential unbounded from below.

arXiv:1301.5812

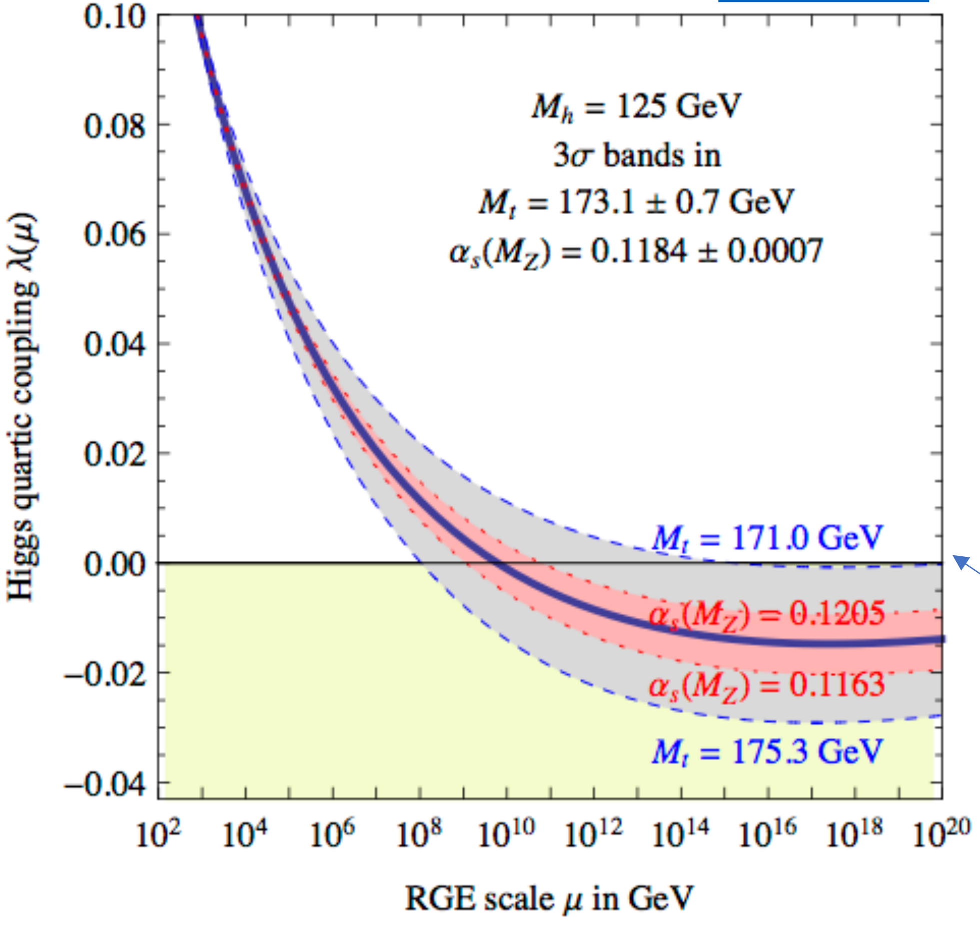
Back to the Higgs Potential

Another reason λ is exciting: Its energy evolution determines the stability of the universe.

Sensitive dependence on Higgs and top masses.

Higgs mass too light, top mass too heavy: λ can become negative before the Planck mass.

arXiv:1205.6497



(outdated top mass values: latest from CMS, ATLAS)

New physics must enter to stabilize the potential.

arXiv:1301.5812

Probing λ

We can calculate the SM prediction for λ using v and m_H:

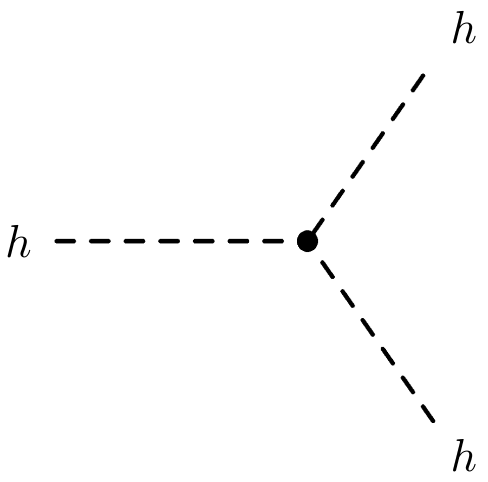
$$\lambda = \frac{m_H^2}{2v^2}$$

Measured directly

Measured from muon decay

The parameter λ controls the strength of the Higgs self-coupling.

→ We can measure it by studying di-Higgs production.

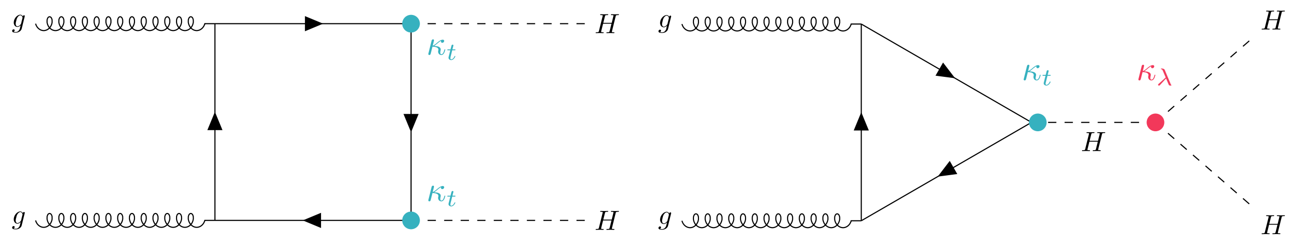


$$= -i\lambda v \cdot 3! = -6i\lambda v = -3i\frac{m_h^2}{v}$$

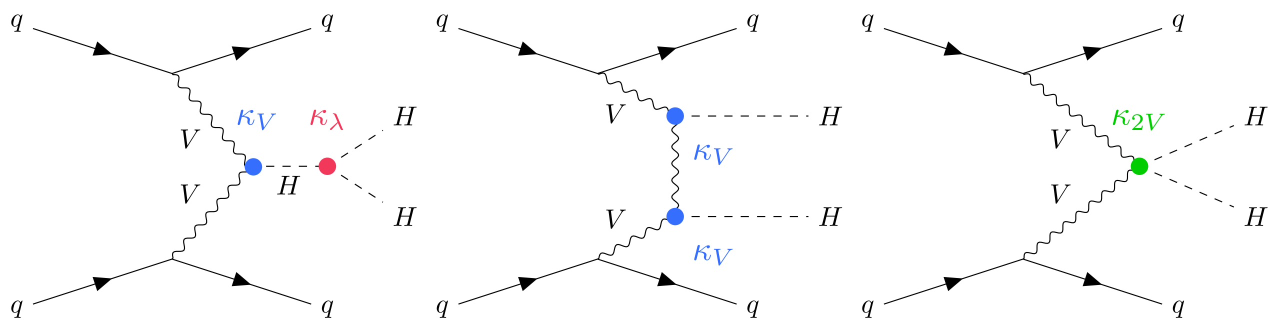
Probing λ

At the LHC, we measure di-Higgs production via the ggF and VBF production modes:

ggF:



VBF:



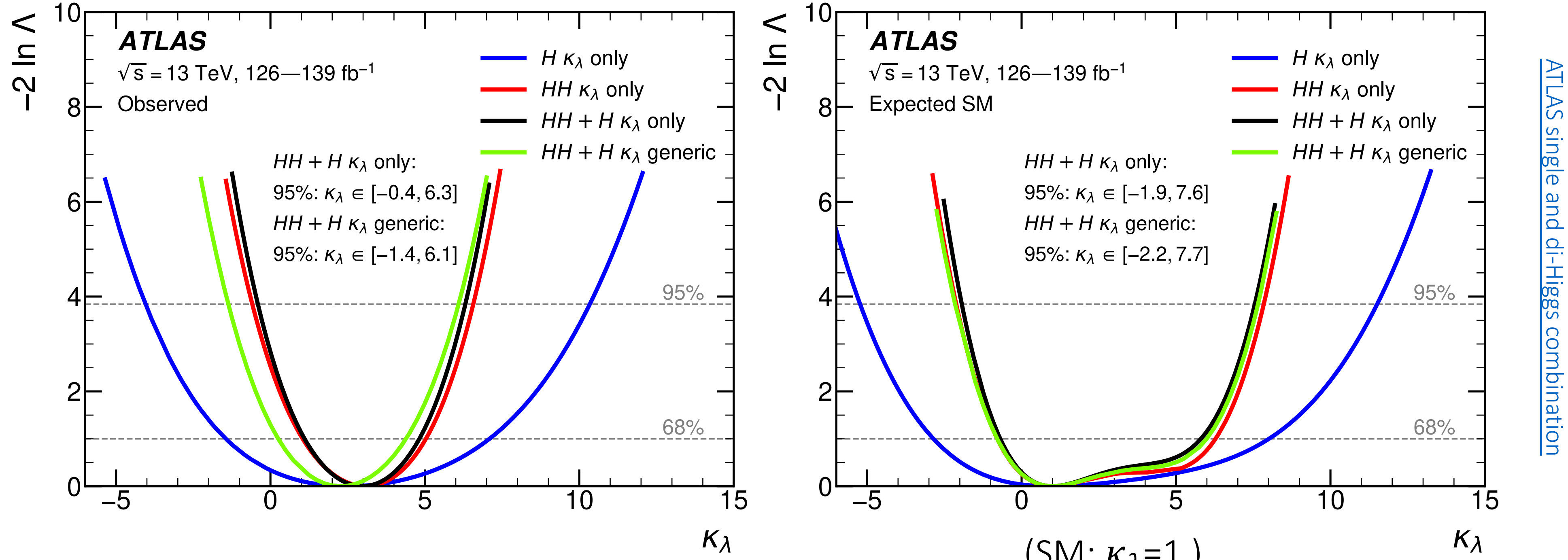
Experimentally:

- Tricky: small cross-section, destructive interference between box and triangle diagrams → production is three orders of magnitude smaller than for single-Higgs.
- Focus on $b\bar{b}$ decay of one Higgs, and $b\bar{b}$ (best stats), $\gamma\gamma, WW, \tau\tau$ (cleaner) decay of the other.

Constraints on λ

- Can combine with single-Higgs measurements (λ couplings enter at higher order) for constraints:

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$



(SM: κ_λ=1)

ATLAS single and di-Higgs combination

Measured: $-0.4 < \kappa_\lambda < 6.3$ at 95% C.L.

$-1.4 < \kappa_\lambda < 6.1$ at 95% C.L. if other Higgs couplings are allowed to be non-SM.

Prospects: 50% precision at HL-LHC.

3. Diboson Scattering Processes

Connection to EWSB and the Higgs Boson

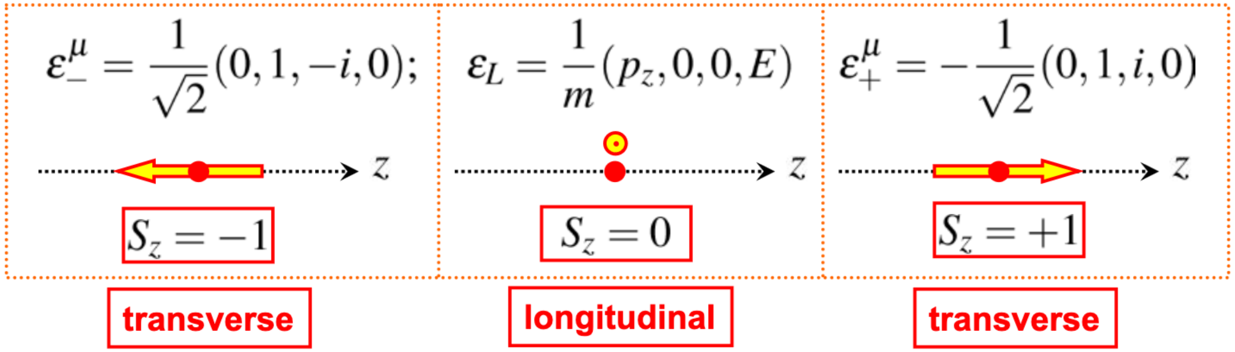
Higgs boson and diboson processes are closely connected via the vector boson longitudinal polarization modes.

Recall that after EWSB, we "gauged away" **three scalar components** of the Higgs field:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \xrightarrow{\text{EWSB, choice of gauge}} \Phi = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ h + v \end{bmatrix}$$

4 degrees of freedom → 1 degree of freedom

These **three degrees of freedom** went on to become the **longitudinal polarizations** of the W^+, W^- and Z bosons.



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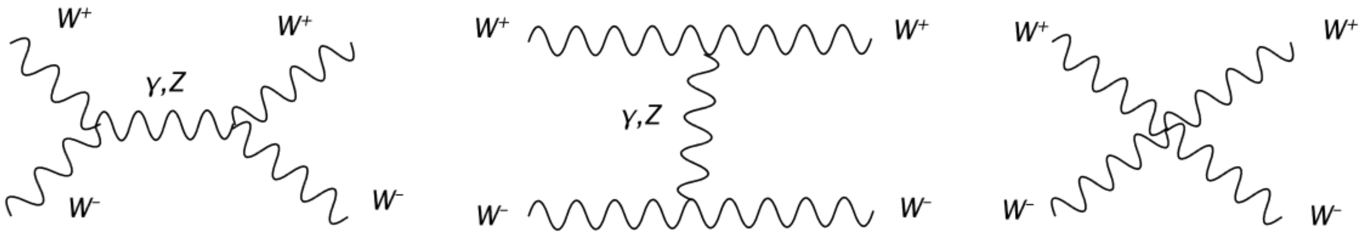
Unitarity Violation

Another connection: The Higgs boson and longitudinal polarization modes of the vector bosons are related via unitarity.

Unitarity: no process must occur with probability greater than 1 over all time.
→ Equivalent to the requirement that a cross-section cannot rise infinitely with energy.

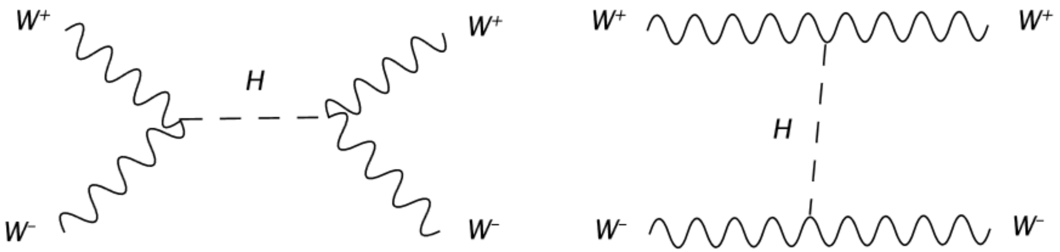
Longitudinal diboson scattering **violates unitarity** without the Higgs boson:

Top row: $\mathcal{M} \sim s$



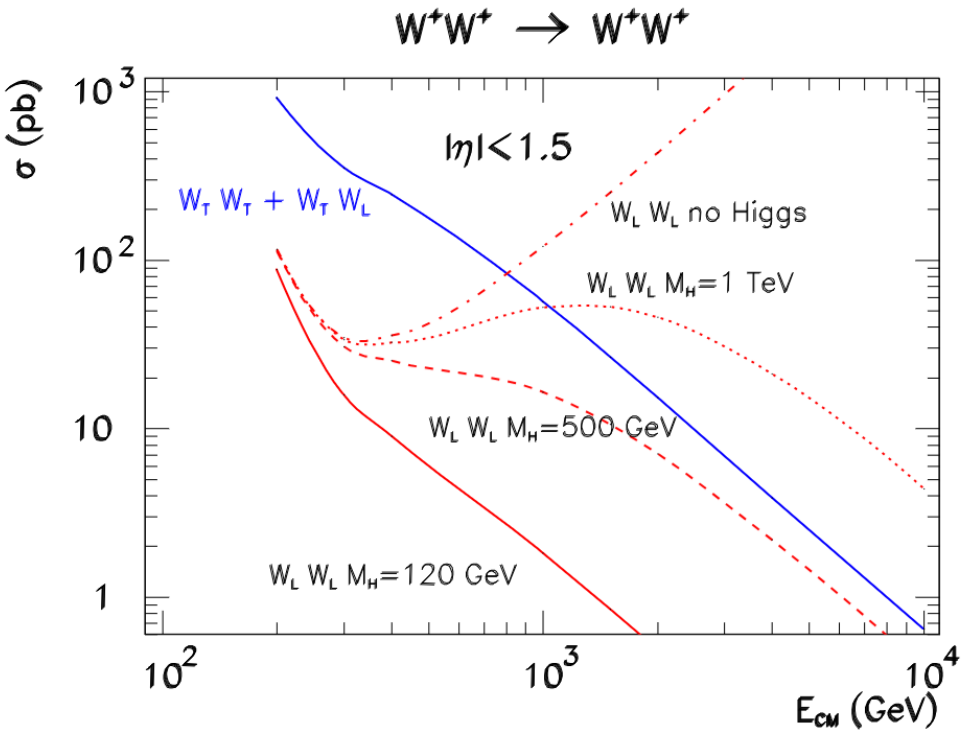
Diagrams

Bottom row: cancels the energy-dependence so that $\mathcal{M}$~flat in high-energy limit.



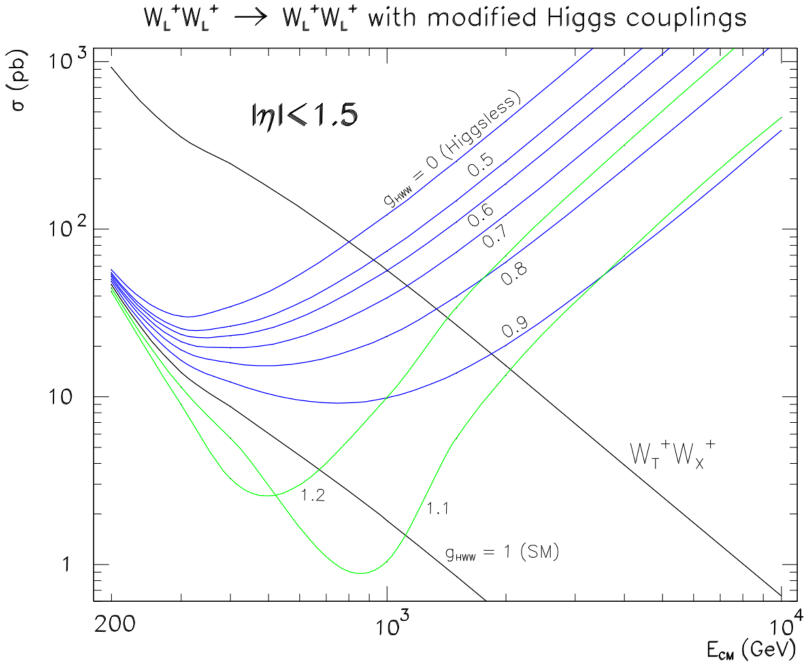
Unitarity Violation

This is one of the reasons that a Higgs boson had to exist below ~1 TeV.



However, this picture depends strongly on couplings:

- The H-V couplings on- and off- mass shell
- The triple and quartic gauge boson couplings



arXiv:1412.8367

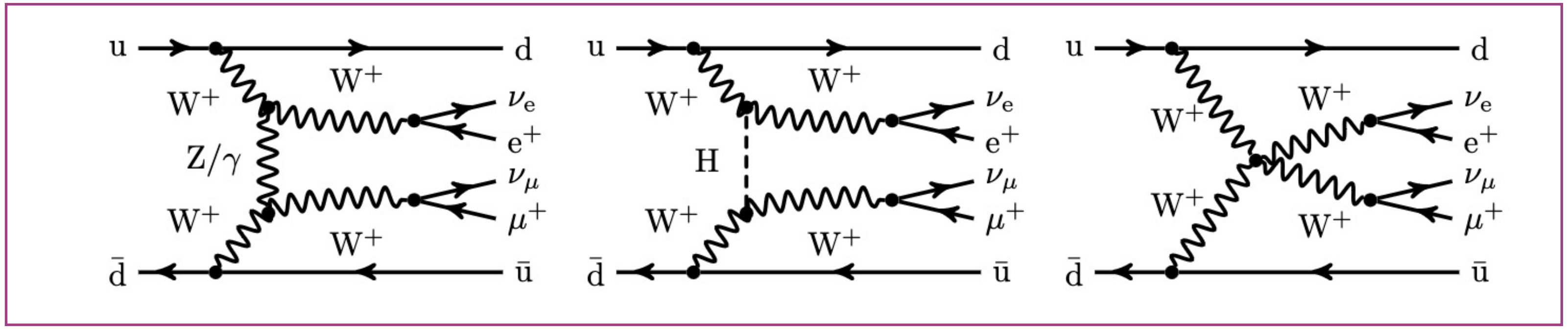
→ Diboson scattering processes probe EWSB from another angle.

Diboson Scattering at the LHC

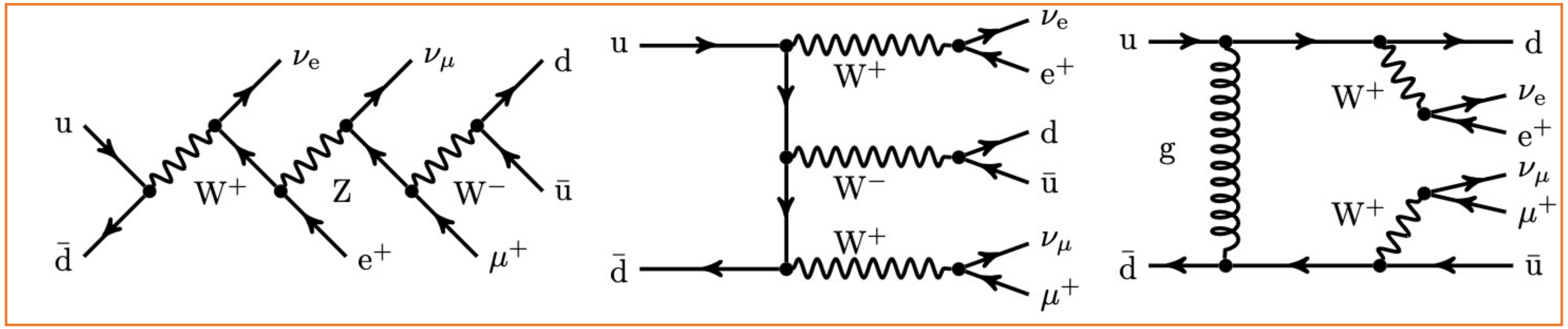
Longitudinal dibosons at the LHC can be probed using vector boson scattering (VBS) processes:

arXiv:1708.00268

Top row: actual VBS



Bottom row: irreducible background.



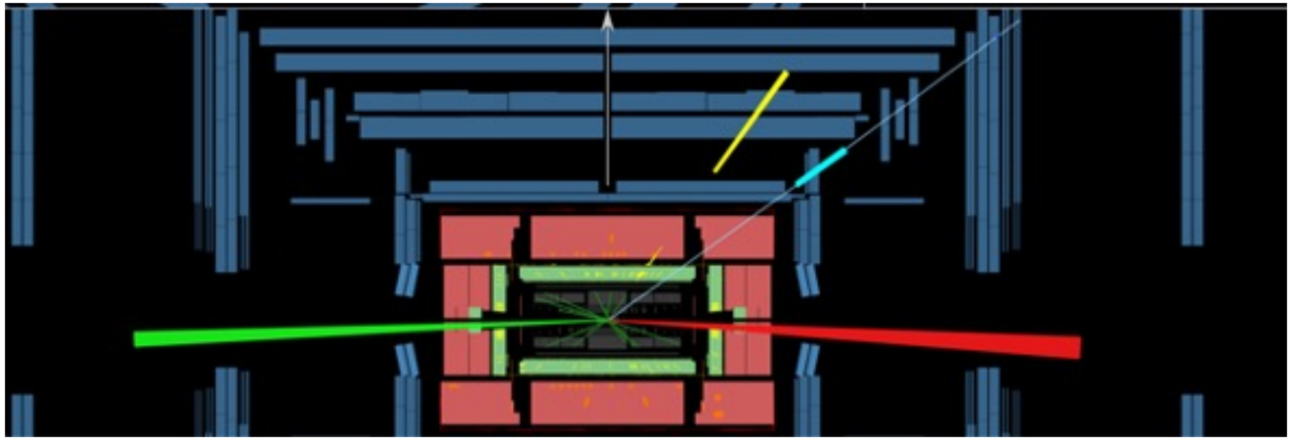
Non-VBS backgrounds in bottom row can't be separated quantum mechanically from actual VBS
→ Rely on cuts to target phase space dominated by VBS diagrams.

Experimental Signatures

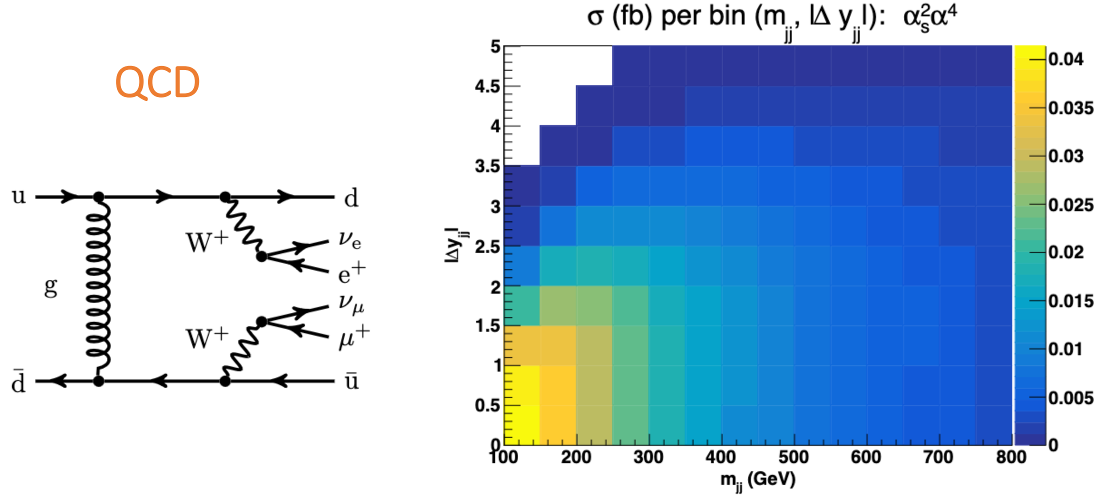
Features of VBS events can be used to distinguish them from non-VBS diboson and other backgrounds:

1. Tagging jets

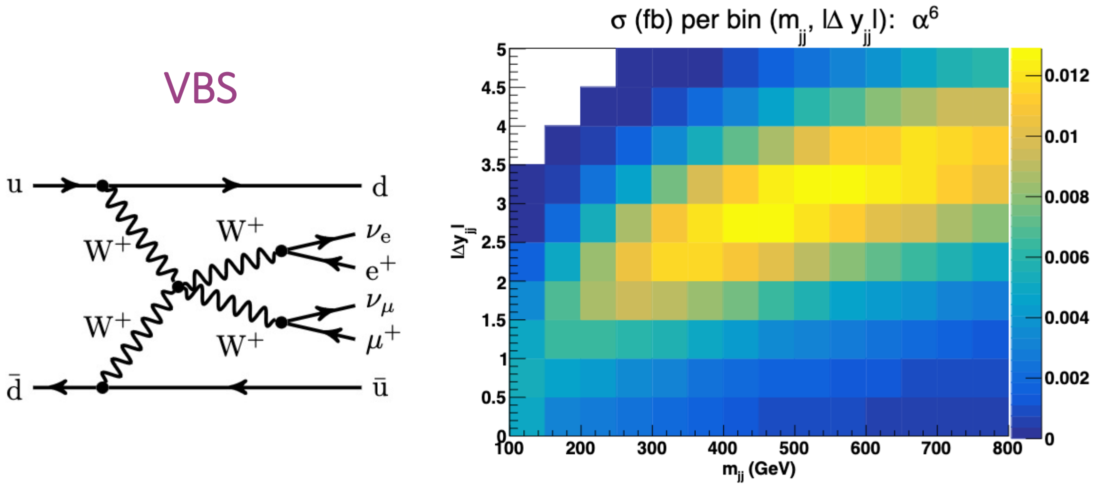
   - Forward direction (high $|\eta|$, close to beamline)
   - Large $m_{jj}, \Delta y_{jj}$ with no hadronic activity between the two leading jets.



QCD



VBS



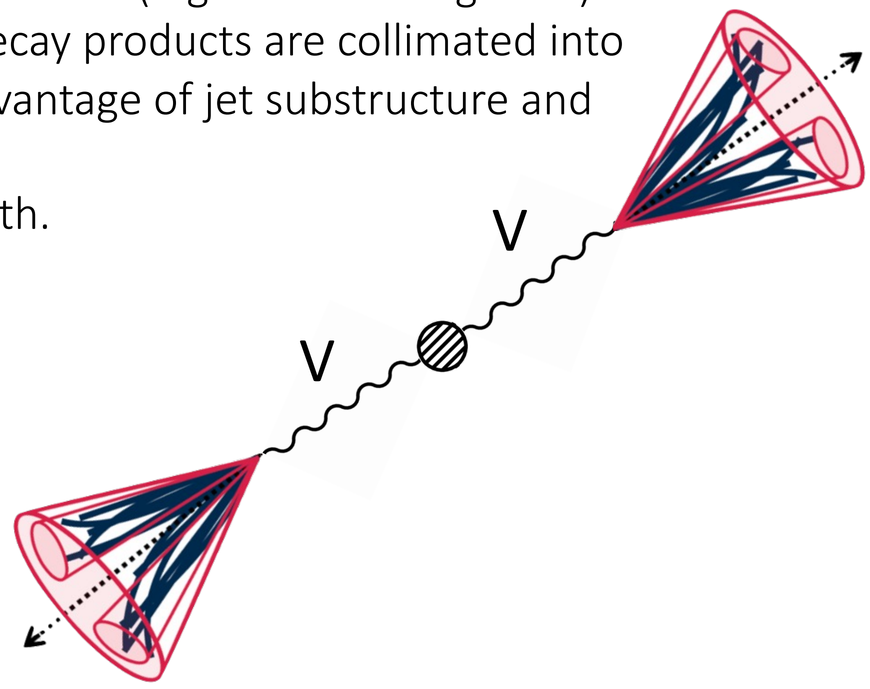
arXiv:2102.10991

Experimental Signatures

Features of VBS events can be used to distinguish them from non-VBS diboson and other backgrounds:

2. Vector boson reconstruction:

- Leptonic channels provide clean signature, better mass resolution.
- Hadronic channels provide improved statistics (higher branching ratio).
    - At high-p_T (>200 GeV), hadronic decay products are collimated into a single large-radius jet → take advantage of jet substructure and jet mass to identify it as a V-jet.
- Semi-leptonic channels offer a bit of both.



Decay products reco'd as a single jet

Boson-tagging using substructure variables and jet mass

Polarization

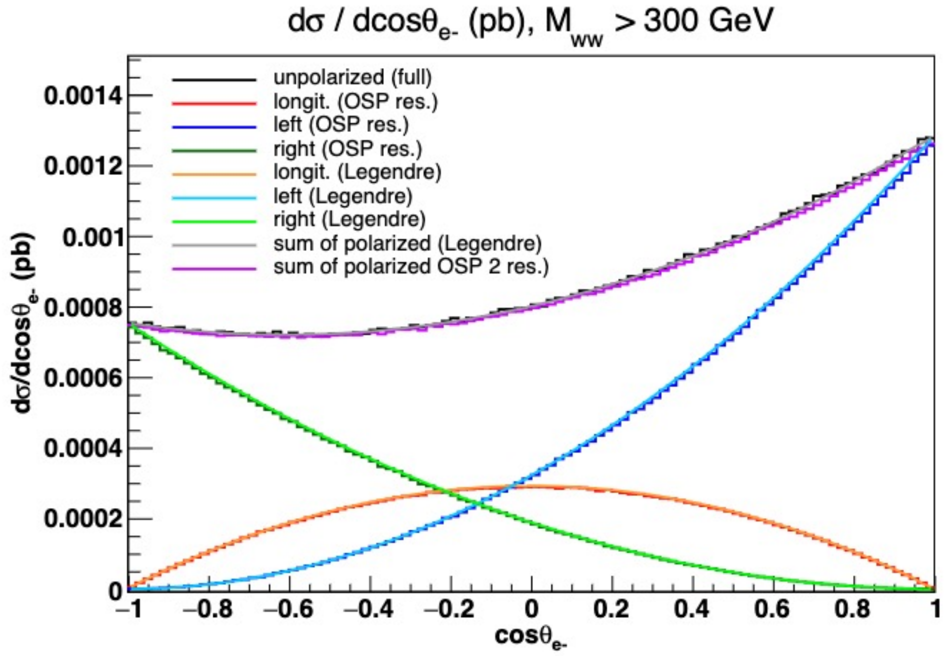
Only the longitudinal polarization mode is a direct consequence of EWSB and the Higgs mechanism
→ would like to study it specifically.

General idea:

- Compute differential cross-section as a function of angular distribution.
- It will depend on the polarization fractions.
- Extract these by fitting simulated single-polarization samples to angular distributions measured in data.

eg. for $I \to V \to f$ process:

$$\frac{1}{\frac{d\sigma(X)}{dX}} \frac{d\sigma(\theta, X)}{d\cos\theta dX} = \frac{3}{8}(1 \mp \cos\theta)^2 f_{\mathrm{L}}(X) + \frac{3}{8}(1 \pm \cos\theta)^2 f_{\mathrm{R}}(X) + \frac{3}{4}\sin^2\theta f_0(X).$$



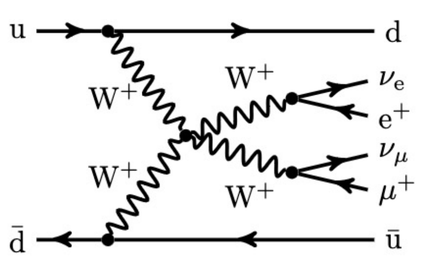
arXiv:1710.09339

Polarization in Practice

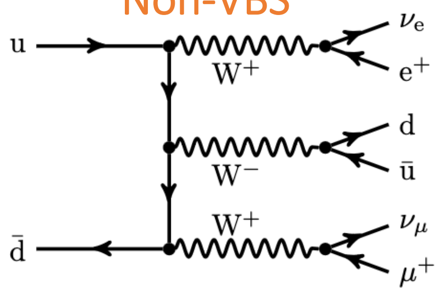
Experimentally tricky:

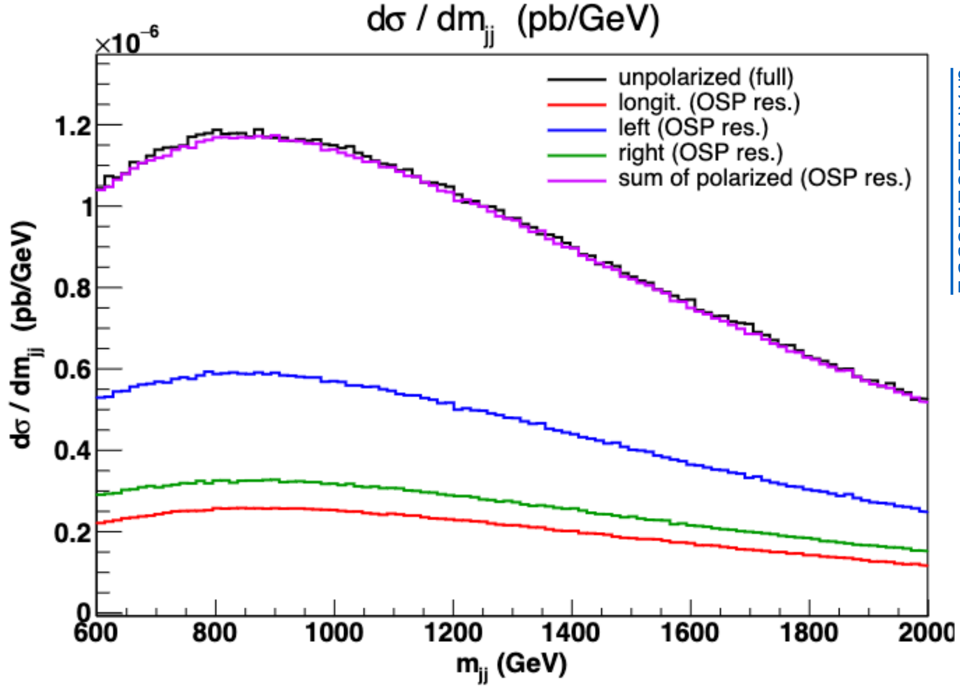
- Polarization isn't interesting for non-VBS diagrams.
- Polarizations interfere→ interference effects cancel over full angular distribution, but not necessarily when acceptance is limited by cuts.
- Polarization vectors aren't Lorentz-invariant → need to choose a reference frame (often diboson COM frame, but difficult to reconstruct with missing energy).
- Longitudinal polarization fractions are smaller than transverse.

VBS



Non-VBS





arXiv:2102.10991

Polarization Measurements

ATLAS has measured joint-polarization states of W and Z gauge bosons in $W^{\pm}Z$ production: STDM-2022-01

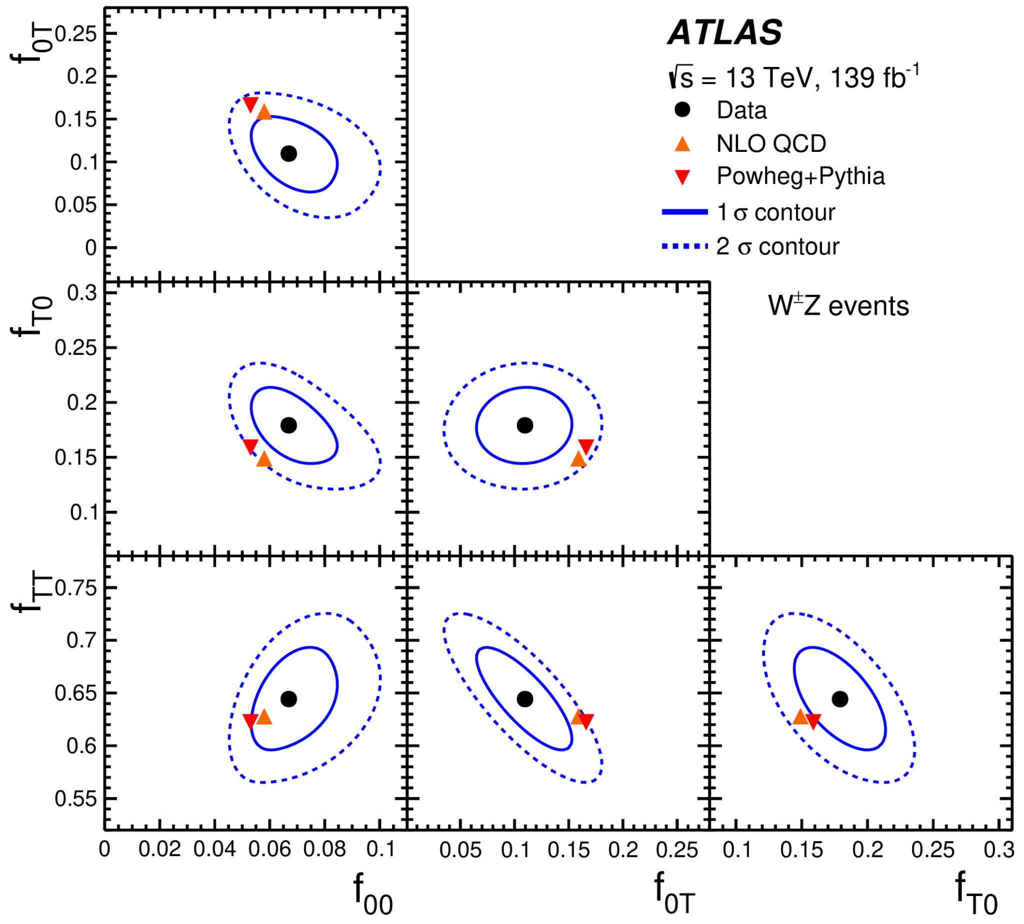
Methodology:

- Using leptonic decays
- Fit distributions of angles in the rest frames of the bosons.

Results:

- First measurement of $V_L V_L$ pair production: 7.1σ
- Single and joint polarization fractions in agreement with SM prediction.

First step toward $V_L V_L$ VBS measurements.



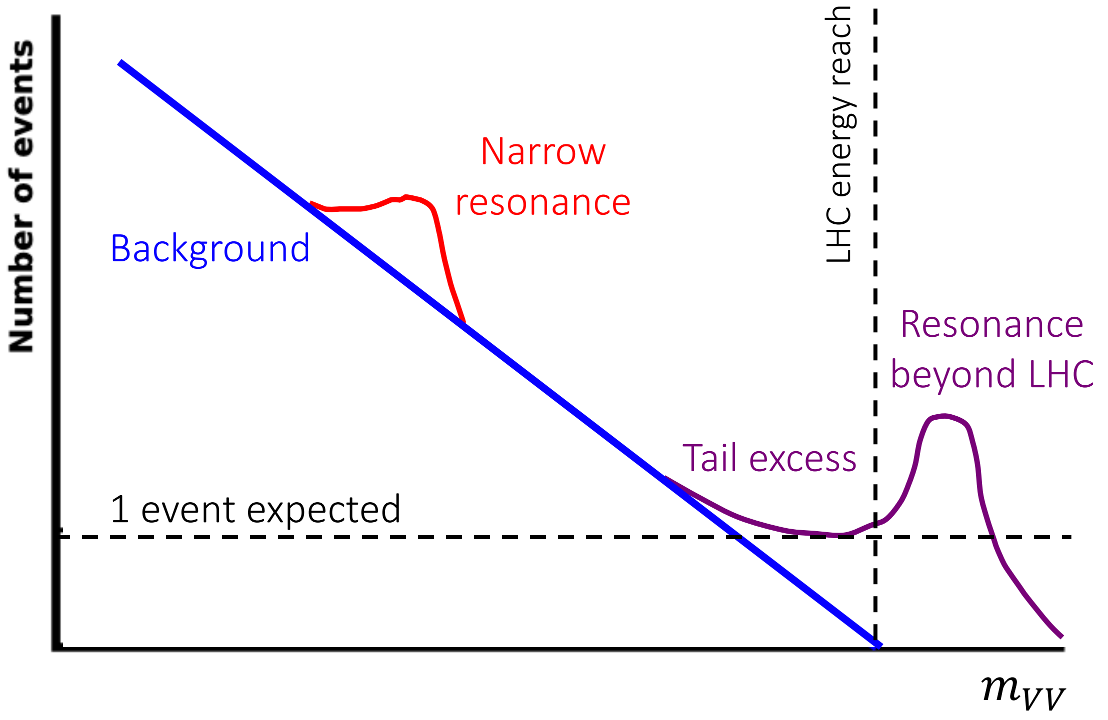
Further Probing New Physics with Dibosons

- New physics relevant to EWSB could appear in diboson processes in ways other than the polarization fraction.
- The form of the deviation depends on the scale of new physics, Λ:

Λ within LHC energy reach:

New physics appears as narrow bump over smooth bkg-only m_{JJ} spectrum

→ *Target with direct search*



Λ above LHC energy reach:

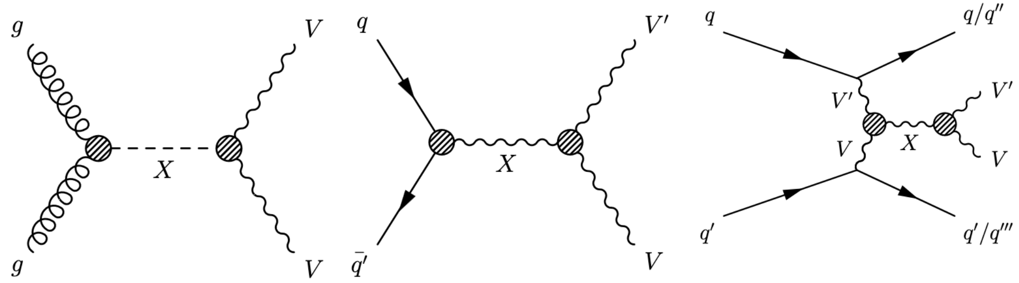
New physics appears as small deviation in the tail of the m_{JJ} spectrum

→ *Target with Effective Field Theory interpretation*

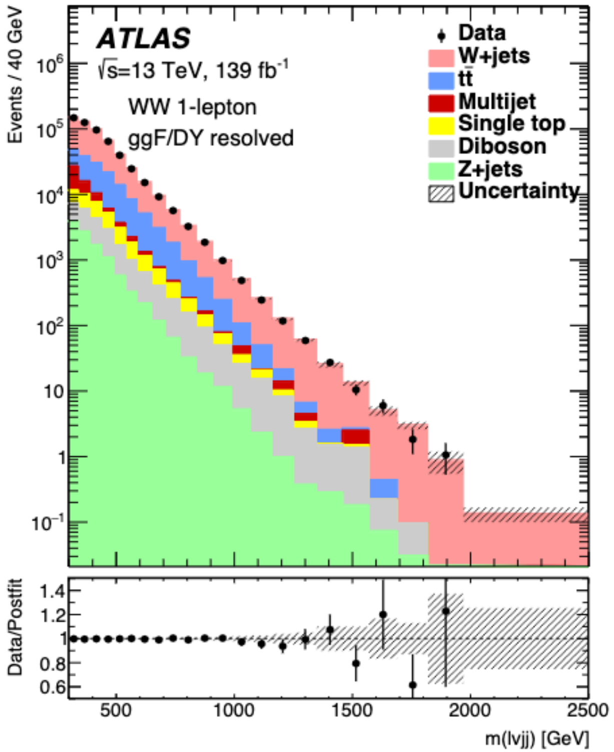
Both direct searches and EFT interpretations can be performed on VV events.

Direct Searches

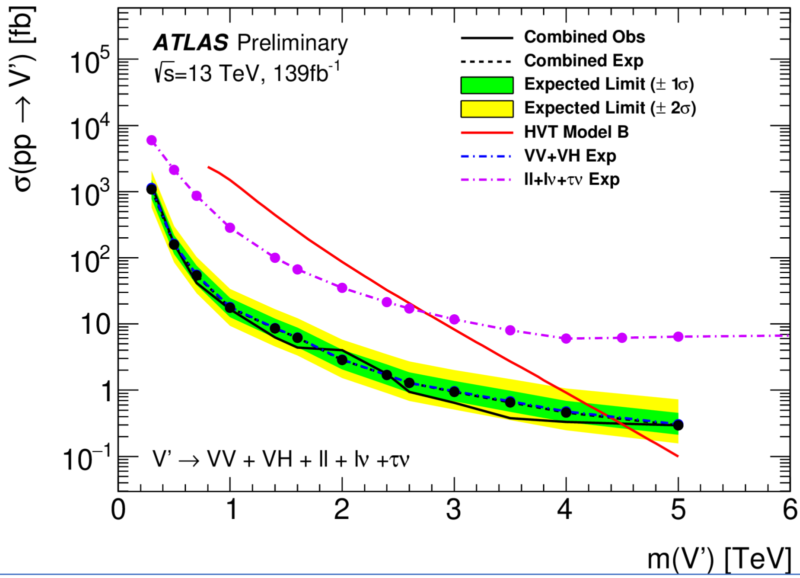
- **Experimentally:**
  - Apply selection cuts to target signal.
  - Construct invariant mass distribution from collected events.
  - Compare to background-only and signal+background prediction



- **Results:** ATLAS [heavy resonance combination]:
  - Consider spin-1 Heavy Vector Triplet model
  - Consistent with SM: exclude range of masses for *X*.



arXiv:2004.14636



Effective Field Theory

Standard Model Effective Field Theory (SMEFT): New physics enters at scale Λ.

- SM Lagrangian extended with higher-dimensional operators suppressed by powers of that scale.

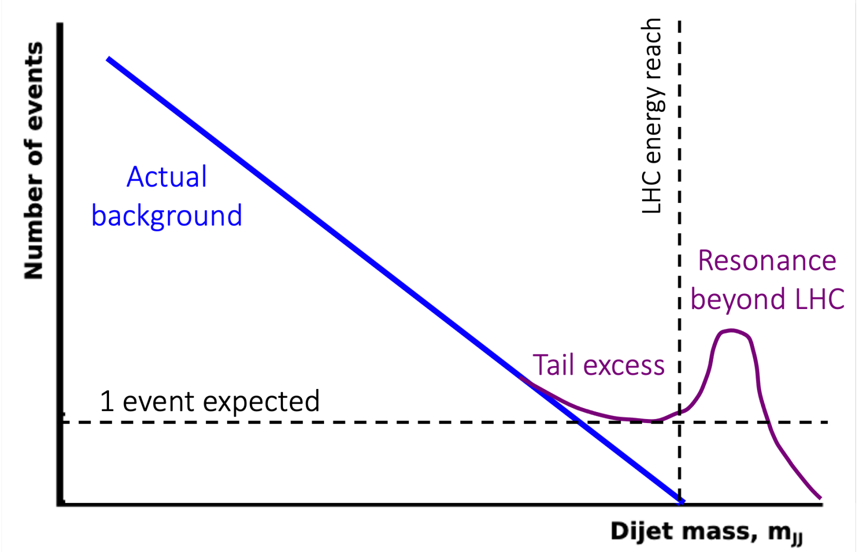
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots .$$

Truncate expansion at some order

Lepton and baryon number violation

Non-zero coefficients c_i enhance the tails of invariant mass distributions.

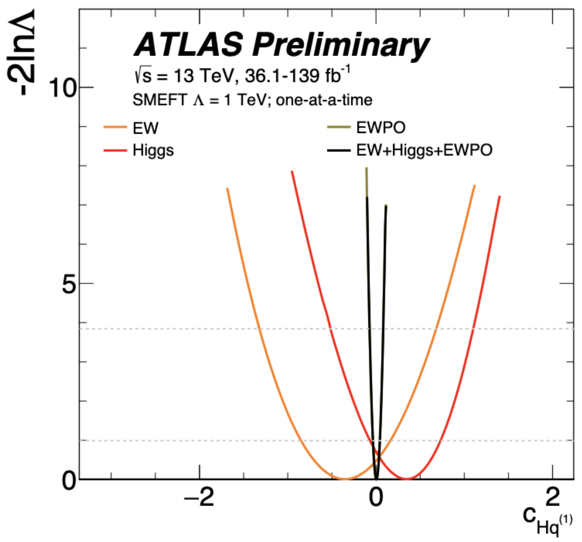
Goal: Use invariant mass distributions to place limits on the coefficients.

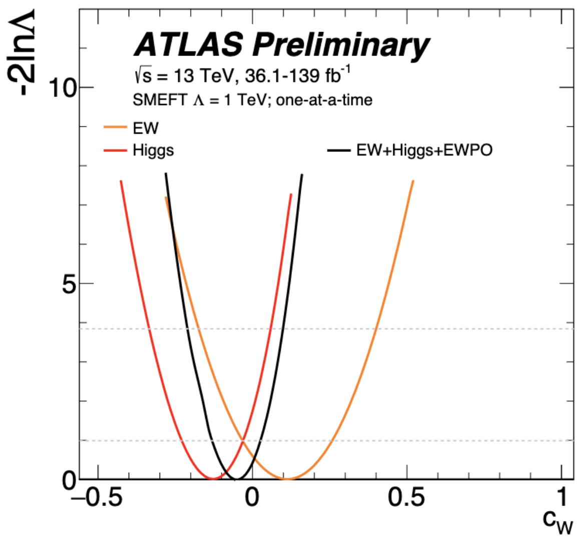


EFT Constraints

Operators that can be constrained depend on the physics process.

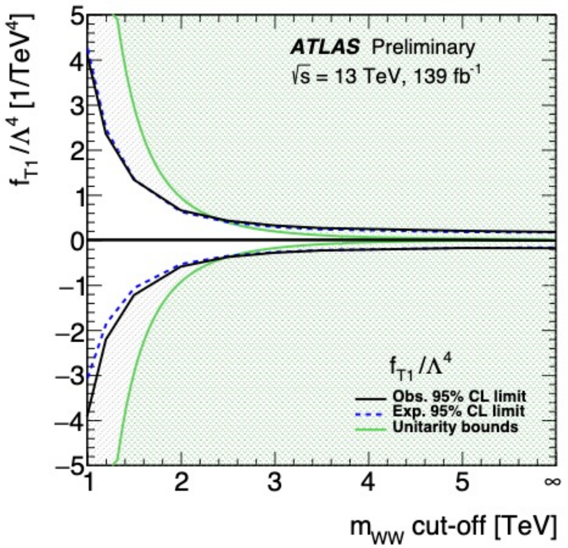
ATLAS combination of weak boson + Higgs + EW precision observable results [PUB note]: constraints placed on dim(6) operators

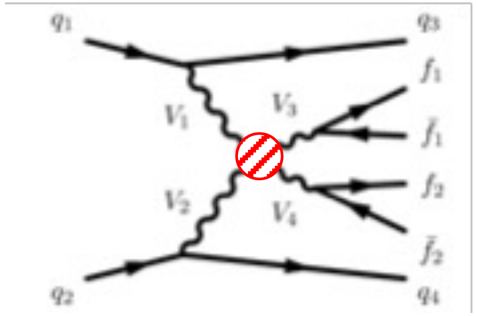




VBS processes interpreted via EFT too: Used to constrain dim(8) operators

ssWW in ATLAS





Conclusions

- Electroweak symmetry breaking is a key ingredient of the SM.
- Since Higgs and diboson processes are sensitive to its consequences, studying them at the LHC can test this cornerstone of the SM.
- No deviation from the SM found so far, but Run 3 and the HL-LHC might have more to say!