

Opportunities at HL-LHC

Twilight of a precision Higgs
era

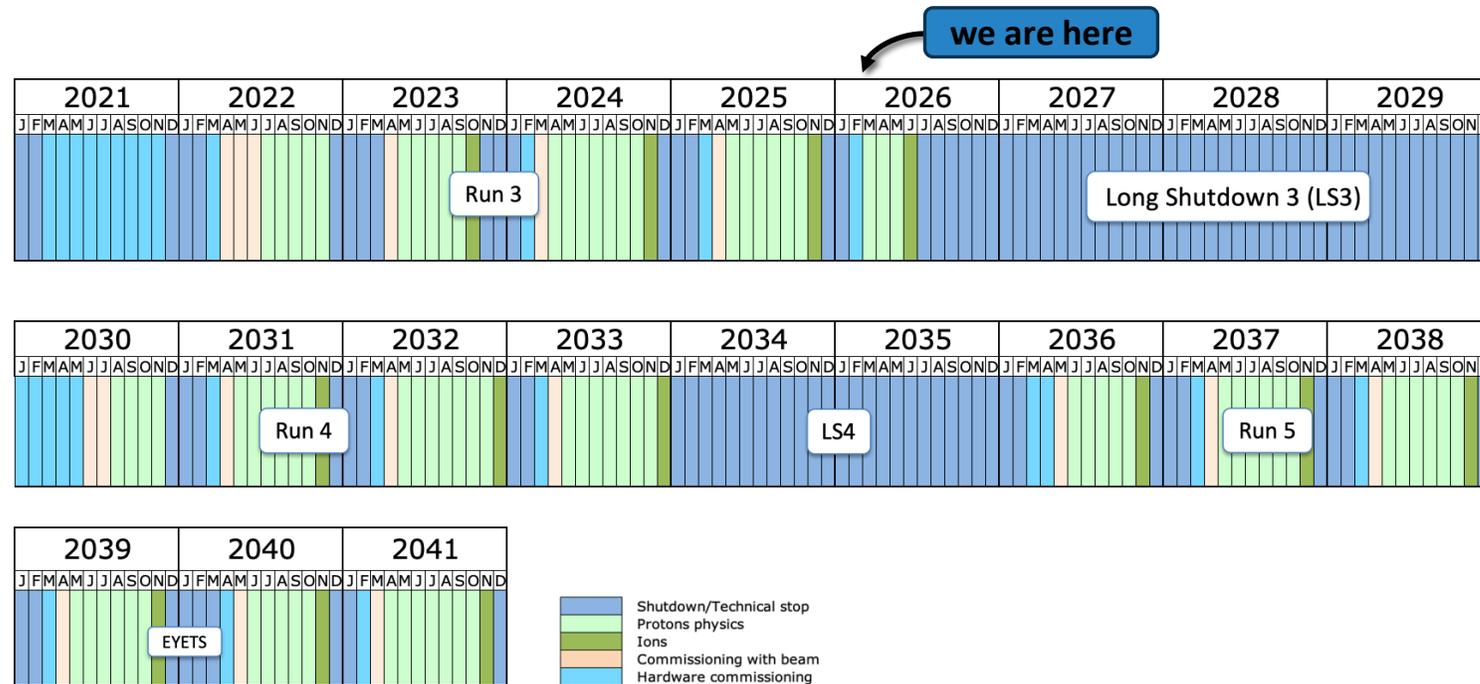
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PNWC meetup Feb 18, 2026



The sacred timeline

- Soon, we are going to have a long period without beam time.
 - While we progress towards for **HL-LHC** there is a lot to do with the current data!



Last update: November 24

Theory opportunities of LHC Run 3

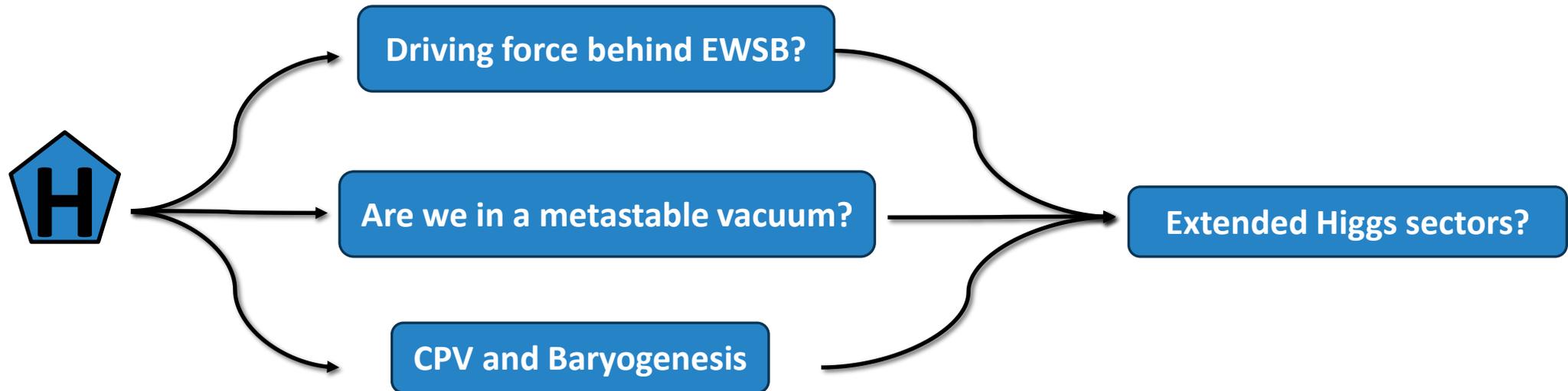
- Run 3 have two important upgrades compared to Run 2:
 - \sqrt{s} from 13 TeV to **13.6 TeV**.
 - Integrated Luminosity from $\sim 140 \text{ fb}^{-1}$ to $\sim 450 \text{ fb}^{-1}$.
- Opportunity to explore **everything** that we can do with this data while waiting for Run 4.
- Start to tackle **more challenging analyses** which can also be used in **HL-LHC**.

Theory opportunities of LHC Run 3

- Run 3 is the perfect time to:
 - Challenge ourselves to tackle new physics searches with **difficult background**.
 - **Revise assumptions** that go into new physics searches.
 - Create more **realistic new physics templates** for future searches.
- In this presentation, I use **Higgs** related physics to draw attention to some of these points.

Higgs from end to means

- Since the discovery of the Higgs, we have entered in a **precision era**:
 - We are now certain of the low energy properties of the SM, but many open questions remain that **could be answered in the lifetime of the LHC**.



Higgs from end to means

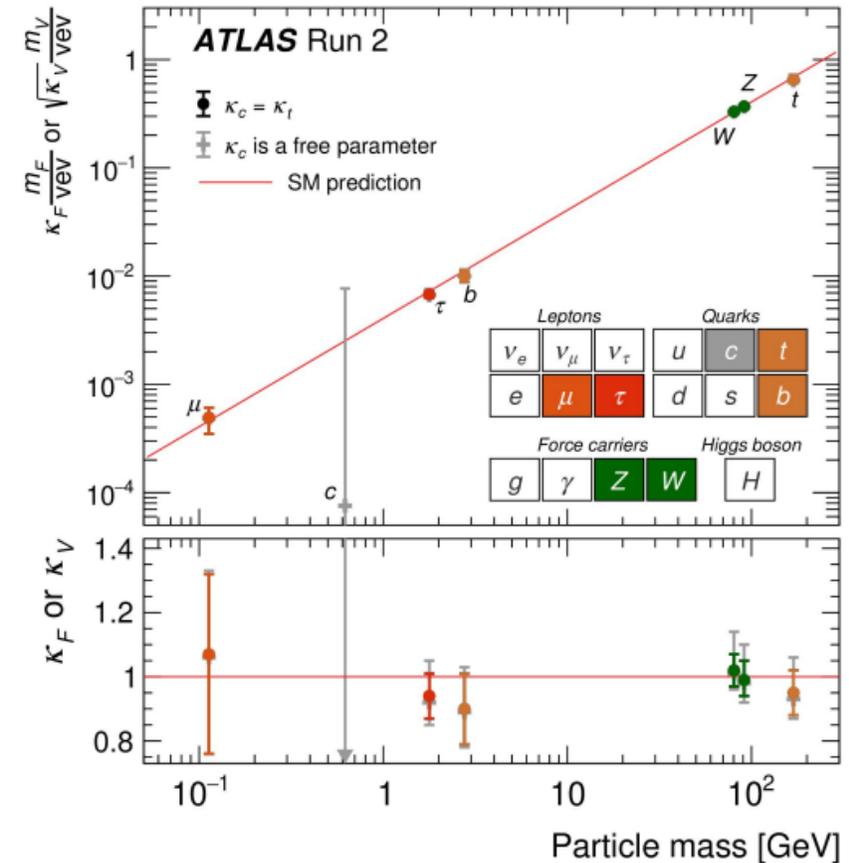
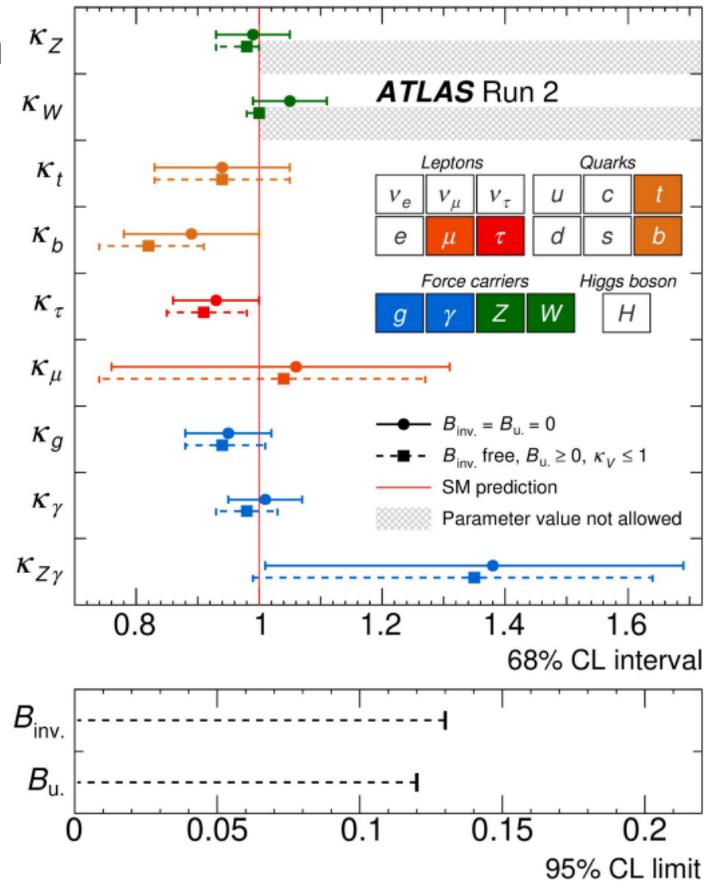
- Is the Higgs field responsible alone for electroweak symmetry breaking?
 - SM + Singlet, two Higgs-doublet, 2HDM+Singlet, Georgi-Machacek, Composite Higgs...
 - Any extension that affects EWSB has **both** deviations of Higgs couplings and new states that should not be arbitrarily heavy. (Especially if they modify Higgs-gauge couplings, affecting the unitarization of VBS...)
- We can search in the LHC for both **Higgs coupling deviations** and **new exotic states**.

(They can also be interconnected more deeply, spoilers...)
- New physics that affects electroweak symmetry breaking **cannot be too far from the EW scale**

(in the decoupling regime the contributions to the EWSB becomes heavily suppressed)

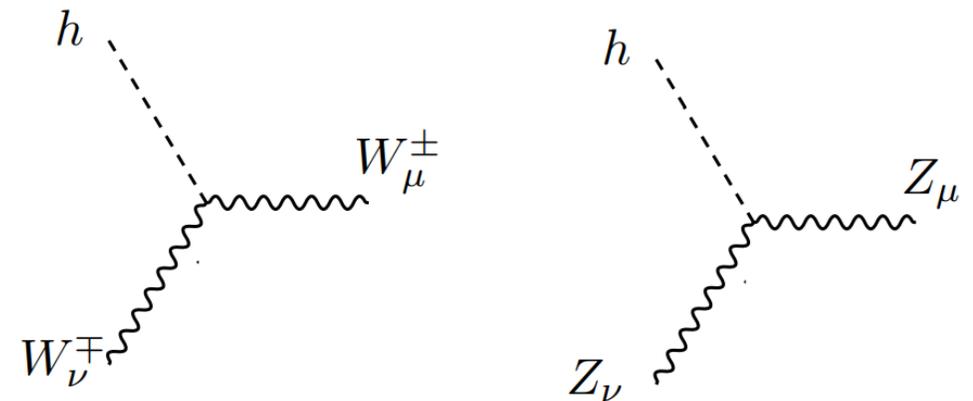
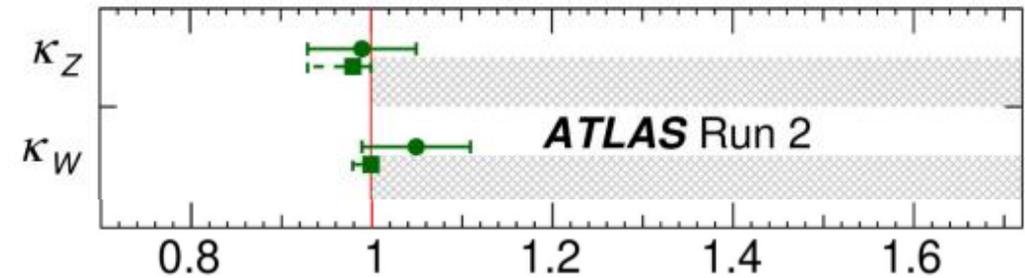
Higgs couplings and the SM

- The LHC shows that corrections from new physics **appear to be small**.
- This could be an artifact of the **way we are accessing information**.
- We could also be **overlooking** certain processes/regions.
- One example comes from models that predict a **relative sign** between the gauge-Higgs couplings.



New physics may be hiding in plain sight

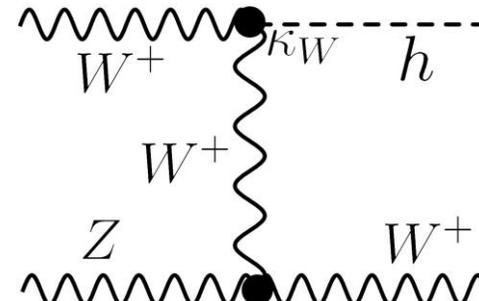
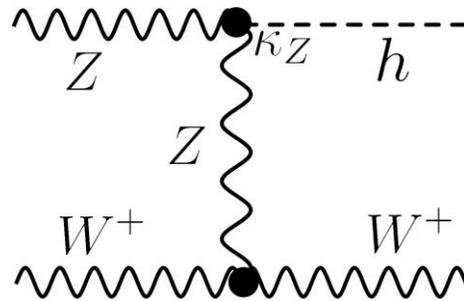
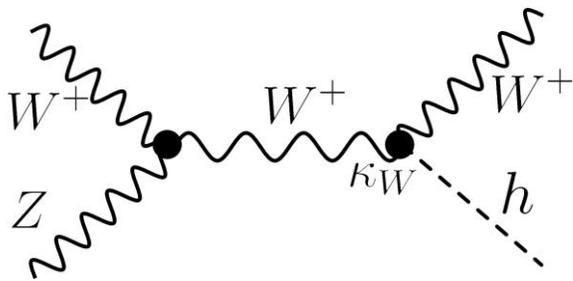
- The measurements of the **gauge-Higgs couplings are all consistent with the SM prediction**.
- **Very little sensitivity to the relative sign** between κ_W and κ_Z .
- **Most analysis are insensitive to the relative sign**, and then it becomes custom to only look for positive values, but some processes are sensitive to the relative sign!



Relative sign from VBF Vh

- The VBF Vh process is **highly sensitive** to interference effects in the κ -framework:

$$\mathcal{M}(W_L^+ Z_L \rightarrow W_L^+ h) = \frac{g^2(3 + \cos \theta)}{8m_W^2} (\kappa_W - \kappa_Z) s + \mathcal{O}(s^0)$$



Higgs becomes insufficient to unitarize longitudinal gauge boson scattering!

- LHC can look for VBF Wh and measure this relative sign!

Determination of the relative sign of the Higgs boson couplings to W and Z bosons using WH production via vector-boson fusion with the ATLAS detector

The ATLAS Collaboration

The associated production of Higgs and W bosons via vector-boson fusion (VBF) is highly sensitive to the relative sign of the Higgs boson couplings to W and Z bosons. In this Letter, two searches for this process are presented, using 140 fb^{-1} of proton–proton collision data at $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS detector at the LHC. The first search targets scenarios with opposite-sign couplings of the W and Z bosons to the Higgs boson, while the second targets Standard Model-like scenarios with same-sign couplings. Both analyses consider Higgs decays into a pair of b -quarks and W decays with an electron or muon. **The opposite-sign coupling hypothesis is excluded with significance much greater than 5σ** , and the observed (expected) upper limit set on the cross-section for VBF WH production is 9.0 (8.7) times the Standard Model value.

Study of WH production through vector boson scattering and extraction of the relative sign of the W and Z couplings to the Higgs boson in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$

The CMS Collaboration*

Abstract

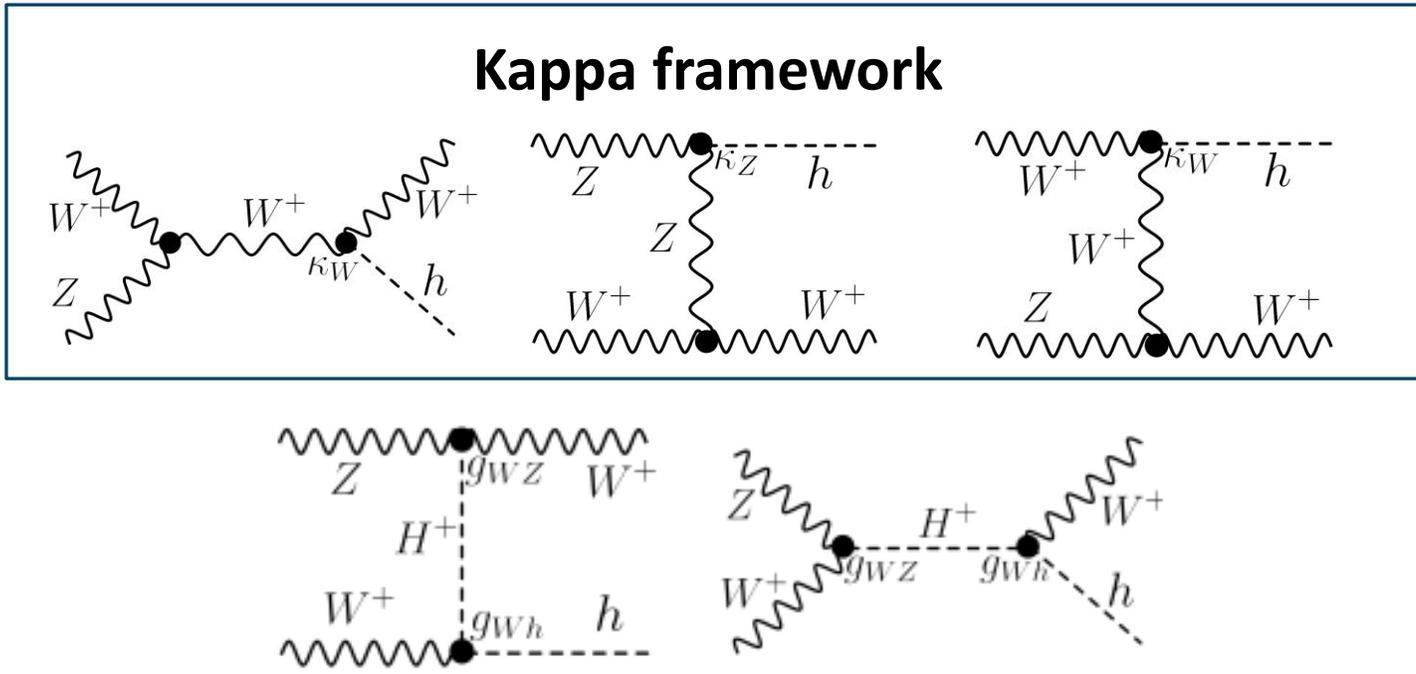
A search for the production of a W boson and a Higgs boson through vector boson scattering (VBS) is presented, using CMS data from proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ collected from 2016 to 2018. The integrated luminosity of the data sample is 138 fb^{-1} . Selected events must be consistent with the presence of two jets originating from VBS, the leptonic decay of the W boson to an electron or muon, and a Higgs boson decaying into a pair of b quarks, reconstructed as either a single merged jet or two resolved jets. A measurement of the process as predicted by the standard model (SM) is performed alongside a study of beyond-the-SM (BSM) scenarios. The SM analysis sets an observed (expected) 95% confidence level upper limit of 14.3 (9.0) on the ratio of the measured VBS WH cross section to that expected by the SM. **The BSM analysis, conducted within the so-called κ framework, excludes all scenarios with $\lambda_{WZ} < 0$ that are consistent with current measurements, where $\lambda_{WZ} = \kappa_W/\kappa_Z$ and κ_W and κ_Z are the HWW and HZZ coupling modifiers, respectively. The significance of the exclusion is beyond 5 standard deviations**, and it is consistent with the SM expectation of $\lambda_{WZ} = 1$.

Effects of new physics on VBF Vh

- In a UV completion, the theory is inconsistent without new states. **Those new states change the signal kinematics and thus the interference effect!**

UV completion

Kappa framework



To contribute to this process
requires representations
larger than doublet.
arXiv:2111.02533

Effects of new physics on VBF Vh

- Generically, for VBF Vh process only a charged Higgs can contribute at tree level:

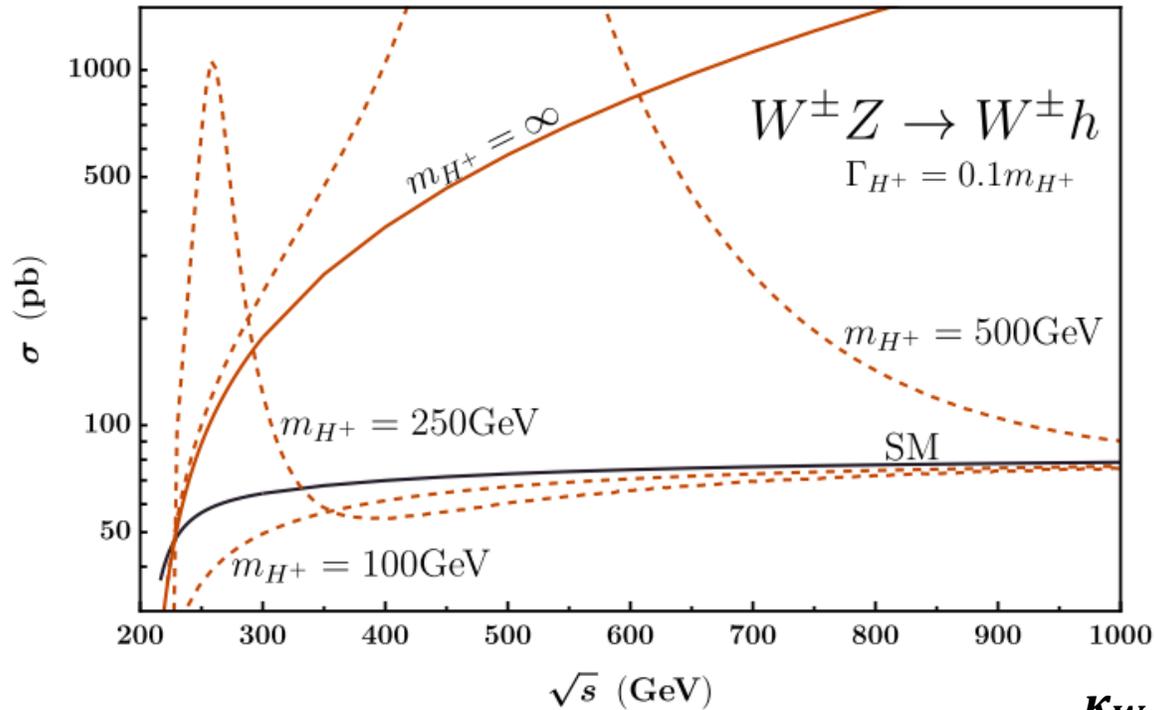
$$\mathcal{L}_{H^\pm} = g m_Z g_{WZ}^i H_i^\pm W_\mu^\mp Z^\mu - i g g_{Wh}^i h \partial_\mu H_i^\pm W^{-\mu} + \text{h.c.}$$

- Even without a UV completion in mind, the **coefficients are fixed by unitarity**:

$$\mathcal{M}(W_L^+ Z_L \rightarrow W_L^+ h) = \frac{g^2 (3 + \cos \theta)}{8m_W^2} \left(\sum_i g_{wZ}^i g_{Wh}^i + \kappa_W - \kappa_Z \right) s + \mathcal{O}(s^0)$$

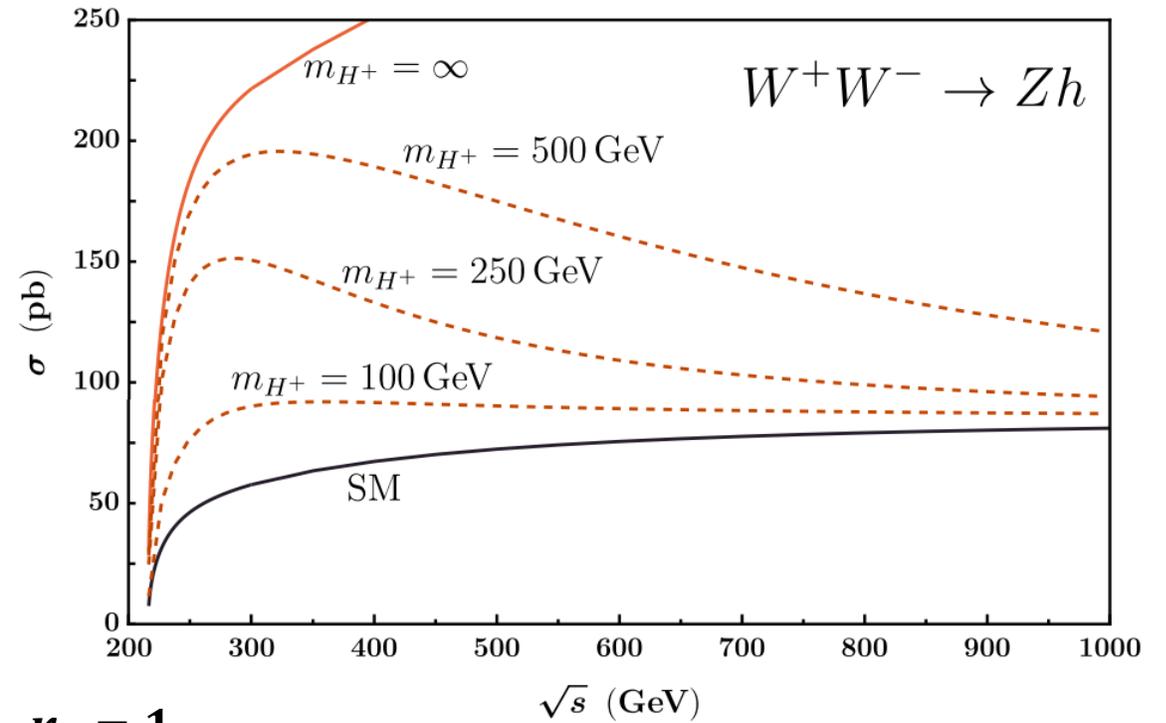
$$\sum_i g_{wZ}^i g_{Wh}^i = \kappa_Z - \kappa_W$$

Effects of new physics on VBF Vh



Wh sensitive to heavy H^+

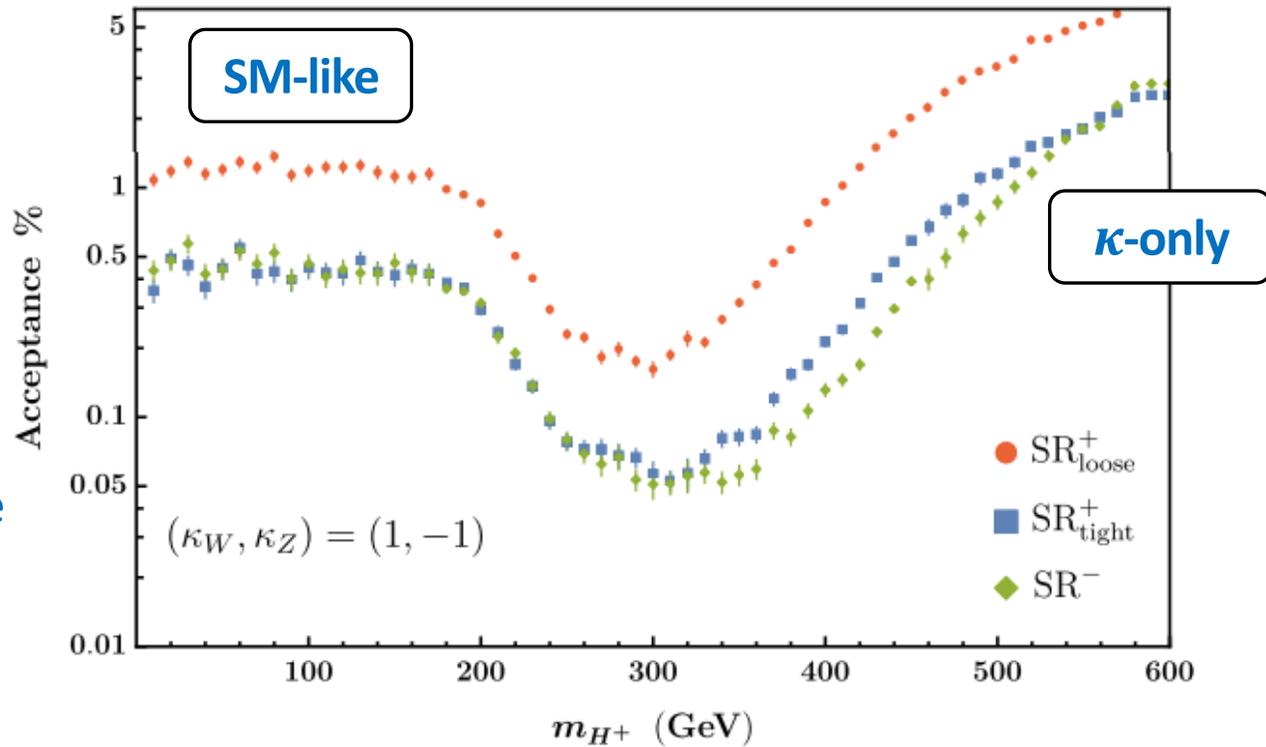
$$\kappa_W = -\kappa_Z = 1$$



Zh sensitive to light H^+

Effects of new physics on VBF Vh

- Recast of the ATLAS analysis for VBF Wh under this more general hypothesis shows the **sensitivity of the kinematics** to these states
- The ATLAS analysis optimizes for:
 - SM signal (low mass under the new hypothesis)
 - Kappa framework signal (high mass under the new hypothesis)
- Sensitivity drops in the intermediary region, may be possible to improve there using different cuts!

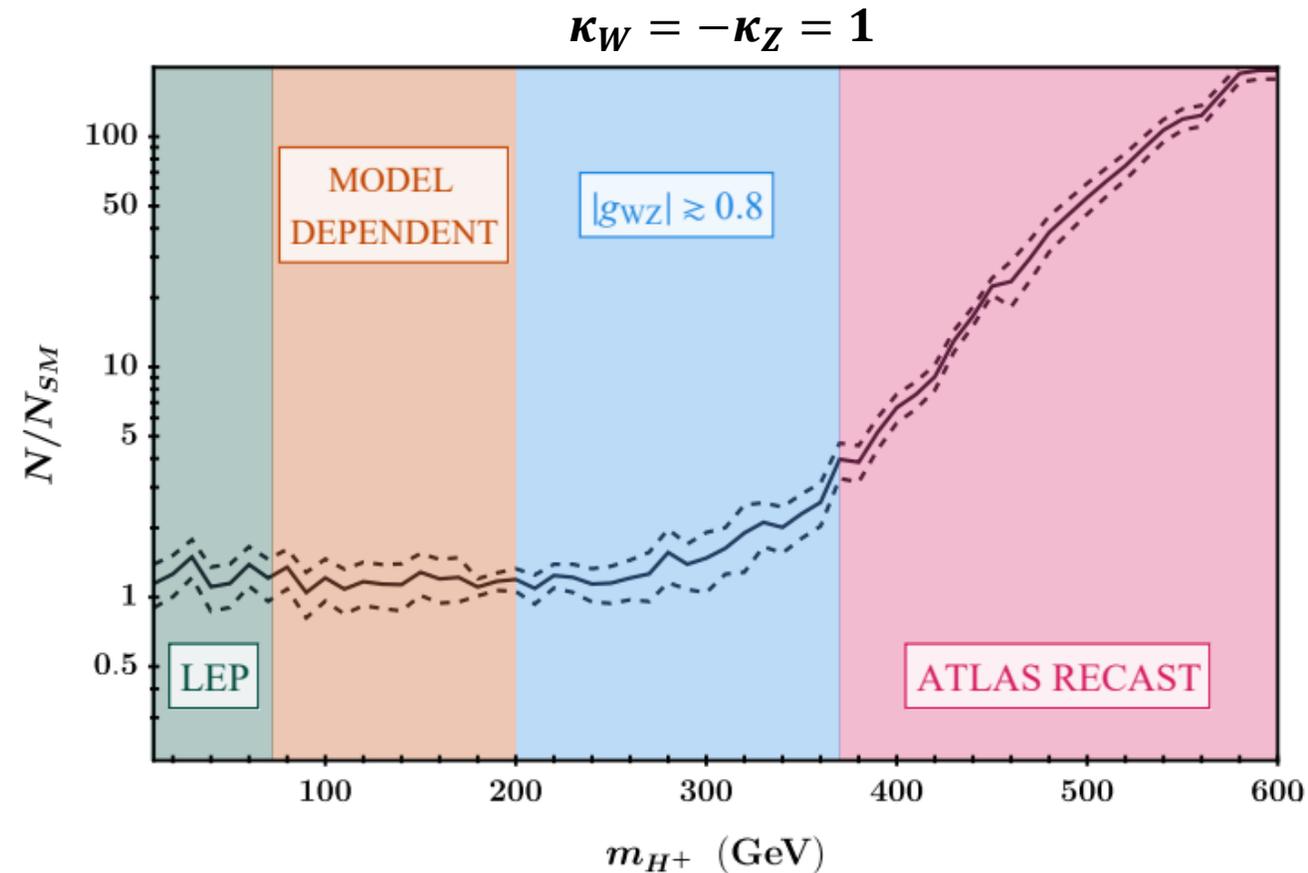


Recast done using **RIVET**, makes the lives of theorist much easier!

2404.10815

What the LHC has measured?

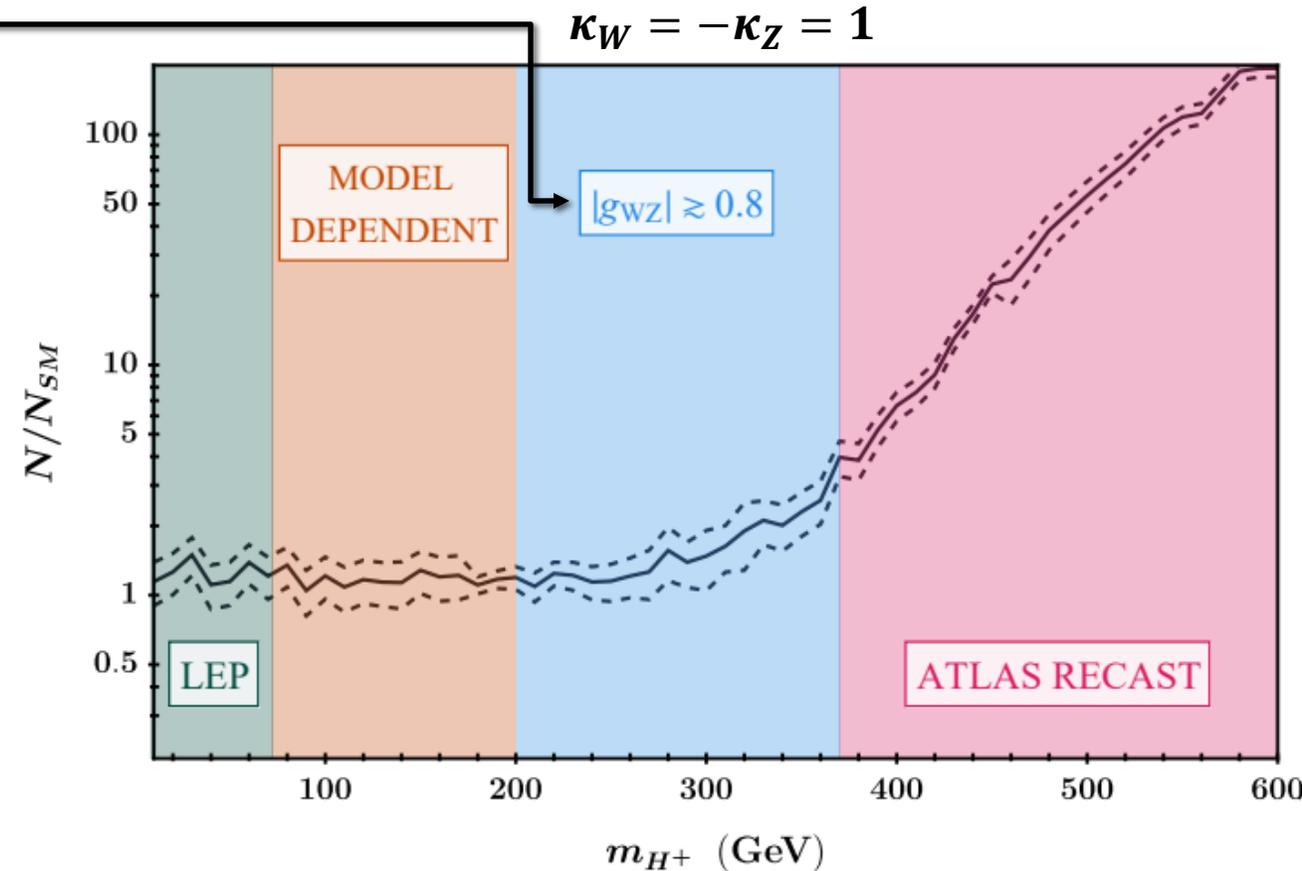
- Recasting the analysis to a scenario with one charged state **changes** a high confidence exclusion of negative coupling modifier to an exclusion of masses above 370 GeV!
- Current LHC data cannot model-independently exclude the negative gauge-Higgs coupling hypothesis!



2404.10815

What the LHC has measured?

- The search for VBF WZ(2104.04762) does not consider masses below 200 GeV. Background and Signal becomes difficult, but maybe doable?
- We should be looking to clear any blind spot where new physics could hide that are accessible at LHC.
- Is a light fermiophobic charged scalar excluded?
- How general are the model dependent searches for light charged Higgs?



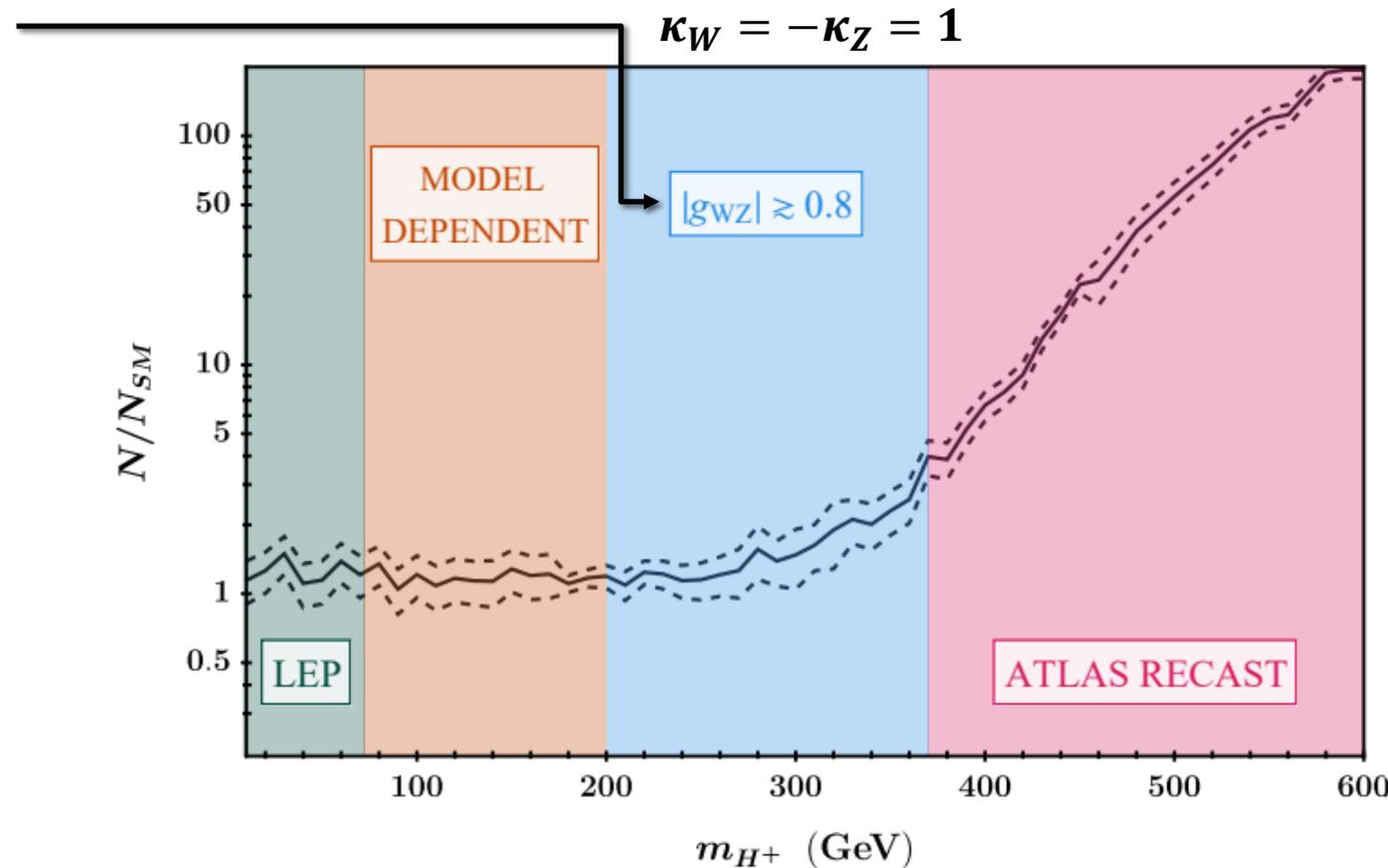
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What the LHC has measured?

- In this region, because of unitarity: $g_{Wh} > 2.5!$
- This coupling is not well searched currently
(would not be the leading bound in most Higgs extensions)

$$\mathcal{L}_{H^\pm} = -i g g_{Wh}^i h \partial_\mu H_i^\pm W^{-\mu} + \text{h.c.}$$

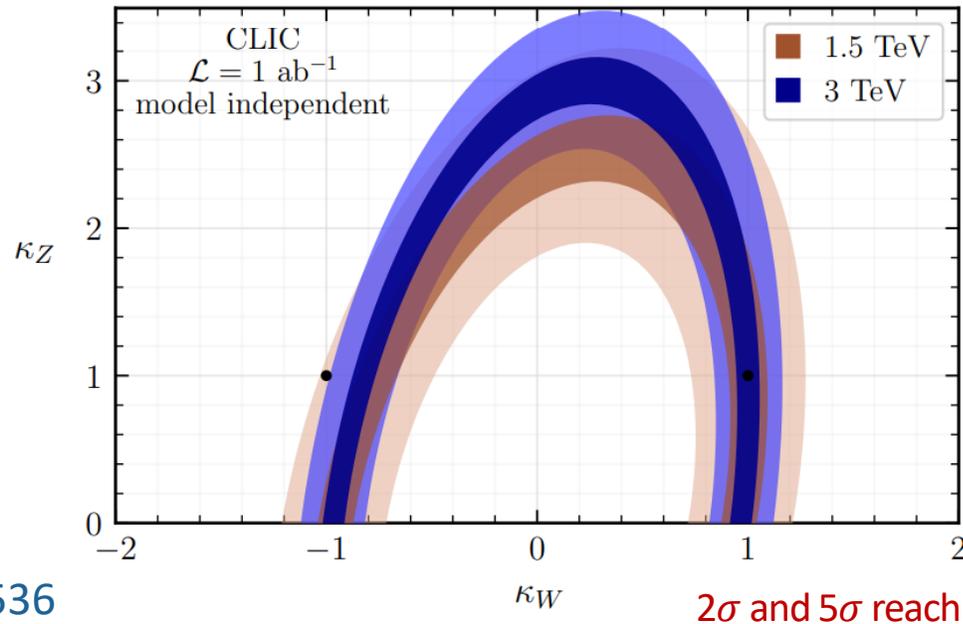
- Currently looking at $pp > H^\pm(W^\pm h|W^\pm Z)h$ to reach down to the model dependent region.



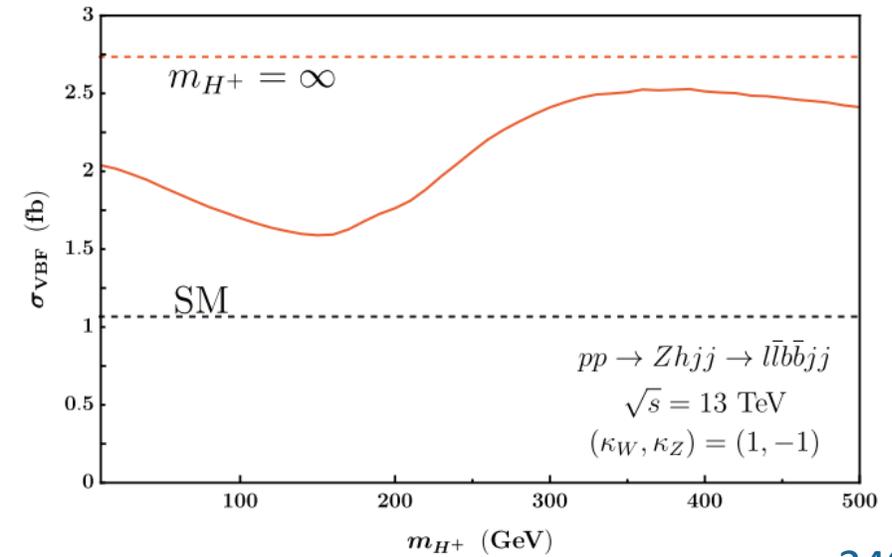
What the LHC could measure?

- VBF Zh was not looked for in LHC, **can we measure in the near future?**
(cross section 20 times smaller than VBF Wh)

- Easily reachable with **TeV lepton colliders**



Challenging channel but with irreducible modification from the SM in these scenarios!

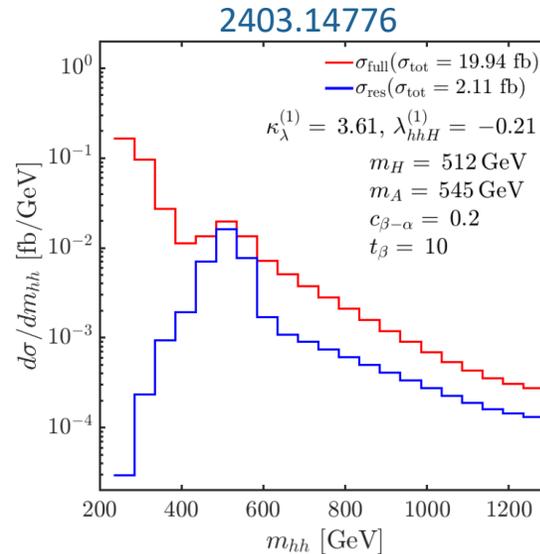


Blind spots... Opportunity!

- Any statistical test is as good as the hypothesis to be tested.
- It's time to confront our assumptions: **coupling signs, kinematic regimes, decay modes.**
- There may be **new physics** hiding where we did not look and the only way to know is to see.

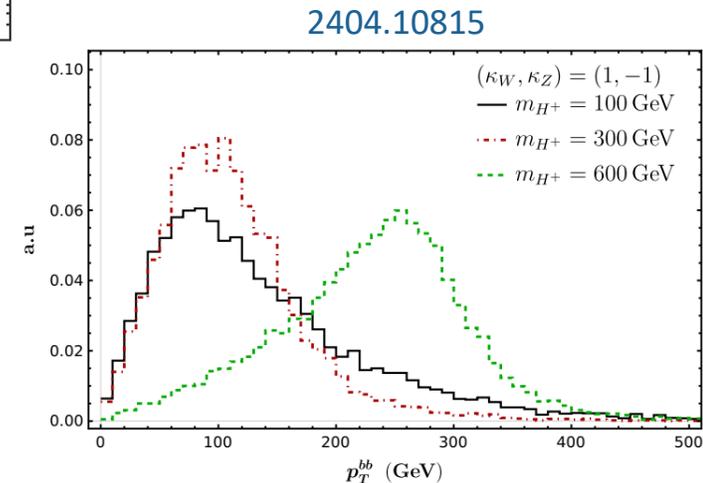
Improved hypothesis for new physics search

- Most LHC analysis assume **either** resonant or non-resonant processes.
 - While most of the UV completions **have both**, and this affects the hypothesis testing!
- Look for **realistic model templates** that describe these effects. (Challenging to remain model-independent at the same time)
- In extended Higgs sectors they will usually look like kappa framework + minimal set of new states.



hh production in 2HDM which shows both resonant and non-resonant

VBF Wh which shows different distributions than pure kappa-framework



Improved hypothesis for new physics search

- Another point to be careful is with EFT interpretations.
 - **The EFT that you use has built in information about the UV!**
- **SMEFT** ~ Heavy new states that **do not** contribute to EWSB
- **HEFT** ~ **SMEFT** plus the possibility of heavy new states that contribute to EWSB
- **Even HEFT can breakdown** if there are (relatively) light states.
 - **In this case the only way to explore is template models!** (not all non-decoupling models are excluded yet!)
- Any of the three choices gives different kinematics which affects the analysis!
 - Challenging for model-independent/agnostic searches.

Conclusion

- The SM works remarkably well, but that doesn't mean it's complete.
- Blind spots exist—in **mass ranges**, **coupling signs**, and **overlooked rare channels**.
- Run 3 provides not just more data, but new **opportunities** to challenge assumptions and expand our search strategy.
- **If new physics is out there, it may already be in the data**—we just need to look the right way.
- And if its not there, we wait for **HL-LHC**...