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

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Outline

- Introduction
- EW Symmetry/Theory
- Parton Level
- Experimental Challenges
- Detector Level Results
    - Channels and Backgrounds
    - Simulation, cuts, and statistics

Introduction

- The Standard Model (SM) is already widely successful
- One major component of the SM is electroweak (EW) symmetry breaking
- Future colliders probe higher energies above this EW scale where some interesting SM physics occurs
- Above this scale EW particles become massless. Must treat things as partons

Our Goal

- We want to study the nature of this EW symmetry breaking
- The key to studying this is the Goldstone boson equivalence theorem (GBET)
  - At high energies the EW gauge bosons become massless and their longitudinal modes can be replaced by goldstones
- Want to create an analysis to test GBET and thus EW symmetry

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Electroweak (EW) Symmetry

Broken Phase

- $U(1)_{EM}$
- Massive VBs:
  - $Z, W^{\pm}$
- Massless Photon: A
- Massive Fermions
- Higgs scalar h

Unbroken Phase

- $SU(2)_L x U(1)_y$
- Massless VBs
  - W^i, B
- Massless Goldstone
- Massless Fermions
- Higgs doublet Φ

Theory

- The EW SM only has 3 free parameters.
- Take your favorite set of parameters (i.e. M_Z, α_{EW}, G_F)
- Calculate and fix couplings (g and g')
- Now take the limit as vev → 0 (M_W → 0)

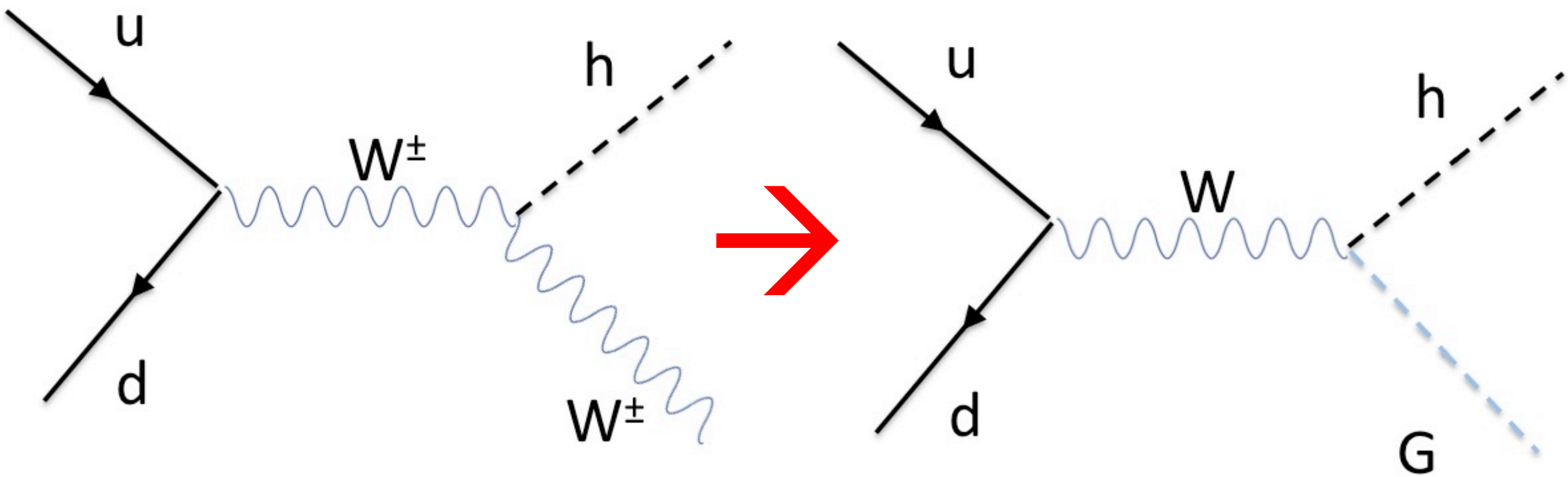
$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + i\,G^0\right) \end{pmatrix}$$

$$\mathcal{L}_{\rm kin} = \left|D_\mu H\right|^2 \qquad V(H) = -\mu^2 H^\dagger H + \lambda\left(H^\dagger H\right)^2$$

EW Restoration

Broken Phase

Unbroken Phase



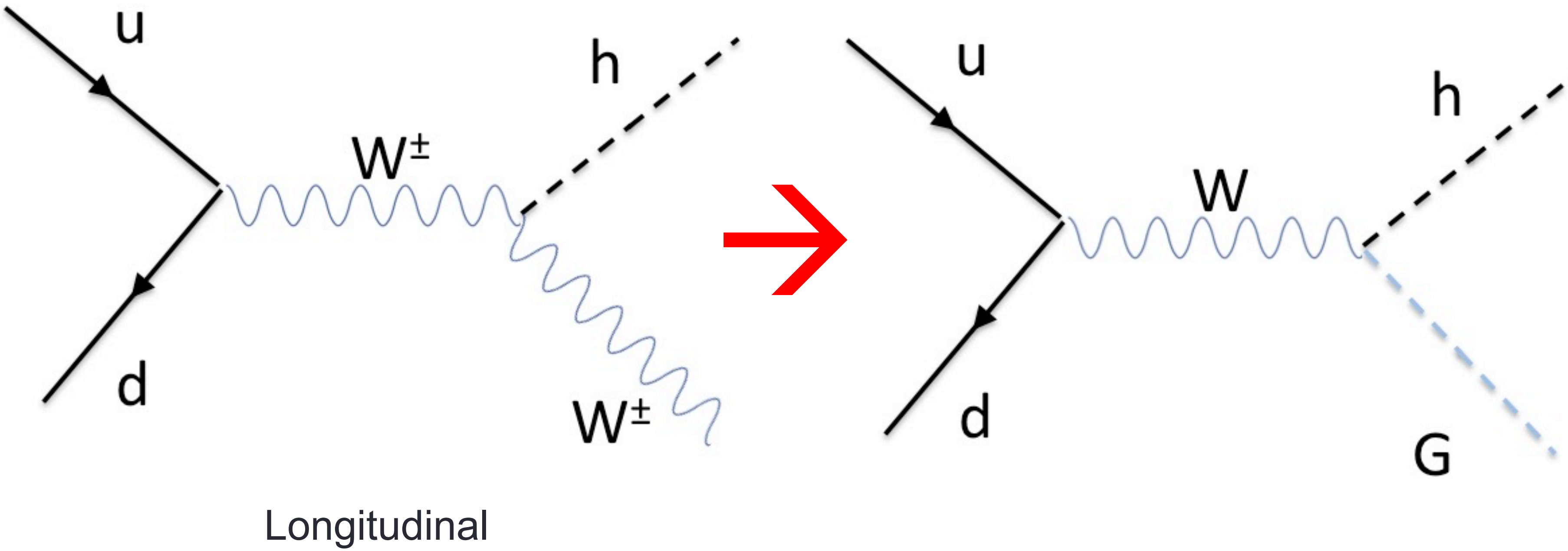
Longitudinal

In the limit s → ∞

EW Restoration

Broken Phase

Unbroken Phase



We want to measure this convergence

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Parton Level Vh Signal Strength

- Want to calculate a signal strength at parton level between Vh and Gh
- Calculate some helicity amplitudes, integrate over parton distribution functions (pdfs), take ratio of Pt distrubtions

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

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

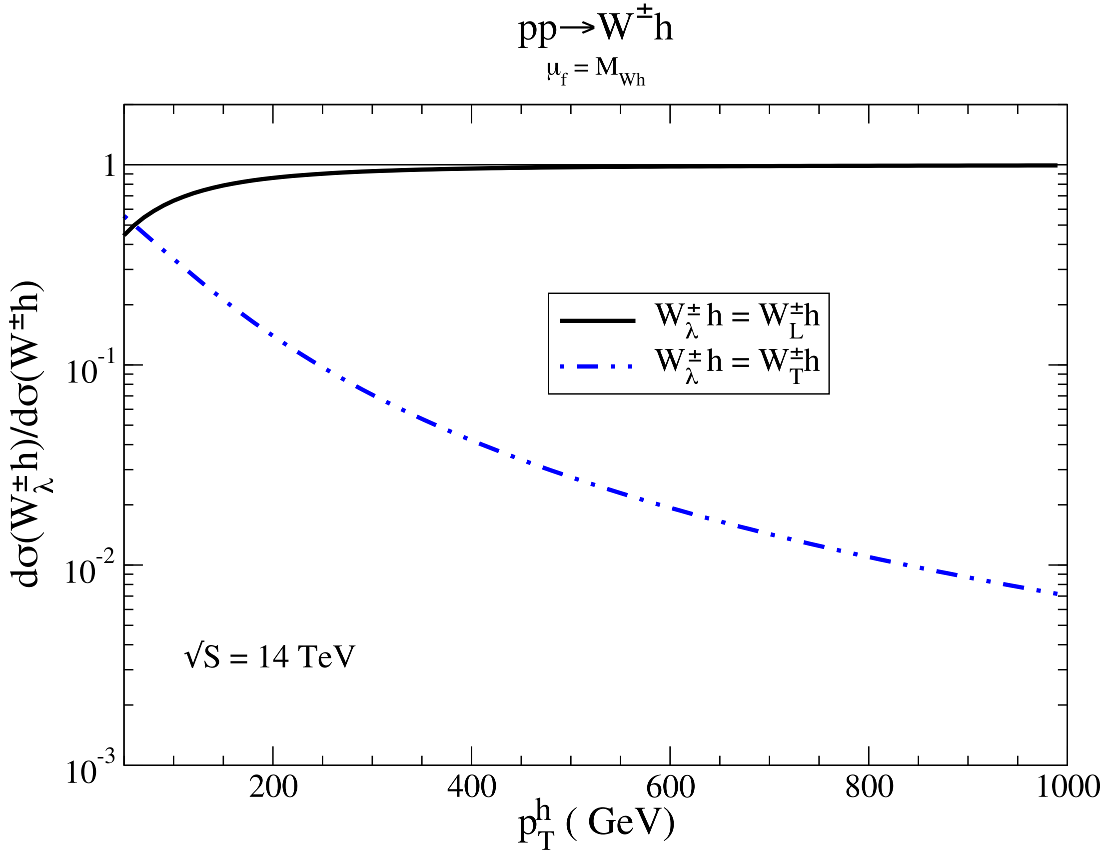
Why don't we look at WW or WZ?

- The GBET still applies
- Comes down to cross sections polarization
- For Vh production the cross sections are longitudinally dominated at high energy
- While WV is transverse dominated
- This means need to disentangle polarizations for WV. Which is somewhat tricky to do

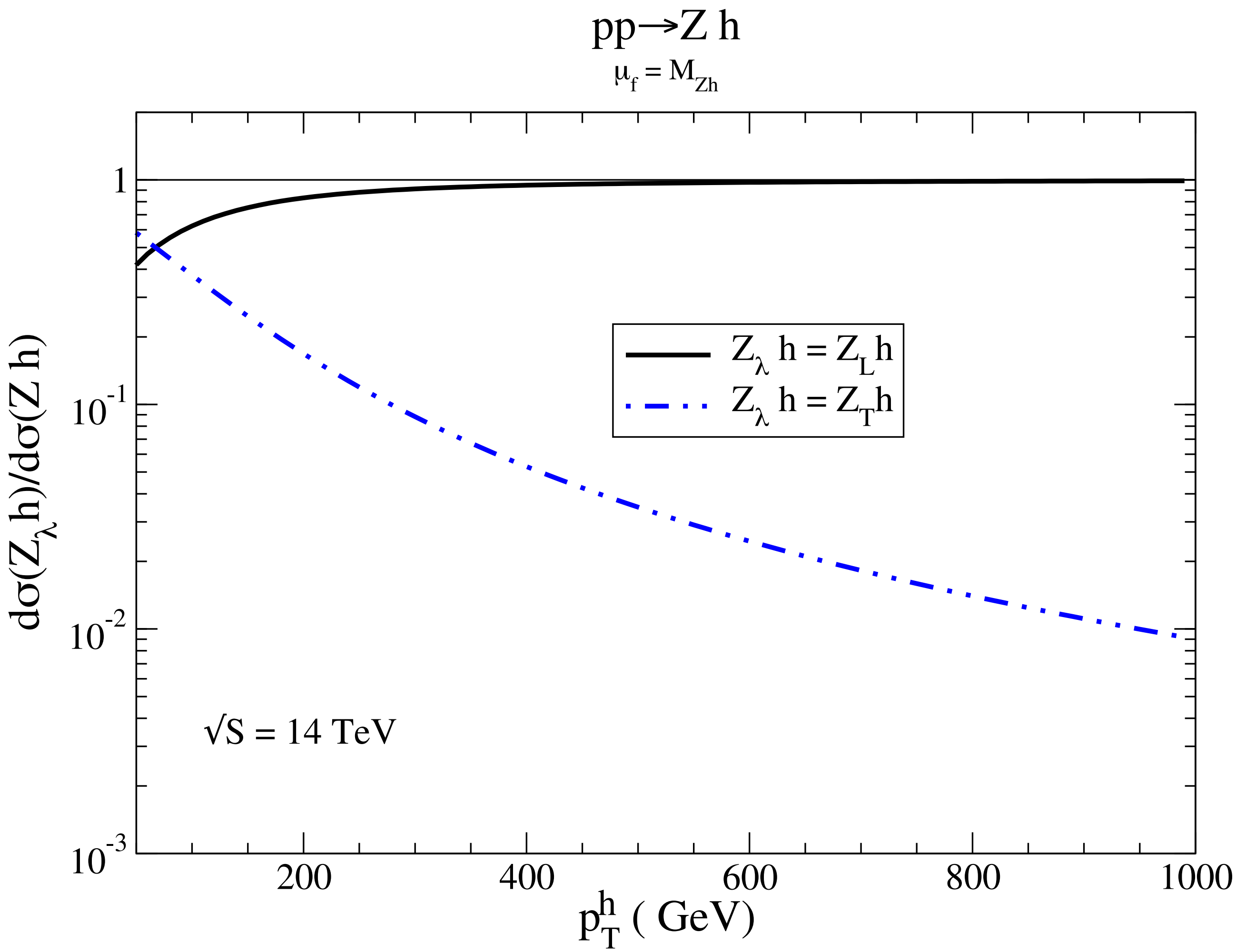
Wh Parton Helicity Dependence

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

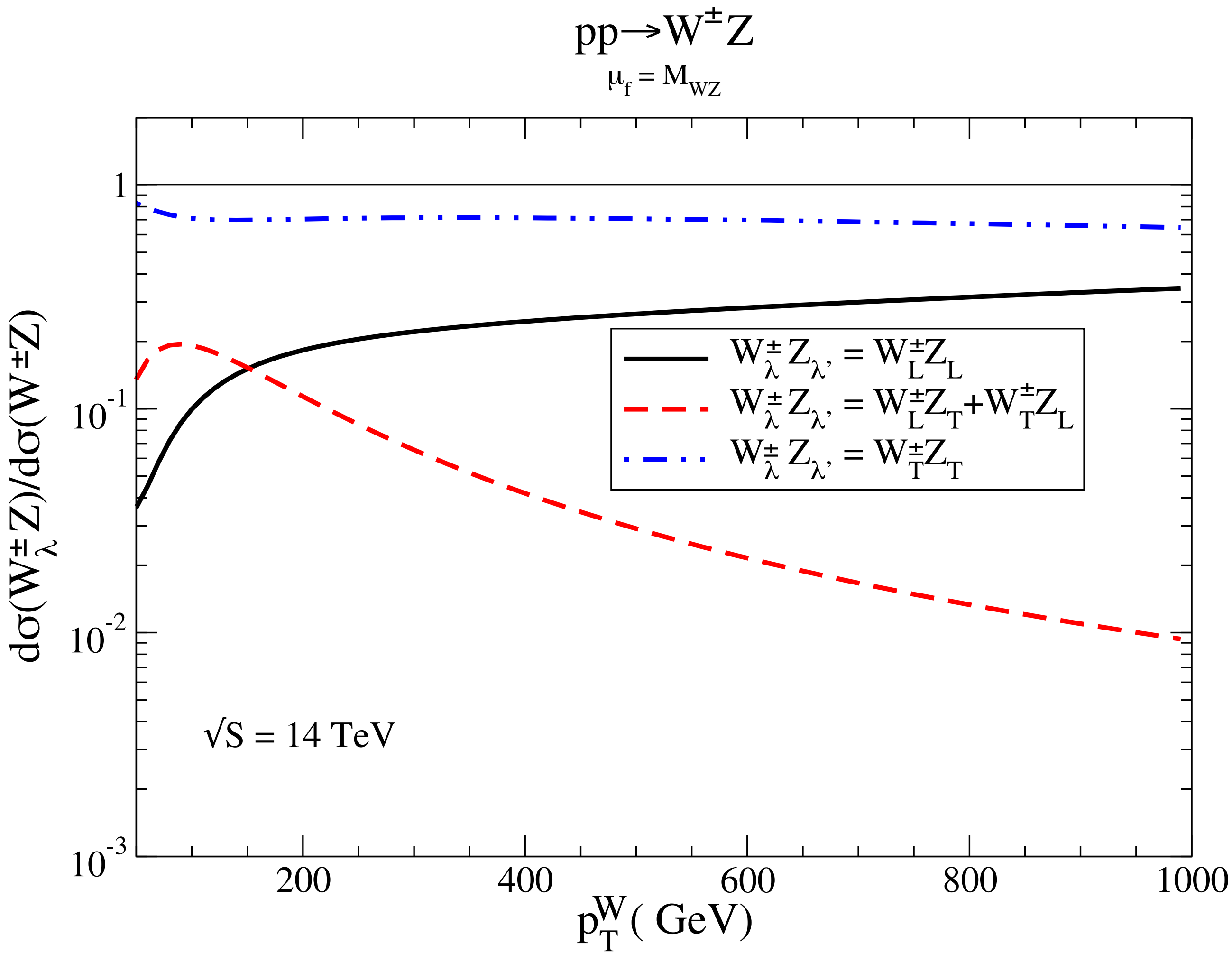
$$\mathcal{A}(q_-\bar{q}_+ \to G^\pm h) \;=\; \mp i\frac{e^2}{2\sqrt{2}s_W^2}\,\sin\theta,$$



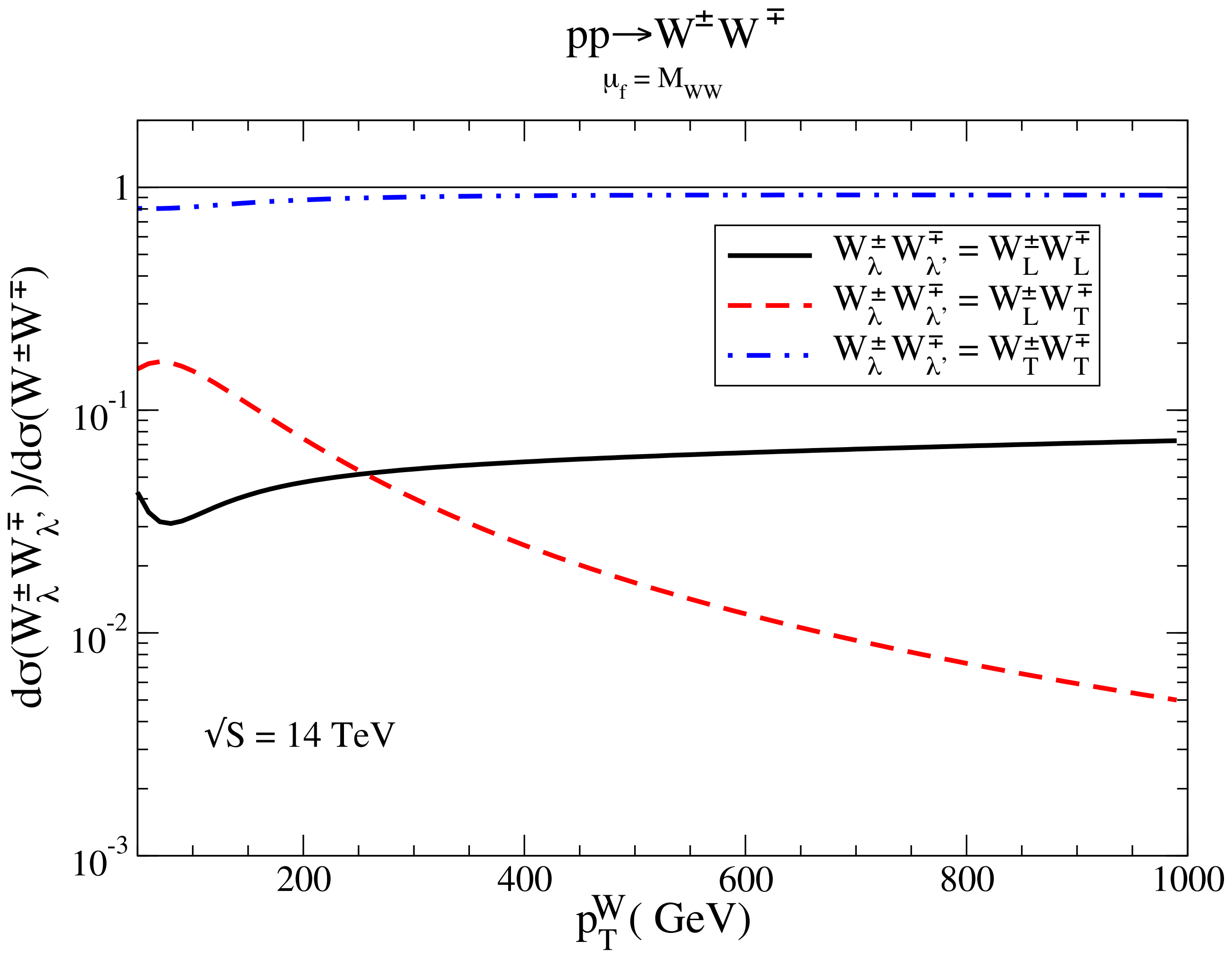
Zh Parton Helicity Dependence



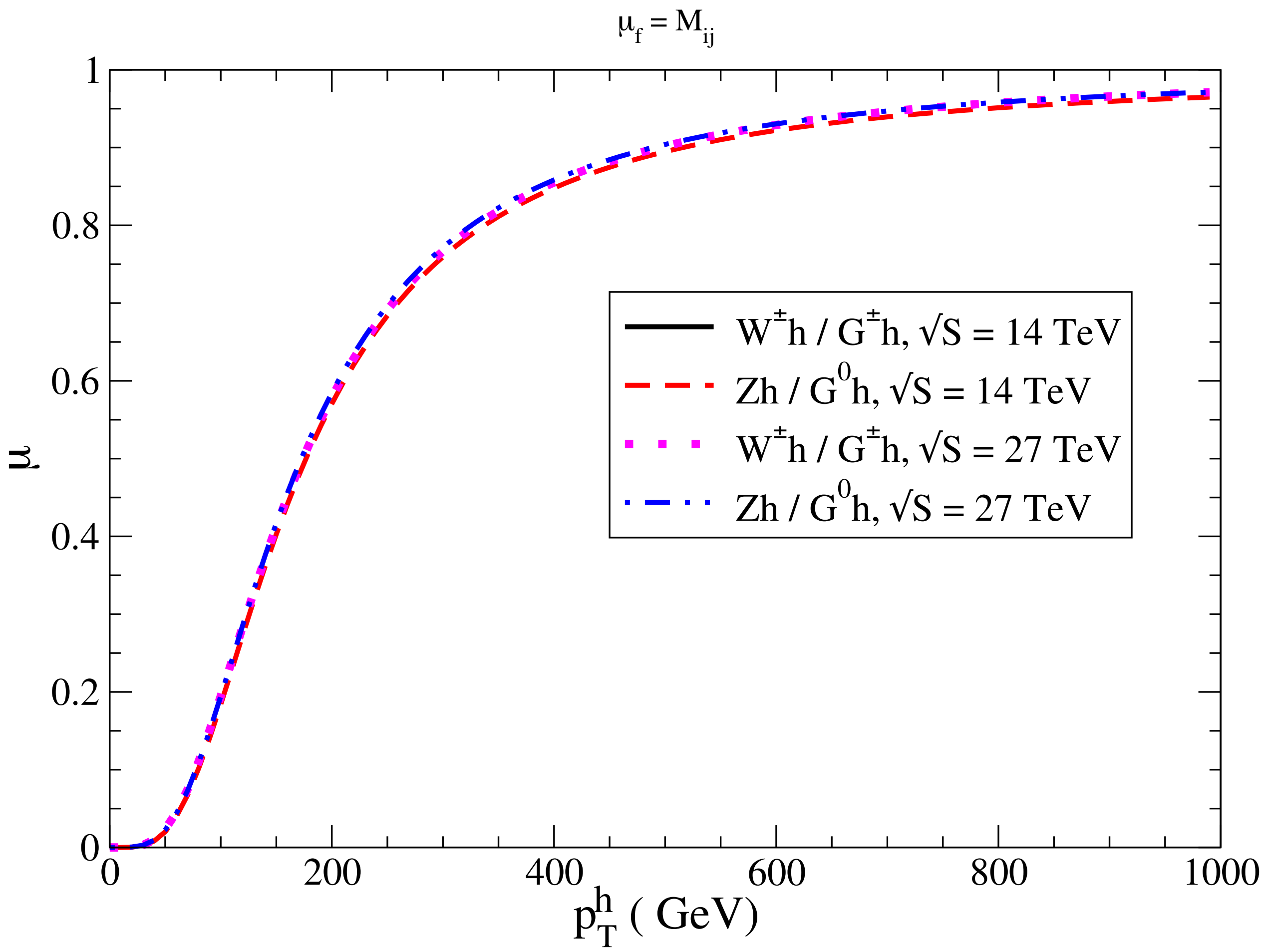
WZ Parton Helicity Dependence



WW Parton Helicity Dependence



Parton Level Signal Strength



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Experimental Challenges

- In a collider experiment we know the Higgs and Z both decay
- In the unbroken phase the massless Goldstones do not decay
- How do we compare this 2→2 process with a 2→4 process?
- We will do MC simulation so how do we precisely determine the uncertainties

Experimental Challenges

- Get the hV cross section by using likelihood
- We have to worry about pdfs, showering, hadronization and detector effects.
- We sweep all of that into an efficiency matrix
- We don't actually measure s of the system
- Need to find a good placeholder.
- P_{Th} and M_{Vh} seem like good candidates. They should measure the energy going through the hVV/hVG vertex

Outline

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  - Broken vs Unbroken Phase
  - Challenges and Technicalities
- Amplitudes/Parton Level
- Detector Level Results
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Channel Breakdown

- The analysis considers three decay channels
  - $Zh \to \ell^+\ell^- b\bar{b}$
  - $Wh \to \ell\nu b\bar{b}$
  - $Zh \to \nu\nu b\bar{b}$
- In each of these decay channels we consider 2 jet and 3 jet final states giving a total of 6 categories

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

- Z+jet and W+jet
  - Heavy flavor (HF) - At least one b jet
  - Charm (cj) – at least one c jet (but no b jets)
  - Light (lj) - anything else
- Single top production
- Top pair production
- Diboson pair production

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

	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

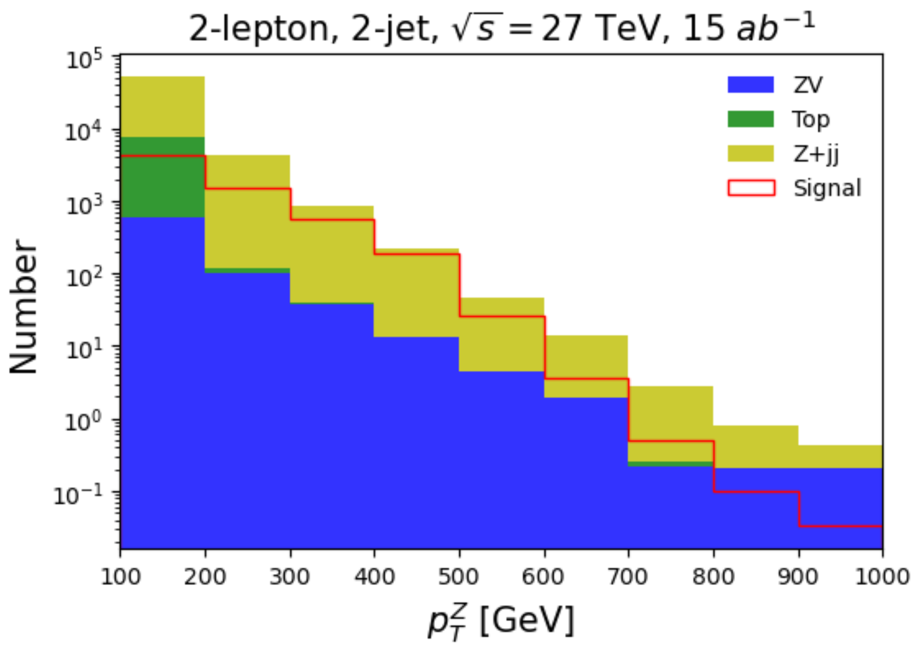
Simulation Details

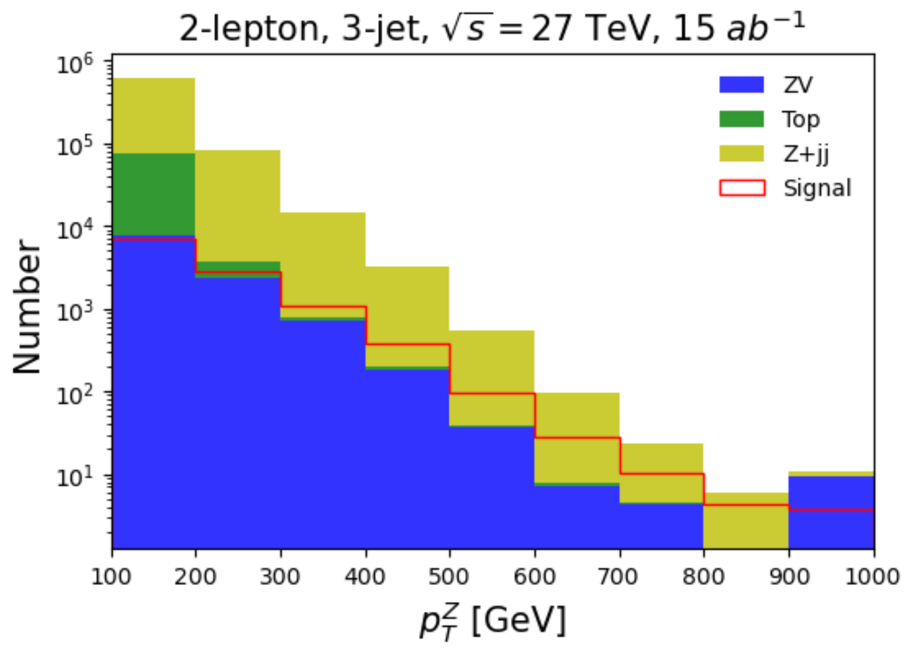
- There are lots of backgrounds to consider for each channel
- Use MG5/Pythia/Delphes Chain
- We consider one additional jet matching
- Use DNN to separate signal and background

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

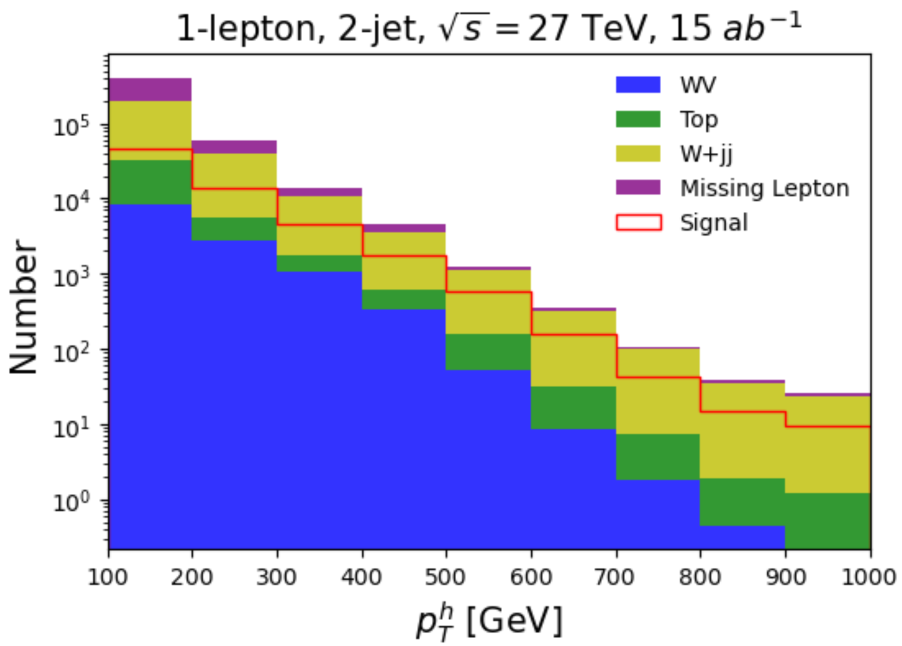
- Cheat and keep track of parton level information to get efficiency matrix
  - Simply maps bins at detector level to bins at parton level. Includes all detector/parton effects

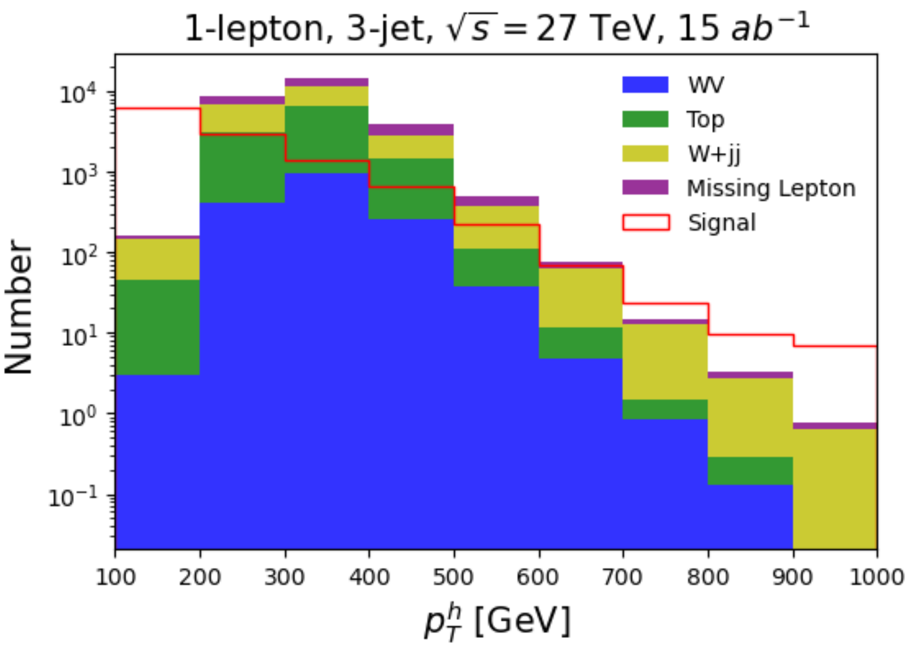
Event Numbers after DNN: 2 lepton



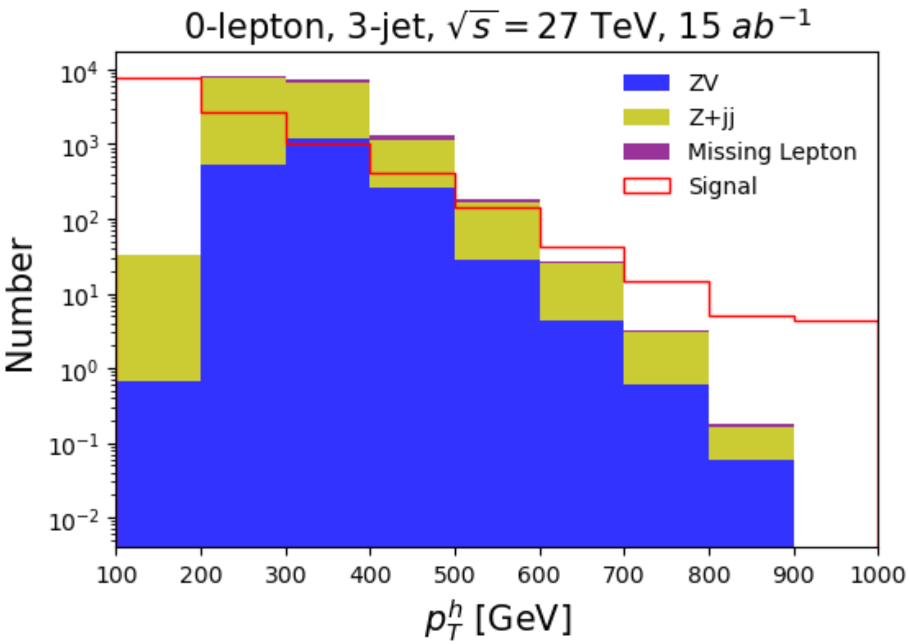


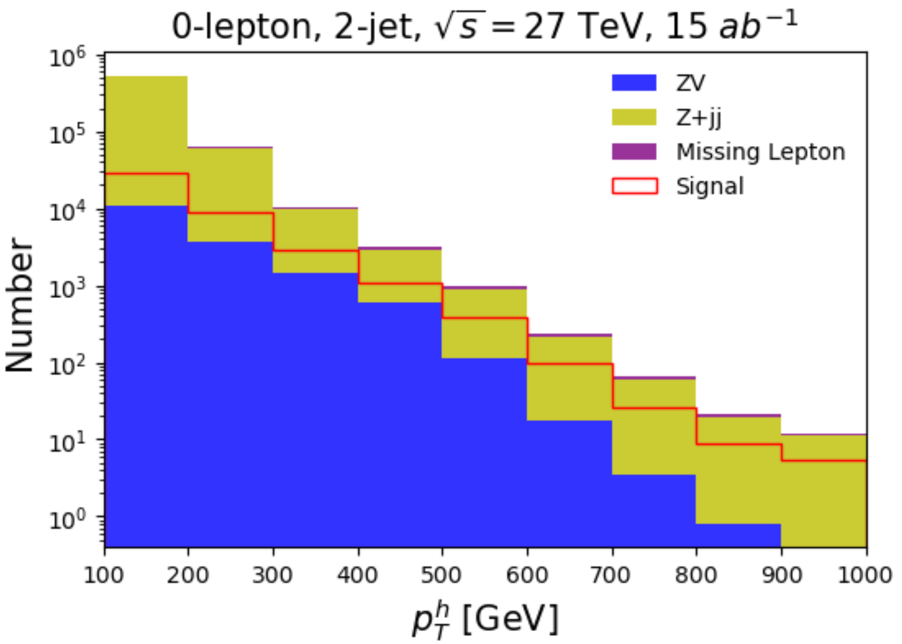
Event Numbers after DNN: 1 lepton



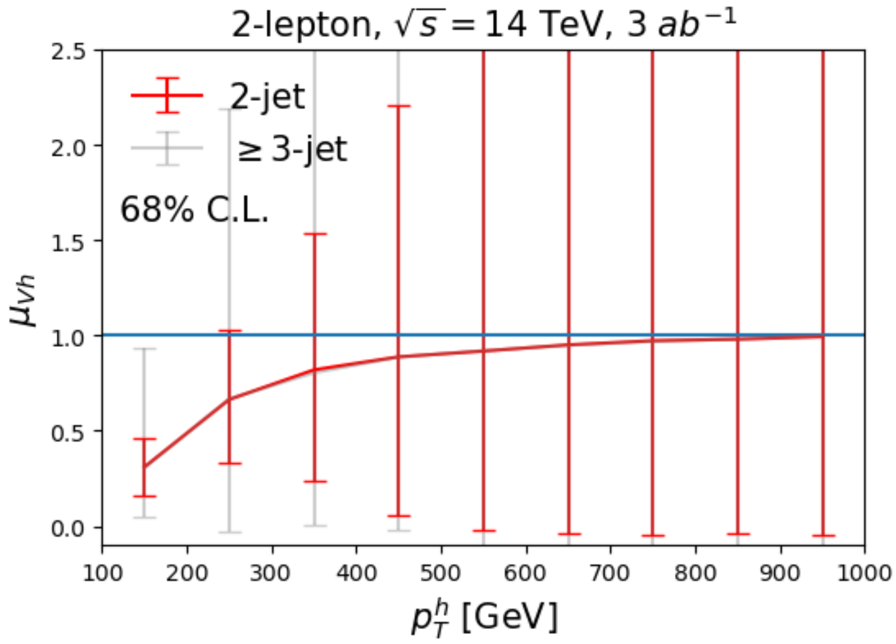


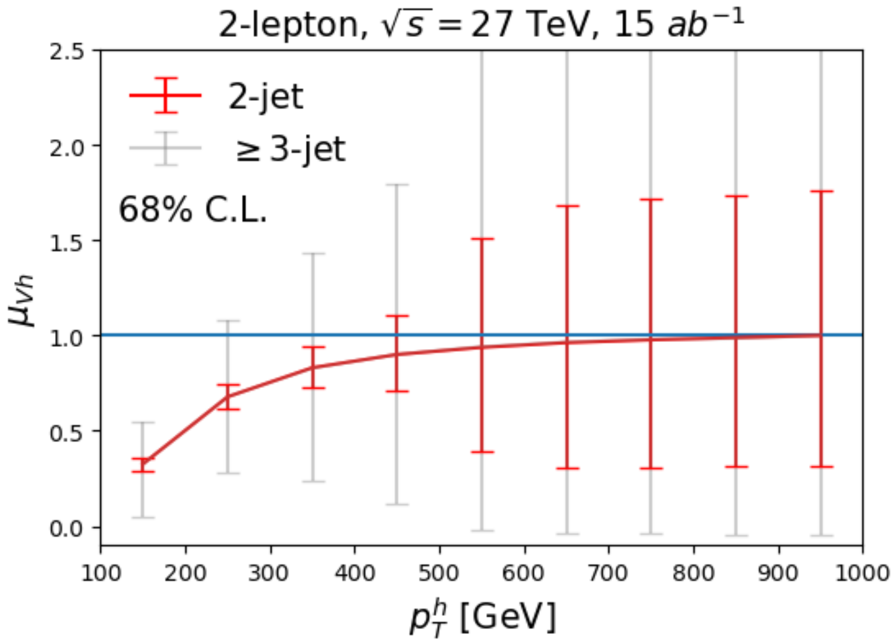
Event Numbers after DNN: 0 lepton



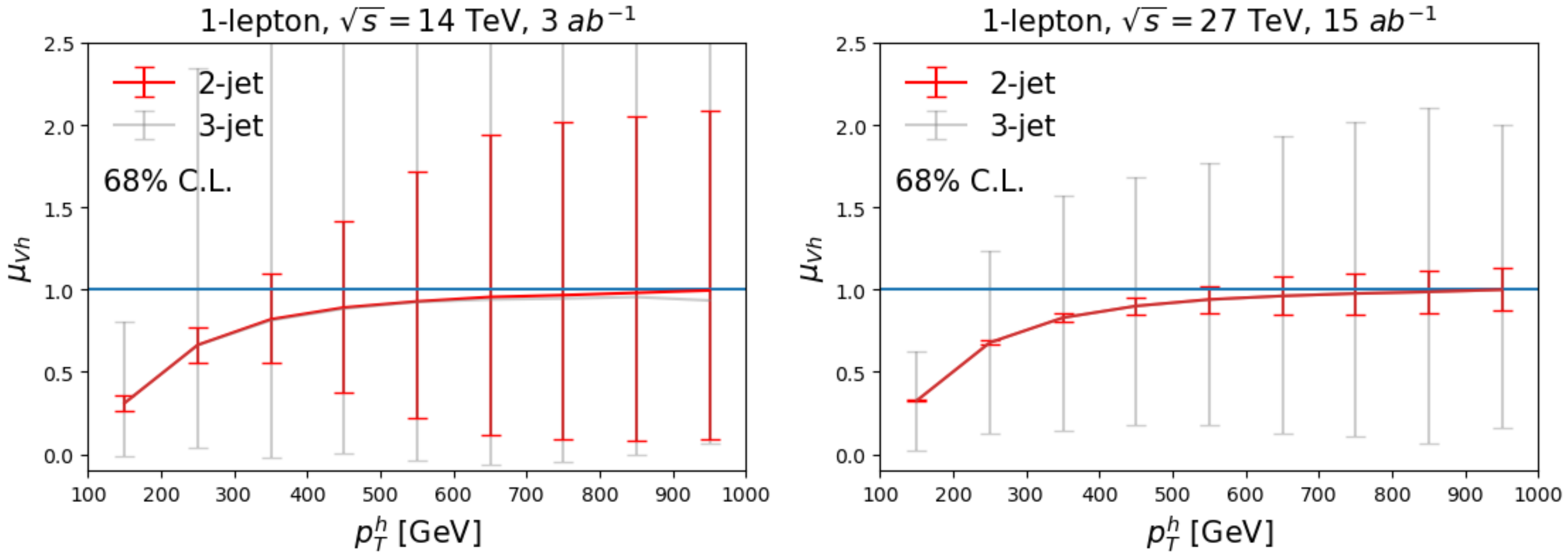


Signal Strength: 2 Lepton

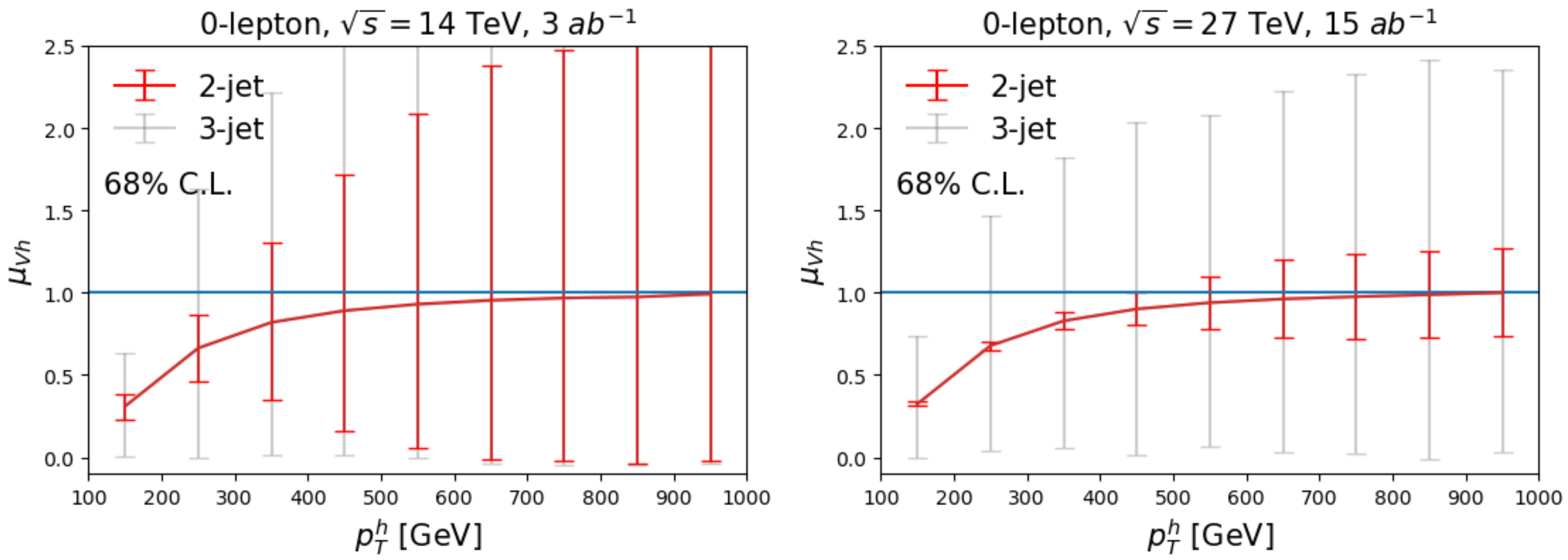




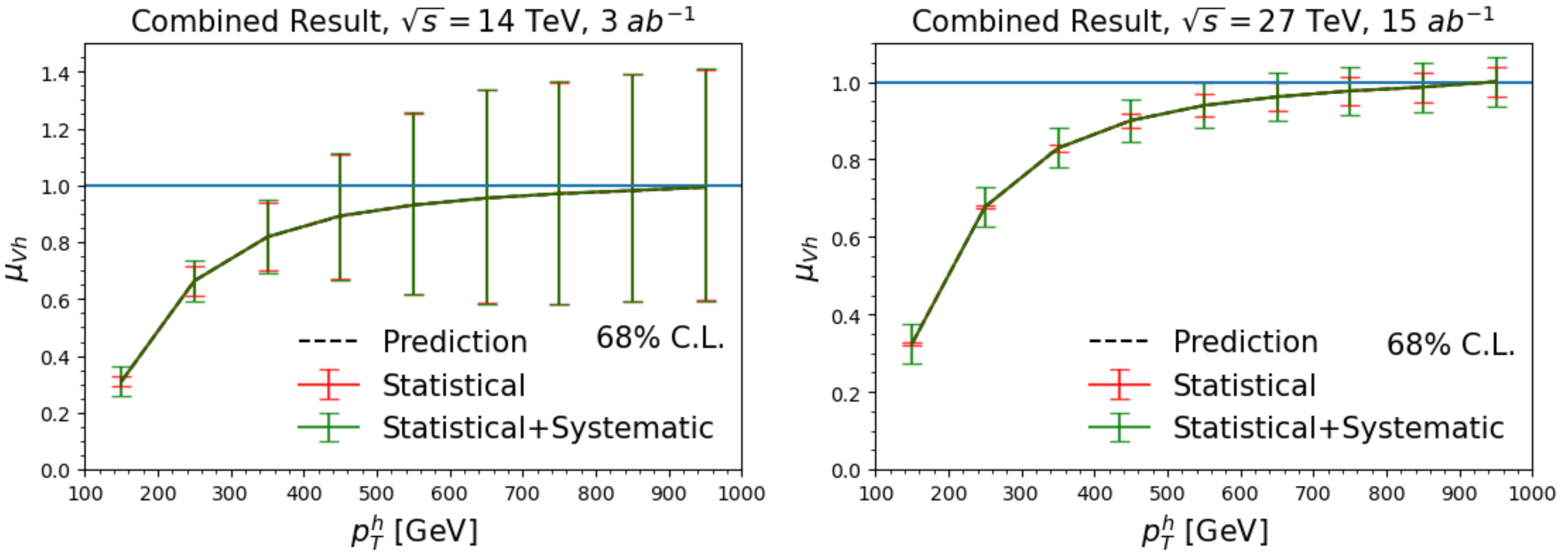
Signal Strength: 1 Lepton



Signal Strength: 0 Lepton



Signal Strength: Combined



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

Delta Chi Square

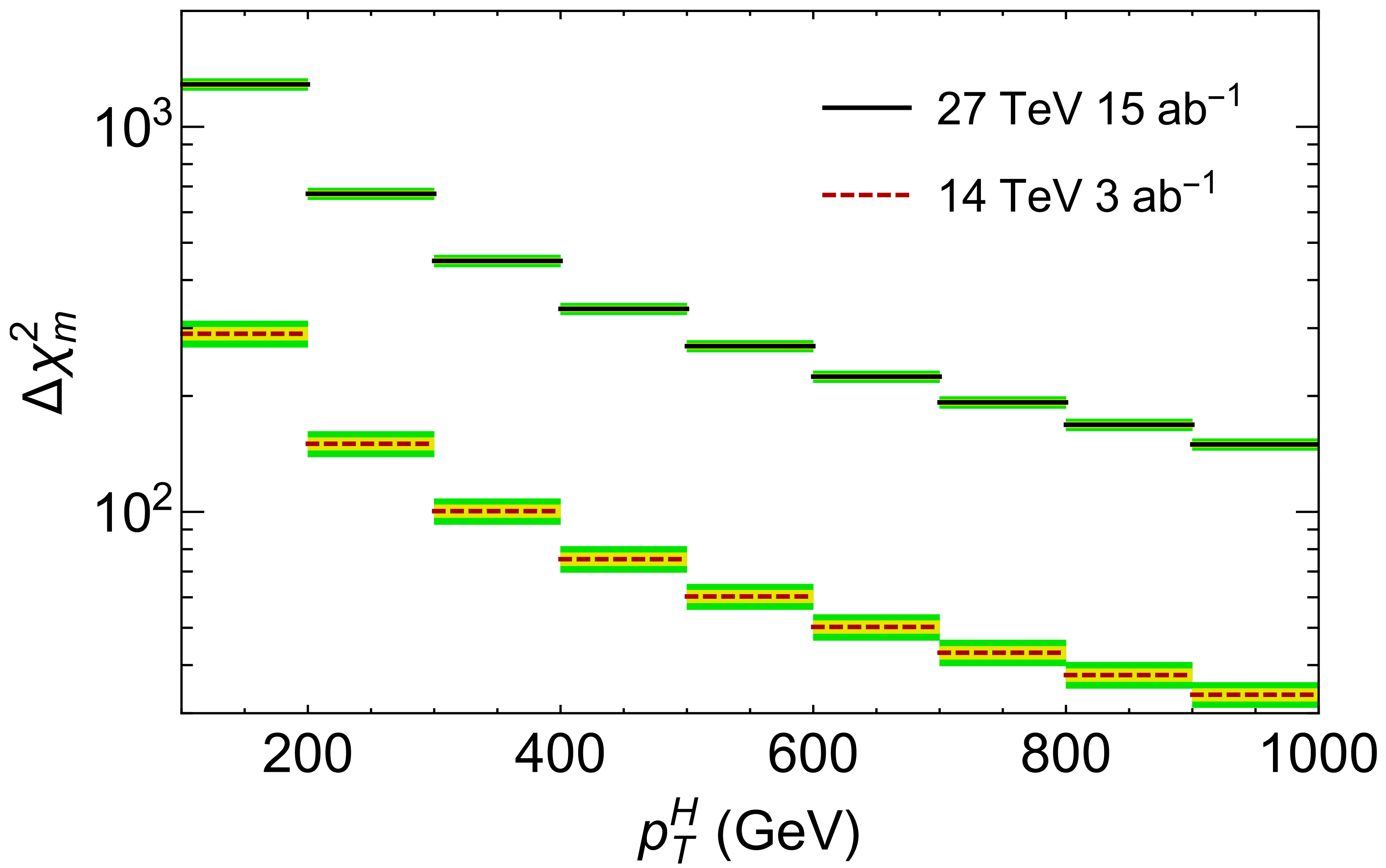
Chi Square

- Chi square per degree of freedom is a standard and simple test
- Use standard Poisson statistics to calculate

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

- Lets look at the results but keep in mind we need a slightly better statistical test.

Chi Square



27 TeV 15 ab^{-1}
14 TeV 3 ab^{-1}
10^3
10^2
$\Delta\chi^2_m$
200
400
600
800
1000
p_T^H (GeV)

Kullback-Leibler (KL) Divergence

KL Divergence

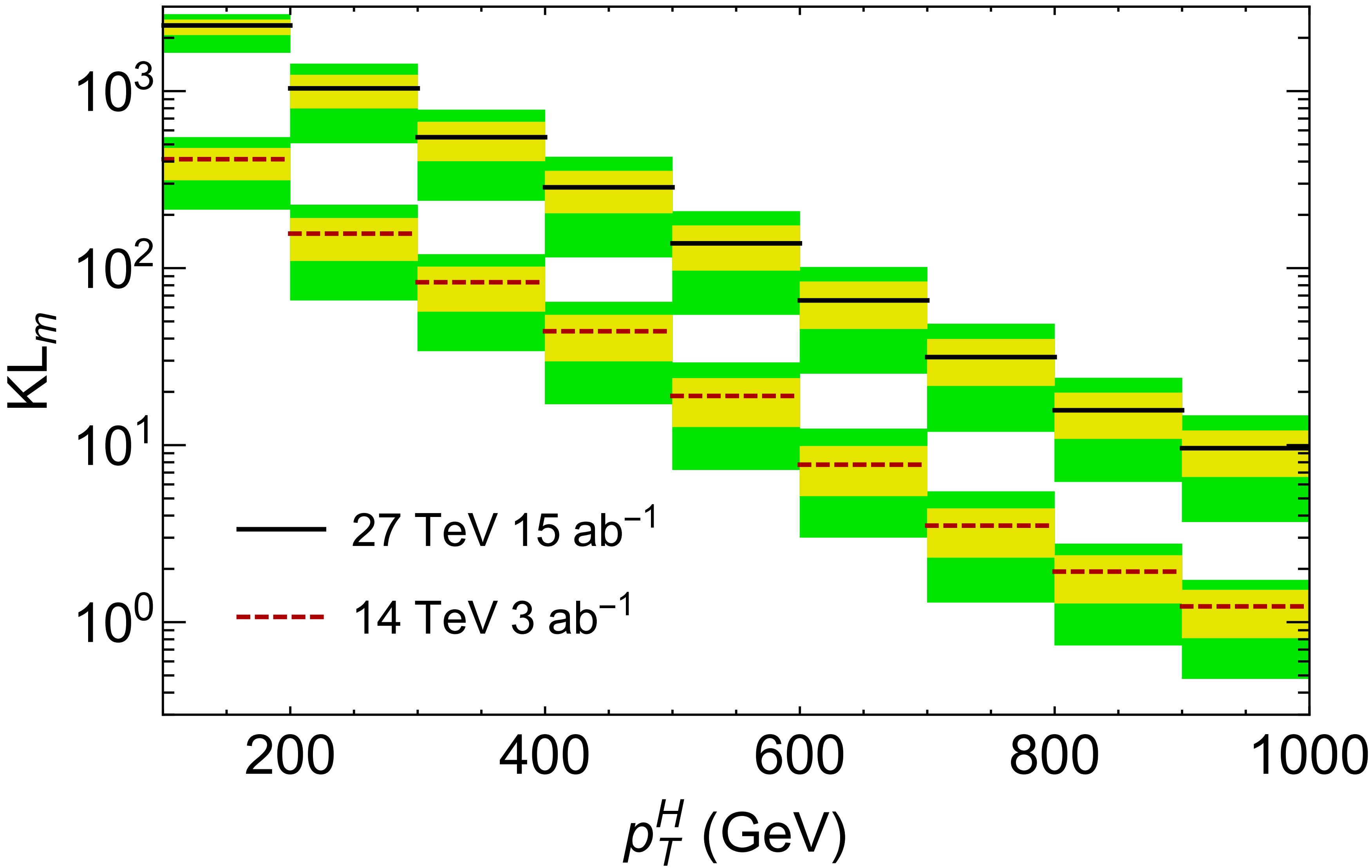
$$p_i^{\leq m} = \prod_{\substack{\text{6 signal} \\ \text{categories}}} \frac{\text{Pois}(n_{obs,i} | S_i + B_i)}{\sum_{l=1}^{m} \text{Pois}(n_{obs,l} | S_l + B_l)}$$

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

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

- 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!

Any Questions?

$Z\,h$ and $W\,h$ Amplitudes

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

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

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

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

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

WZ, WW, and ZZ Amplitudes

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

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

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

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

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

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

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

Relevant Goldstone Amplitudes

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

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

$$\mathcal{A}(q_-\bar{q}_+ \to G^\pm h) = \mp i\frac{e^2}{2\sqrt{2}s_W^2}\sin\theta,$$

$$\mathcal{A}(q_-\bar{q}_+ \to G^\pm G^0) = \frac{e^2}{2\sqrt{2}\, s_W^2}\sin\theta,$$

$$\mathcal{A}(q_+\bar{q}_- \to G^+ G^-) = -i\,\frac{e^2 Q_q}{2\, c_W^2}\sin\theta,$$

$$\mathcal{A}(q_-\bar{q}_+ \to G^+ G^-) = -i\,\frac{e^2\, T_3^q}{6\, c_W^2 s_W^2}\left(3\, c_W^2 + 2\, T_3^q s_W^2\right)\sin\theta.$$

	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

	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

	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