Prospects for New Physics Searches in the ssWW Channel for HL-LHC

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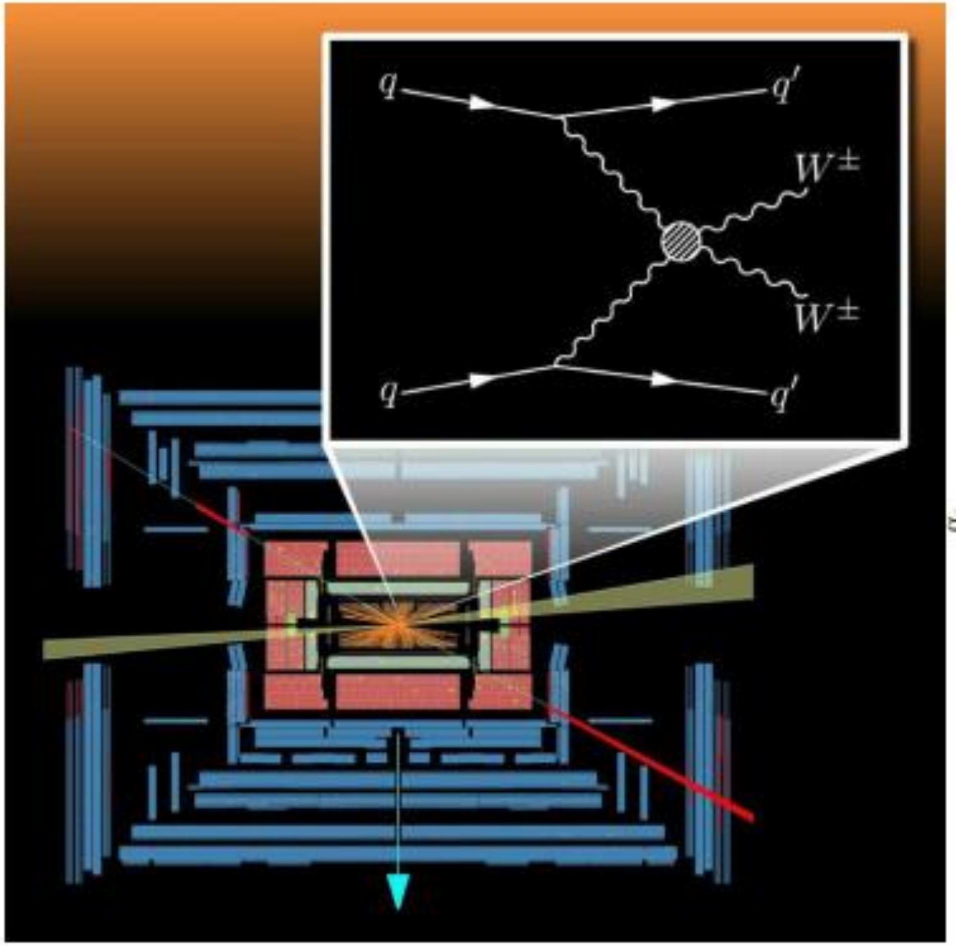
Introduction and Motivation

- With the most recent LHC 8 TeV proton-proton collision experimental data, we recently witnessed for the first time the production of electroweak same-sign WW boson scattering (ssWW-EW) and gave us our first insights into anomalous Quartic Gauge Coupling (aQGC) limits.
- This is exciting because it's a SM process that produces Vector Boson Scattering (VBS), which violates unitarity at ~1 TeV
  - The Higgs may provide a mechanism to conserve unitarity at higher energies
  - Alternatively, there may be new physics to conserve unitarity for electroweak symmetry breaking.



VBS ssWW-EW

- We have chosen to study fully-leptonic decay channels since they don't suffer from high top-antitop quark background.
- Specifically, we the pick ssWW-EW process because it has the highest signal-to-background ratio.

Final state	Process	VVjj-EW	VVjj-QCD
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$ (same sign, arbitrary flavor)	$W^{\pm}W^{\pm}$	19.5 fb	18.8 fb
$\ell^{\pm}\nu\ell'^{\mp}\nu' jj$ (opposite sign)	$W^{\pm}W^{\mp}$	91.3 fb	3030 fb
$\ell^{+}\ell^{-}\nu'\nu' jj$	ZZ	2.4 fb	162 fb
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2 fb	687 fb
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp} jj$	ZZ	1.5 fb	106 fb

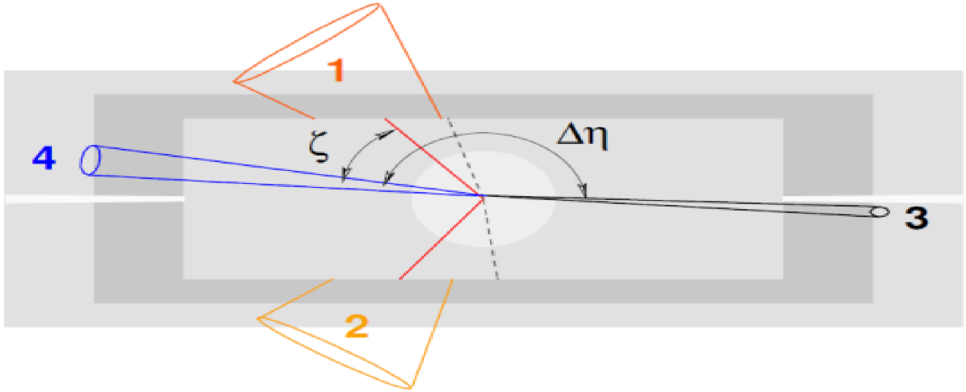
(8 TeV)

➔ p p -> $W^{\pm}$ $W^{\pm}$ + j j -> $l^{\pm}$ υ $l^{\pm}$ υ + j j

VBS ssWW-EW

- Characteristic signature
  - Two forward “tagging jets”
    - $|\Delta\eta| \geq 2.5$ and $\eta_{j1} \times \eta_{j2} < 0$
    - Large invariant mass M_{jj}
  - More central same-sign lepton pair

➔ allows for efficient reduction of SM backgrounds



- Two analysis regions for this study
  - The “inclusive analysis region” (a.k.a. looser cut) is defined as the region where the two jets have an invariant mass $m_{jj} \geq 500$ GeV to measure the fiducial cross section.
  - The “VBS analysis region” (a.k.a. pure signal) imposes an extra cut that the jets are well separated in rapidity ($|\Delta\eta| > 2.4$) to extract only the ssWW-EW signal.

EFT

- In the generic form of the EFT Lagrangian only operators of even dimensions are desired if lepton and baryonic number are to be conserved.
- While the dimension-6 operator does provide some aQGC processes in addition to aTGC, it doesn't allow for many, for example neutral gauge boson processes.
- The dimension-8 operator is the lowest order term solely for aQGC, our focus for new physics at the LHC.

Dim-6 Dim-8

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \beta_1 \mathcal{L}'_0 + \sum_i \alpha_i \mathcal{L}_i + \frac{1}{\Lambda} \sum_i \alpha_i^{(5)} \mathcal{L}_i^{(5)} + \frac{1}{\Lambda^2} \sum_i \alpha_i^{(6)} \mathcal{L}_i^{(6)} + \frac{1}{\Lambda^4} \sum_i \alpha_i^{(8)} \mathcal{L}_i^{(8)} + \ldots$$

Dim-6 Dim-8

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2} \mathcal{O}_i + \boxed{\sum_{j=0,1} \frac{f_{S,j}}{\Lambda^4} \mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4} \mathcal{O}_{M,j}}$$

EFT

- Dim-8: $$\sum_{j=0,1} \frac{f_{S,j}}{\Lambda^4} \mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4} \mathcal{O}_{M,j}$$

$$\left.\begin{aligned} \mathcal{O}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\ \mathcal{O}_{S,1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \end{aligned}\right\} \text{Higgs Fields}$$

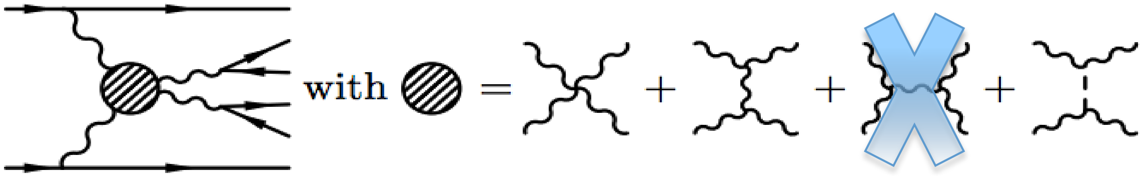
$$\left.\begin{aligned} \mathcal{O}_{T,0} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] \\ \mathcal{O}_{T,1} &= \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] \\ \mathcal{O}_{T,2} &= \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right] \end{aligned}\right\} \text{Gauge Boson Fields}$$

$$\left.\begin{aligned} \mathcal{O}_{M,0} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\ \mathcal{O}_{M,1} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\ \mathcal{O}_{M,6} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right] \\ \mathcal{O}_{M,7} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right] \end{aligned}\right\} \text{Higgs and Gauge Boson Fields}$$

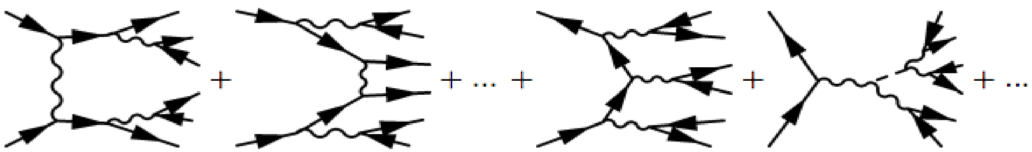
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

$W^{\pm}W^{\pm}$ + jj -> $l^{\pm}\upsilon l^{\pm}\upsilon$ + jj Feynman Diagrams

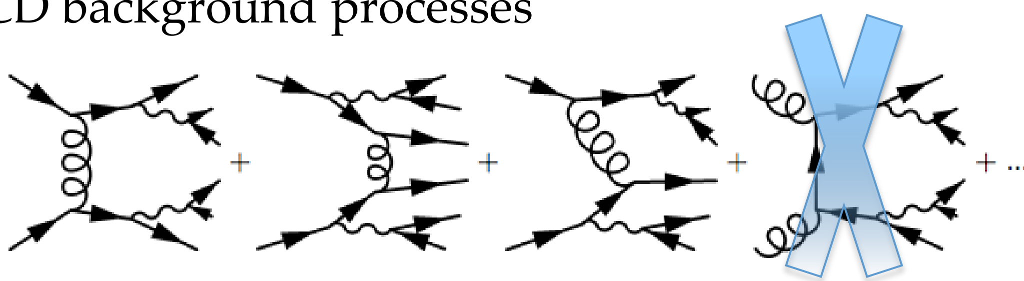
- ssWW-EW VBS processes with quartic boson couplings



- ssWW-EW processes that give same end result but are not VBS



- ssWW-QCD background processes



  – Some diagrams do not contribute to the final $l^{\pm}\upsilon l^{\pm}\upsilon$ state. The absence of QCD diagrams with initial gluon-gluon states improves the signal to background ratio.

Simulation Procedure

- We simulate VBS ssWW-EW at 14 TeV
- The new physics candidate signals and backgrounds are created by Madgraph through Monte Carlo simulations, and parton showered through Pythia8.
- The detector smearing is simulated using Delphes with both 0 pileup and the more realistic 80 pileup.
- The WZ (lllv final state) and the ssWW-QCD were the only samples generated. The rest were scaled accordingly by a factor of 1.71, the best estimate given the data from the 8 TeV results.
- Use Root for analysis cuts and extrapolate the yield of the HL-LHC at 3000 fb^{-1} using the following formula:

$$Event\,Yield = \frac{Cross\,Section * Luminosity * Analysis\,Cuts}{Number\,of\,Events}$$

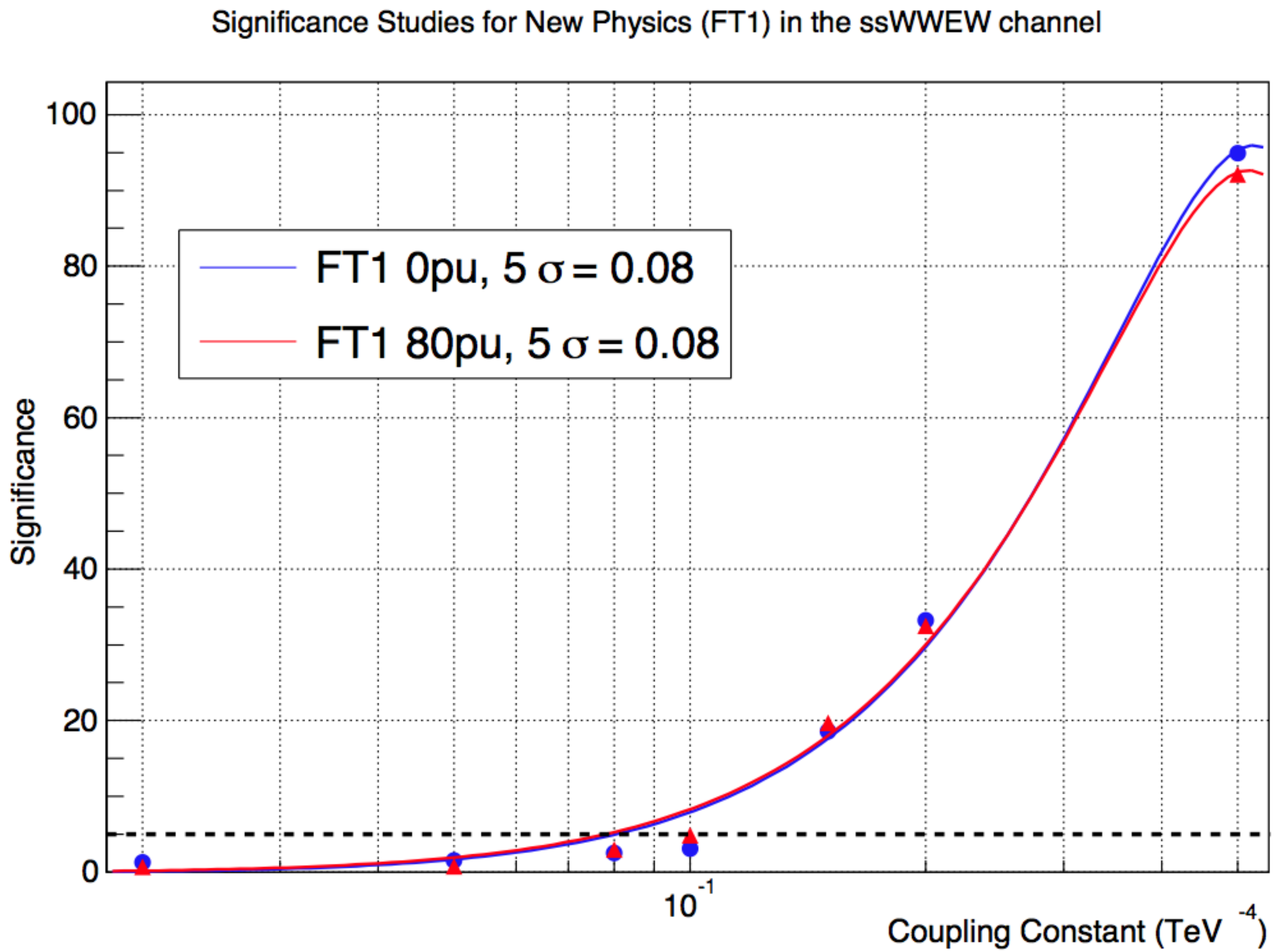
- Look for a 5σ significance with a combination of the log likelihood ratio and the frequentist method.

MadGraph + Pythia8 → **Delphes 0pu, 80pu** → **Root: Analysis and 5σ significance**

New Physics in FT1 0 vs 80 pu

Coupling Constant (TeV^4)	Cross Section (fb)	Event Yield (0 Pileup)	Event Yield (80 Pileup)
0.005	14.49	4079	2211
0.01	14.52	3866	2105
0.02	14.54	4052	2229
0.05	14.52	4128	2158
0.08	14.6	4110	2195
0.1	14.61	4184	2339
0.15	14.78	4187	2306
0.2	15.1	4444	2582
0.5	18.53	5027	3397
SM	14.48	4064	2181

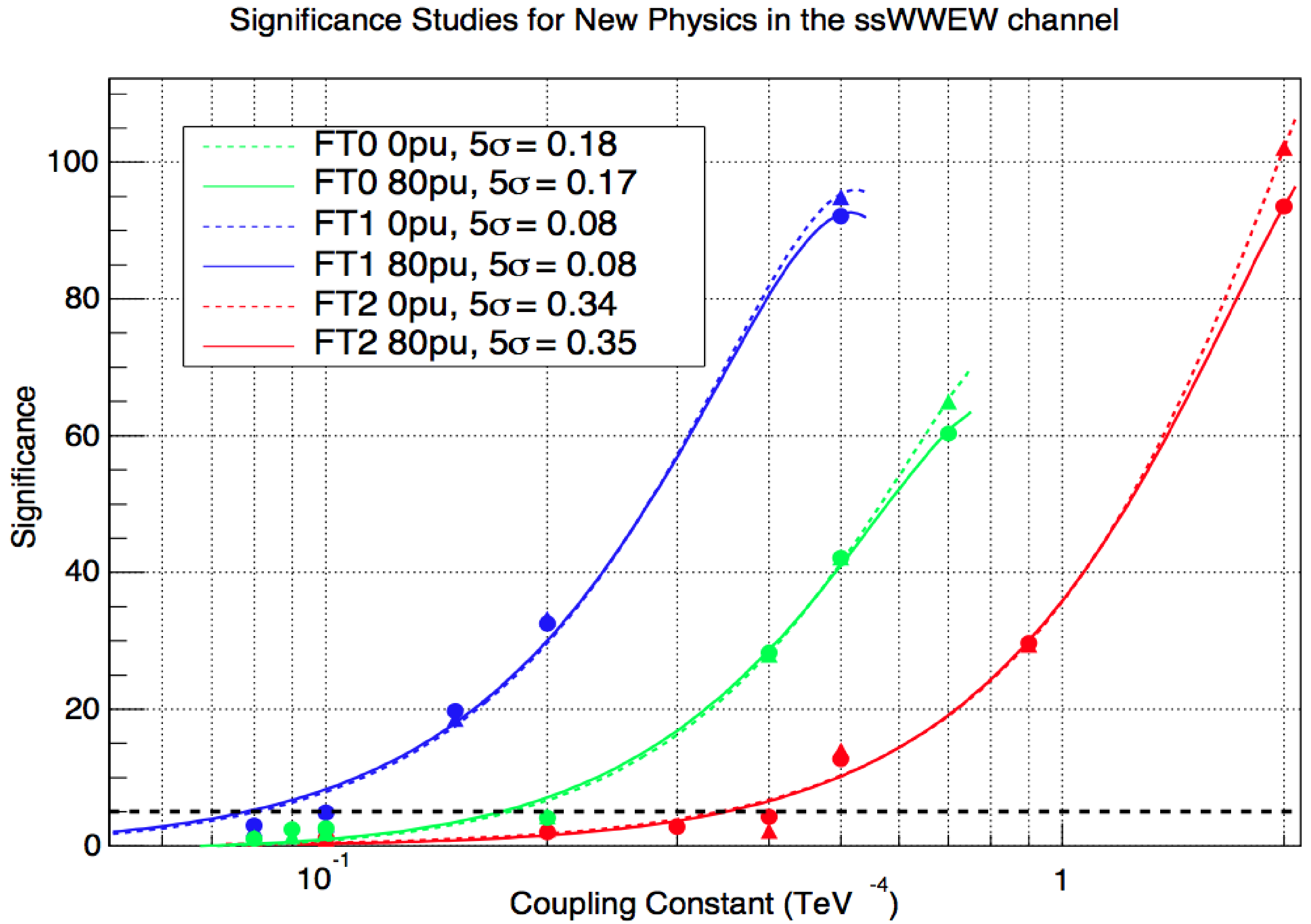
FT1 New Physics Significance



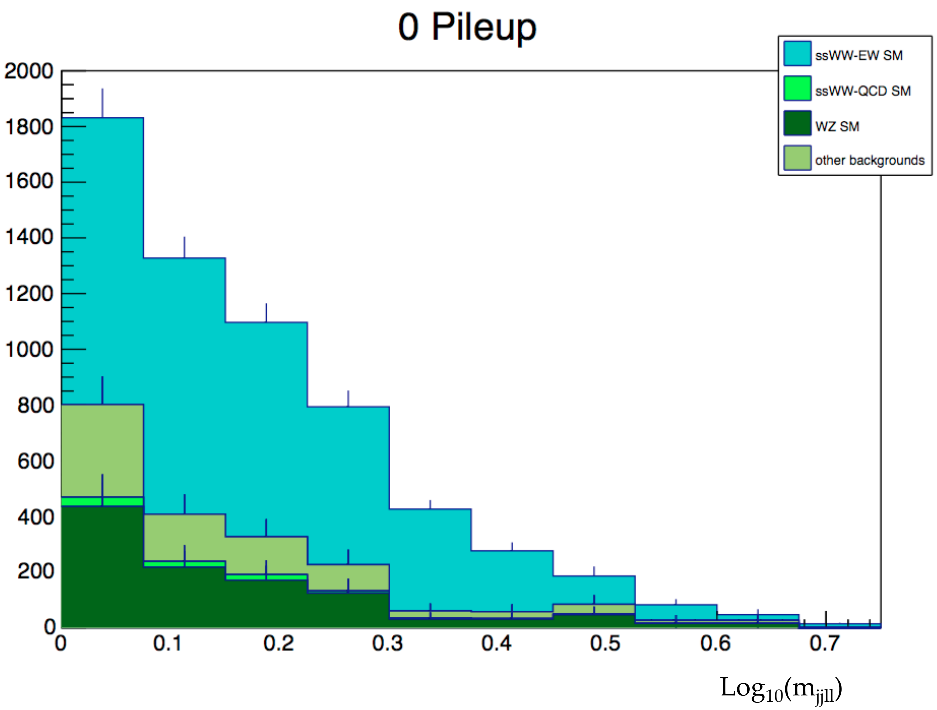
- Significance calculated by log likelihood ratio / frequentist concatenation

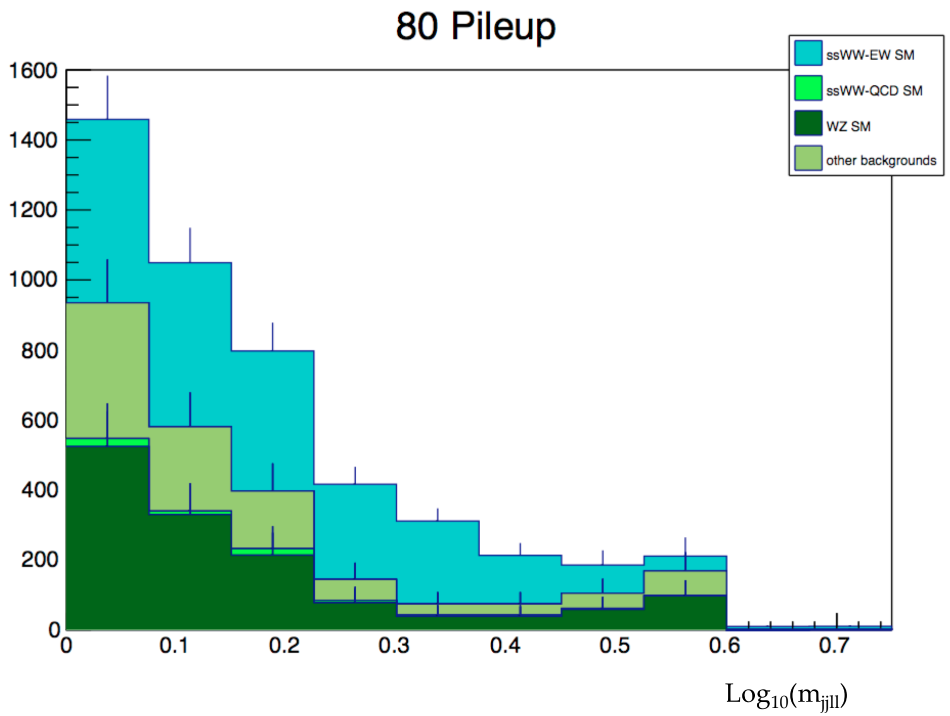
FT (Gauge Field Only) New Physics

- FT1 is the shows more sensitivity to new physics by a factor 2
- Is it attainable?



SM Signal: 0 vs 80 pileup

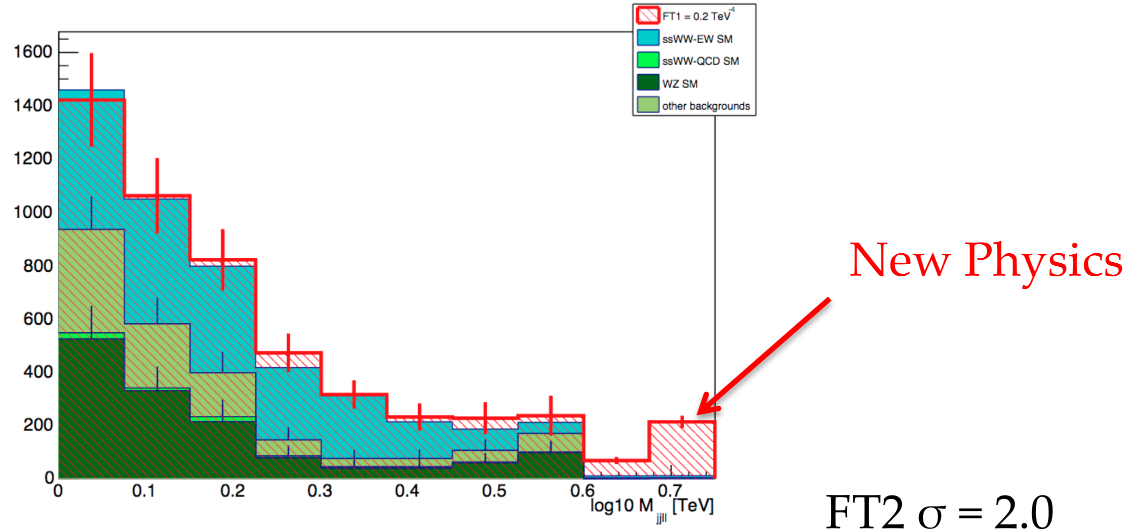




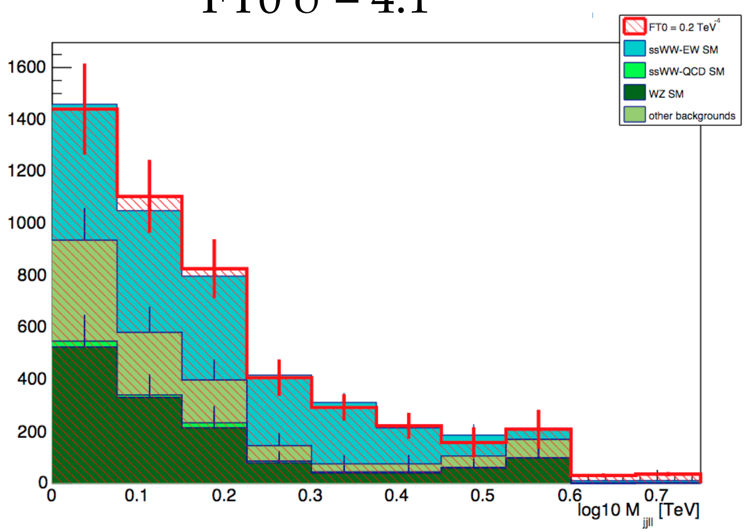
- 14 TeV signal at 3000 fb^{-1} luminosity
- Lower ratio of signal to background at 80 pileup
- Expect to see new physics in the last few bins

FT Signal at 0.2 TeV^{-4} with 80 pu

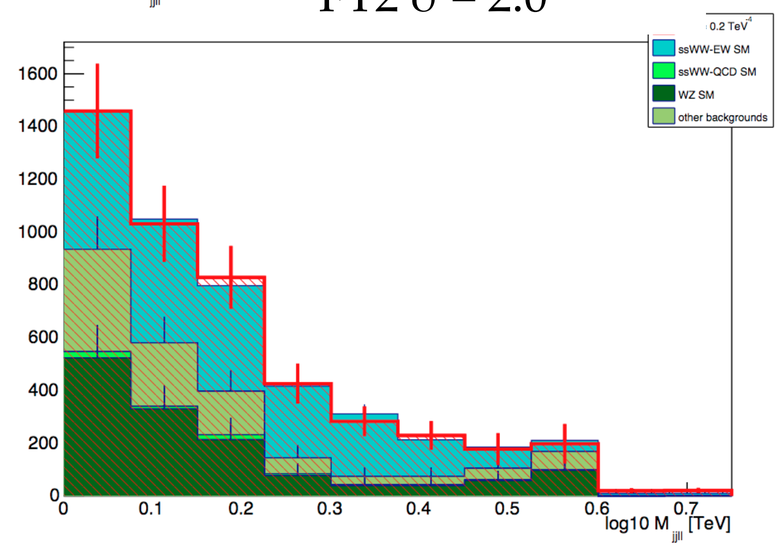
FT1 $\sigma = 33.2$



FT0 $\sigma = 4.1$



FT2 $\sigma = 2.0$



Conclusion

- Summary
  - There is promising potential to find New Physics in the ssWW-EW channel
    - High Signal to Noise Ratio
    - aQGC allows for the study of dimension-8 operators in the Lagrangian
  - FT1 is the most promising Gauge Field for new physics discovery.
- Plans
  - Continue to explore the Higgs Fields (FS0, FS1) and the Higgs and Gauge Fields (FM0, FM1, FM6, FM7)
  - Redo current work with new analysis cuts that are currently being developed.

Traveling Europe

Backup

Analysis Cuts

- Leptons
  - Exactly 2 same charge leptons
  - Transverse momentum $p_T > 25$ GeV
  - $|\eta| < 4.0$
  - Single lepton trigger
  - Third lepton veto
- Jets
  - At least 2 jets of high transverse momentum ($p_T > 30$ GeV)
  - $|\eta| < 4.5$
- Other Cuts
  - $m_{ll} > 20$ GeV
  - Lepton centrality > 0.2
  - $m_{jj} > 900$ GeV
  - $|\Delta\eta_{jj}| < 2.4$