Electroweak Restoration at the LHC and Beyond: The $V h$ Channel

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Outline

- Introduction/Theory
- Parton Level
- Results
  - Simulation (Detector Level)
  - Signal Strength
- Statistics
  - Chi Square vs KL Divergence

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- **Introduction/Theory**
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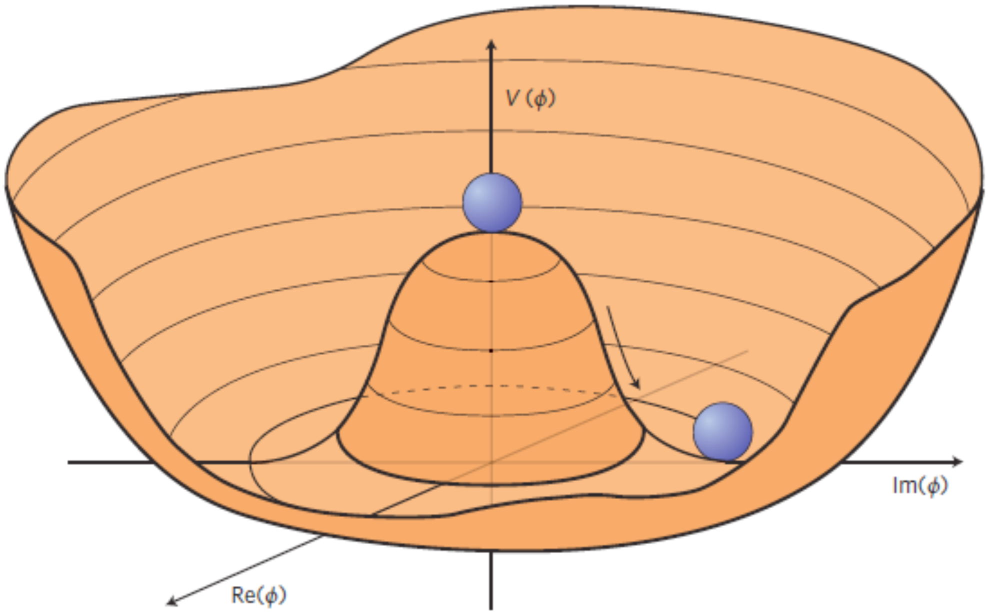
Introduction

- The Standard Model (SM) is successful
  - But what about dark matter, matter asymmetry, ...
- Strategies to learn more
  - Direct search
  - Look for deviations from the SM
- Electroweak (EW) symmetry breaking is a critical component of SM.

Theory (EW Symmetry Breaking)

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

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



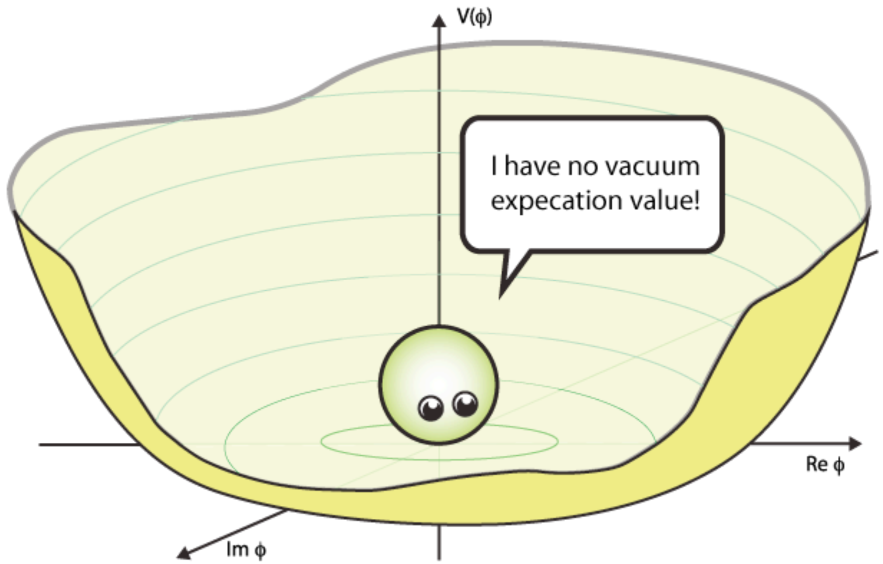
$$\mathcal{L}_{\text{kin}} = \left|D_\mu H\right|^2$$ → W and Z mass terms

Theory (EW Restored)

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

Fix EW couplings

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(\cancelto{0}{v} + h + i\,G^0\right) \end{pmatrix}$$



$$\mathcal{L}_{\text{kin}} = \left|D_\mu H\right|^2$$

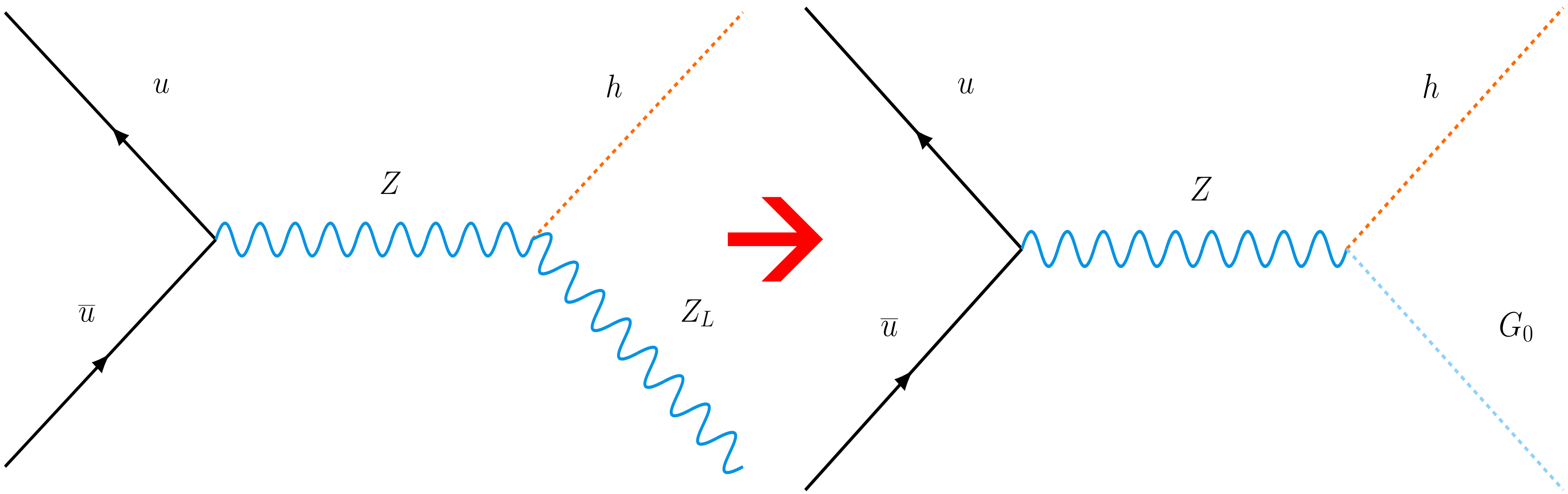
→

W and Z are massless

W_i and H

Goldstone Boson Equivalence

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



$$\mathcal{A}(q_-\bar{q}_+ \to G^0 h) \; = \; \frac{e^2\, g_L^{qZ}}{2\, c_W^2\, s_W^2} \sin\theta$$

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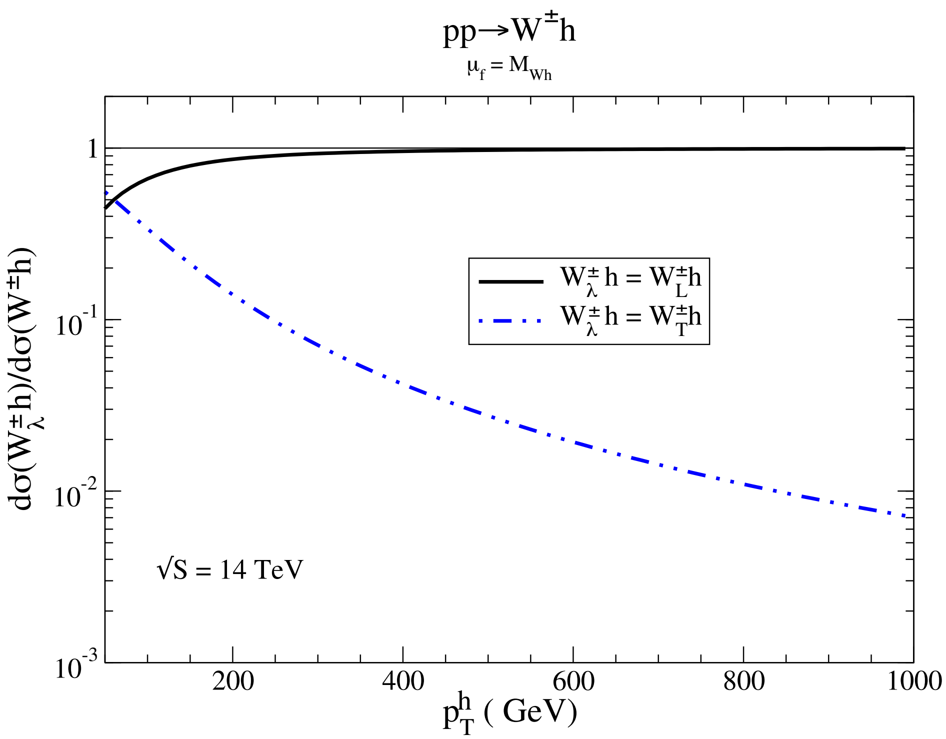
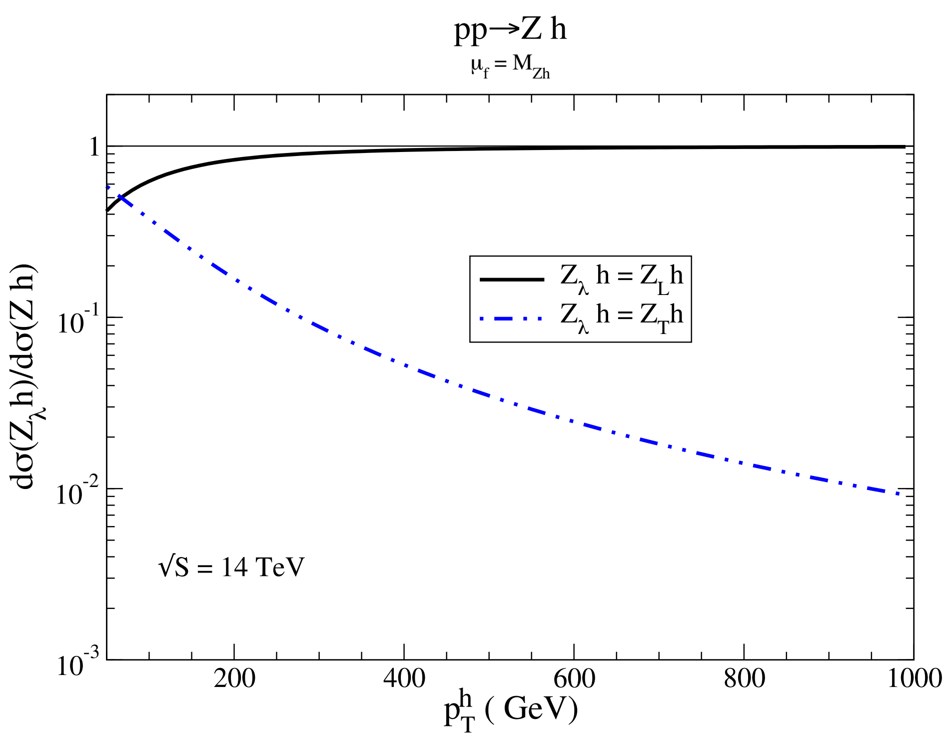
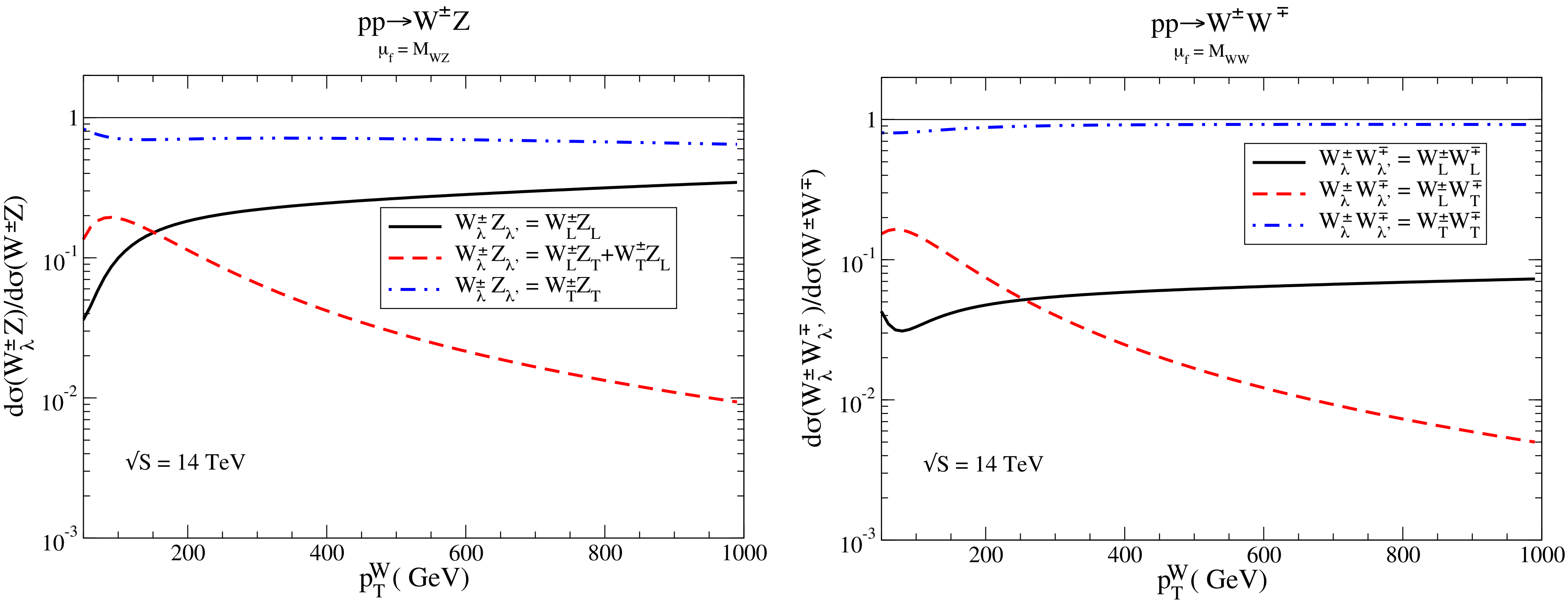
Vh Helicity Dependence





Longitudinally Dominated

WV Helicity Dependence



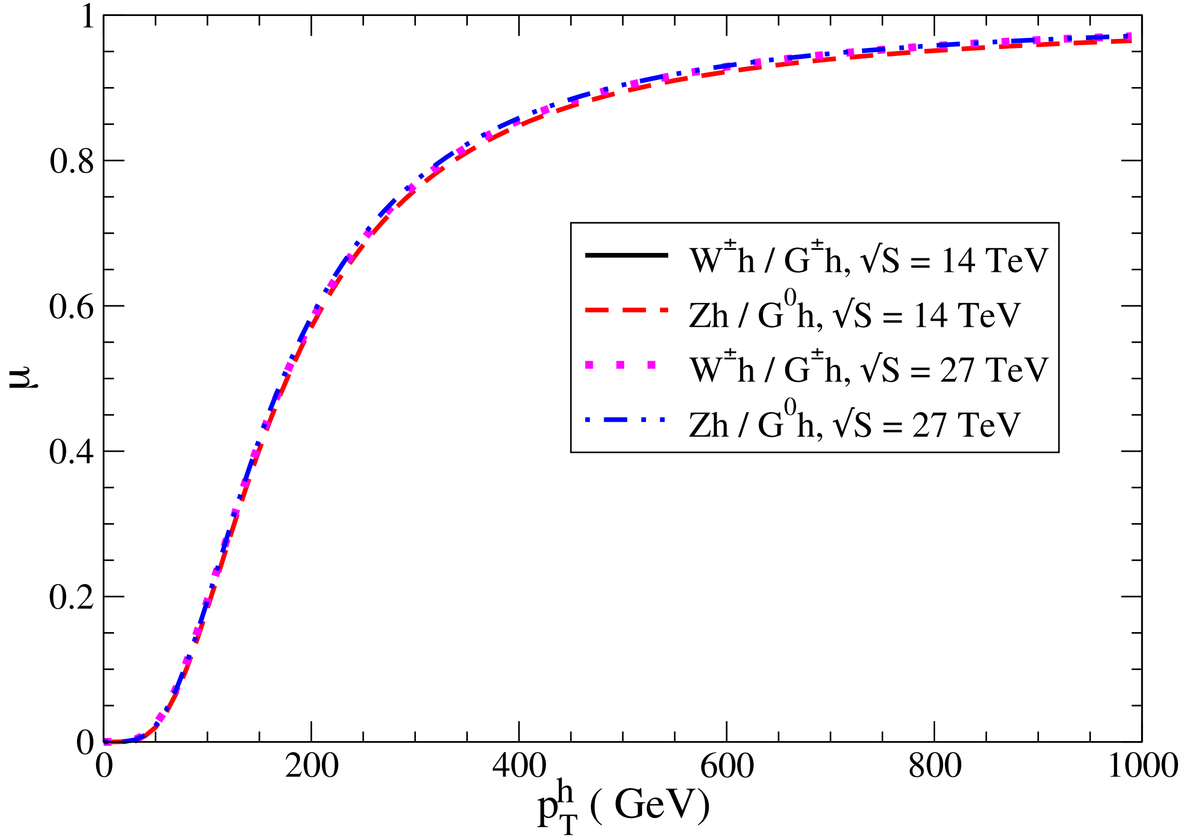
Transverse Dominated

Parton Level Signal Strength

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

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

$$= \frac{\text{SM VH cross section}}{\text{EW restored GH cross section}}$$



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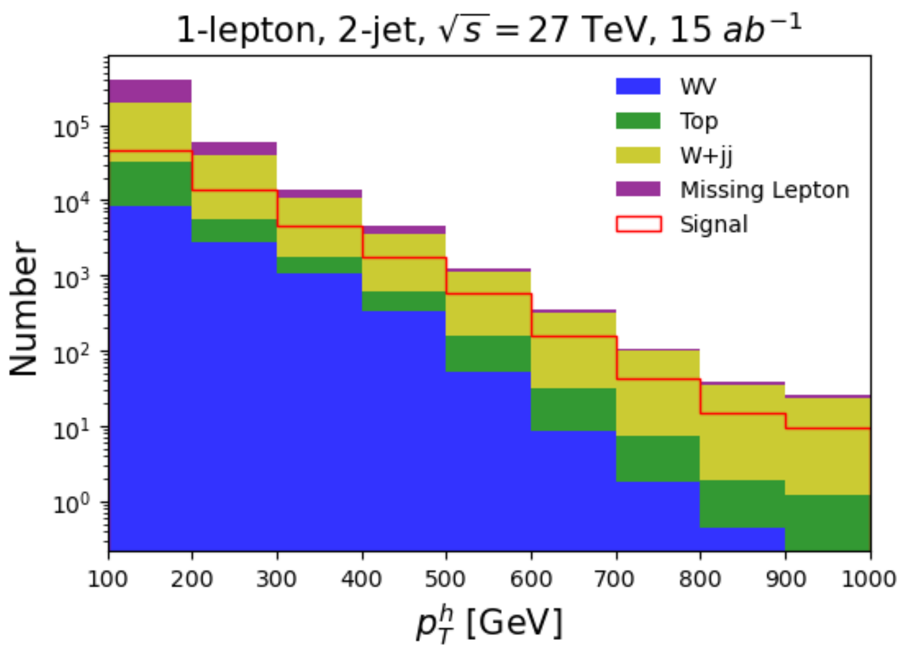
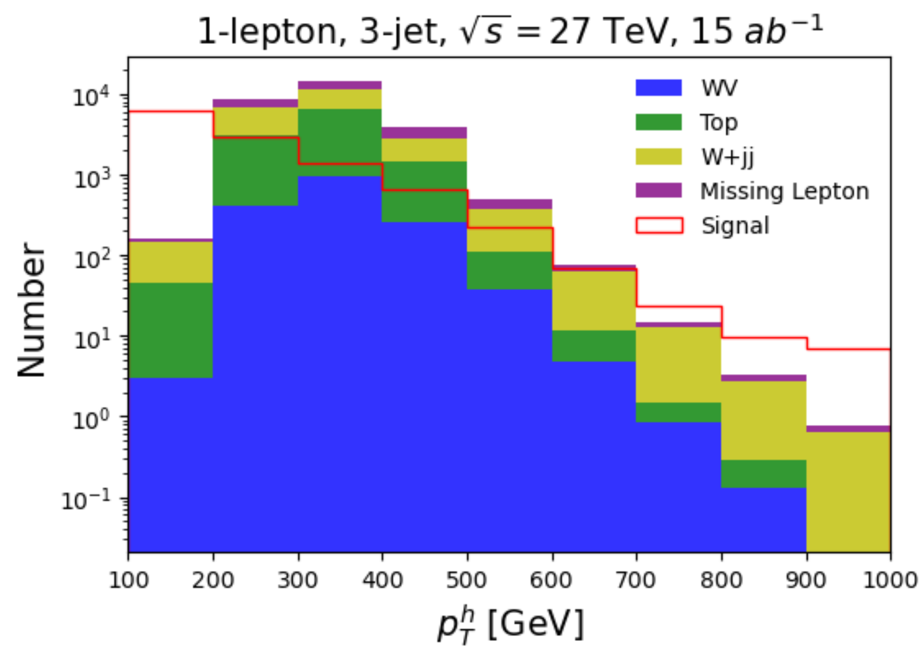
Channel Breakdown

- The analysis considers three decay channels
  - $Zh \to \ell^+\ell^- b\bar{b}$
  - $Wh \to \ell\nu b\bar{b}$
  - $Zh \to \nu\nu b\bar{b}$
- Treat the simulated data as an experiment
- Compare with EW Restored expectation

Event after DNN: 1 lepton

Use MG5/Pythia/Delphes Chain to generate SM data





Use DNN to separate signal and backgrounds

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

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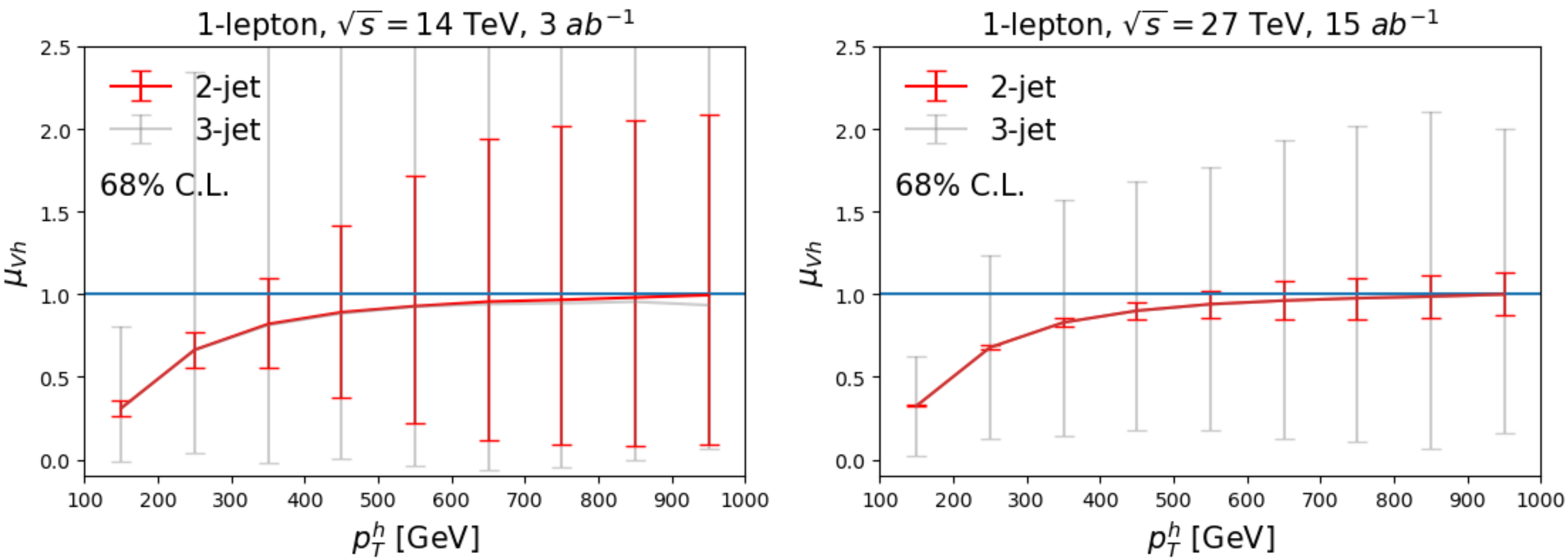
Signal Strength: 1 Lepton

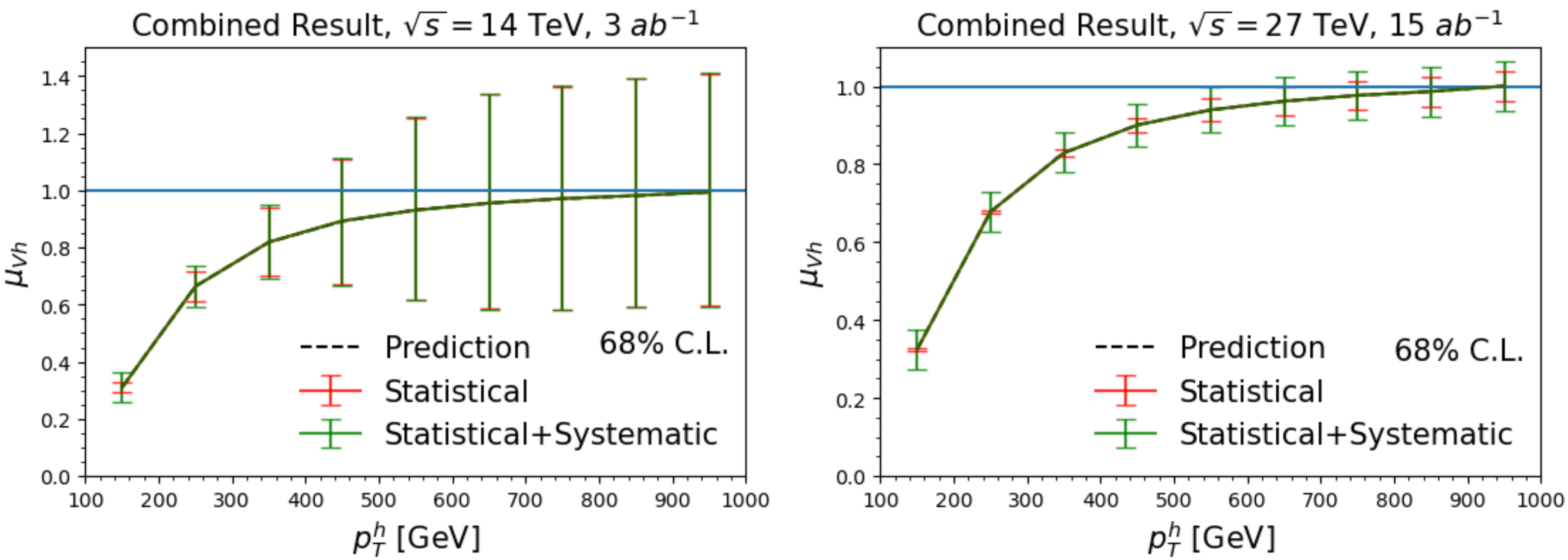


$$\mu_{Wh} = \frac{d\sigma(pp \to W^\pm h)/dp_T^h}{d\sigma(pp \to G^\pm h)/dp_T^h},$$

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

$$\frac{\text{SM VH cross section}}{\text{EW restored GH cross section}}$$

Signal Strength: Combined



$$\mu_{Vh} = \begin{cases} 1 \pm 0.4 & \text{at the HL} - \text{LHC} \\ 1 \pm 0.06 & \text{at the HE} - \text{LHC} \end{cases}$$

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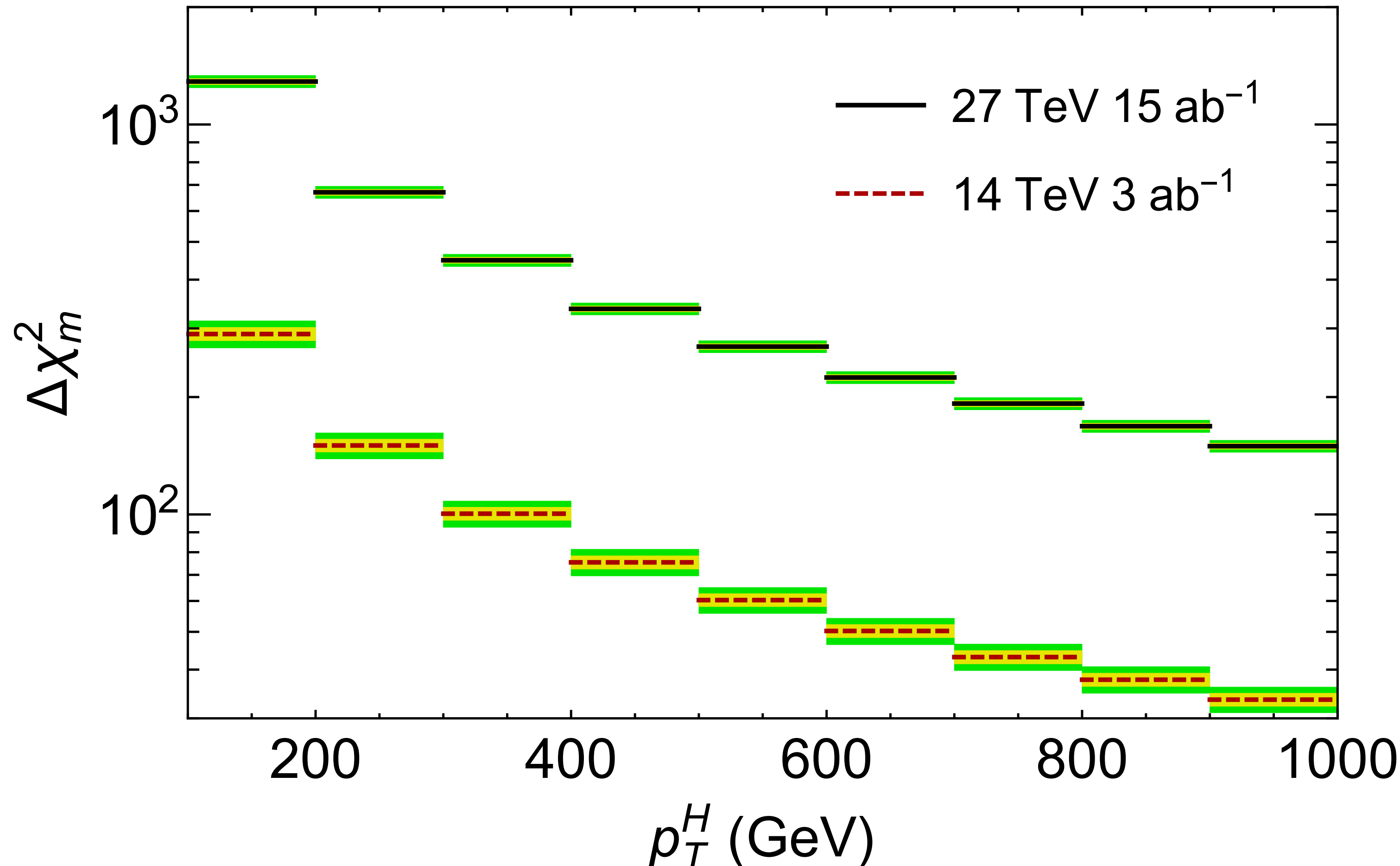
Delta Chi Square

Chi Square

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



KL Divergence

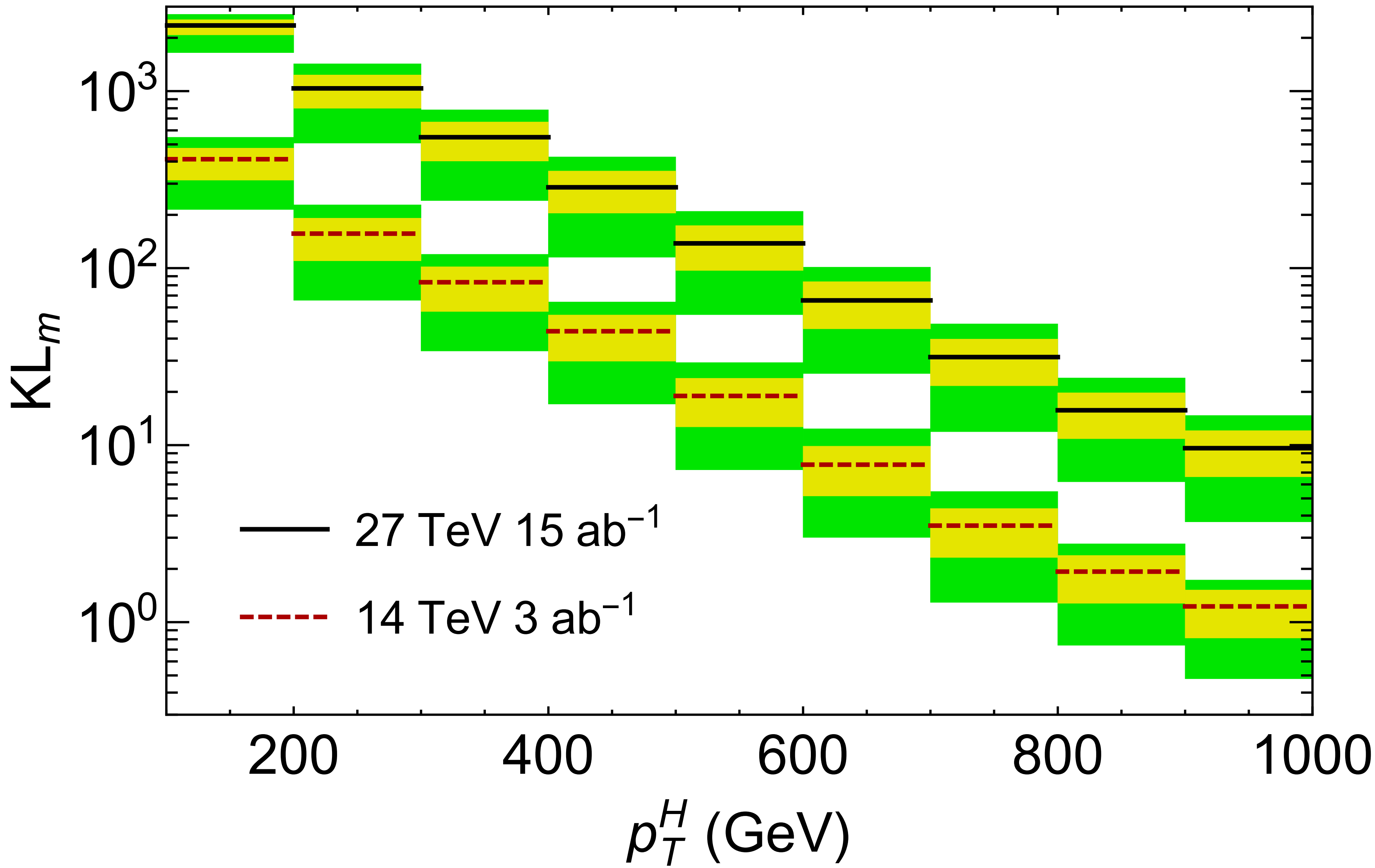
$$p_i^{\leq m} = \prod_{\substack{\text{6 signal} \\ \text{categories}}} \frac{\text{Pois}(n_{obs,i}|S_i + B_i)}{\sum_{l=1}^{m} \text{Pois}(n_{obs,l}|S_l + B_l)}$$

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

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

- Small KL implies agreement with hypothesis
- Expect KL to decrease as we include more P_T bins

KL Diveregence



Conclusions

- We have shown the capabilities of HL-LHC and HE-LHC in observing the GBET and Electroweak restoration.
- We find for $p_t^h > 400\ GeV$ the $G\ h$ and the $V\ h$ distributions agree at about 80%.
- The KL divergence shows that the two hypotheses agree at high energy.
- HL can confirm electroweak restoration to 40%.
- HE can confirm it to 6%.

Thank You!