Electroweak Restoration at the LHC and Beyond: The Vh Channel

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Phys. Rev D 103 (2021) 5, 053007
arXiv: 2012.00774

Outline

- Introduction/Theory
- Parton Level
- Simulation (Detector Level)
- Results
- Statistics (if have time)

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- **Introduction/Theory**
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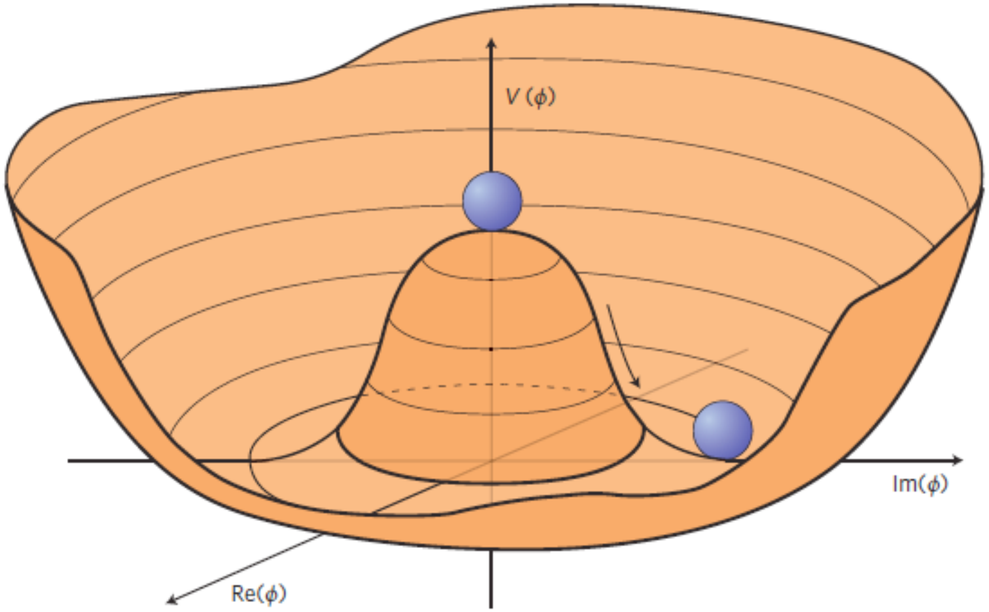
Introduction/ Theory

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

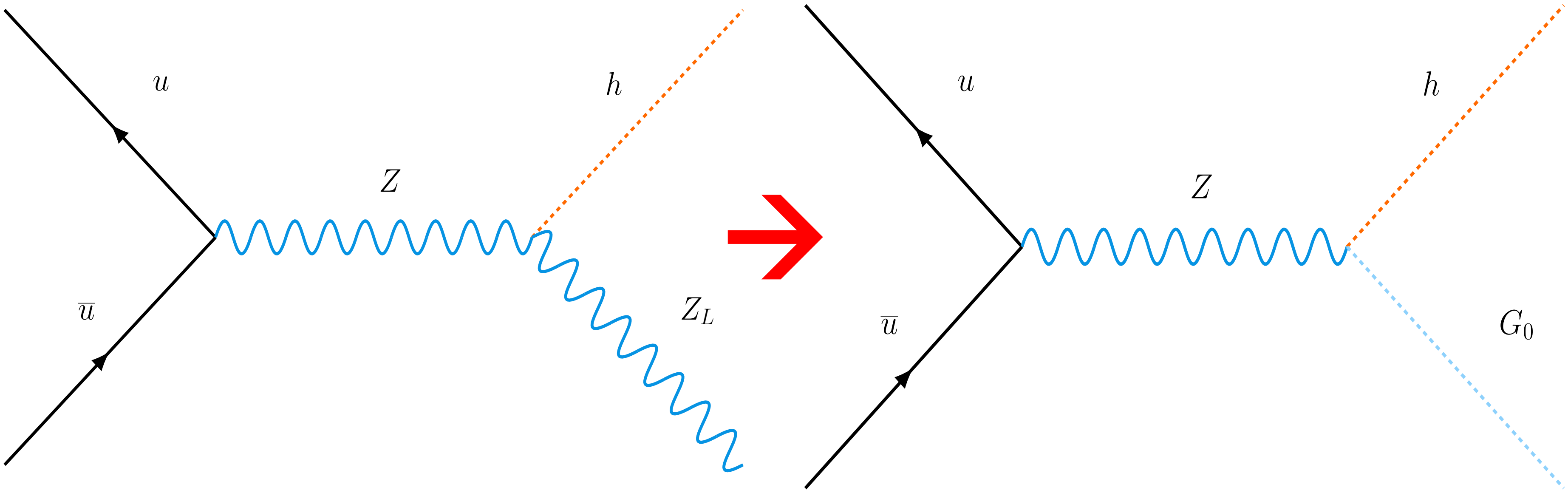
$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + i\,G^0\right) \end{pmatrix}$$



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

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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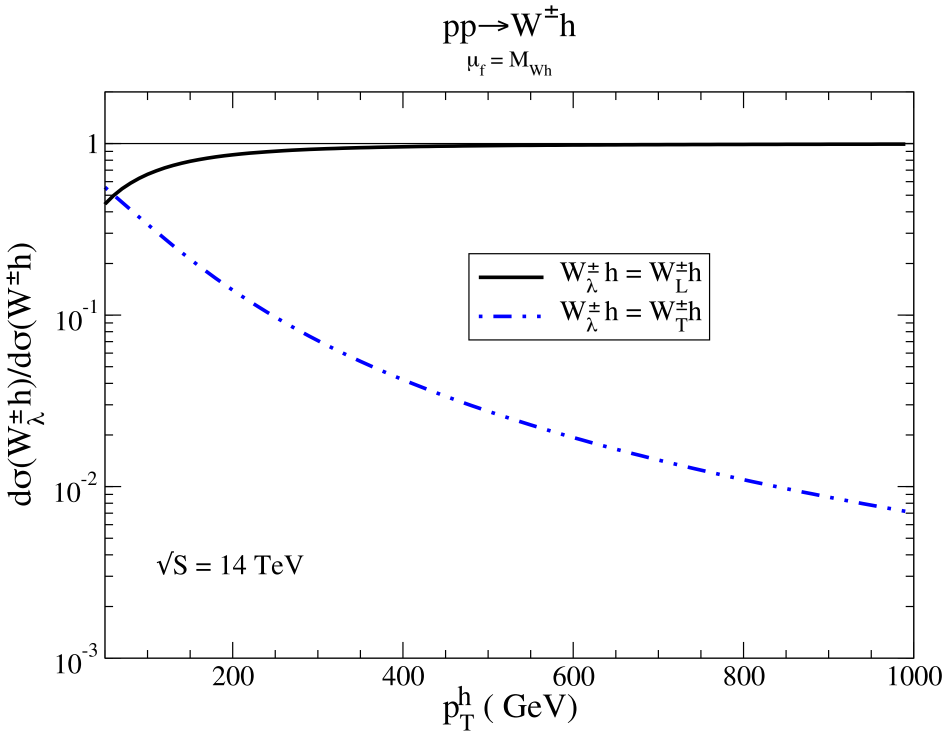
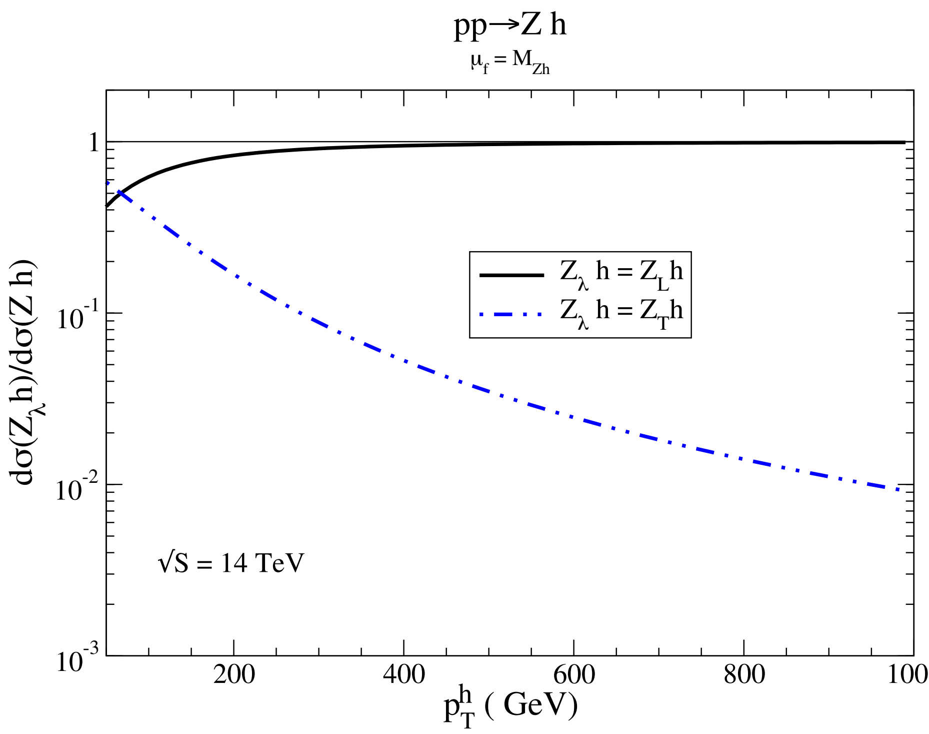
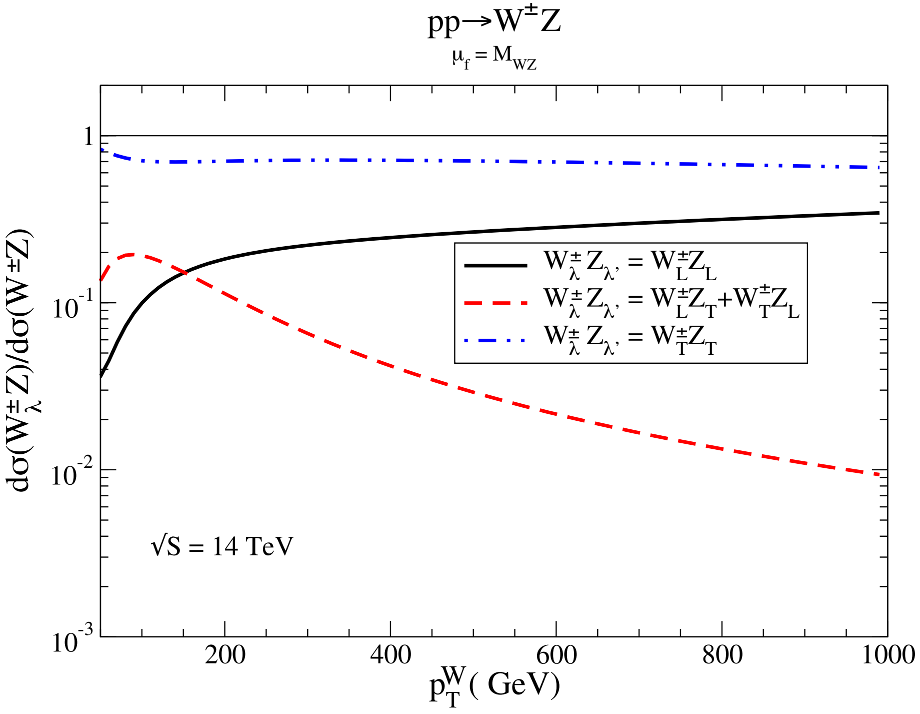
Vh Helicity Dependence

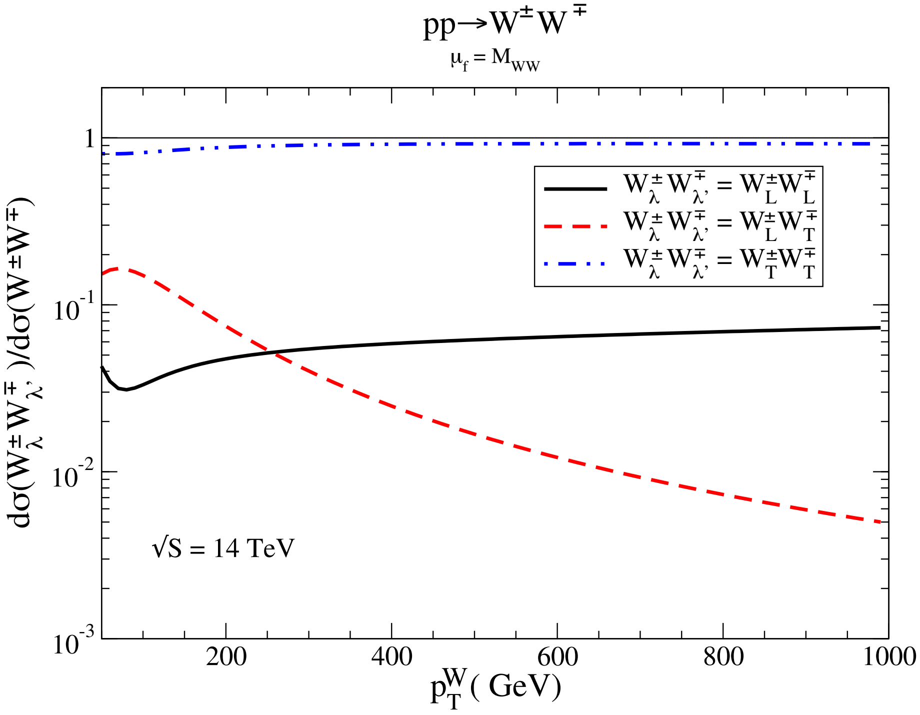




Longitudinally Dominated

WV Helicity Dependence





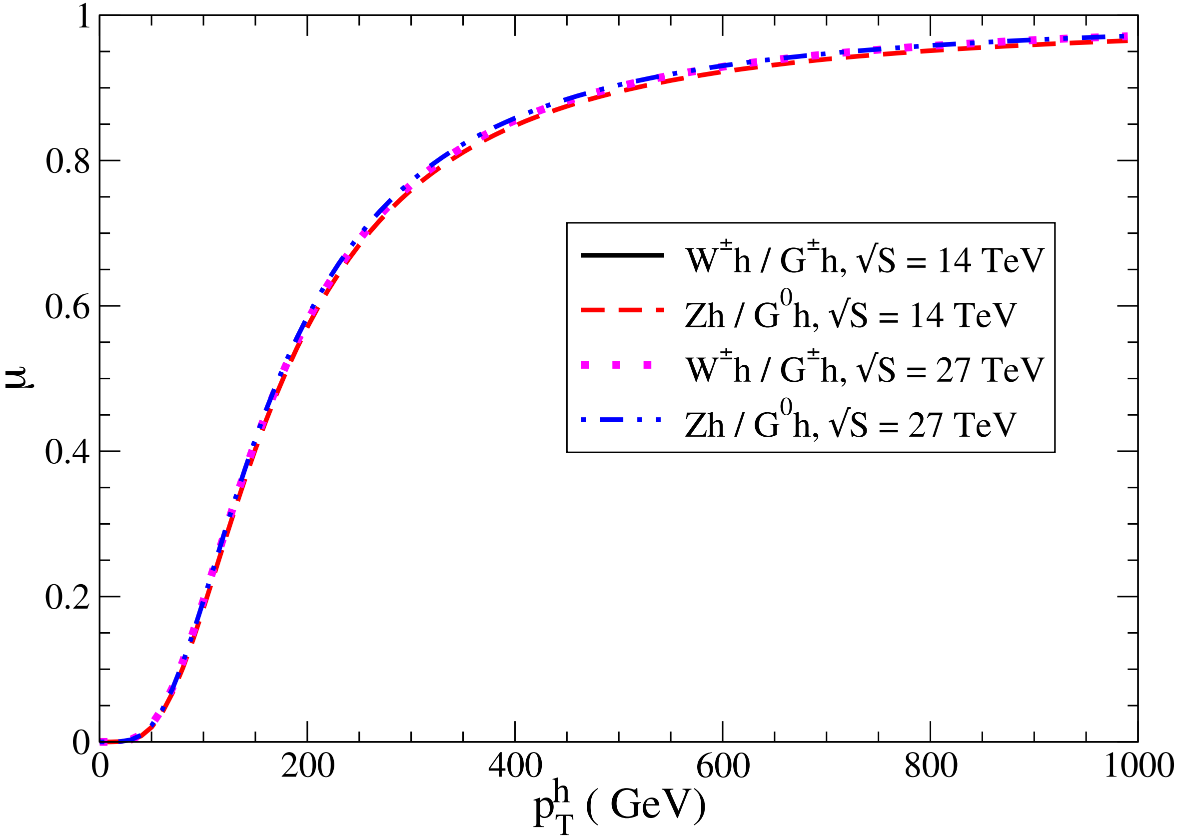
Transverse Dominated

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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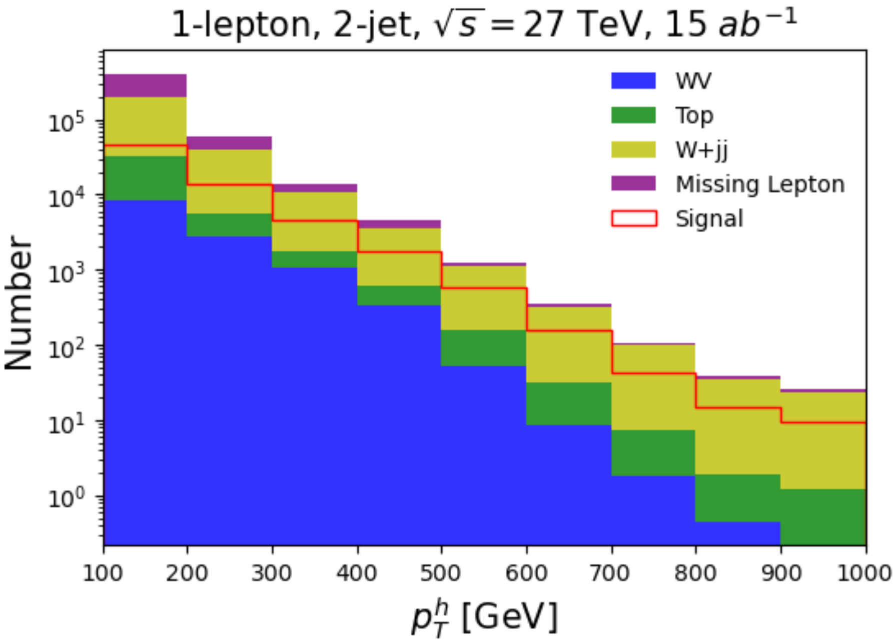
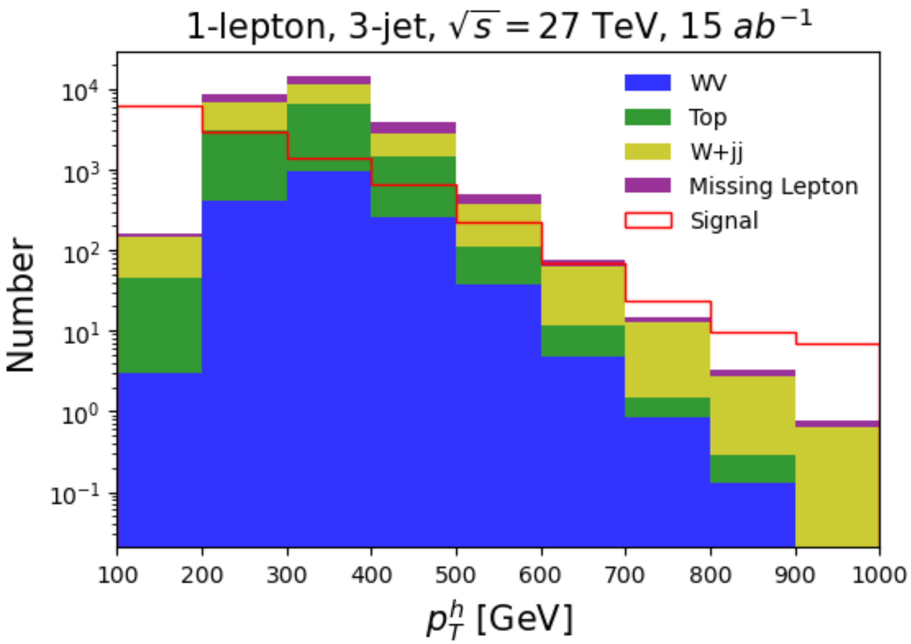
Event after DNN: 1 lepton

Use MG5/Pythia/Delphes Chain to generate 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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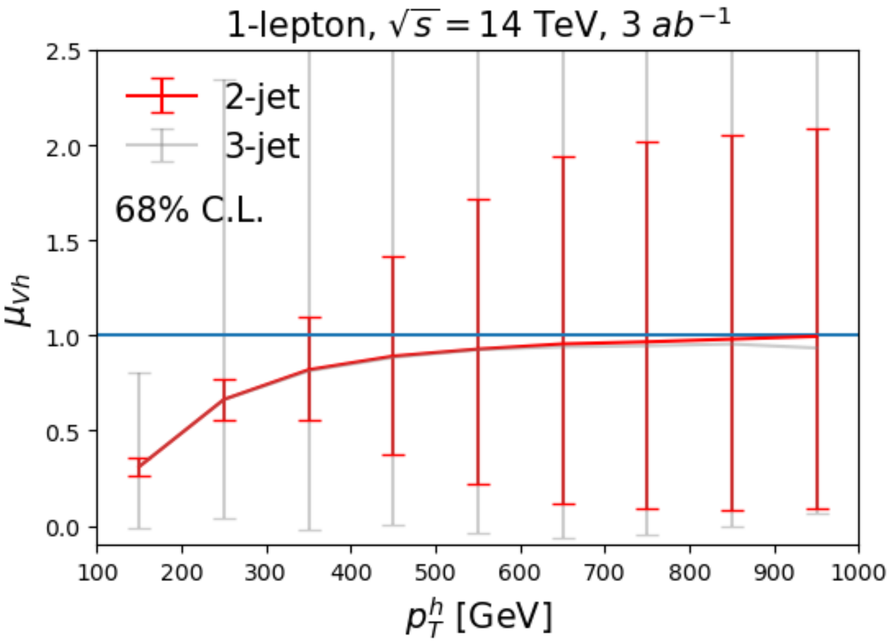
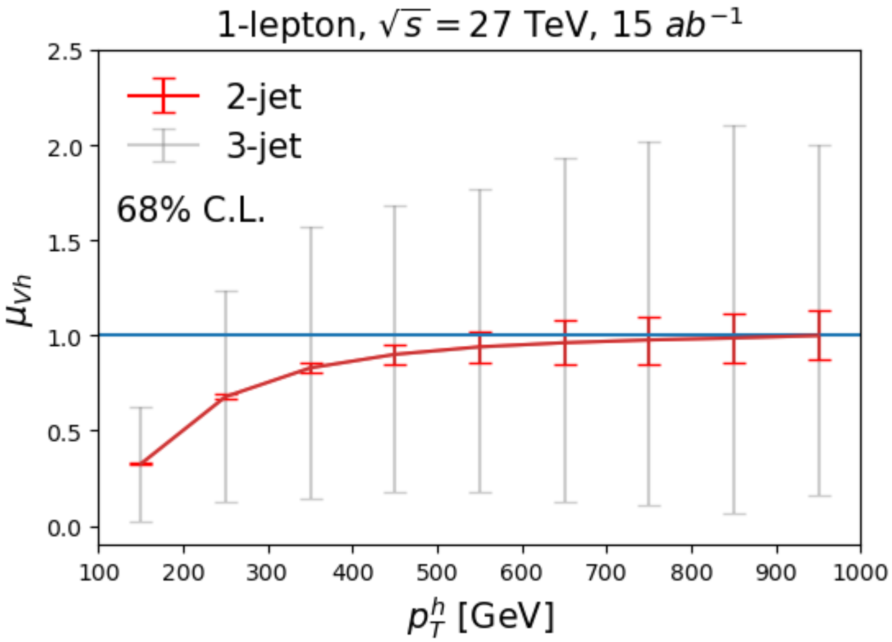
Signal Strength: 1 Lepton



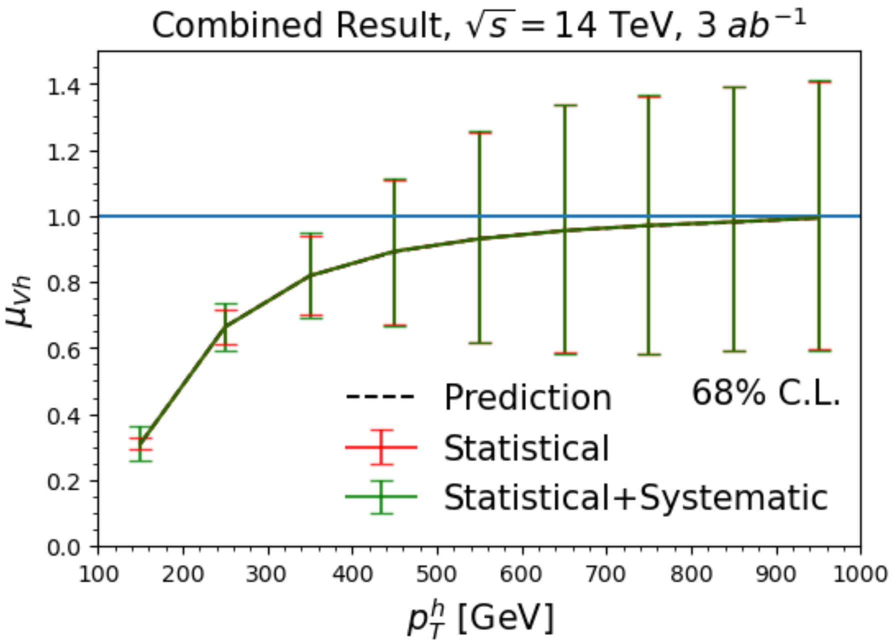


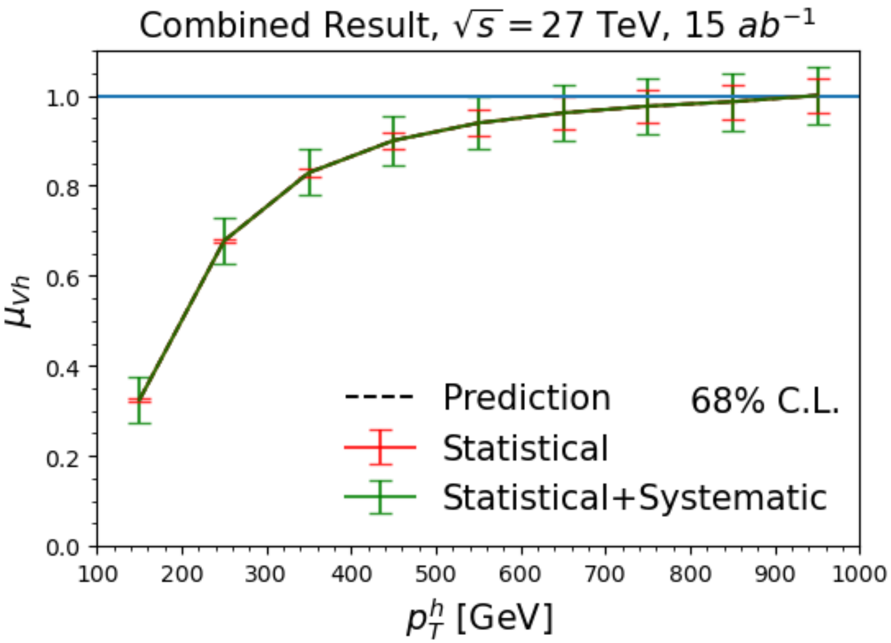
$$\mu_{Wh} = \frac{d\sigma(pp \to W^{\pm}h)/dp_T^h}{d\sigma(pp \to G^{\pm}h)/dp_T^h},$$

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

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

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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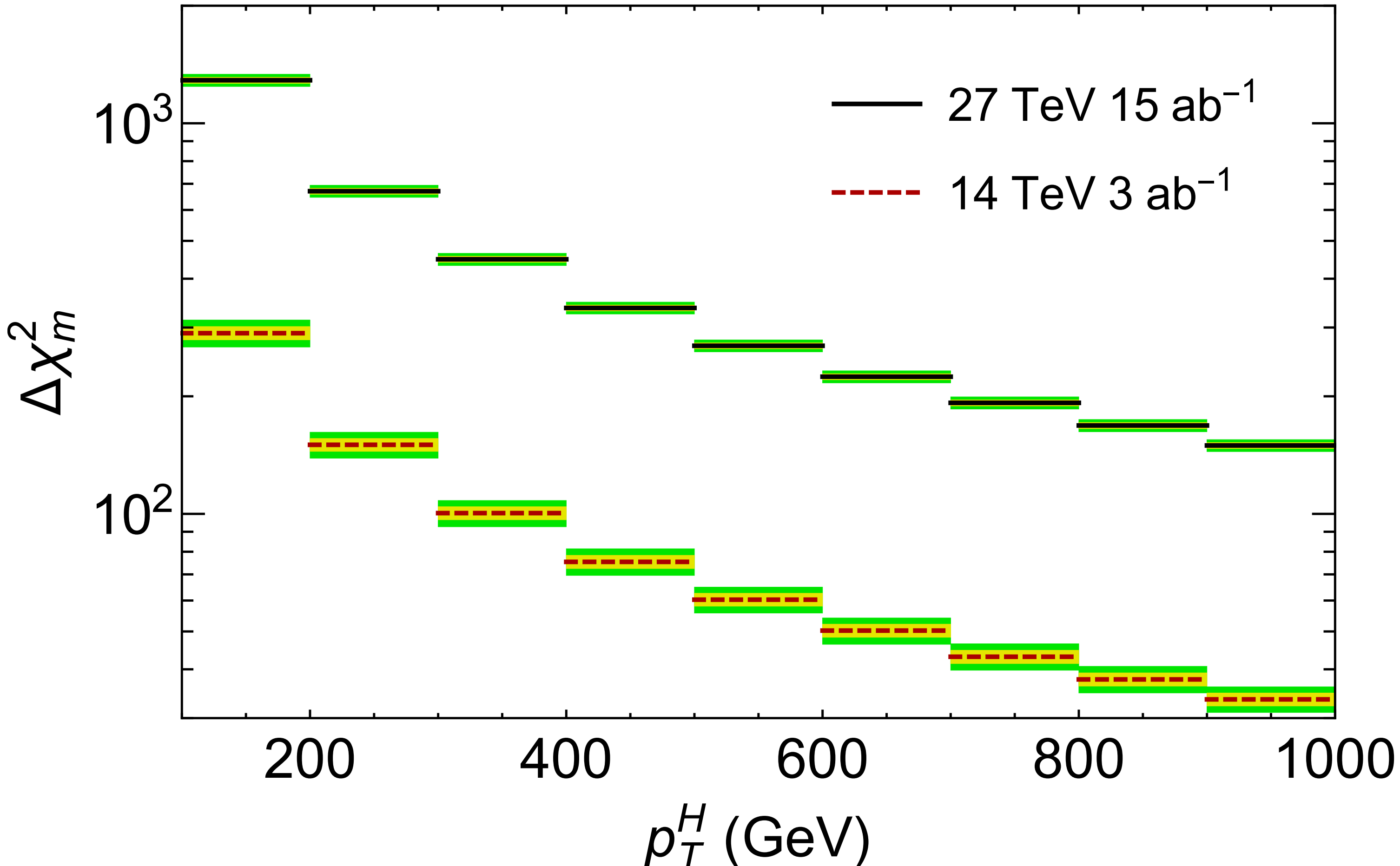
Delta Chi Square

Chi Square

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



KL Divergence

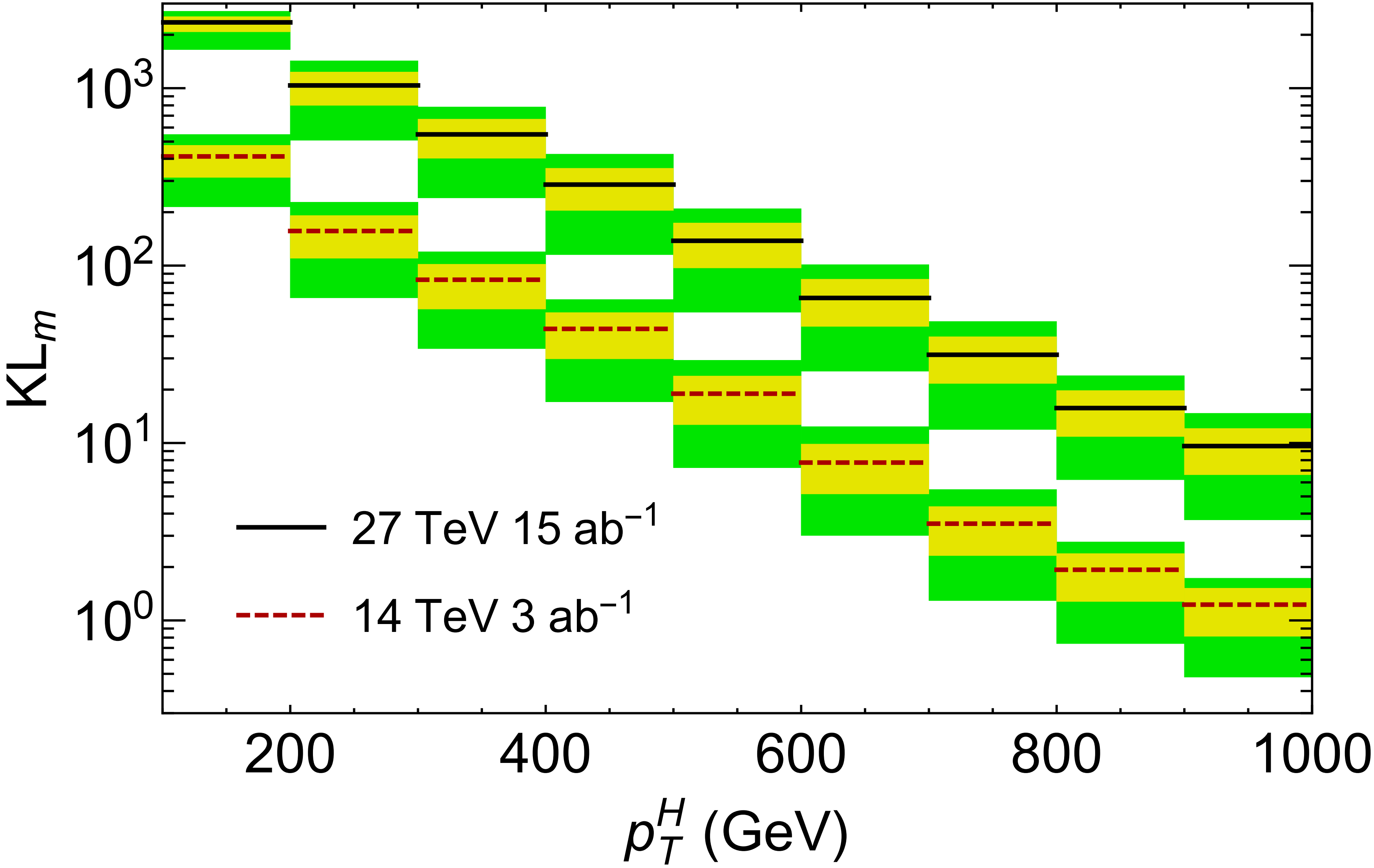
$$p_i^{\leq m} = \prod_{\substack{\text{6 signal}\\ \text{categories}}} \frac{\mathrm{Pois}(n_{obs,i}|S_i + B_i)}{\sum_{l=1}^{m} \mathrm{Pois}(n_{obs,l}|S_l + B_l)}$$

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

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

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

KL Diveregence



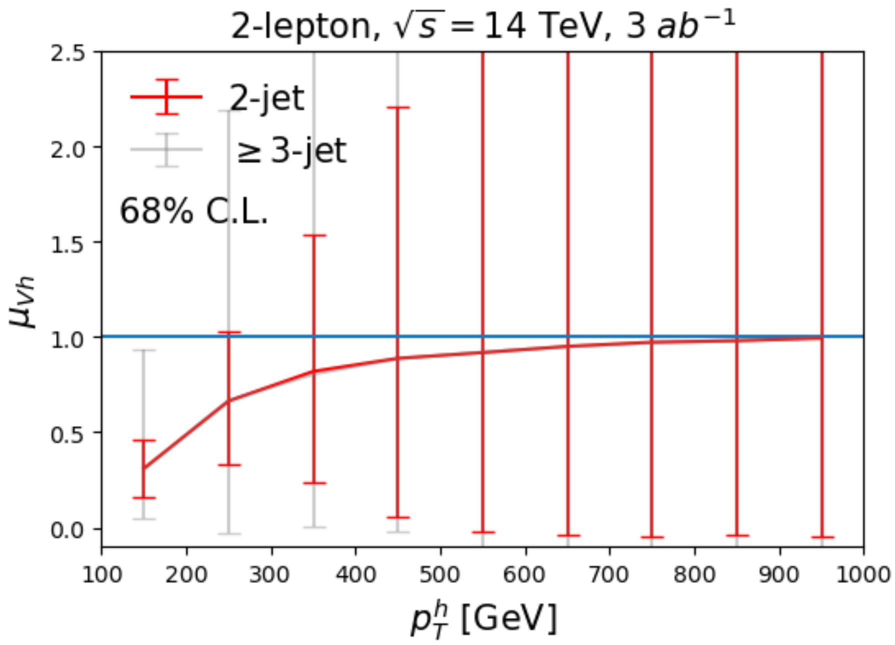
Conclusions

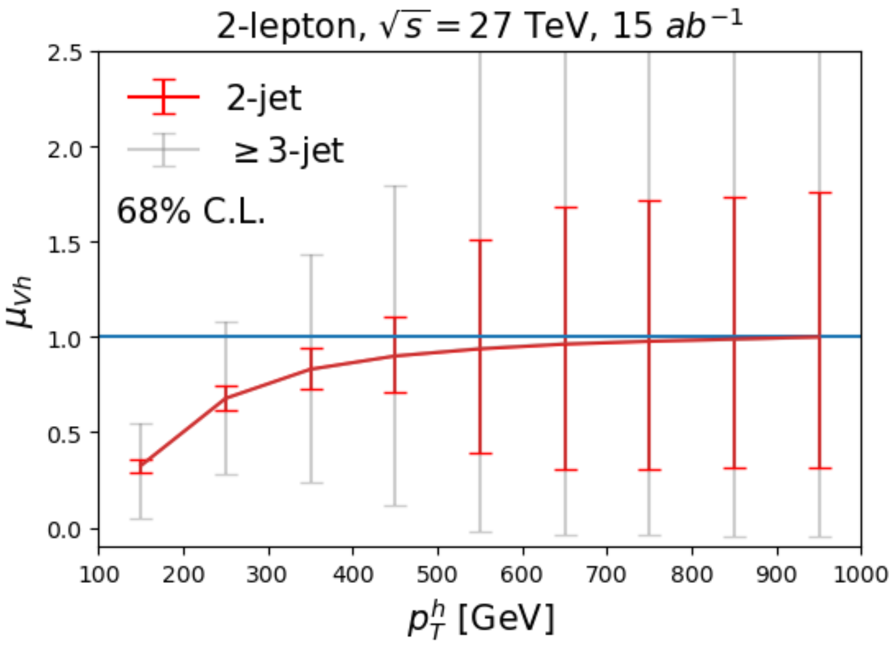
- We have shown the capabilities of HL-LHC and HE-LHC in observing the GBET and Electroweak restoration.
- We find for $p_t^h > 400\ GeV$ the $G\ h$ and the $V\ h$ distributions agree at about 80%.
- The KL divergence shows that the two hypotheses agree at high energy.
- HL can confirm electroweak restoration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

Thank You!

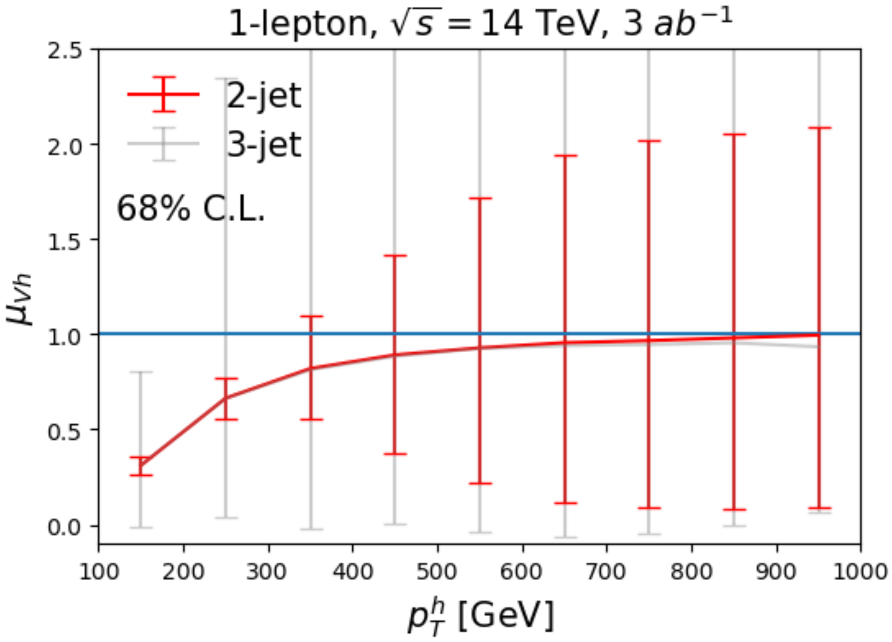
Any Questions?

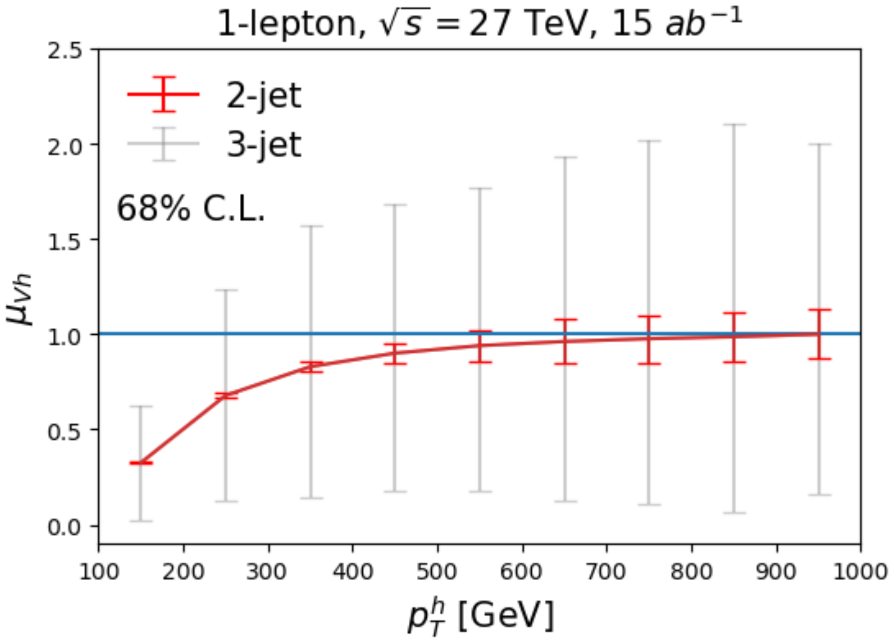
Signal Strength: 2 Lepton



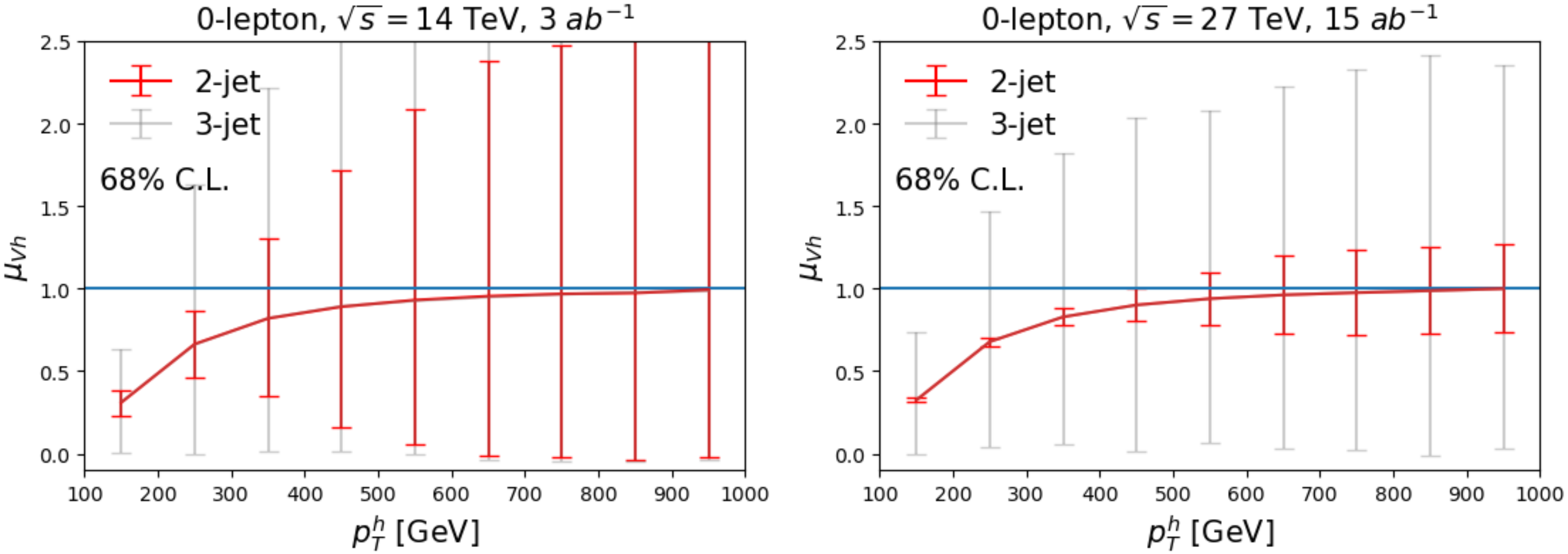


Signal Strength: 1 Lepton





Signal Strength: 0 Lepton



Z h and *W h* Amplitudes

$$\begin{aligned}
\mathcal{A}(q_+\bar{q}_- \to Z_L h) &= \pm i\, \frac{e^2\, g_R^{qZ}}{2\, c_W^2\, s_W^2} \sin\theta + \mathcal{O}(\hat{s}^{-1}), \\
\mathcal{A}(q_-\bar{q}_+ \to Z_L h) &= \pm i\, \frac{e^2\, g_L^{qZ}}{2\, c_W^2\, s_W^2} \sin\theta + \mathcal{O}(\hat{s}^{-1}), \\
\mathcal{A}(q_-\bar{q}'_+ \to W_L^\pm h) &= -i\, \frac{e^2}{2\sqrt{2}\, s_W^2} \sin\theta + \mathcal{O}(\hat{s}^{-1}), \\
\mathcal{A}(q_\pm\bar{q}_\mp \to Z_\pm h) &\sim \mathcal{A}(q_-\bar{q}'_+ \to W_L^\pm h) \sim \mathcal{O}(\hat{s}^{-1/2}), \\
\mathcal{A}(q_+\bar{q}'_- \to W_\pm^\pm h) &= \mathcal{A}(q_+\bar{q}'_- \to W_\mp^\pm h) = 0.
\end{aligned}$$

WZ, WW, and ZZ Amplitudes

$$\mathcal{A}(q_-\bar{q}_+ \to W^+_\pm W^-_\mp) = \mp i \frac{e^2}{2\,s_W^2} \frac{1 + 2\,T_3^q\,\cos\theta}{1 \pm \cos\theta} \sin\theta + \mathcal{O}(\hat{s}^{-1})\,,$$

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

$$\mathcal{A}(q_-\bar{q}_+ \to Z_+ Z_-) = 2\,i\,\frac{e^2}{s_W^2 c_W^2} g_L^{qZ\,2} \sqrt{\frac{1 - \cos\theta}{1 + \cos\theta}} + \mathcal{O}(\hat{s}^{-1})\,,$$

$$\mathcal{A}(q_+\bar{q}_- \to Z_+ Z_-) = -2\,i\,\frac{e^2}{s_W^2 c_W^2} g_R^{qZ\,2} \sqrt{\frac{1 + \cos\theta}{1 - \cos\theta}} + \mathcal{O}(\hat{s}^{-1})\,,$$

$$\mathcal{A}(q_\pm\bar{q}_\mp \to W^\pm_\pm W^\mp_L) \sim \mathcal{A}(q_-\bar{q}'_+ \to W^\pm_\pm Z_L) \sim \mathcal{A}(q_-\bar{q}'_+ \to Z_\pm W^\pm_L \sim \mathcal{A}(q_\pm\bar{q}_\mp \to Z_\pm Z_L) \sim \mathcal{O}(\hat{s}^{-1/2})$$

$$\mathcal{A}(q_\pm\bar{q}_\mp \to W^+_\pm W^-_\pm) \sim \mathcal{A}(q_-\bar{q}'_+ \to W^\pm_\pm Z_\pm) \sim \mathcal{A}(q_\pm\bar{q}_\mp \to Z_\pm Z_\pm) \sim \mathcal{O}(\hat{s}^{-1})\,,$$

$$\mathcal{A}(q_+\bar{q}_- \to W^+_\pm W^-_\mp) = \mathcal{A}(q_+\bar{q}'_- \to W^\pm_\lambda Z_{\lambda'}) = 0.$$

Relevant Goldstone Amplitudes

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

$Zh \to \ell^+\ell^-b\bar{b}$

	14 TeV				27 TeV			
	$n_j = 2$		$n_j = 3$		$n_j = 2$		$n_j = 3$	
	Pre-Cut	DNN	Pre-Cut	DNN	Pre-Cut	DNN	Pre-Cut	DNN
$h_{bb}Z_{\ell\ell}$	1.1 fb	0.22 fb	1.1 fb	0.23 fb	2.0 fb	0.87 fb	1.6 fb	1.2 fb
Z+HF	300 fb	1.4 fb	530 fb	3.3 fb	580 fb	16 fb	780 fb	120 fb
tt	27 fb	0.14	69 fb	0.095 fb	92 fb	1.6 fb	180 fb	19 fb
single top	0.85 fb	0.0036 fb	3.5 fb	0.0041 fb	2.9 fb	0.047 fb	11 fb	1.0 fb
Zcl	0.18	0.0036 fb	2.1 fb	0.025 fb	0.75 fb	0.034 fb	6.4 fb	0.94 fb
Zll	0.68	0.019 fb	13 fb	0.20 fb	2.0 fb	0.096 fb	27 fb	4.1 fb
VV'	4.8 fb	0.026 fb	5.4 fb	0.051 fb	6.5 fb	0.22 fb	7.8 fb	1.5 fb
Signal Significance		9.4		6.5		25		13

$Wh \to \ell\nu b\bar{b}$

	14 TeV				27 TeV			
	$n_j = 2$		$n_j = 3$		$n_j = 2$		$n_j = 3$	
	Pre-Cut	DNN	Pre-Cut	DNN	Pre-Cut	DNN	Pre-Cut	DNN
$h_{bb}W_{\ell\nu}$	12 fb	6.1 fb	7.3 fb	0.38 fb	19 fb	9.6 fb	9.8 fb	1.2 fb
W+HF	580 fb	38 fb	640 fb	0.035 fb	790 fb	43 fb	940 fb	0.33 fb
Z+HF	310 fb	8.5 fb	380 fb	9.7×10^{-5} fb	640 fb	21 fb	670 fb	0.048 fb
tt	150 fb	15 fb	560 fb	0.30 fb	580 fb	28 fb	1500 fb	0.93 fb
single top	11 fb	1.1 fb	68 fb	0.053 fb	36 fb	1.7 fb	100 fb	0.12 fb
Wcl	4.9 fb	0.46 fb	12 fb	2.5×10^{-3} fb	8.0 fb	0.56 fb	19 fb	0.027 fb
Wll	10 fb	1.2 fb	36 fb	0.021 fb	28 fb	2.7 fb	92 fb	0.34 fb
Zcl	0.15 fb	4.2×10^{-3} fb	0.51 fb	0 fb	0.62 fb	0.012 fb	1.8 fb	7.2×10^{-5} fb
Zll	0.49 fb	0.014 fb	2.0 fb	4.7×10^{-5} fb	1.5 fb	0.032 fb	5.2 fb	6.0×10^{-4} fb
VV'	34 fb	2.0 fb	28 fb	0.015 fb	41 fb	1.9 fb	33 fb	0.11 fb
Signal Significance		40		28		120		98

$Zh \to \nu\nu b\bar{b}$

	14 TeV				27 TeV			
	$n_j = 2$		$n_j = 3$		$n_j = 2$		$n_j = 3$	
	Pre-Cut	DNN	Pre-Cut	DNN	Pre-Cut	DNN	Pre-Cut	DNN
$h_{bb}Z_{\nu\nu}$	9.8 fb	4.7 fb	6.3 fb	1.6 fb	18 fb	7.9 fb	9.6 fb	1.4 fb
W+HF	310 fb	7.6 fb	440 fb	0.020 fb	420 fb	14 fb	680 fb	0.028 fb
Z+HF	2900 fb	110 fb	2900 fb	0.35 fb	5700 fb	260 fb	5000 fb	0.72 fb
tt	7.6 fb	0.16 fb	170 fb	0.041 fb	42 fb	0.22 fb	460 fb	0.020 fb
single top	1.3 fb	0.035 fb	22 fb	0.0091 fb	1.5 fb	0.0057 fb	19 fb	0.0019 fb
Wcl	1.1 fb	0.026 fb	4.2 fb	5.3×10^{-4} fb	2.4 fb	0.059 fb	7.4 fb	0.0010 fb
Wll	3.7 fb	0.087 fb	19 fb	0.014 fb	13 fb	0.38 fb	49 fb	0.028 fb
Zcl	1.4 fb	0.15 fb	4.7 fb	0.0065 fb	3.3 fb	0.23 fb	9.0 fb	0.013 fb
Zll	6.8 fb	0.78 fb	26 fb	0.12 fb	22 fb	1.6 fb	80 fb	0.20 fb
VV'	68 fb	3.9 fb	51 fb	0.084 fb	89 fb	4.7 fb	65 fb	0.15 fb
Signal Significance		23		84		58		140