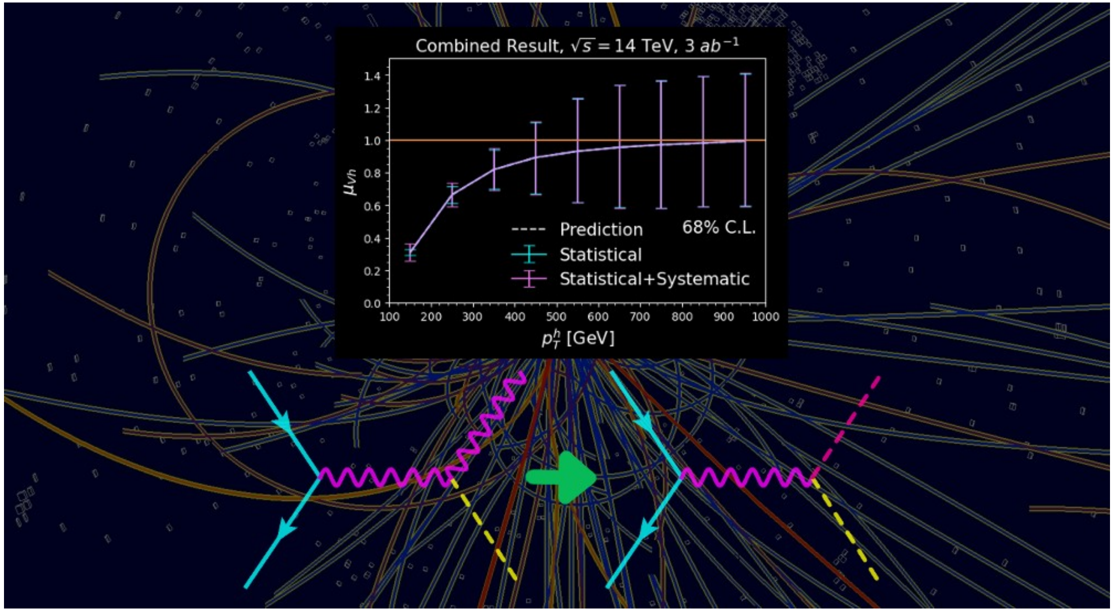
# Electroweak Restoration at the LHC and Beyond





Ian Lewis
(University of Kansas)


Huang, Lane, Lewis, Liu, PRD103 053007, arXiv:2012.00774 [hep-ph]

# Electroweak Restoration

- The LHC is operating at the energies necessary to thoroughly explore the electroweak sector at the scale it is broken.
- As the LHC and future collider measure the Standard Model to ever higher energies, we should be able to start probing not only the breaking of EW symmetry, but the restoration.
  - At high energies the SM particles are essentially massless.
  - This is equivalent to the Higgs vev going to zero:

$$v \to 0$$

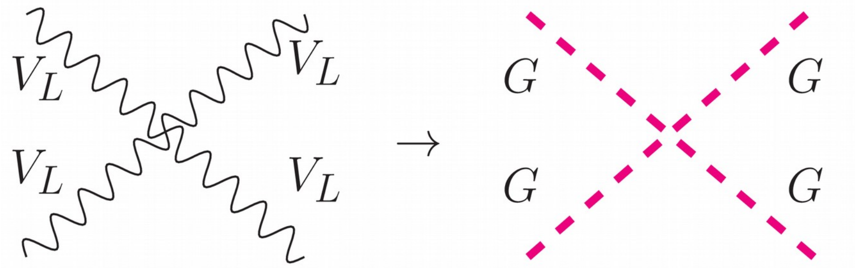
  - When the vev is zero, EW symmetry is restored.
- At colliders, EW symmetry is always broken.
  - However, the SM converges to an EW symmetric theory at high energies.
  - This convergence should be directly measurable
- In the limit of zero vev, the longitudinal gauge bosons are replaced with the Goldstone bosons.
  - Hence, measuring EW symmetry restoration is essentially measuring the convergence of the Goldstone boson equivalence theorem

# Electroweak Restoration

- These ideas have been important for developing parton showers including EW bosons Cuomo, Vecchi, Wulzer, SciPost 8 (2020) 078; Hook, Katx JHEP09 (2014) 175; Chen, Han, Tweedie JHEP11 (2017) 093; Bauer, Provasoli, Webber JHEP11 (2018) 030, as well as understanding the transition between the broken and unbroken phases Cuomo, Vecchi, Wulzer, SciPost 8 (2020) 078.
- It is interesting to find a process to directly measure the convergence of the Goldstone Boson Equivalence Theorem and the restoration of EW symmetry.
- Measurement of EW restoration would be a nice test of our understanding of SM physics.
  - Note: Throughout this talk, will focus on purely SM physics.

# Motivation

- Long history of trying to observe Goldstone boson equivalence theorem. Llewellyn Smith PLB46 (2973) 233; Veltman Acta Phys. Polon. (1977) 475; Lee, Quigg, Thacker PRD16 (1977) 1519; Bagger, Barger, Cheung, Gunion, Han, Ladinksy, PRD49 (1994) 1246; Han, Krohn, Wang, Zhu, JHEP03 (2010) 082; Brehmer Jaeckel, Plehn, PRD90 (2014) 054023; etc.
  - Mostly focused on longitudinal vector boson scattering.
  - By the Goldstone Boson Equivalence Theorem:




- The Goldstone boson quartic coupling arises from the Higgs potential:

$$V(H) = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 \qquad H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + i\, G^0\right) \end{pmatrix}$$

  - Hence, in principle, measuring longitudinal vector boson scattering probes the Higgs potential shape.

# Longitudinal Vector Boson Scattering

- Problem: we have discovered a SM-like Higgs.
  - Without a SM Higgs, longitudinal vector boson scattering does not obey perturbative unitarity.
  - We know it couples to Ws and Zs mostly with SM strength.
  - This effectively unitarizes longitudinal vector boson scattering to multi-TeV regions. Lee, Quigg, Thacker, PRD16 (1977) 1519; Brehmer, Jaeckel, Plehn, PRD90 (2014) 054023; Belyaev, Oliverira, Rosenfeld, Thomas, JHEP05 (2013) 005; Corbett, Eboli, Gonzalez-Garcia, PRD96 (2017) 035006; Ballestrero, Maina, Pelliccioli, JHEP03 (108) 170; Falkowski, Rattazi, JHEP10 (2019) 255; Chang, Luty, JHEP03 (2020) 14; etc.

- Goal: test EW symmetry restoration at high energies.
  - Longitudinal vector boson scattering unitarized.
  - In SM, Goldstones couple to fermions like mass
    - Goldstone-fermion couplings come from same interactions as Higgs-fermion interactions.
    - Basically impossible to directly produce Goldstones off massless initial state quarks.
  - However, there is another way.

# Kinetic Term

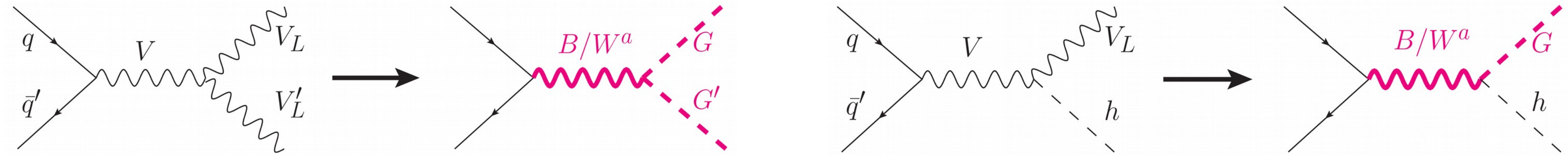
- The kinetic terms gives rise to the interactions between gauge and Goldstone bosons.

$$\mathcal{L}_{\rm kin} = |D_\mu H|^2 \qquad H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + i\, G^0\right) \end{pmatrix}$$

- These can contribute to di-boson production:

$$Z - G^0 - h,\ W^\pm - G^\mp - h \qquad Z/\gamma - G^+ - G^-,\ W^\pm - G^\mp - G^0.$$

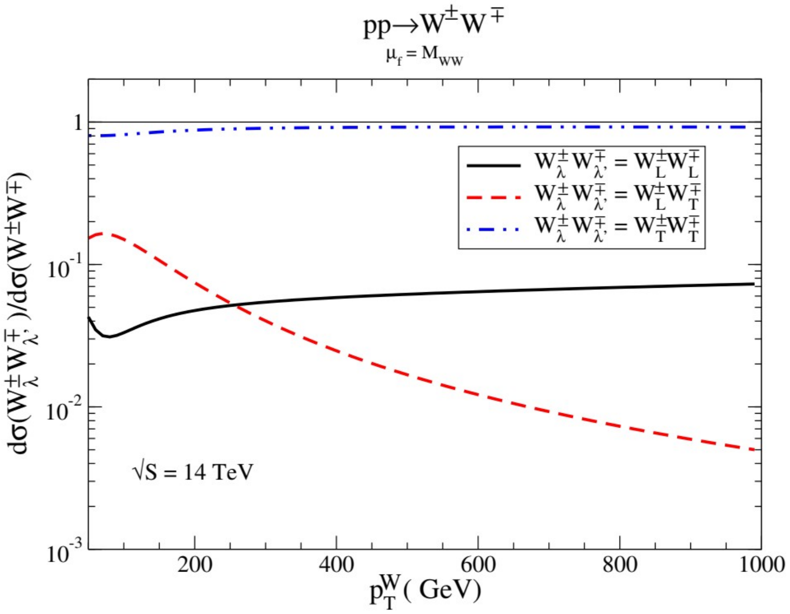
- Can produce Goldstone's in s-channel processes with quark initial states.
  - Can search for them in $q\bar{q}' \to VV'$ and $q\bar{q}' \to Vh$, $V = W^\pm, Z$



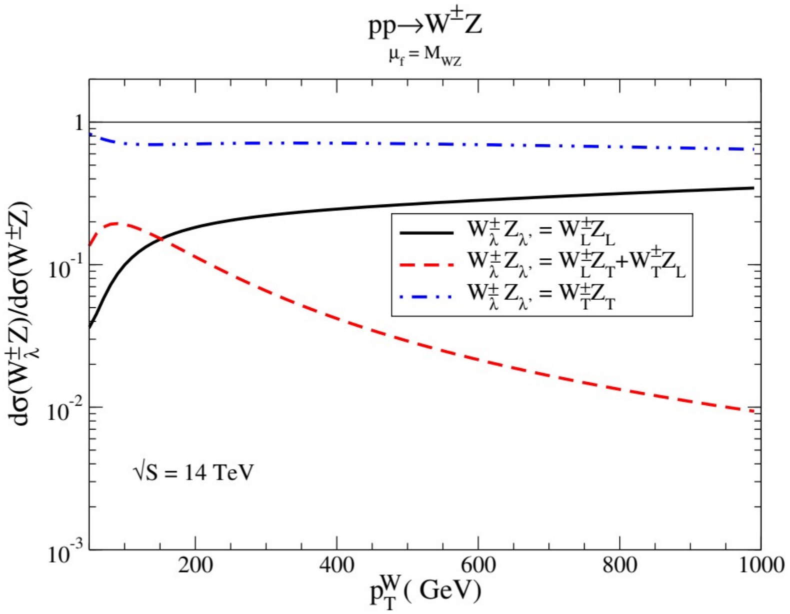

- Easiest to test in production modes automatically dominated by longitudinal modes.
  - Transverse modes exist in both broken and unbroken phases

# Polarization Fractions for WW/WZ

WW Production




WZ Production

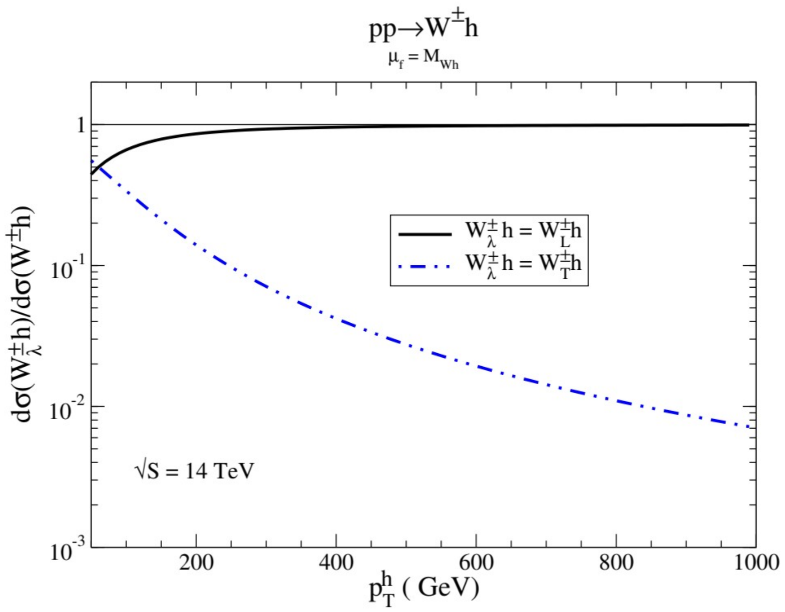



WW and WZ production dominated by transverse polarizations to high energy.

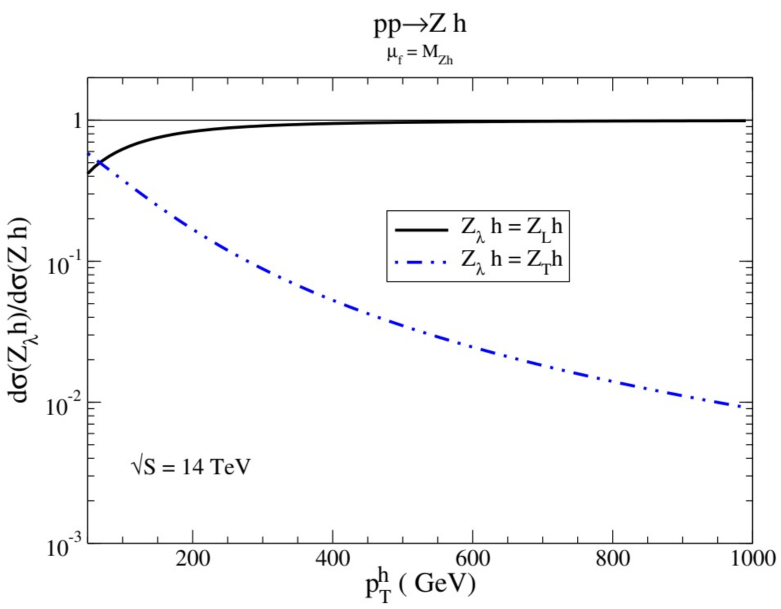
Black: Longitudinal+Longitudinal, Red: Longitudinal+Transverse, Blue:Transverse+Transverse

# Wh/Zh Polarization Fractions

Wh Production




Zh Production




Wh and Zh production dominated by longitudinal polarizations very quickly.

Black: Longitudinal+Longitudinal, Red: Longitudinal+Transverse, Blue:Transverse+Transverse

# EW Symmetry Restoration

- Higgs Potential:

$$V(H) = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$

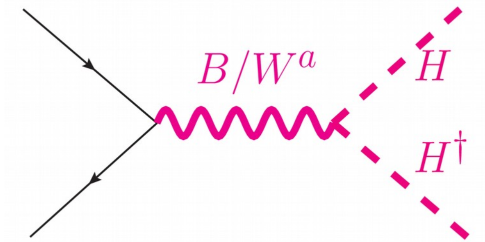
- In general, just need $\mu^2$ to be negative or zero to have zero vev.
  - Then the Higgs doublet could have a non-zero mass.
- Here we impose the SM relations and take the vev to zero:

$$\mu^2 \ = \ \lambda\, v^2 \xrightarrow[v\to 0]{} 0 \qquad m_h^2 \ = \ 2\,\lambda\, v^2 \xrightarrow[v\to 0]{} 0.$$

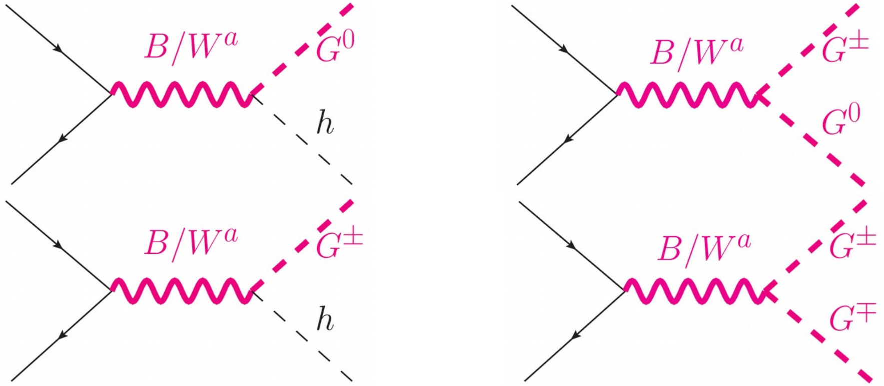
- For calculation in the symmetric phase, the relevant degrees of freedom are:
  - The massless Higgs doublet.
  - Massless hypercharge gauge boson.
  - Massless SU(2) gauge bosons.

# Goldstone production

- In principle, if EW symmetry is restored should calculate production of Higgs doublet:




- Once decays are accounted for, detectors can separate electric charge.
  - Breaks SU(2)xU(1).
- So, we calculate component-by-component in the doublet:
  - For Goldstone calculation, massless SU(2)xU(1) gauge bosons used as intermediate particles.



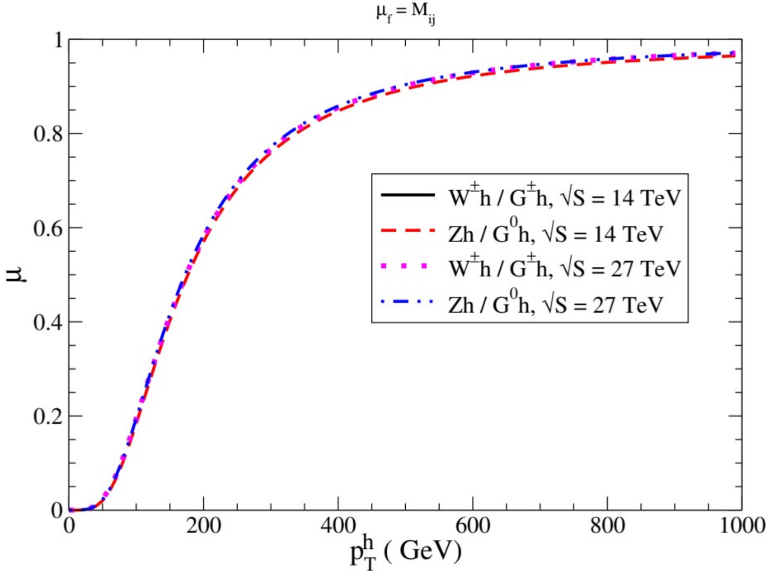
# Signal Strength

- To measure EW restoration, will define a signal strength as a ratio of the broken phase to unbroken phase processes:

$$\mu_{Wh} = \frac{d\sigma(pp \to W^{\pm}h)/dp_T^h}{d\sigma(pp \to G^{\pm}h)/dp_T^h},$$

$$\mu_{Zh} = \frac{d\sigma(pp \to Zh)/dp_T^h}{d\sigma(pp \to G^0 h)/dp_T^h}.$$

- If EW symmetry is restored, at high energies the signal strength will converge to one.



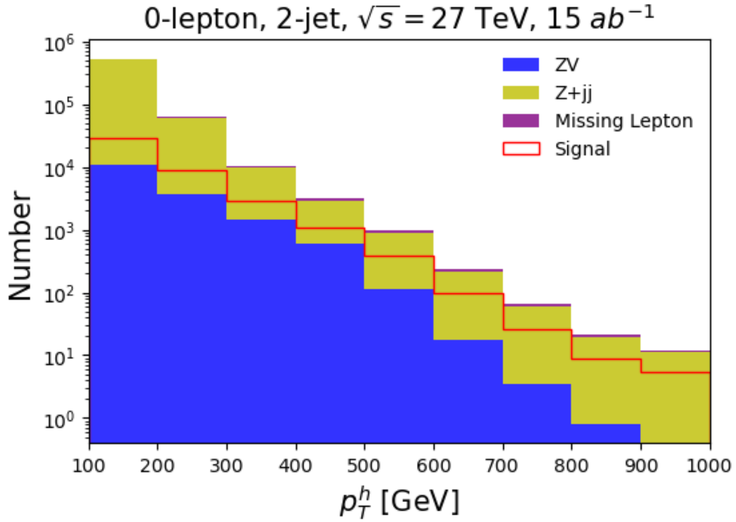

- Define global signal strength:

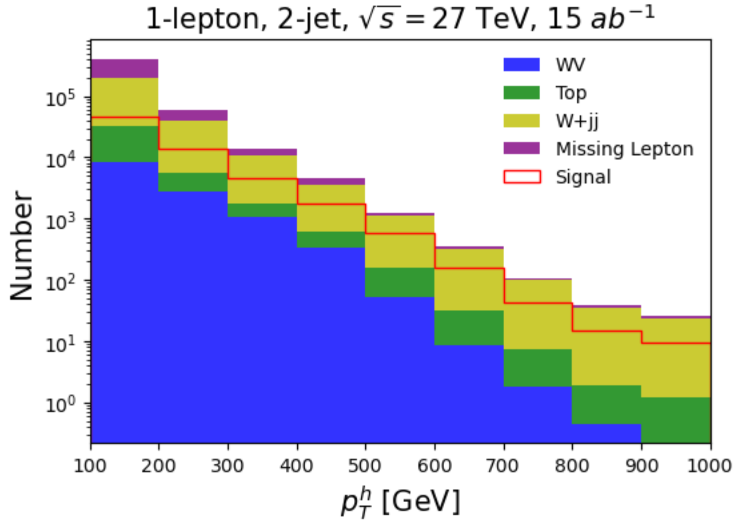
$$\mu_{Vh} = \mu_{Wh} = \mu_{Zh}.$$

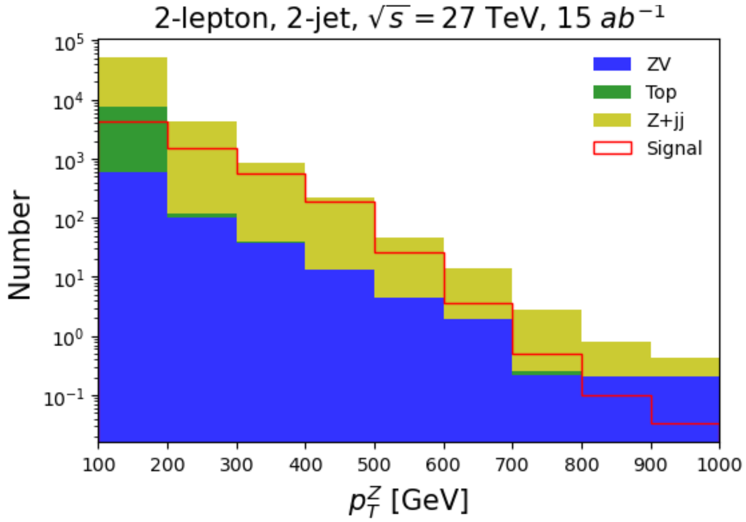
# Collider Analysis

- We performed a full collider analysis to see how well we can measure.
- Considered 6 signal categories:
  - Two lepton final state, $Zh \to \ell^+\ell^- b\bar{b}$ , with either
    - Exactly two jets from Higgs
    - Three or more jets.
  - One lepton final state, $Wh \to \ell\nu b\bar{b},$ with either
    - Exactly two jets from the Higgs
    - Exactly three jets
  - Zero lepton final state, $Zh \to \nu\nu b\bar{b}$, with either
    - Exactly two jets from Higgs
    - Exactly three jets
- Backgrounds:
  - QCD $V + ll,\ V\text{+HF},\ V + cl$
    - HF = $bb,\ bc,\ cc,\ bl.$
    - $l = u,\ d,\ s,\ g$
  - Top pair, single top, and vector boson pair production.

# Two jet signal and background

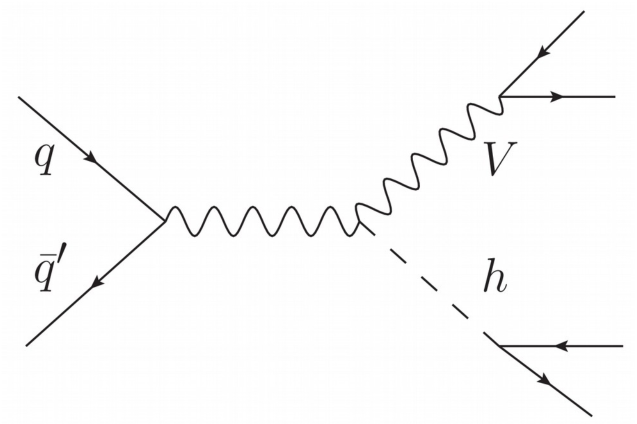


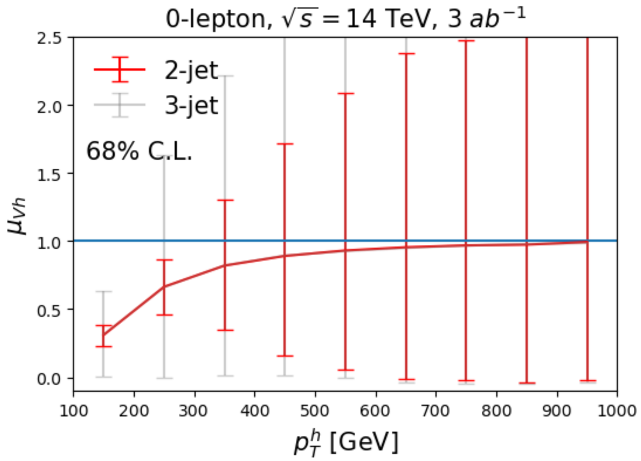



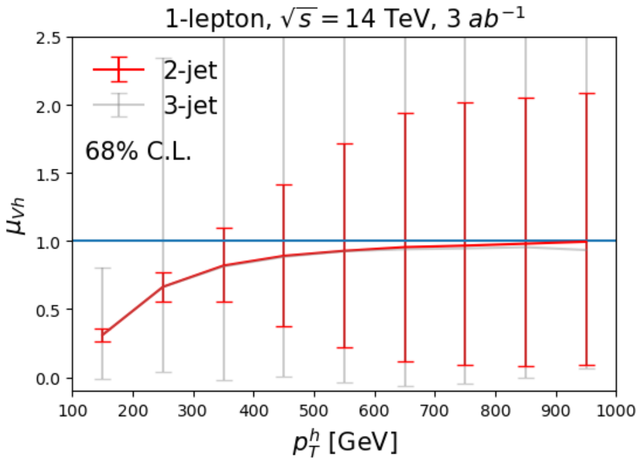
# Unfolding

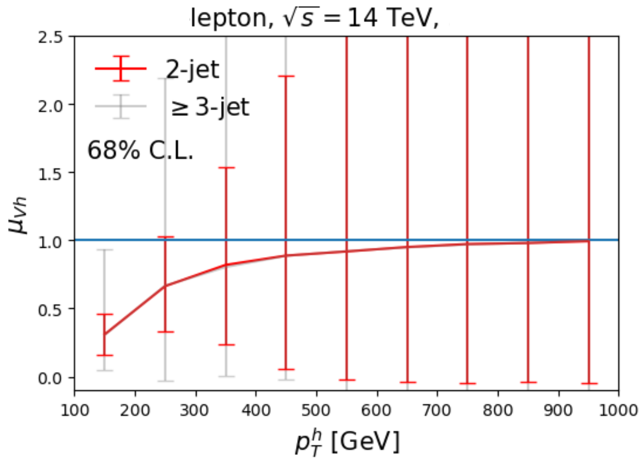
- Immediate problem at colliders:
  - The bosons decay mostly on shell at $\mathcal{O}(100\ \mathrm{GeV})$
  - Cannot simply decay Goldstones and define new signal strength.
  - Gauge boson decays have flavor universal properties.
  - Goldstones couples like mass.
- Decays break EW symmetry.
- However, the $q\bar{q}' \to Vh$ process does genuinely occur at high energy.
- So, we "unfold" events back to the 2-to-2 process.
  - Correct for decays, parton showering, hadronization, and detector effects.
  - Extract the 2-to-2 cross section.
- Once we unfold, we can then fit the signal strength to the signal.



# Signal strengths



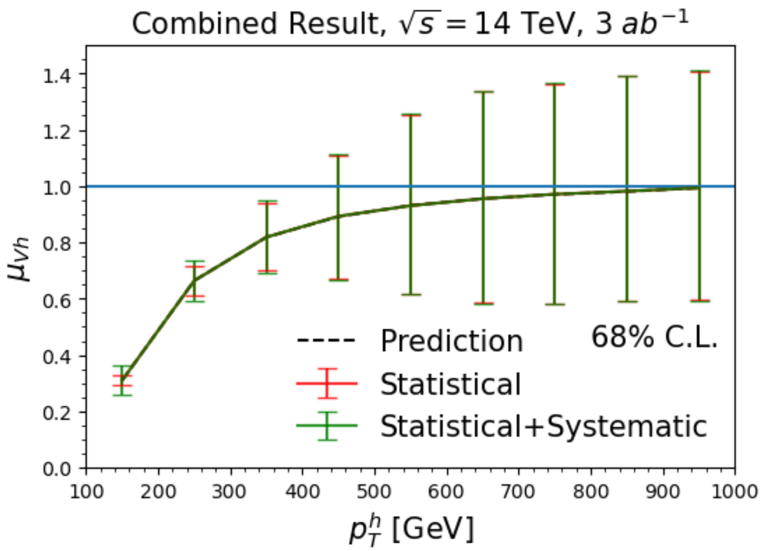



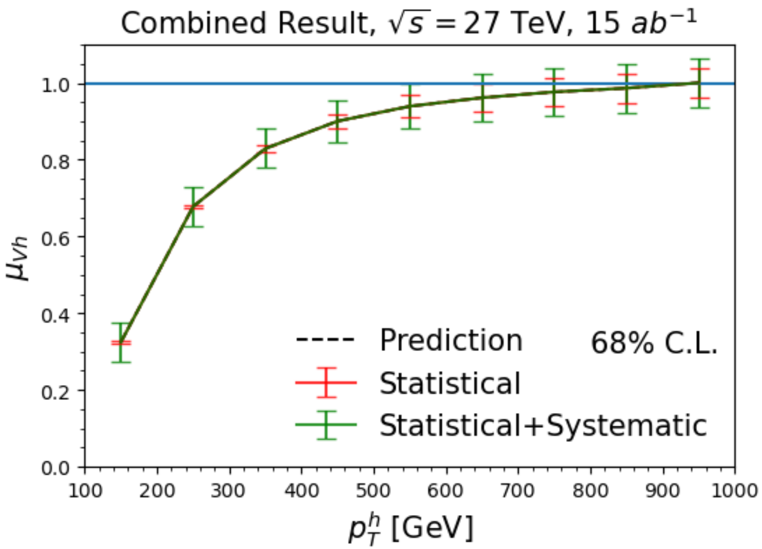

Grey: 3-jet, Red: 2-jet

# Combination

14 TeV HL-LHC




27 TeV HE-LHC




- In highest transverse momentum bin: $\mu_{Vh} = \begin{cases} 1 \pm 0.4 & \text{at the HL}-\text{LHC} \\ 1 \pm 0.06 & \text{at the HE}-\text{LHC} \end{cases}.$

# Quantifying convergence

- The Kullback-Leibler (KL) divergence contrasts the information between two distributions.
- Let *P* and *Q* be probability distributions.
- The KL-divergence tests the agreement between the two probabilities distributions:

$$KL = \Sigma_x P(x) \log\left(\frac{P(x)}{Q(x)}\right)$$

- KL-divergence is positive definite.
  - If P and Q agree well, KL-divergence is small.
  - If they agree well in the most probable locations, KL-divergence is small.
  - Similar to a chi-square, but include the information about which bins are most probable.

# Modified KL-Divergence

- We want a binned KL-Divergence.
- First we define a probability for each bin *i* for the $q\bar{q}' \to Vh$ hypothesis:

$$p_i^{\leq m} = \prod_{\substack{6\,\text{signal}\\ \text{categories}}} \frac{\text{Pois}(n_{obs,i}|S_i + B_i)}{\sum_{l=1}^{m} \text{Pois}(n_{obs,l}|S_l + B_l)}$$

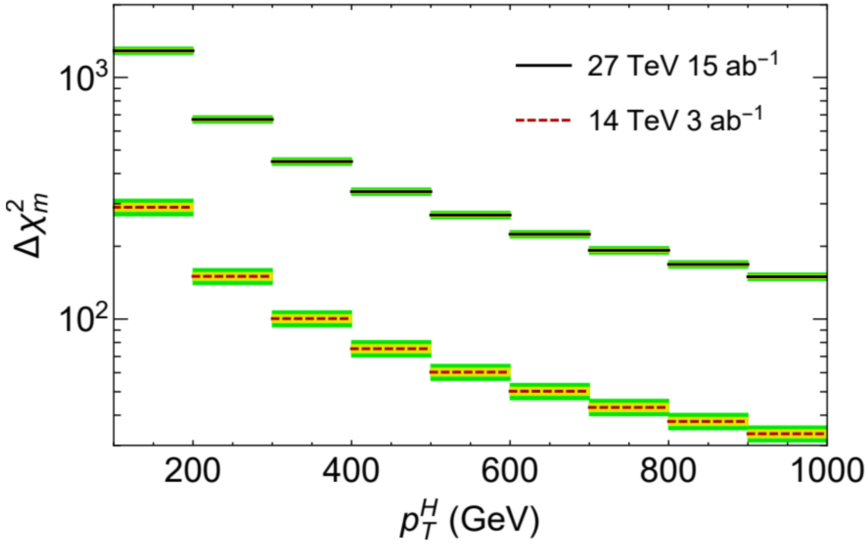
  - All bins up to *m* are included, and the probability is properly normalized.
- We define a similar probability for the $\mu_{Vh}^{j} = 1$ hypothesis for $q\bar{q}' \to Gh$:

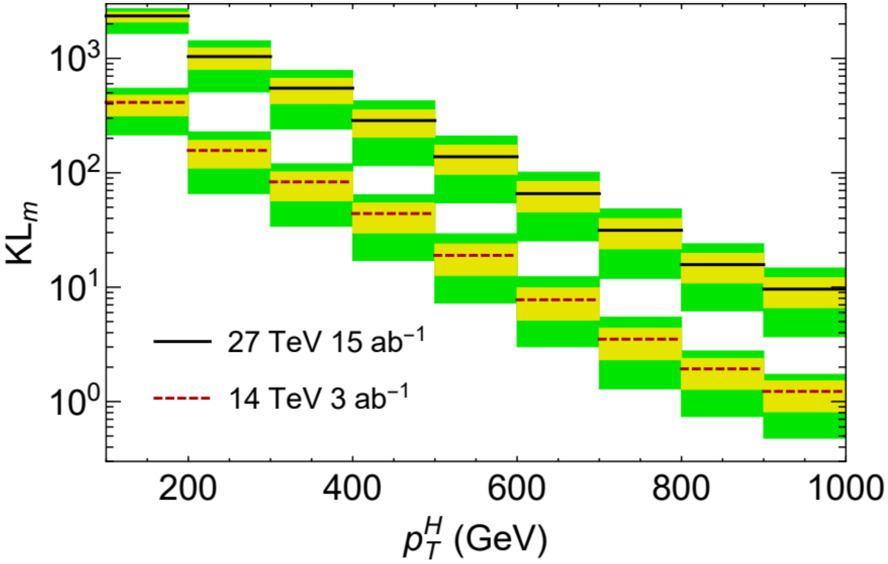
$$q_i^{\leq m} = \prod_{\substack{6\,\text{signal}\\ \text{categories}}} \frac{\text{Pois}(n_{obs,i}|\sum_j \Delta\sigma_j^{Gh}\epsilon_{ij}L + B_i)}{\sum_{l=1}^{m} \text{Pois}(n_{obs,l}|\sum_j \Delta\sigma_j^{Gh}\epsilon_{lj}L + B_l)}$$

- The KL-divergence for the first *m* bins is then:

$$KL_m = \sum_{i=1}^{m} p_i^{\leq m} \log\left(\frac{p_i^{\leq m}}{q_i^{\leq m}}\right)$$

# Chi-Square and KL-Divergence




- Problem with comparing different machines.
  - In low bins, HE-LHC has smaller uncertainty bands, two hypotheses agree worse (as they should.)
  - Increases the chi-square and KL-divergence in low bands relative to 14 TeV.
- While the chi-square plateaus and stops decreasing at higher energy, the KL-divergence keeps decreasing.
  - The KL-divergence has more information and measures convergence better.

# Conclusions

- As the LHC and future collider measure the Standard Model to ever higher energies, we should be able to start probing not only the breaking of EW symmetry, but the convergence of the SM to a EW symmetric theory.
- Due to the longitudinal dominance, we focused on Vh production is a good candidate..
- We defined a new signal strength to test EW restoration.

$$\mu_{Vh} = \mu_{Wh} = \mu_{Zh}.$$

$$\mu_{Wh} = \frac{d\sigma(pp \to W^{\pm}h)/dp_T^h}{d\sigma(pp \to G^{\pm}h)/dp_T^h},$$

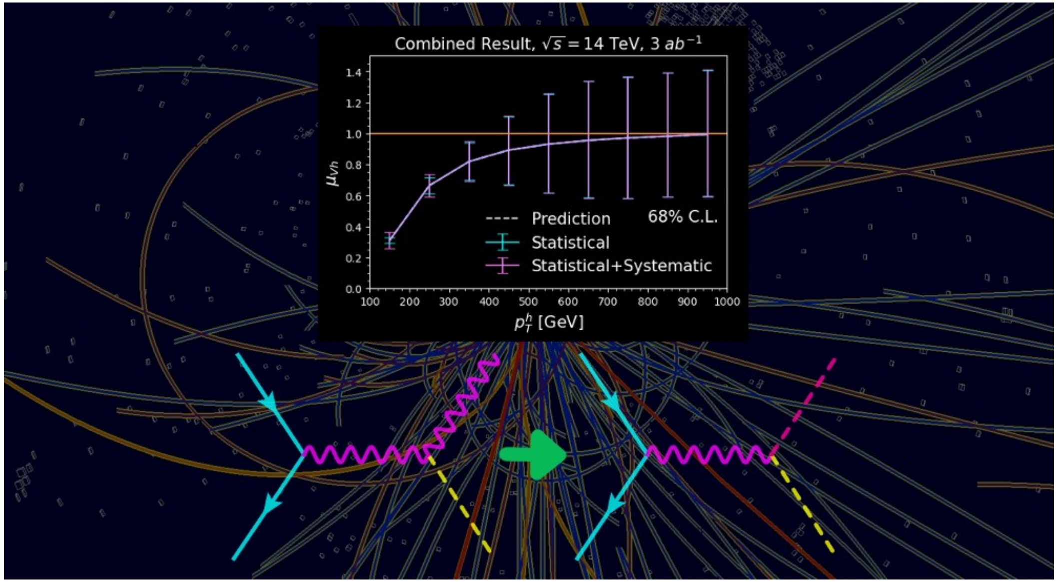
$$\mu_{Zh} = \frac{d\sigma(pp \to Zh)/dp_T^h}{d\sigma(pp \to G^0 h)/dp_T^h}.$$

- At high energies, this signal strength approaches one.
- We showed via a complete collider analysis, that both the 14 TeV HL-LHC and 27 TeV HE-LHC can observe this convergence.
  - The 14 TeV HL-LHC may be able to observe EW restoration at 40%.
  - The 27 TeV HE-LHC may be able to observe EW restoration at 6%.
- Finally, we investigated statistical tests of EW restoration.
  - A modified Kullback-Leibler divergence appears to be the most promising so far.

# Outlook

- Tagging polarizations important.
- We are working on WW and WZ
  - Signal strengths defined with respect to fully longitudinal production.
  - Need to separate polarizations at different energies in order to see convergence of Goldstone boson equivalence theorem.
- Need all di-boson channels to try to reconstruct pair production of Higgs doublets.
  - In EW restored theory the components of the Higgs doublet are not separated.

# Thank You



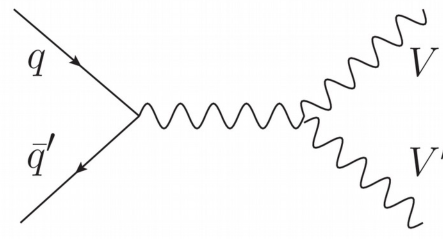
Combined Result, $\sqrt{s} = 14$ TeV, 3 $ab^{-1}$
$\mu_{Vh}$
$p_T^h$ [GeV]
Prediction
68% C.L.
Statistical
Statistical+Systematic

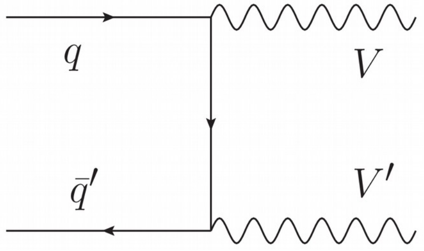
# Extra Slides

# WW/WZ Production

- Both fully longitudinal and fully transverse amplitudes survive to high energy.
- Longitudinal amplitudes survive:

$$
\begin{aligned}
\mathcal{A}(q_+\bar{q}_- \to W_L^+ W_L^-) &= -i\,\frac{e^2\,Q_q}{2\,c_W^2}\sin\theta + \mathcal{O}(\hat{s}^{-1})\,,\\
\mathcal{A}(q_-\bar{q}_+ \to W_L^+ W_L^-) &= i\,\frac{e^2\,T_3^q}{6\,c_W^2\,s_W^2}\left(3\,c_W^2 + 2\,T_3^q\,s_W^2\right)\sin\theta + \mathcal{O}(\hat{s}^{-1})\,,\\
\mathcal{A}(q_-\bar{q}'_+ \to W_L^\pm Z_L) &= -i\,\frac{e^2\,T_3^q}{\sqrt{2}s_W^2}\sin\theta + \mathcal{O}(\hat{s}^{-1})\,,\\
\mathcal{A}(q_\pm\bar{q}'_\mp \to Z_L Z_L) &= \mathcal{O}(\hat{s}^{-1})\,,
\end{aligned}
$$




- Transverse amplitudes survive:

$$
\begin{aligned}
\mathcal{A}(q_-\bar{q}_+ \to W_\pm^+ W_\mp^-) &= \mp i\frac{e^2}{2\,s_W^2}\frac{1+2\,T_3^q\,\cos\theta}{1\pm\cos\theta}\sin\theta + \mathcal{O}(\hat{s}^{-1})\,,\\
\mathcal{A}(q_-\bar{q}'_+ \to W_\pm^\pm Z_\mp) &= \mp i\frac{e^2}{\sqrt{2}\,s_W^2\,c_W}\left(g_L^{q'Z}(1+\cos\theta) + g_L^{qZ}(1-\cos\theta)\right)\frac{\sin\theta}{1\pm\cos\theta} + \mathcal{O}(\hat{s}^{-1})\,,\\
\mathcal{A}(q_-\bar{q}_+ \to Z_+ Z_-) &= 2\,i\,\frac{e^2}{s_W^2 c_W^2}g_L^{qZ\,2}\sqrt{\frac{1-\cos\theta}{1+\cos\theta}} + \mathcal{O}(\hat{s}^{-1})\,,\\
\mathcal{A}(q_+\bar{q}_- \to Z_+ Z_-) &= -2\,i\,\frac{e^2}{s_W^2 c_W^2}g_R^{qZ\,2}\sqrt{\frac{1+\cos\theta}{1-\cos\theta}} + \mathcal{O}(\hat{s}^{-1})\,,
\end{aligned}
$$

# WW EFT Interactions

$$\mathcal{O}_{3W} = \epsilon^{abc} W_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{c\mu},$$

$$\mathcal{O}_{HD} = |\,\Phi^\dagger (D_\mu \Phi)\,|^2,$$

$$\mathcal{O}_{HWB} = \Phi^\dagger \sigma^a \Phi W^a_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}^{(3)}_{HF} = i\left(\Phi^\dagger \overleftrightarrow{D}^a_\mu \Phi\right) \overline{f}_L \gamma^\mu \sigma^a f_L,$$

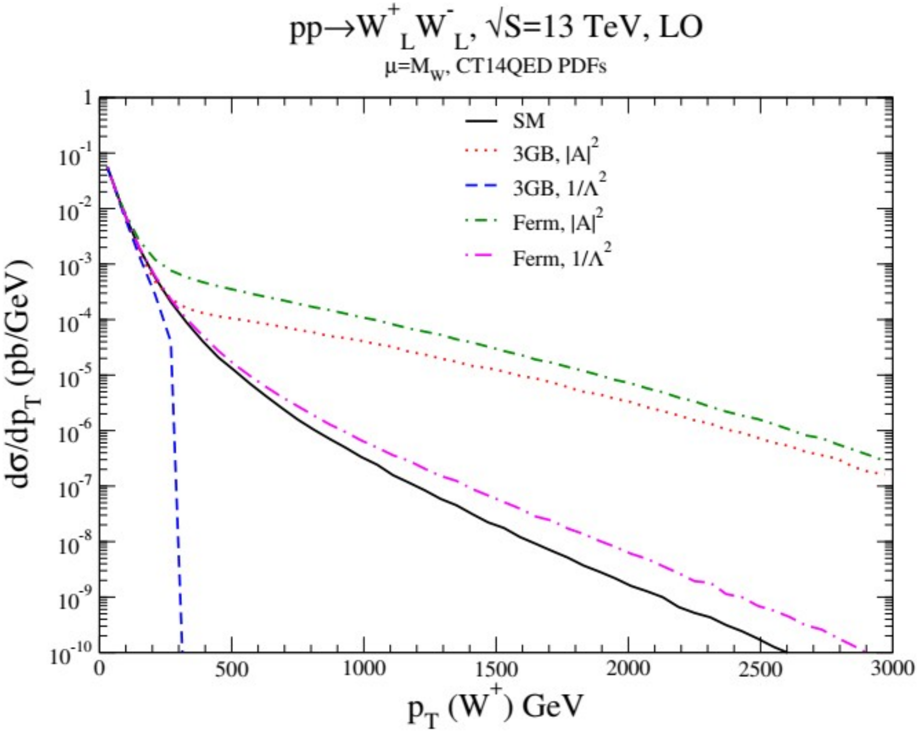
$$\mathcal{O}^{(1)}_{HF} = i\left(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right) \overline{f}_L \gamma^\mu f_L,$$

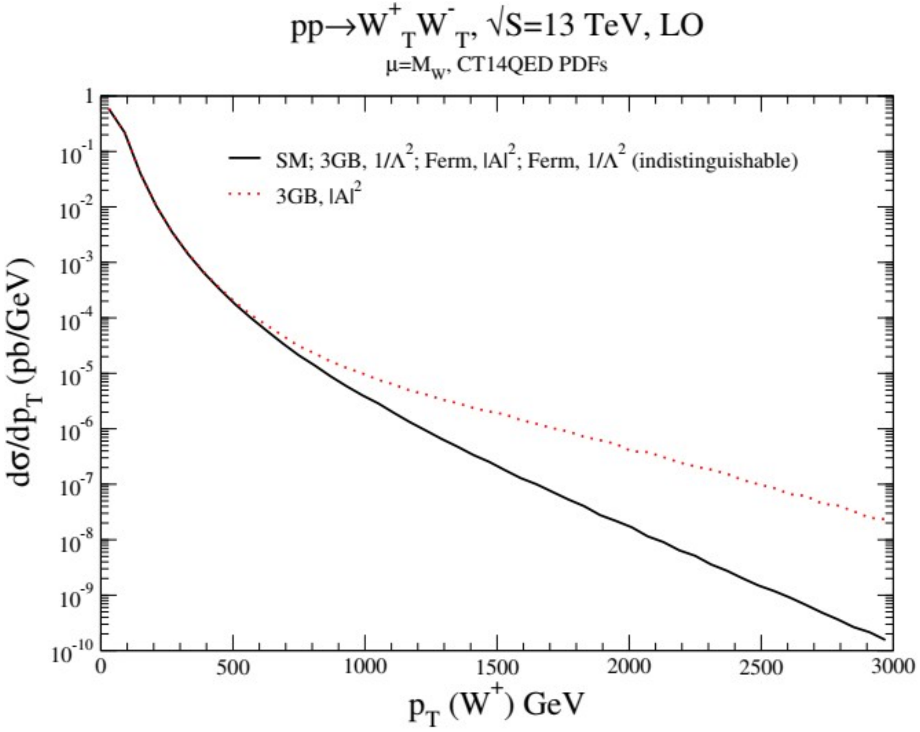
$$\mathcal{O}_{Hf} = i\left(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right) \overline{q}_R \gamma^\mu q_R,$$

$$\mathcal{O}_{Hud} = i\left(\widetilde{\Phi}^\dagger D_\mu \Phi\right) \overline{u}_R \gamma^\mu d_R,$$

$$\mathcal{O}_{ll} = (\bar{l}_L \gamma^\mu l_L)(\bar{l}_L \gamma_\mu l_L),$$

# WW/WZ Polarizations in EFT

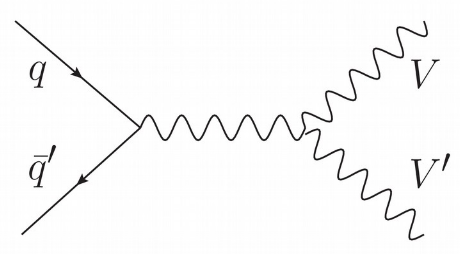


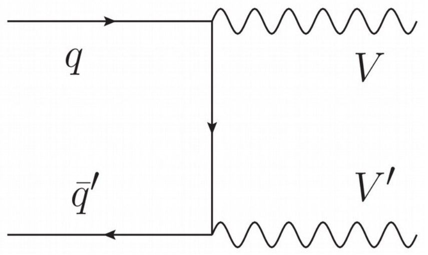




Baglio, Dawson, I.M. Lewis, PRD96 (2017) 073003

- The previous conclusions about longitudinal dominance are for the SM.
  - Picture changes in SM Effective Field Theory.
  - For our purposes, we will focus observing EW restoration in the SM.

# WW/WZ Production




- Problems:
  - Dominated by transverse polarizations even to very high energies. Baglio, Dawson, I.M. Lewis, PRD96 (2017) 073003; Baglio, Le Duc, JHEP04 (2019) 065; Denner Pellicciolli JHEP09 (2020) 164
  - There is no perturbative unitarity violation in these processes in the SM, even without a Higgs.
  - The transverse polarizations exist in the symmetric phase of the SM, so do not decouple.
  - Indeed the problem is that there is a t-channel contribution from opposite helicity case that does not decouple.
- A solution would be to tag polarizations to get a signal rich in longitudinal polarizations.
  - Much work on defining polarizations after decays, calculating higher order corrections, and tagging polarizations Liu, Wang PRD99 (2019) 055001; Panico, Riva, Wulzer PLB776 (2018) 473; Kim, Martin arXiv:2102.05124;; Baglio, Le Duc, JHEP04 (2019) 065; Denner Pellicciolli JHEP09 (2020) 164;  etc.

# Wh/Zh Production

- Simpler solution: find di-boson process naturally longitudinally dominated:
  - There is no h-V-V coupling in unbroken phase.
  - Transverse modes do not survive.

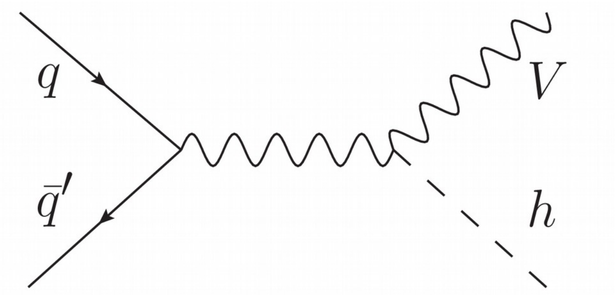
$$\mathcal{A}(q_+\bar{q}_- \to Z_L h) \;=\; \pm i\,\frac{e^2\, g_R^{qZ}}{2\,c_W^2\, s_W^2}\sin\theta + \mathcal{O}(\hat{s}^{-1}),$$

$$\mathcal{A}(q_-\bar{q}_+ \to Z_L h) \;=\; \pm i\,\frac{e^2\, g_L^{qZ}}{2\,c_W^2\, s_W^2}\sin\theta + \mathcal{O}(\hat{s}^{-1}),$$

$$\mathcal{A}(q_-\bar{q}'_+ \to W_L^\pm h) \;=\; -i\,\frac{e^2}{2\sqrt{2}\, s_W^2}\sin\theta + \mathcal{O}(\hat{s}^{-1}),$$

$$\mathcal{A}(q_\pm\bar{q}_\mp \to Z_\pm h) \;\sim\; \mathcal{A}(q_-\bar{q}'_+ \to W_L^\pm h) \sim \mathcal{O}(\hat{s}^{-1/2}),$$

$$\mathcal{A}(q_+\bar{q}'_- \to W_\pm^\pm h) \;=\; \mathcal{A}(q_+\bar{q}'_- \to W_\mp^\pm h) = 0.$$



# Goldstone production

- Comparison of amplitudes in high energy limit:

$$
\begin{aligned}
\mathcal{A}(q_+\bar{q}_- \to G^0 h) &= -\frac{e^2\, g_R^{qZ}}{2\, c_W^2\, s_W^2}\sin\theta,\\
\mathcal{A}(q_-\bar{q}_+ \to G^0 h) &= \frac{e^2\, g_L^{qZ}}{2\, c_W^2\, s_W^2}\sin\theta,\\
\mathcal{A}(q_-\bar{q}_+ \to G^\pm h) &= \mp i\frac{e^2}{2\sqrt{2}s_W^2}\sin\theta,\\
\mathcal{A}(q_-\bar{q}_+ \to G^\pm G^0) &= \frac{e^2}{2\,\sqrt{2}\, s_W^2}\sin\theta,\\
\mathcal{A}(q_+\bar{q}_- \to G^+ G^-) &= -i\,\frac{e^2 Q_q}{2\, c_W^2}\sin\theta,\\
\mathcal{A}(q_-\bar{q}_+ \to G^+ G^-) &= -i\,\frac{e^2\, T_3^q}{6\, c_W^2 s_W^2}\left(3\, c_W^2 + 2\, T_3^q s_W^2\right)\sin\theta.
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{A}(q_+\bar{q}_- \to Z_L h) &= \pm\, i\,\frac{e^2\, g_R^{qZ}}{2\, c_W^2\, s_W^2}\sin\theta + \mathcal{O}(\hat{s}^{-1}),\\
\mathcal{A}(q_-\bar{q}_+ \to Z_L h) &= \pm\, i\,\frac{e^2\, g_L^{qZ}}{2\, c_W^2\, s_W^2}\sin\theta + \mathcal{O}(\hat{s}^{-1}),\\
\mathcal{A}(q_-\bar{q}'_+ \to W_L^\pm h) &= -i\,\frac{e^2}{2\,\sqrt{2}\, s_W^2}\sin\theta + \mathcal{O}(\hat{s}^{-1}),\\
\mathcal{A}(q_-\bar{q}'_+ \to W_L^\pm Z_L) &= -i\,\frac{e^2\, T_3^q}{\sqrt{2} s_W^2}\sin\theta + \mathcal{O}(\hat{s}^{-1})\\
\mathcal{A}(q_+\bar{q}_- \to W_L^+ W_L^-) &= -i\,\frac{e^2\, Q_q}{2\, c_W^2}\sin\theta + \mathcal{O}(\hat{s}^{-1})\,,\\
\mathcal{A}(q_-\bar{q}_+ \to W_L^+ W_L^-) &= i\,\frac{e^2\, T_3^q}{6\, c_W^2\, s_W^2}\left(3\, c_W^2 + 2\, T_3^q\, s_W^2\right)\sin\theta + \mathcal{O}(\hat{s}^{-1})
\end{aligned}
$$

# Likelihood Analysis

- We unfold events using a likelihood analysis.
  - Mainly interested in one variable: the Higgs transverse momentum.
  - Use a simple unfolding of one variable.
  - There are multi-variate, and full phase space unfolding techniques that could be used. Blobel Unfolding; Gagunashvili, arXiv:1004.2006; Glazov, arXiv:1712.01814; Datta, Kar, Roy, arXiv:1806.00433; Andreassen, Komiske, Metodiev, Nachman, Thaler, arXiv:1911.09107
- Likelihood function binned in Higgs transverse momentum based on CMS JHEP 01 (2019 ) 183

$$\mathcal{L}_i(\Delta\sigma_1^{Vh}, \Delta\sigma_2^{Vh}, \ldots) = \frac{\left(\sum_j \Delta\sigma_j^{Vh}\epsilon_{ij}L + B_i\right)^{n_{obs,i}}}{n_{obs,i}!} e^{-\sum_j \Delta\sigma_j^{Vh}\epsilon_{ij}L - B_i} = \frac{\left(\sum_j \mu_{Vh}^j \Delta\sigma_j^{Gh}\epsilon_{ij}L + B_i\right)^{n_{obs,i}}}{n_{obs,i}!} e^{-\sum_j \mu_{Vh}^j \Delta\sigma_j^{Gh}\epsilon_{ij}L - B_i}$$

  - $\Delta\sigma_i^{Vh}$ and $\Delta\sigma_j^{Gh}$ are the $q\bar{q}' \to Vh$ and $q\bar{q}' \to Gh$ cross sections in the *j*th bin of
  - $\mu_{Vh}^j$ is the signal strengths in the *j*th bin of
  - $n_{obs,i}$ is the number of observed events
  - $B_i$ are the number of predicted background events.
  - $L$ is the luminosity

# Likelihood analysis

$$\mathcal{L}_i(\mu^1_{Vh}, \mu^2_{Vh}, \ldots) = \frac{\left(\sum_j \mu^j_{Vh} \Delta\sigma^{Gh}_j \epsilon_{ij} L + B_i\right)^{n_{obs,i}}}{n_{obs,i}!} e^{-\sum_j \mu^j_{Vh} \Delta\sigma^{Gh}_j \epsilon_{ij} L - B_i},$$

- Efficiency matrix $\epsilon_{ij}$ :
  - Basically the probability that a parton level event in the *j*th bin appears in the ith bin at detector level.
  - Generate parton level event with MadGraph5_aMC@NLO, shower and hadronize with Pythia8, and simulate detector events with DELPHES3.
  - Find the efficiency matrix by tracing from parton level through detector effects.
  - Also takes care of the branching ratios of the vector bosons.
  - Allows us to unfold to the base 2-to-2 event
- Assume bins are independent, then combine all bins into a total likelihood:

$$\mathcal{L}(\mu^1_{Vh}, \mu^2_{Vh}, \ldots) = \prod_i \mathcal{L}_i(\mu^1_{Vh}, \mu^2_{Vh}, \ldots) \mathrm{Pois}(n_{obs,i} | S_i + B_i),$$

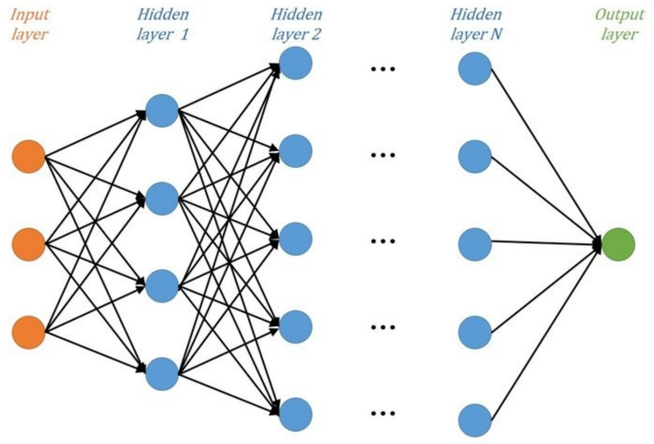
  - $S_i$ is the expected number of signal events.

# Collider Analysis

- Pre-selection cuts at both 14 TeV HL-LHC and 27 TeV HE-LHC.
  - Lepton transverse momentum: $p_T^\ell \geq 27$ GeV
  - Lepton and jet rapidity: $|\eta_\ell| \leq 2.5, \quad |\eta_j| \leq 5.0$
  - Minimum separation: $\Delta R_{jj} \geq 0.4, \quad \Delta R_{j\ell} \geq 0.4, \quad \Delta R_{\ell\ell} \geq 0.4$
  - Require the electrons and muons are isolated.
  - We require exactly two b-tagged jets for all signal categories.
  - For two lepton category, we require the Z-mass is reconstructed within 10 GeV: $|m_{\ell\ell} - m_Z| \leq 10$ GeV
- Jet transverse momentum cuts:
  - At 14 TeV: $p_T^j \geq 20$ GeV
  - At 100 TeV: $p_T^j \geq 30$ GeV

# Deep Neural Network

- After pre-selections, we use a deep neural network to classify signal and background.
  - Has three hidden layers with $2^{10}$, $2^{12}$, and $2^{10}$ nodes.
  - We adopted **LeakyReLU** for non-linearity and used batch normalization between layers.
  - The output layer used softmax to create a probability.

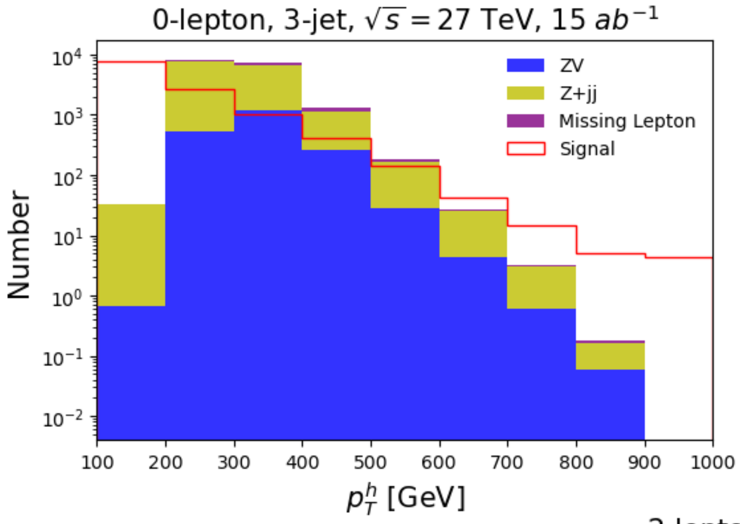


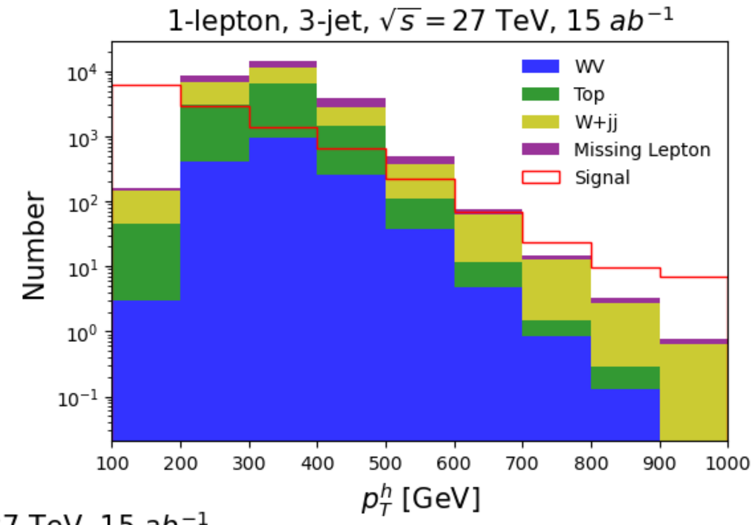

- Finally, we used a cross entropy loss function with an *L2* penalty, for a binary classification:

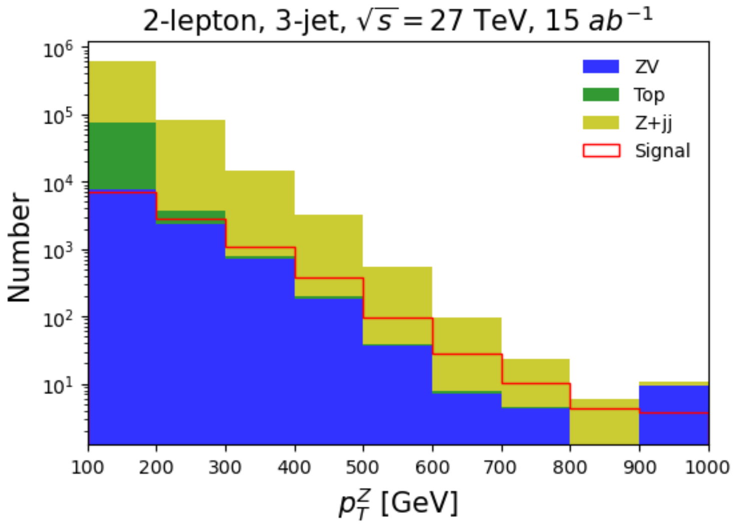
$$L = -y_s \log p - (1 - y_s) \log(1 - p) + \lambda \parallel W \parallel^2$$

  - $y_s = 1$ for signal, $y_s = 0$ for background.
  - *p* is the predicted signal probability.
  - $\parallel W \parallel^2$ is the matrix norm of the weight matrices.

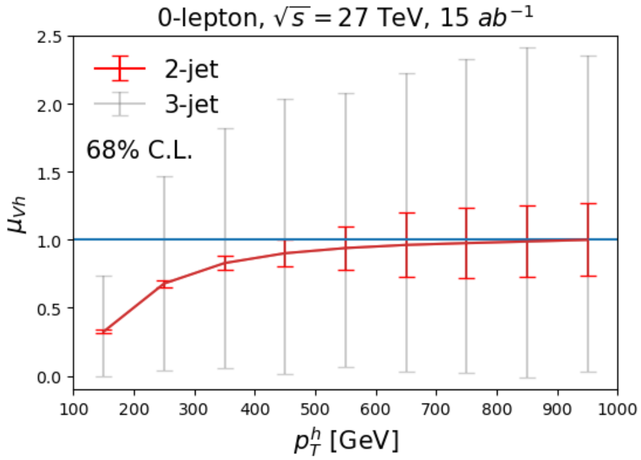
# Three jet signal and background

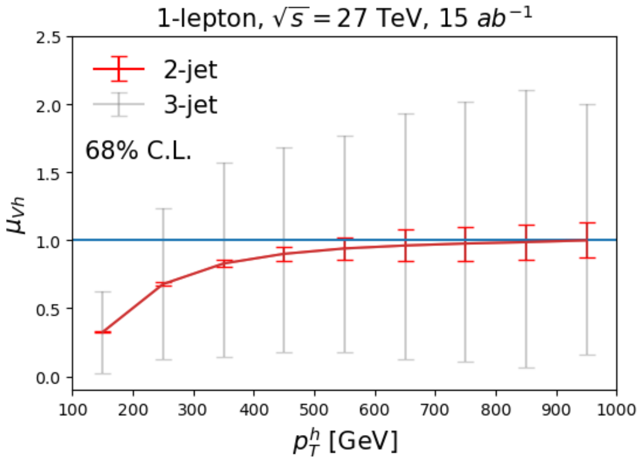


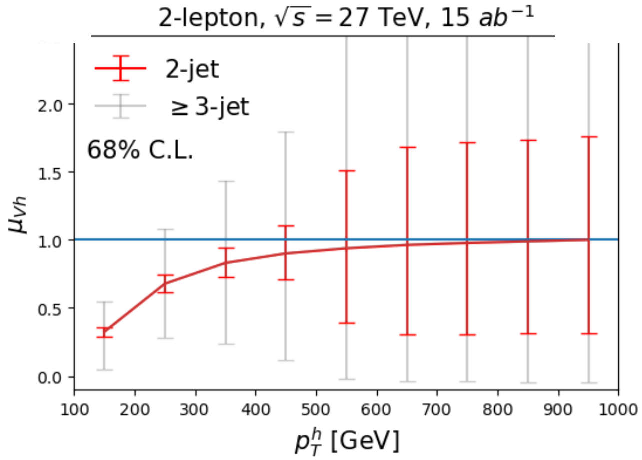



# 27 TeV



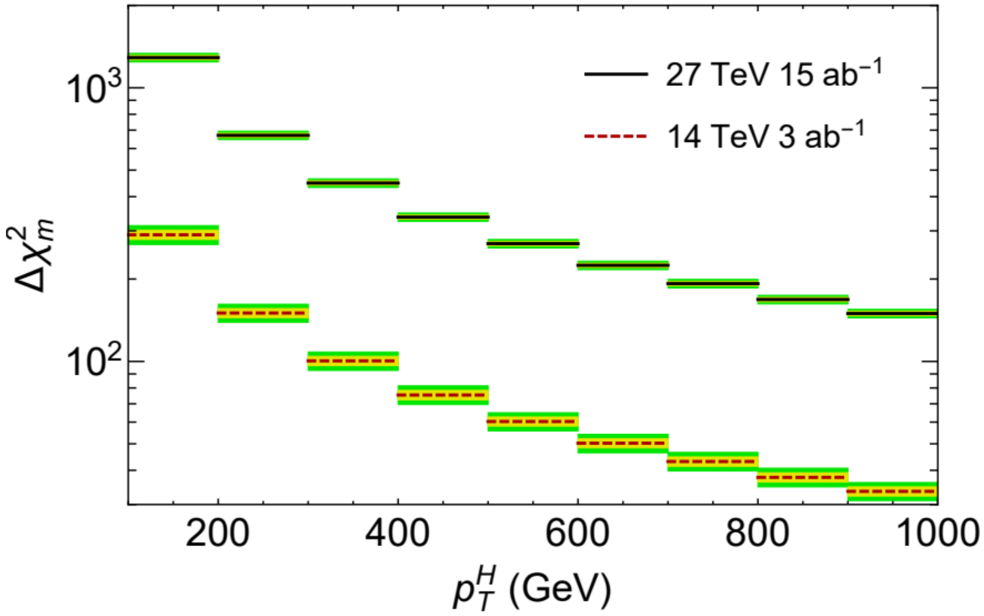

Grey: 3-jet, Red: 2-jet

# Quantifying Convergence

- Trying to see convergence, not just that the signal strengths is one at high transverse momentum.
- Tried several methods to quantify how well $q\bar{q}' \to Vh$ is converging to $q\bar{q}' \to Gh$ .
- First tried a chi-square testing the $\mu^j_{Vh} = 1$hypothesis against SM prediction.

$$\Delta\chi^2_m = \frac{1}{m}\sum_{l=1}^{m} \log\left(\frac{\text{Pois}(n_{obs,l}|\sum_j \Delta\sigma_j^{Gh}\epsilon_{lj}L + B_l)}{\text{Pois}(n_{obs,l}|S_l + B_l)}\right)$$

  - Sum over the transverse momentum bins ordered from low to high transverse momentum.
  - $n_{obs,l}$ is the number of observed events in bin $l$ .
  - $\Delta\sigma_j^{Gh}$ is the prediction for the Goldstone boson cross section in bin j.
  - $B_l$ and $S_l$ are the predicted number of signal and background SM events.
  - $\epsilon_{lj}$ is the efficiency matrix
  - *L* is luminosity.
- At low momentum, significant difference between hypotheses, so chi-square should be big
- As high momentum bins are added, hypotheses agree more, chi-square should decrease.




- Cannot directly compare 14 TeV HL-LHC and 27 TeV HE-LHC
  - In low bins, HE-LHC has smaller uncertainty bands.
  - Increase the chi-square in low bands relative to 14 TeV.
- Other problem:
  - In high bins, uncertainty gets larger.
  - Even if central values do not converge, their agreement will get better.
  - Chi-square will decrease whether or not central values converge.

# DNN Observables

- 2-lepton, 2-jet:
  - $M_{Zh}$, $M_h^{recon}$, $M_Z^{recon}$.
  - MET, $p_T^h$, $p_T^Z$, $p_T^{b_0}$, $p_T^{b_1}$, $p_T^{\ell_0}$, $p_T^{\ell_1}$, $H_T$.
  - $\Delta\phi_{Zh}$, $\Delta\eta_{Zh}$, $\Delta R_{Zh}$.
  - $\Delta R_{b_0 b_1}$, $\Delta R_{\ell_0 \ell_1}$, $\Delta R_{b_0 \ell_0}$, $\Delta R_{b_1 \ell_1}$.
  - Transverse mass of reconstructed Higgs and Z, $M_{T,Zh}$.
- 2-lepton, 3-jet: Same as 2-lep+2-jet with:
  - $p_T^j$, $\Delta R_{hj}$, $\Delta R_{Zj}$.
  - $n_j$.
- 1-lepton, 2-jet:
  - $M_{WH}$, $M_h^{recon}$, $M_W^{recon}$.
  - MET, $p_T^h$, $p_T^W$, $p_T^{b_0}$, $p_T^{b_1}$, $H_T$.
  - $\Delta\phi_{Wh}$, $\Delta R_{b0b1}$, $\min\{\Delta\phi_{\ell 0b0}, \Delta\phi_{\ell 0b1}\}$.
  - Transverse mass of reconstructed Higgs and W, $M_{T,Wh}$.
  - Transverse mass of $W$: $M_{T,W}$.
  - Transverse mass of $W + b_0$: $M_{T,Wb_0}$.
  - Transverse mass of $W + b_1$: $M_{T,Wb_1}$.
  - $|\Delta Y_{hW}| = |\eta_h - \eta_W|$, where $\eta_{h,W}$ are the Higgs and $W$ rapidities.
- 1-lepton, 3-jet: Same as 1-lepton, 2-jet with:
  - $p_T^j$, $M_{hj}$

# DNN Observables

- 0-lepton, 2-jet:
  - $M_h^{recon}$.
  - MET, $p_T^h$, $p_T^{b_0}$, $p_T^{b_1}$, $H_T$.
  - $\Delta\phi_{Zh}$, $\Delta\eta_{b_0 b_1}$, $\Delta R_{b_0 b_1}$.
  - Transverse momentum of reconstructed Higgs and Z, $M_{T,Zh}$.
- 0-lepton, 3-jet: Same as 0-lepton, 2-jet with:
  - $M_{hj}$, $p_T^j$.