aQGC *Anomalous quartic couplings*

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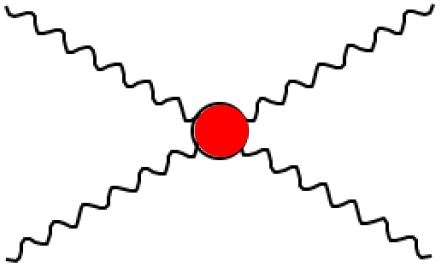
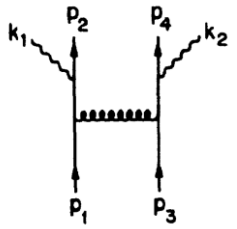


- *No new resonance found so far, after Higgs discovery*
  - ➔ *need to search for new physics by testing SM nature of Higgs*
  - *Couplings?*
  - *Unitarity in VV scattering, non-resonant excess?*
    - *High QCD background (gluon exchange diagrams) in pp colliders, absent in ep colliders*



Some references:

- CMS: same-sign leptons in WW scattering
  - 8 TeV: 1410.6315
  - 13 TeV: 1709.05822
- CMS: 4leptons, 1708.02812
- MadGraph FeynRules: feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling
  - See quartic.pdf
  - Degrande et al., 1205.4231
- Eboli et al., hep-ph/0606118

- Dimension 8 operators
  - L_{S0}, L_{S1} : contain $D_\mu \phi$, present in SM, but strength can be anomalous
  - $L_{M0} - L_{M7}$: contain $D_\mu \phi$ and $B_{\mu\nu}, W_{\mu\nu}$
  - $L_{T0} - L_{T7}$: contain $B_{\mu\nu}, W_{\mu\nu}$

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

from quartic.pdf

Previous limits
(may not be latest results)

Table 2: Observed and expected 95% CL limits on the coefficients for higher-order (dimension-eight) operators in the effective field theory Lagrangian. The last column summarizes the previously observed limits obtained by the CMS Collaboration together with the appropriate reference.

	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})	Previously observed limits (TeV^{-4})
f_{S0}/Λ^4	$[-7.7, 7.7]$	$[-7.0, 7.2]$	$[-38, 40]$, [11]
f_{S1}/Λ^4	$[-21.6, 21.8]$	$[-19.9, 20.2]$	$[-118, 120]$, [11]
f_{M0}/Λ^4	$[-6.0, 5.9]$	$[-5.6, 5.5]$	$[-4.6, 4.6]$, [36]
f_{M1}/Λ^4	$[-8.7, 9.1]$	$[-7.9, 8.5]$	$[-17, 17]$, [36]
f_{M6}/Λ^4	$[-11.9, 11.8]$	$[-11.1, 11.0]$	$[-65, 63]$, [11]
f_{M7}/Λ^4	$[-13.3, 12.9]$	$[-12.4, 11.8]$	$[-70, 66]$, [11]
f_{T0}/Λ^4	$[-0.62, 0.65]$	$[-0.58, 0.61]$	$[-0.46, 0.44]$, [37]
f_{T1}/Λ^4	$[-0.28, 0.31]$	$[-0.26, 0.29]$	$[-0.61, 0.61]$, [37]
f_{T2}/Λ^4	$[-0.89, 1.02]$	$[-0.80, 0.95]$	$[-1.2, 1.2]$, [37]

From 1709.05822

$WZ \to WZ \to jj\,\ell\ell$

```
import model SM_LS012
define p = 21 2 4 1 3 -2 -4 -1 -3 5 -5
define j = p
define p = g u d s c b u~ d~ s~ c~ b~
define j = g u d s c b u~ d~ s~ c~ b~
generate p e- > j e- w- z QCD=0 NP=1, w- > j j, z > l+ l-
add process p e- > j e- w+ z QCD=0 NP=1, w+ > j j, z > l+ l-
output pe_SMLS012_NC_WZjjll
```

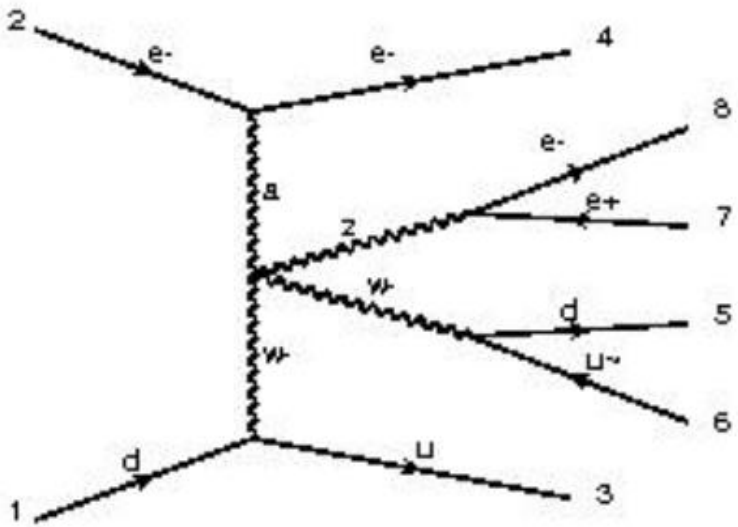


diagram 1 NP=0, QCD=0, QED=6

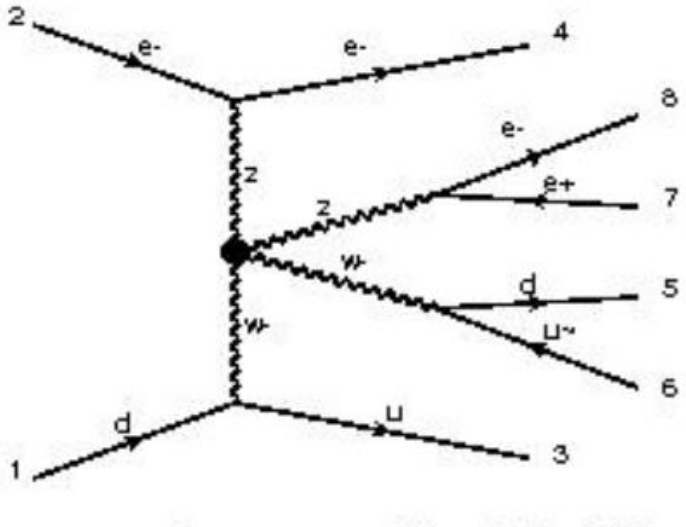
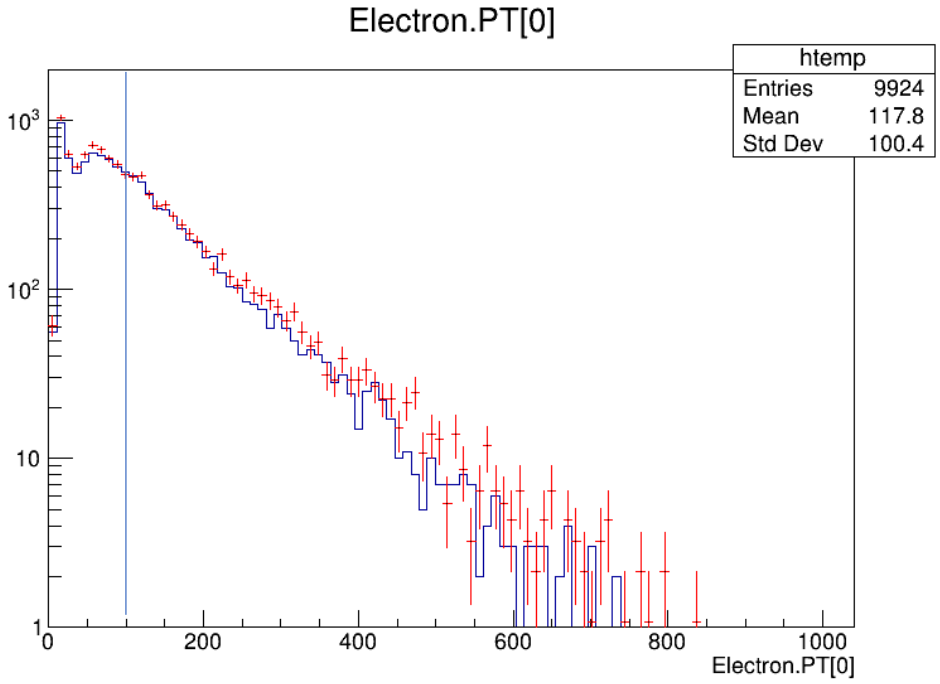
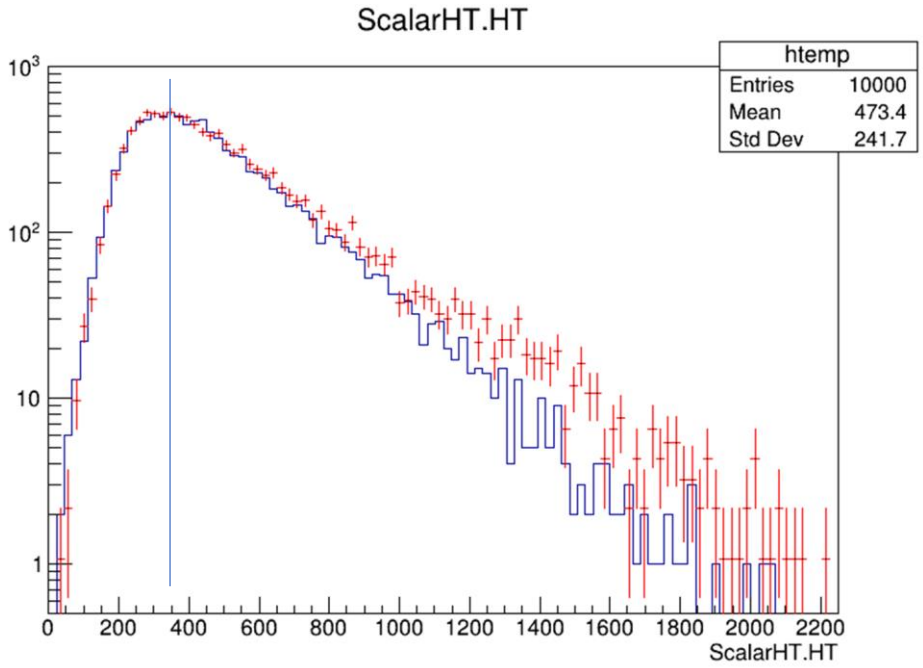


diagram 3 NP=1, QCD=0, QED=4

After Herwig7 → Delphes





Cuts1:

100.0 = ptl1min ! minimum pt for the leading lepton in pt

350.0 = htjmin ! minimum jet HT=Sum(jet pt)

- *0.147 fb excess with* $f_S = 100\ TeV^{-4}$
- *0.117 fb after cuts*

QCD background to $WZ \to WZ \to jj\,\ell\ell$

$e^- j\ jj\ Z \to e^- j\ jj\ ll$

generate p e- > j e- j j z, z > l+ l-

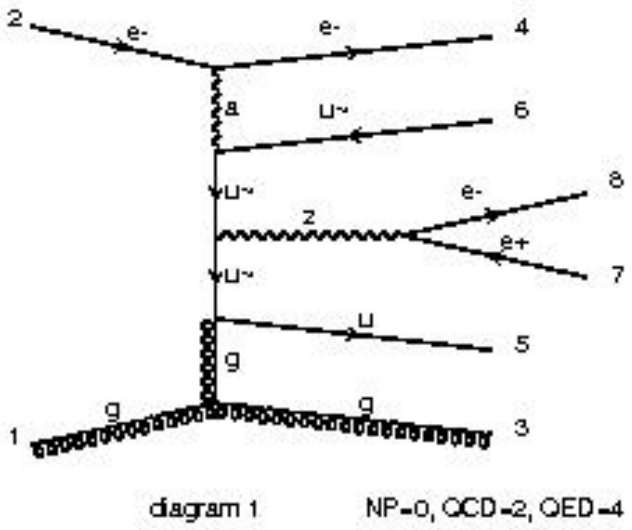


diagram 1 NP=0, QCD=2, QED=4

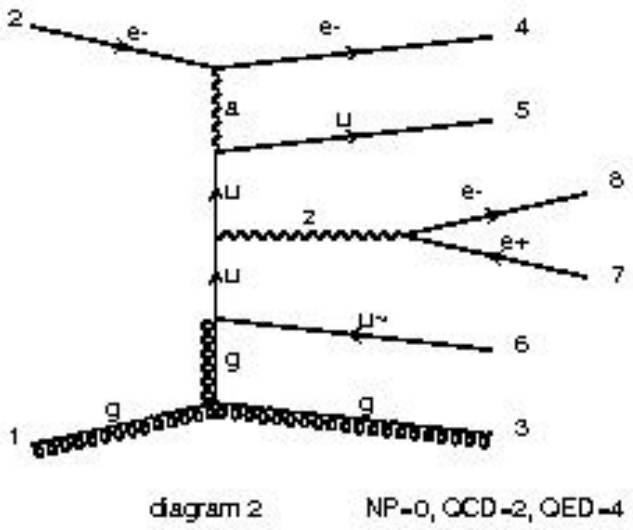


diagram 2 NP=0, QCD=2, QED=4

0.5 fb background after cuts

Same-sign *WW*

generate p e- > j vl l- vl~ l- vl~ QCD=0 NP=1

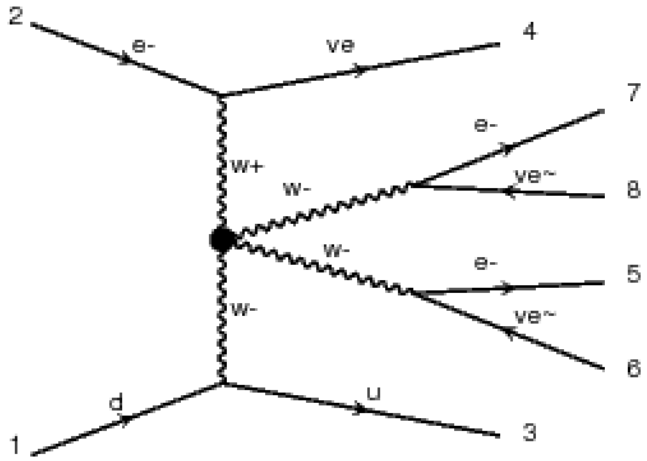


diagram 29 NP=1, QCD=0, QED=4

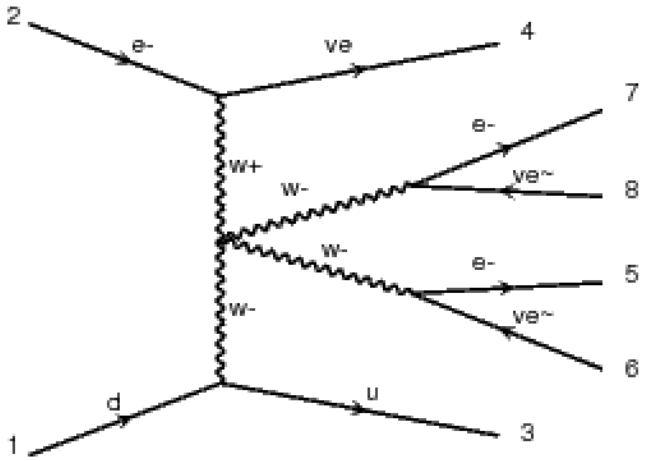


diagram 30 NP=0, QCD=0, QED=6

Signal and SM background extremely small after cuts

Important background, one neutrino: $p\ e^- \rightarrow j\ e^-\ e^-\nu$

generate p e- > j l- vl~ l-

~ 6 pb !

$W\gamma \rightarrow W\gamma$

generate p e- > j e- l- vl~ a QCD=0 NP=1add
process p e- > j e- l+ vl a QCD=0 NP=1

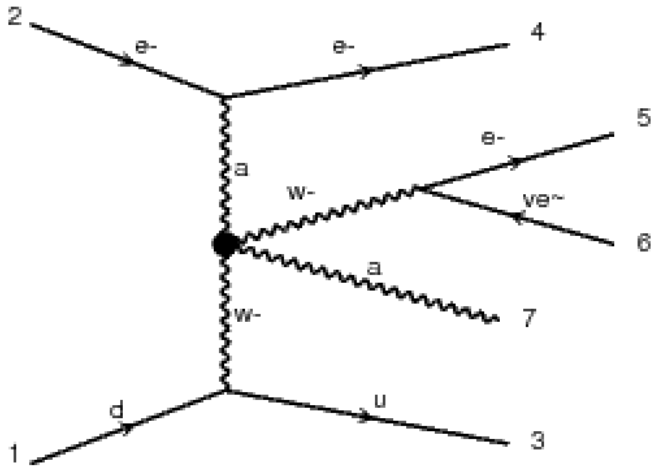


diagram 6 NP=1, QCD=0, QED=3

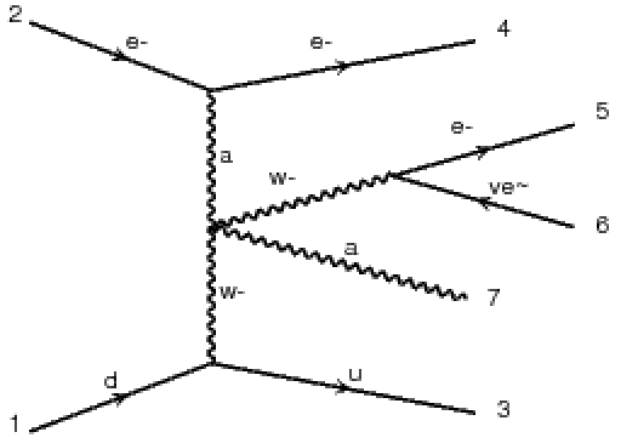


diagram 7 NP=0, QCD=0, QED=5

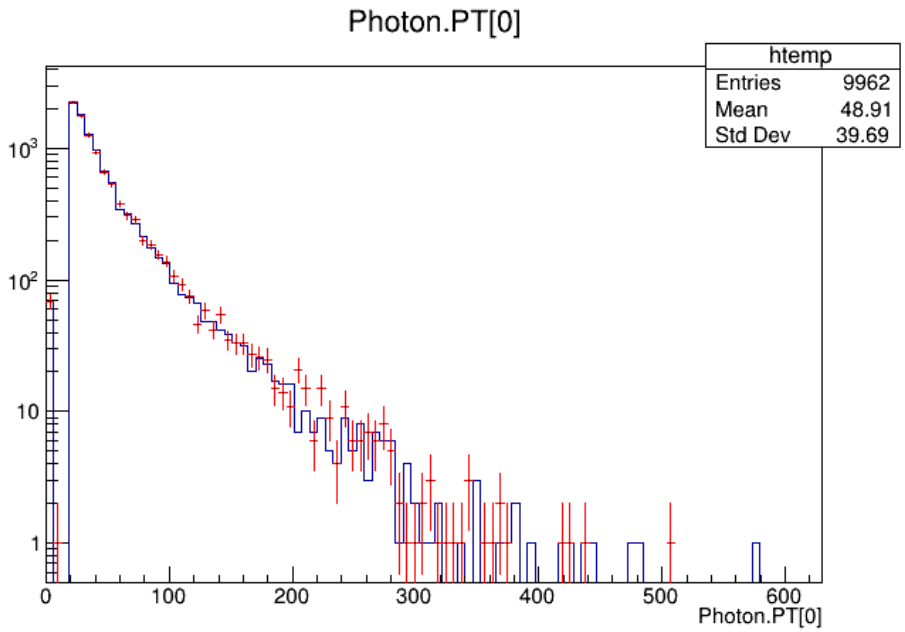
Signal: *1.02 fb after cuts, with* $f_{M0} = 100\ TeV^{-4}$
SM signal: *2.4 fb*

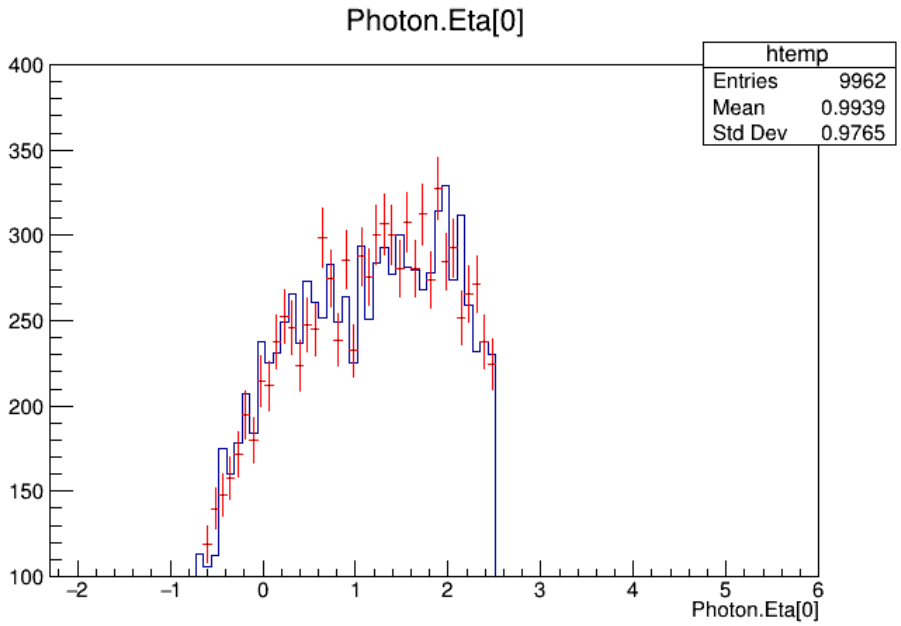
Background, 2l, 3 neutrinos:

generate p e- > j e- l- vl~ a vl vl~add process p
e- > j e- l+ vl a vl vl~

3 v background: *0.01 fb*

After Herwig7 → Delphes





No cuts:
- mmjj, mmbb = 10
- mmnl =15
- etaj = 10
- pta = 20

Cuts1:
- $p_T(\gamma) > 100$
- $|\eta(\gamma)| > 1$

Summary

WZ → jj ll	**f**				Bckg: p e- > j e- j j z, z > l+ l-		
		SM	SM+S	S	B	SM+B	σ_{stat} @ 1 ab^{-1}
no cuts	$f_s = 10^{-10}\ GeV^{-4}$	1.966	2.113	0.147			
cuts1	$f_s = 10^{-10}\ GeV^{-4}$	0.3481	0.4654	0.117	0.497	0.8451	3.95
Same-sign WW					Bckg: p e- > j l- vl~ l-		
		SM	SM+S	S	B	SM+B	σ_{stat} @ 1 ab^{-1}
no cuts	$f_s = 10^{-10}\ GeV^{-4}$	1.085	1.109	0.024	774.7	775.785	0.03
cuts1	$f_s = 10^{-10}\ GeV^{-4}$	0.02948	0.02988	0.00040	5.96	5.98948	0.01
WA					Bckg: j 2l 3v a		
		SM	SM+S	S	B	SM+B	σ_{stat} @ 1 ab^{-1}
no cuts	$f_M = 10^{-10}\ GeV^{-4}$	20.09	20.06	-0.03			
cuts1	$f_M = 10^{-10}\ GeV^{-4}$	2.387	3.406	1.019	0.0096	2.3966	19.55
	$f_M = 10^{-11}\ GeV^{-4}$	2.387	2.4	0.013	0.0096	2.3966	0.27

Sensitivity of operators

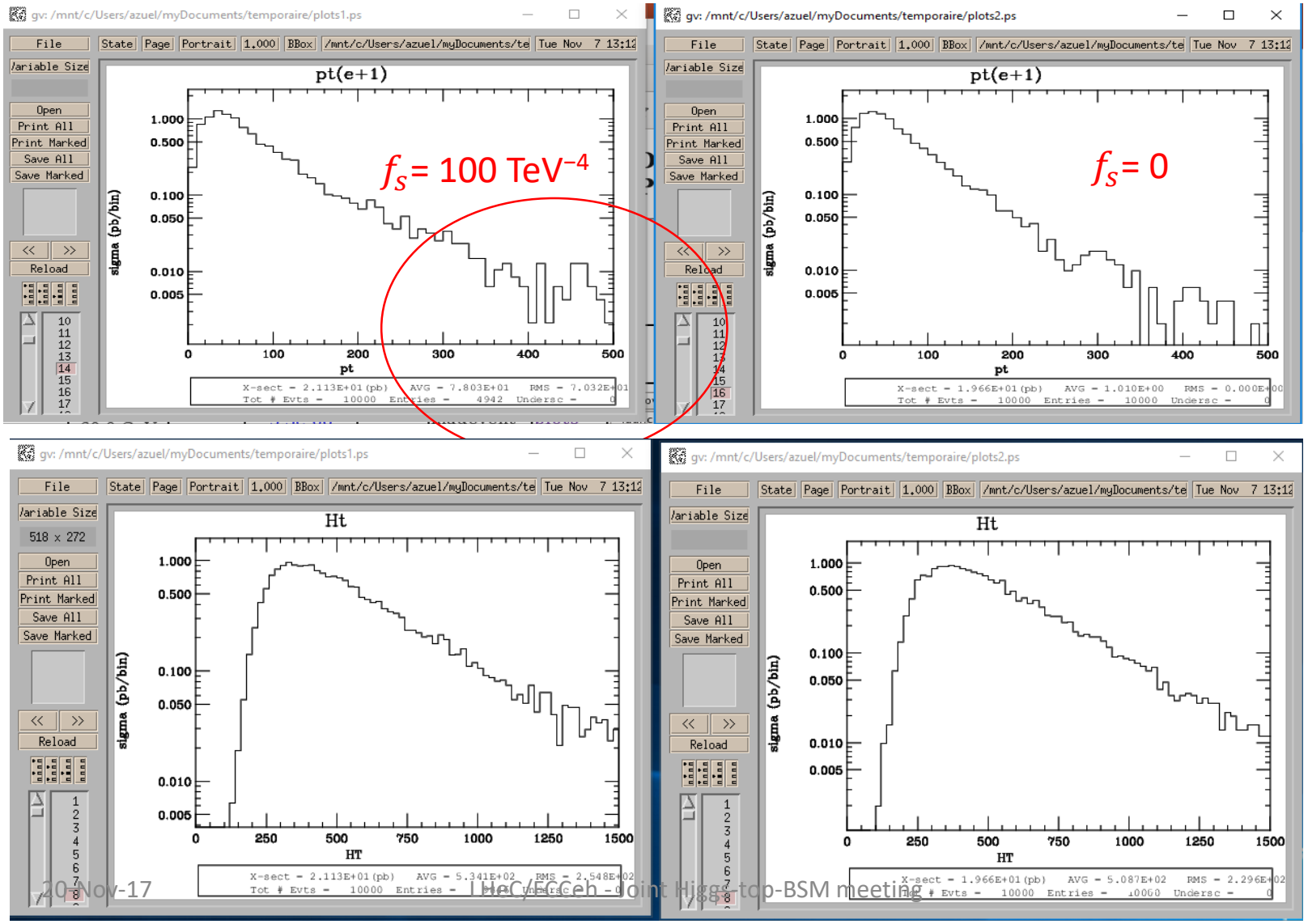
generate p e- > j ve V V, $f_X = 10^{-10}$ GeV^{-4}

	SM	LM0	LM1	LM2	LM3	LM4	LM5	LM7	LT0	LT1	LT2	LT5	LT6	LT7	LS0	LS1	LS2
W^+W^-	**0.053**	1.211	0.146	------	------	------	------	0.080	49.86	23.12	6.840	------	------	------	0.070	0.089	0.089
W^-W^-	**0.031**	0.058	0.041	------	------	------	------	0.037	1.887	8.430	0.948	------	------	------	0.044	0.032	0.032
W^-Z	**0.085**	0.123	0.101	0.101	0.092	0.142	0.097	0.095	2.757	7.072	0.864	0.648	0.713	0.192	0.089	0.086	0.088
$W^\pm\gamma$	**0.052**	0.509	0.505	0.694	0.586	0.525	0.511	0.504	1.470	2.986	0.769	7.043	9.599	1.832	------	------	------
ZZ	**0.021**	0.553	0.053	0.024	0.021	0.028	0.023	0.030	9.975	0.763	0.691	0.952	0.901	0.087	0.022	0.031	0.022
$\gamma\gamma$	**0.267**	0.270	0.267	0.315	0.271	0.270	0.267	0.268	1.191	0.340	0.330	10.14	1.019	0.931	------	------	------

ptjetmin > 20 GeV
backgrounds must be evaluated

conclusion

- *Very good signal to background ratio, compared to LHC*
- *But signal is at high mass, limited by cm energy*
- *Potential from $\gamma\gamma \rightarrow WW$?*

backup

$WZ \to WZ \to jj\,\ell\ell$