



# Full simulation results for IDM scalar searches at high energy CLIC

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# The Inert Doublet Model

SM-like Higgs:

$$\phi_{SM} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + h + i\xi) \end{pmatrix}$$

„Higgs boson”:  $h$

IDM Higgs:

$$\phi_D = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

New particles:  $H^\pm, H, A$

# The Inert Doublet Model

SM-like Higgs:

$$\phi_{SM} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + h + i\xi) \end{pmatrix}$$

„Higgs boson”:  $h$

IDM Higgs:

$$\phi_D = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

New particles:  $H^\pm, H, A$

- One of the simplest extensions of SM
- Additional scalars does not couple to fermions
- **The lightest new scalar H is stable**  
→ **good dark matter particle candidate**
- Some theoretical and experimental constraints already exist

Parameters  $M_{H^\pm}, M_H, M_A + 2$  coupling constants



5 free-parameter space

# Parameter space

Considered benchmark points from [JHEP 1812 \(2018\) 081](#), [arXiv:1809.07712](#),  
for two scenarios:

$$\begin{array}{ll}
 e^+e^- \rightarrow HA & e^+e^- \rightarrow H^+H^- \\
 \rightarrow HHZ^{(*)} & \rightarrow HHW^{+(*)}W^{-(*)}
 \end{array}$$

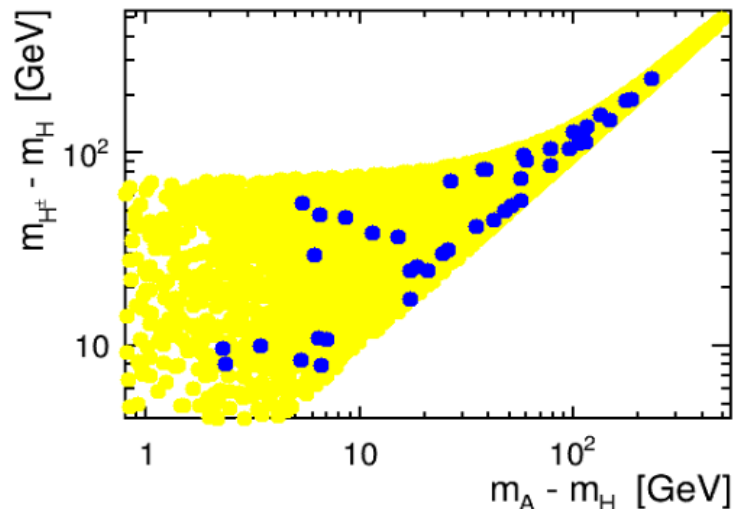
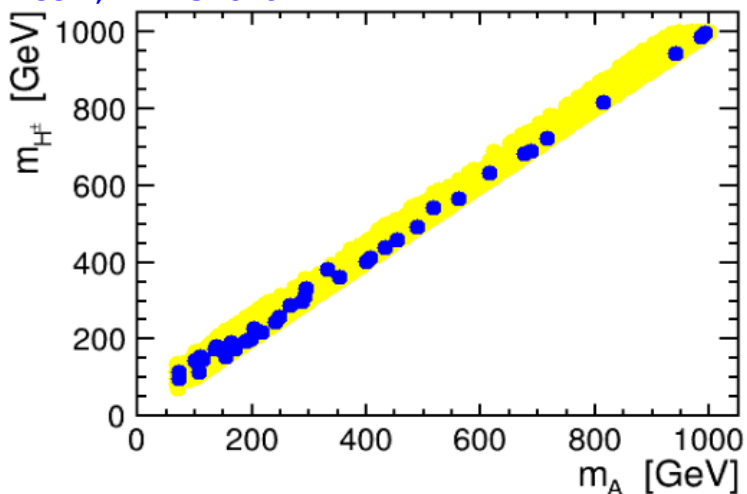
# Parameter space

Considered benchmark points from [JHEP 1812 \(2018\) 081, arXiv:1809.07712](#), for two scenarios:

$$e^+e^- \rightarrow HA \rightarrow HHZ^{(*)}$$

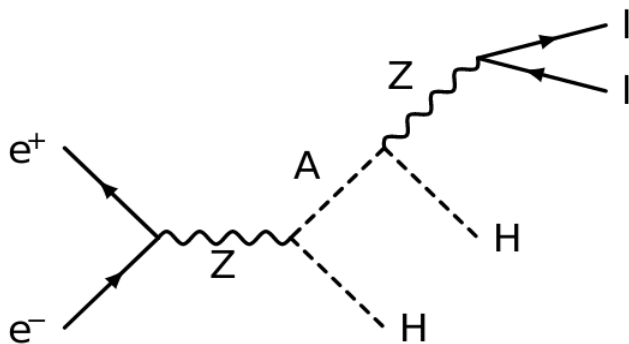
$$e^+e^- \rightarrow H^+H^- \rightarrow HHW^{(*)}W^{(*)}$$

A.F. Żarnecki, ALPS2019

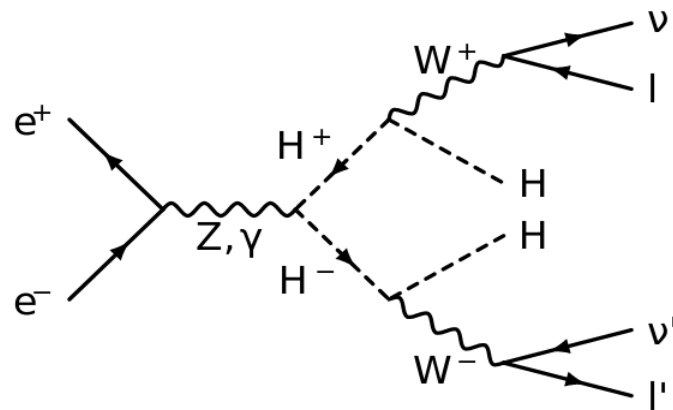


- Consistent with current theoretical and experimental constraints
- Masses up to 1 TeV
- Decay rates predicted from the SM parameters

# Previous strategy (fully-leptonic)



- **Same flavour** leptons
- $\mu\mu$  pair in the final state

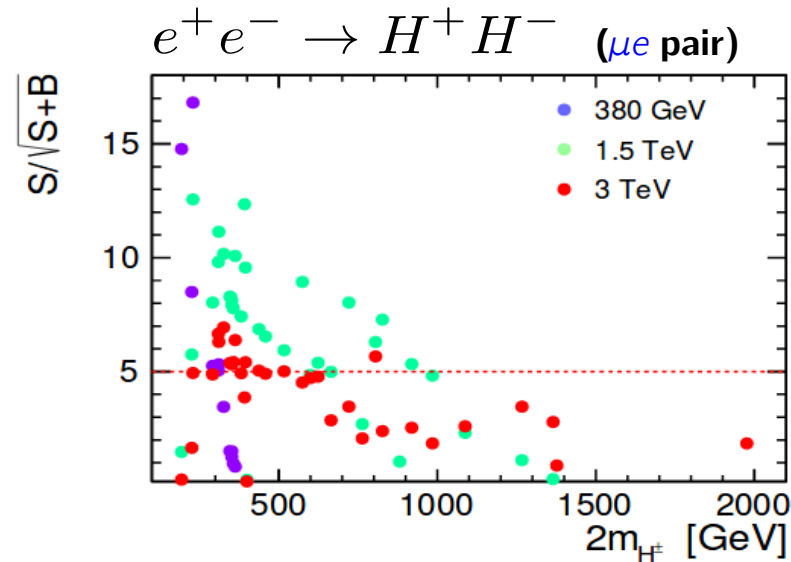
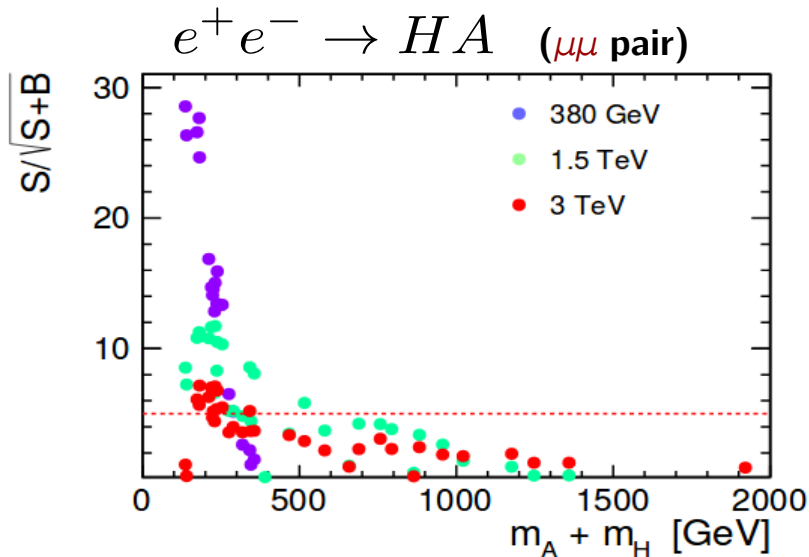


- **Different flavour** leptons
- $\mu e$  pair in the final state

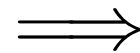
**Generator level cuts** reflecting detector acceptance  
Detector response/efficiency not included

JHEP 1907 (2019) 053, arXiv:1811.06952

# Previous results (fully-leptonic)



- Many high-mass points below  $5\sigma$  threshold
- No discovery potential for  $m_A + m_H > 550\text{GeV}$ ,  
 $m_{H^\pm} > 500\text{GeV}$

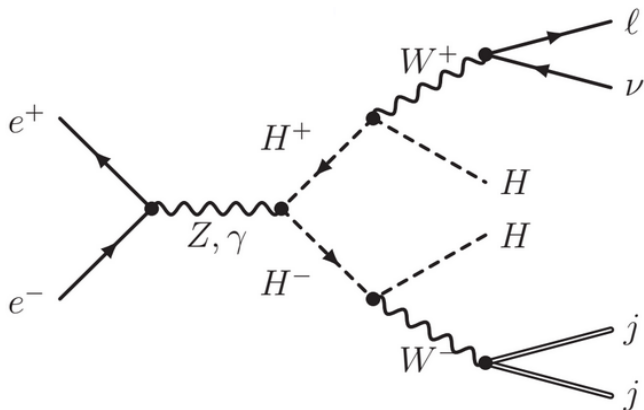


sensitivity limited  
by signal statistics

JHEP 1907 (2019) 053, arXiv:1811.06952

# Strategy (semi-leptonic)

Semi-leptonic channel  $\Rightarrow$  one order **higher statistics!**



Expected **signature** of the final state:

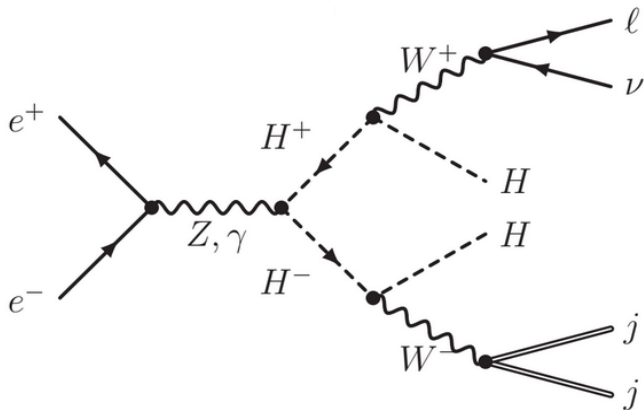
**One lepton**,  $\mu$  or  $e$ , and a **pair of jets**

Dominating background:

$qq\ell\nu$ ,  $qq\ell\ell$ ,  $qq\ell\nu\nu\nu$ ,  $qq\ell\nu\ell\nu$

# Strategy (semi-leptonic, fast sim.)

**Semi-leptonic** channel  $\Rightarrow$  one order **higher statistics!**



Expected **signature** of the final state:

**One lepton**,  $\mu$  or  $e$ , and a **pair of jets**

Dominating background:

$qql\nu$ ,  $qq\ell\ell$ ,  $qql\nu\nu\nu$ ,  $qql\nu\nu$

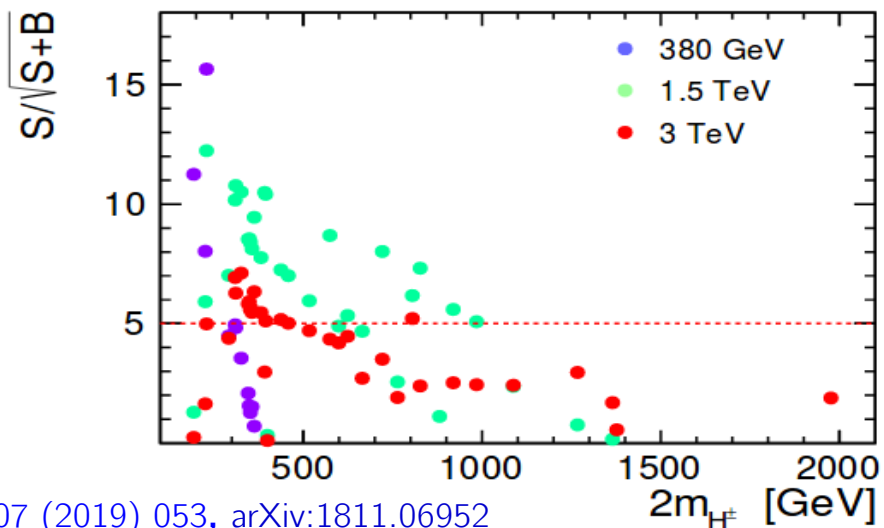
- **23 benchmark points** (BP) considered
- Event samples generated with **Whizard 2.7.0**
- Using CLIC beam spectra for **1.5 TeV (2000 fb<sup>-1</sup>)** and **3 TeV (4000 fb<sup>-1</sup>)**
- Assuming -80% beam polarisation

Output



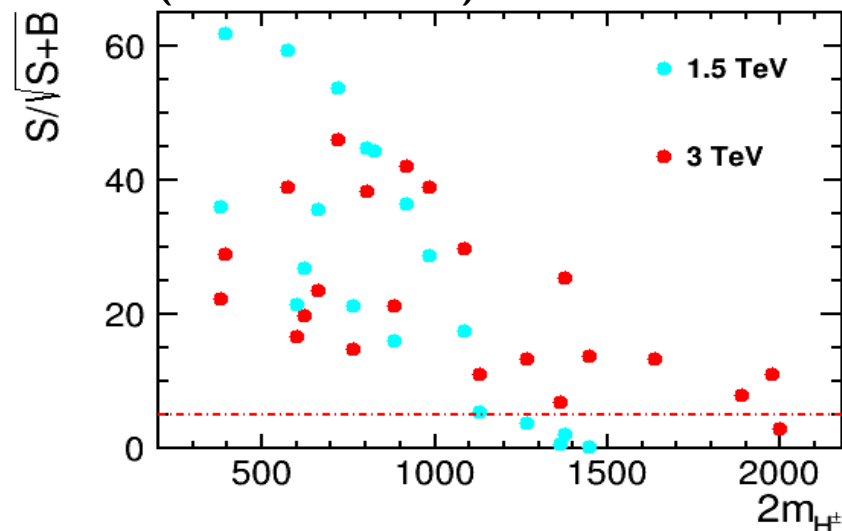
**DELPHES**  
fast simulation

## Full-leptonic channel results:



JHEP 1907 (2019) 053, arXiv:1811.06952

## Semi-leptonic channel results (fast-simulation):



- Big improvement, compared to the full leptonic channel
- **Four BP** below  $5\sigma$  at **1.5 TeV** (and four beyond kinematic reach)
- **Only one BP** (with the lowest cross-section) below  $5\sigma$  at **3 TeV**

Now, let's check the full simulation

Event samples generated with **WHIZARD 2.7.0** for CLICdet (model CLIC\_o3\_v14),  
Polarisation:  $P = -80\%$ , assumed luminosity: **2000 fb<sup>-1</sup>** (1.5 TeV) and **4000 fb<sup>-1</sup>** (3 TeV)

**Lepton reconstruction:** Isolated Lepton Finder

- 1.5 TeV: *SelectedPandoraPFOs* collection
- 3 TeV: *TightSelectedPandoraPFOs* collection

**Jet reconstruction:** Marlin Fast Jet (Pandora PFOs without isolated leptons)

	1.5 TeV				3 TeV			
Sample	<i>qqlv</i>	<i>qqll</i>	<i>ll</i>	<i>qqqq</i>	<i>qqlv</i>	<i>qqll</i>	<i>ll</i>	<i>qqqq</i>
Sample ID	14676, 14677	14692, 14693	14397	13769	14545, 14546	14654, 14655	14382	13394
Cross section [fb]	7001	2715	1406	1943.2	8672	3180	1664.98	902

# Strategy (semi-leptonic, full simulation)

**Lepton reconstruction:** Isolated Lepton Finder

- 1.5 TeV: *SelectedPandoraPFOs* collection
- 3 TeV: *TightSelectedPandoraPFOs* collection

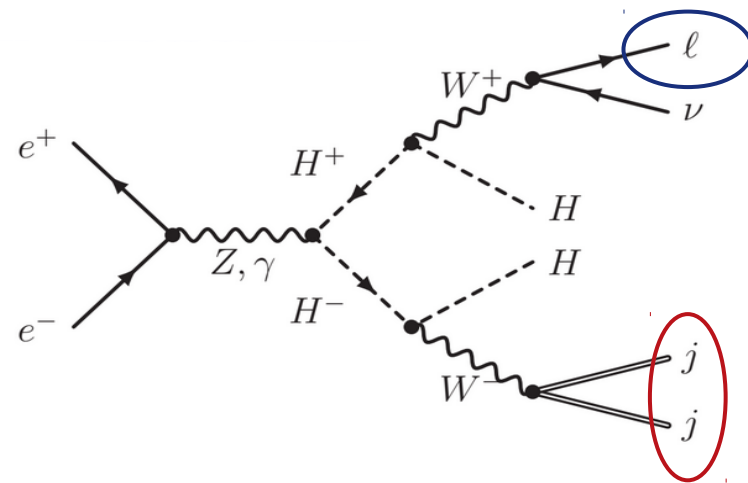
**Jet reconstruction:** Marlin Fast Jet (Pandora PFOs without isolated leptons)

**Only 5 IDM scenarios:** BP21, BP23, HP3, HP17, HP20

- wide range in  $m_{H^\pm}$  and  $\Delta m$
- background also limited

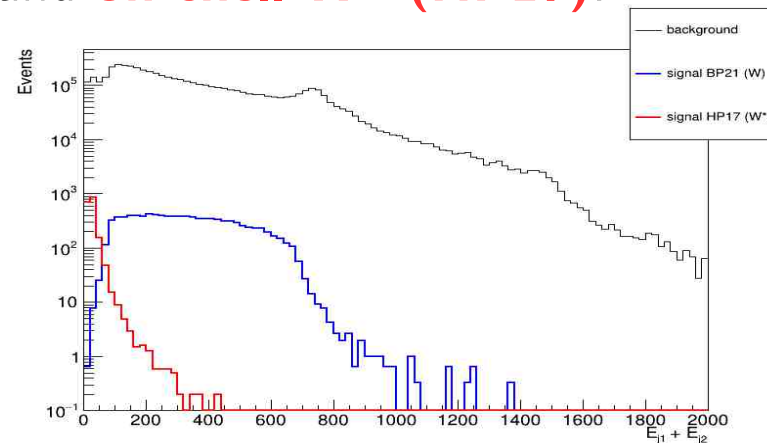
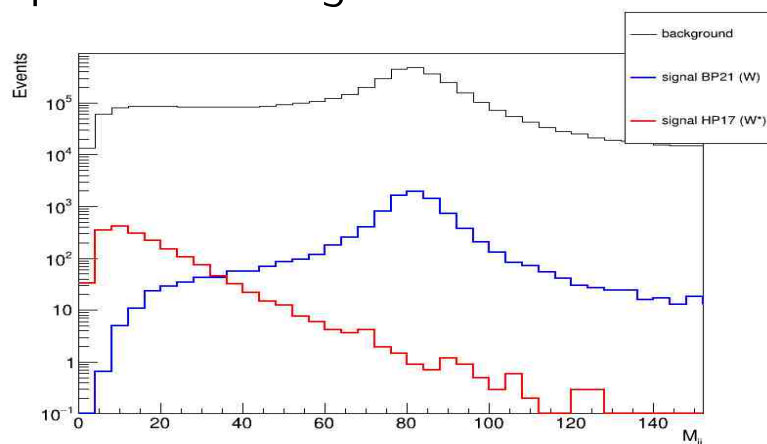
Require:

- exactly **one isolated lepton**
- **no isolated photons** over 10 GeV
- additional objects in the detector with  $p_T$  less than 20 GeV
- **two exclusive jets** (VLC:  $\beta = \gamma = 1$ ,  $R = 0.9$ ,  $R = 1.2$ )  
(1.5 TeV) (3 TeV)

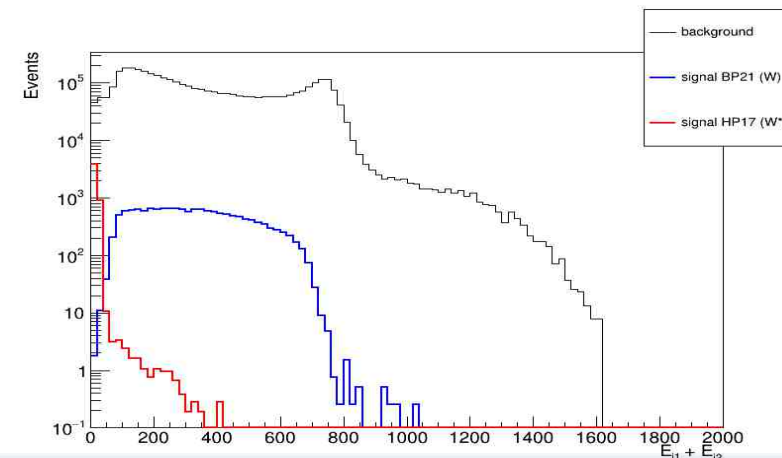
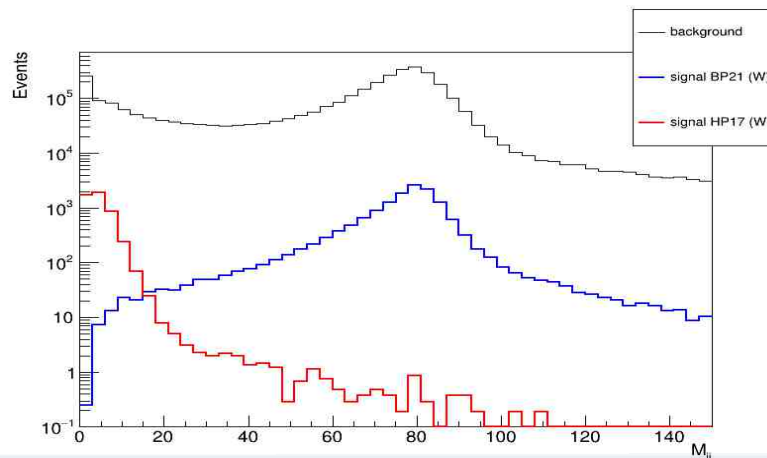


Examples of the signal for **on-shell  $W$  (BP21)** and **off-shell  $W^*$  (HP17)**:

full  
sim.

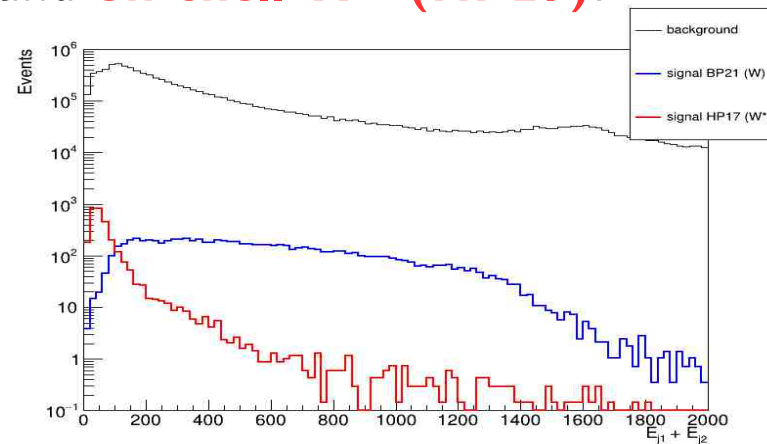
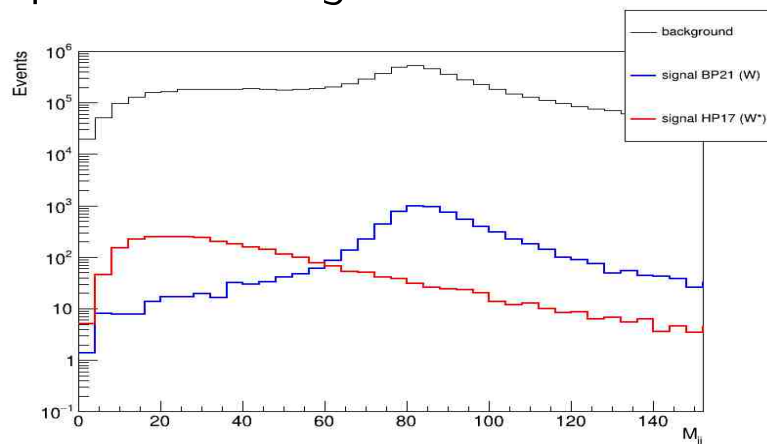


fast  
sim.

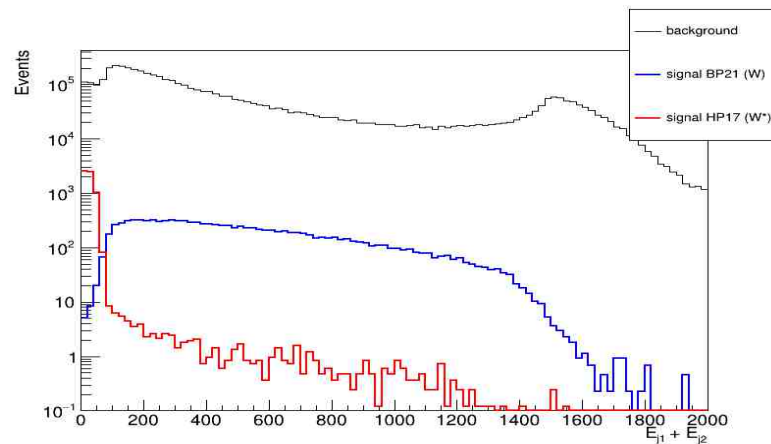
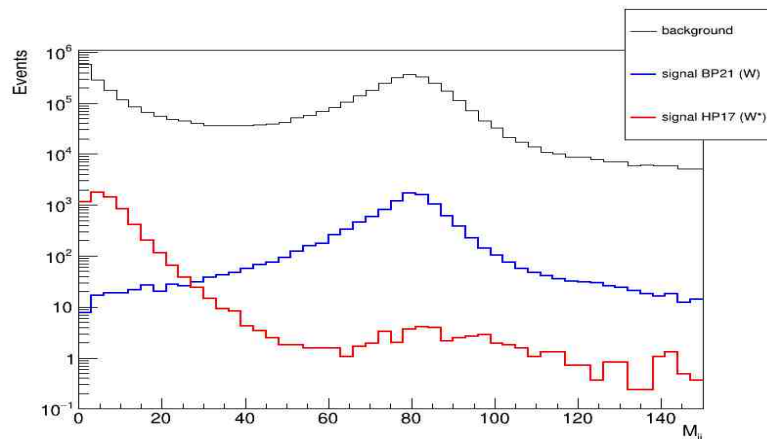


Examples of the signal for **on-shell  $W$  (BP21)** and **off-shell  $W^*$  (HP17)**:

full  
sim.



fast  
sim.



# Preselection results

## 1.5 TeV

$$M_{jj} > 3 \text{ GeV}, \quad E_\ell < 600 \text{ GeV}, \quad 2 \text{ GeV} < p_T^\ell < 550 \text{ GeV}$$

$$M_{miss} > 400 \text{ GeV}, \quad 0.2 < \theta_W < 2.94, \quad 0.25 < \theta_\ell < 2.89$$

channel	all exp. ev.	exp. ev. after preselec.	eff.
$H^+H^-$ (BP21)	16186	9100	56.2%
$H^+H^-$ (HP17)	4860	1588	32.7%
tot. backg.	26130400	1078272	5.3%
$qq\ell\ell$	5430000	232413	4.28%
$qq\ell\nu$	14002000	1002026	7.16%
$\ell\ell$	2812000	139586	4.96%
$qqqq$	3886400	12038	0.31%
signal/backg. (BP21)	0.00062	0.0084	
signal/backg. (HP15)	0.00019	0.0015	

- **Signal to background ratio** improvement

# Preselection results

## 3 TeV

$$M_{jj} > 2 \text{ GeV}, \quad E_{W_{\text{had}}} < 1300 \text{ GeV}, \quad E_\ell < 1000 \text{ GeV}, \quad p_T^\ell < 800 \text{ GeV}$$

$$0.3 < \theta_W < 2.84, \quad 0.5 < \theta_\ell < 2.64$$

channel	all exp. ev.	exp. ev. after preselect.	eff.
$H^+H^-$ (BP21)	16852	6461	38.34%
$H^+H^-$ (HP17)	6712	2016	30.04%
tot. backg.	57675918	1008067	1.75%
$qq\ell\ell$	12720000	203215	1.6%
$qq\ell\nu$	34688000	706843	2.04%
$\ell\ell$	6659918	83101	1.25%
$qqqq$	3608000	14908	0.41%
signal/backg. (BP21)	0.00029	0.0064	
signal/backg. (HP15)	0.00012	0.002	

- **Signal to background ratio** improvement

**BDT**, input variables:

$$M_{jj}, E_{jj}, \theta_{W^\pm},$$

$$p_T^j, \theta_j,$$

$$E_\ell, p_T^\ell, \theta_\ell,$$

$$\text{MET}, M_{\text{miss}}, E_{\text{flow}}^{\text{sum}},$$

$$\Delta\theta_{jW^\pm}, \Delta\phi_{jW^\pm}$$

## Separate trainings:

- for samples with **off-shell  $W^*$**
- for *samples with* ***on-shell  $W$***

Selection was NOT optimised for particular scenario!

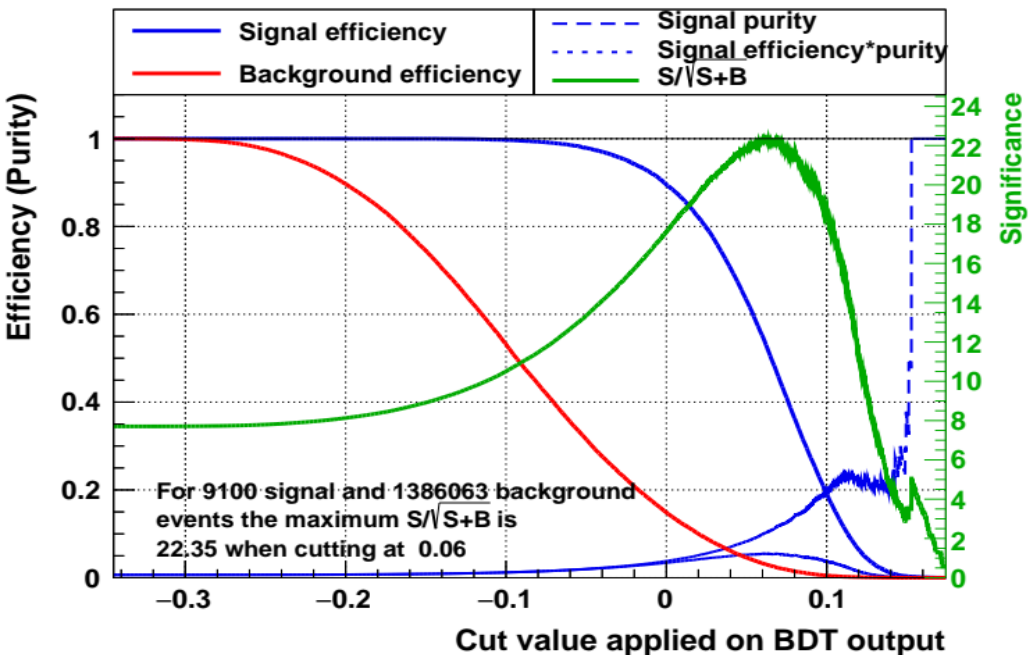
on-shell  $W$

1.5 TeV

off-shell  $W^*$

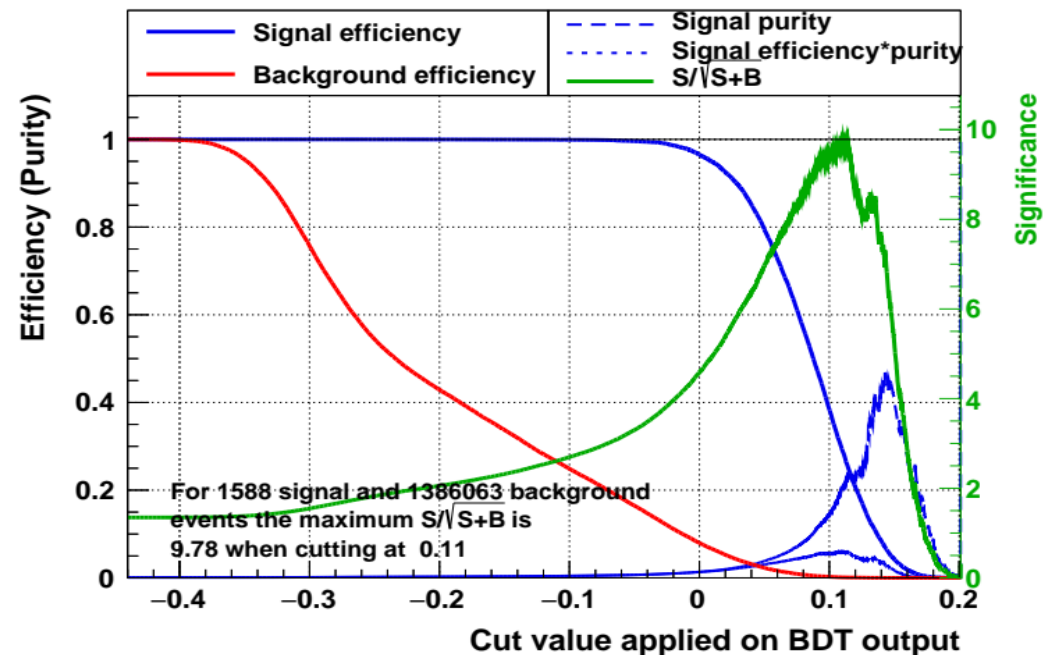
Cut efficiencies and optimal cut value

**BP21**



Cut efficiencies and optimal cut value

**HP17**



- Good signal significance after BDT analysis
- Sufficient signal efficiency after cut on BDT ( $\sim 10\text{-}30\%$ )

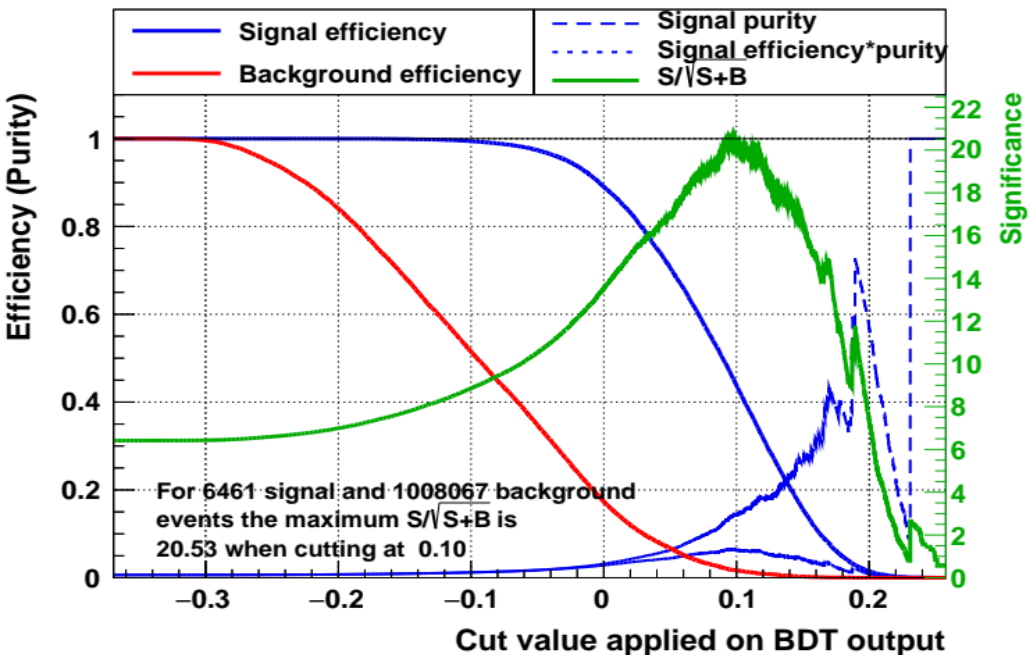
on-shell  $W$

3 TeV

off-shell  $W^*$

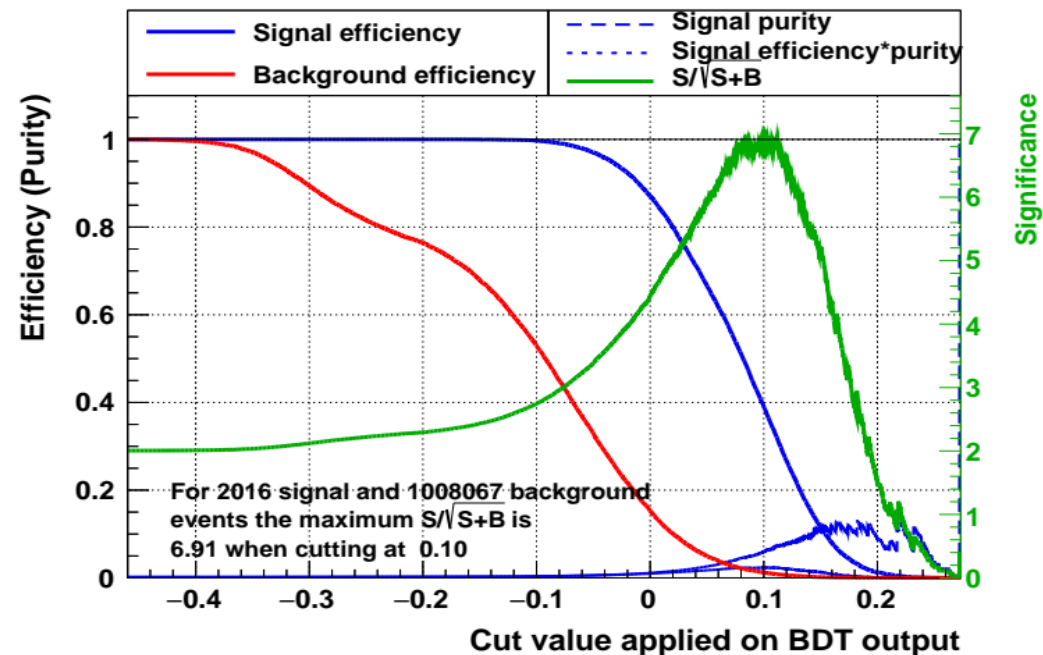
Cut efficiencies and optimal cut value

**BP21**



Cut efficiencies and optimal cut value

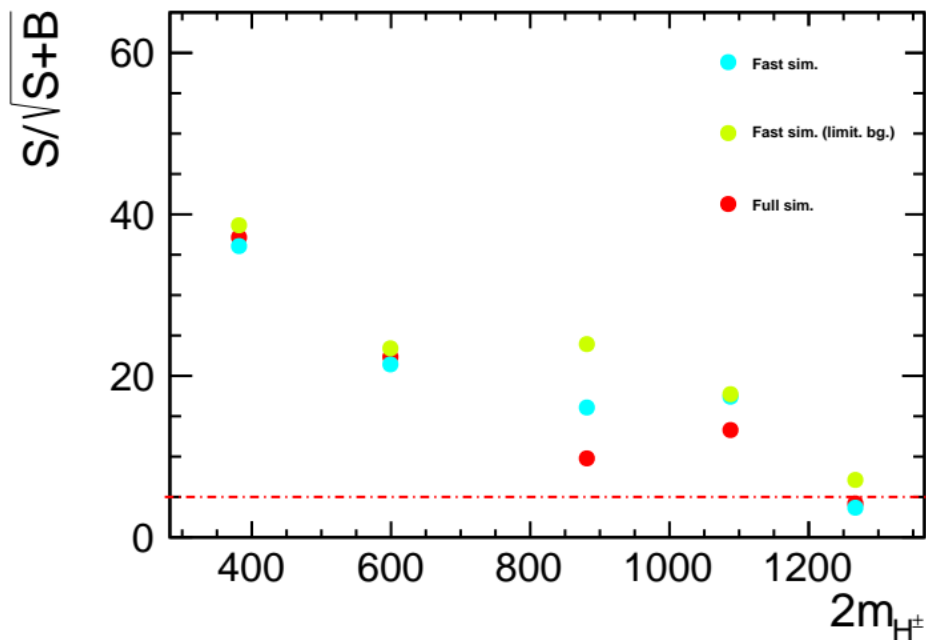
**HP17**



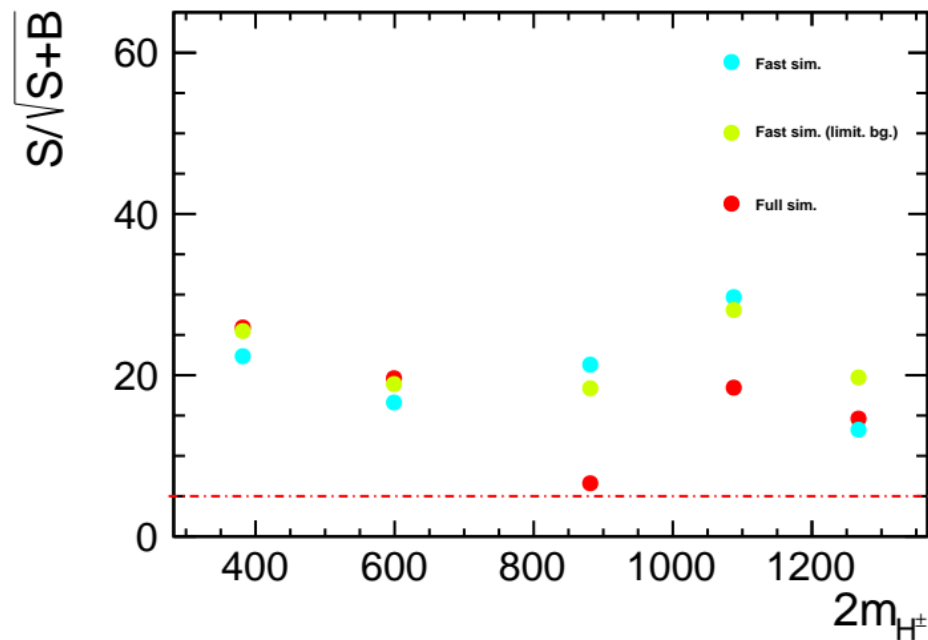
- Decent signal significance after BDT analysis
- Sufficient signal efficiency after cut on BDT (~15%)

# Results (fast vs. full simulation)

1.5 TeV:

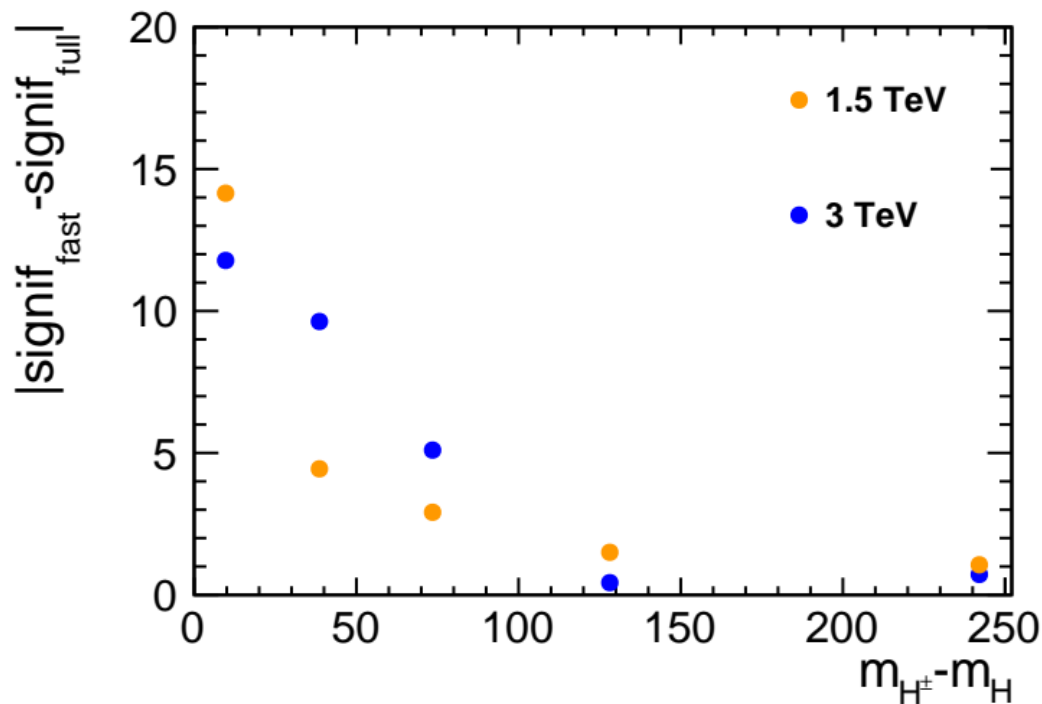


3 TeV:



- Good results at **1.5 TeV**, a little bit worse at **3 TeV**
- **Small gap** for scenarios with **on-shell W**
- Higher decrease in significance for scenarios with smaller  $m_{H^\pm} - m_H$

# Results (fast vs. full simulation)



- Plot shows the difference for the limited background in fast simulation
- **Small gap** for scenarios with **on-shell W**
- Higher decrease in significance for scenarios with smaller  $m_{H^\pm} - m_H$

- Cross-check of **DELPHES fast simulation** analysis of the CLIC potential for discovering IDM scalars was done with the **full simulation**.
- Full simulation confirms earlier estimates.
- Charged IDM scalars pair-production can be observed up to masses of the order of **1 TeV**

## Thank you!

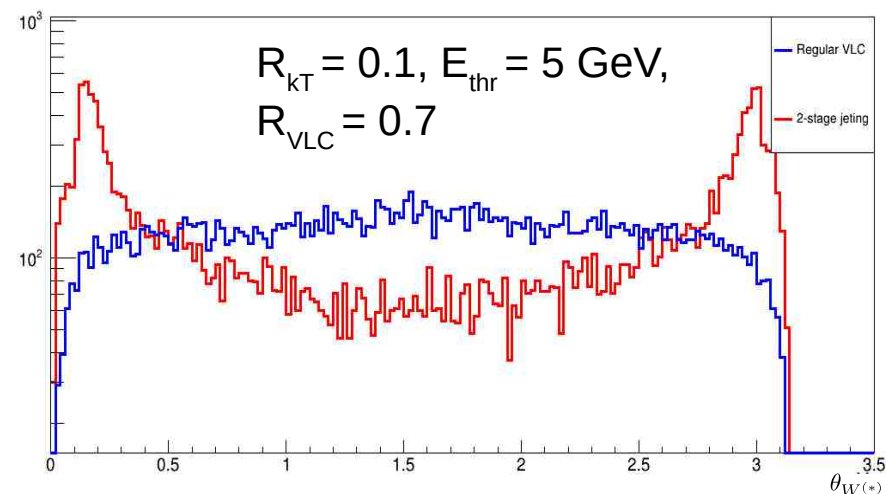
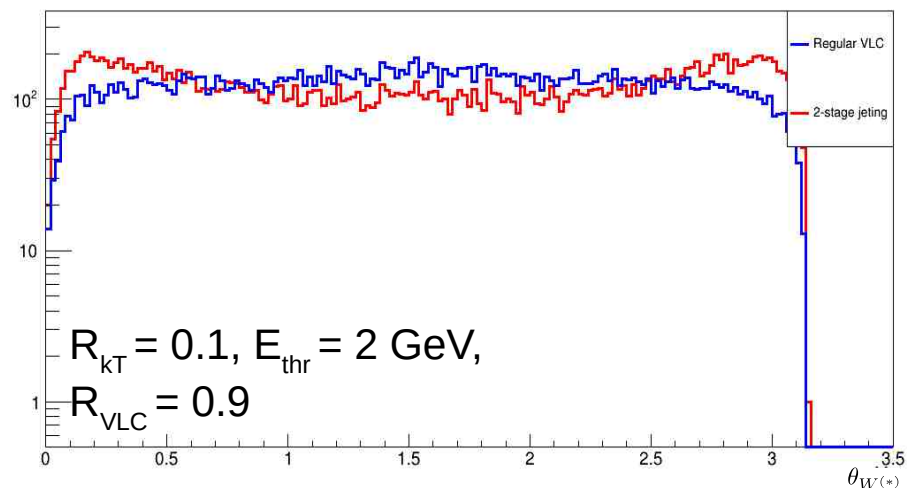
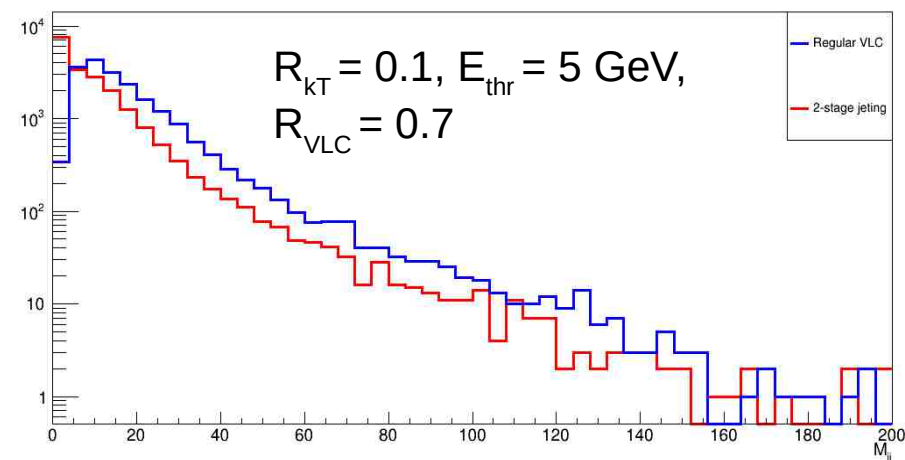
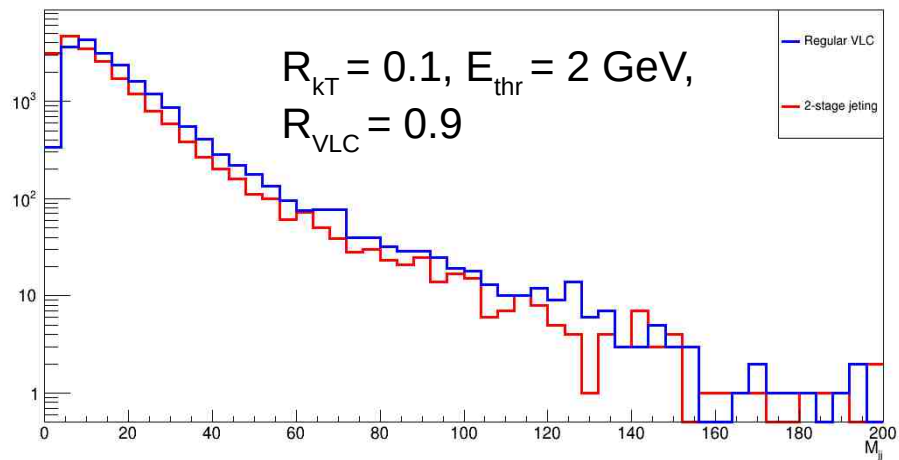
# BACKUP

Benchmark point	1.5 TeV		3 TeV		$m_{H^\pm}$ [GeV]
	signif.	$\sigma$ [fb]	signif.	$\sigma$ [fb]	
on-shell $W$					
BP21	22.35	8.093	20.53	4.213	299.536
BP23	37.15	12.497	26.46	5.767	190.822
off-shell $W^*$					
HP3	4.20	0.6294	14.05	1.775	633.48
HP17	9.78	2.435	6.91	1.678	440.624
HP20	13.29	1.323	17.23	1.506	543.794

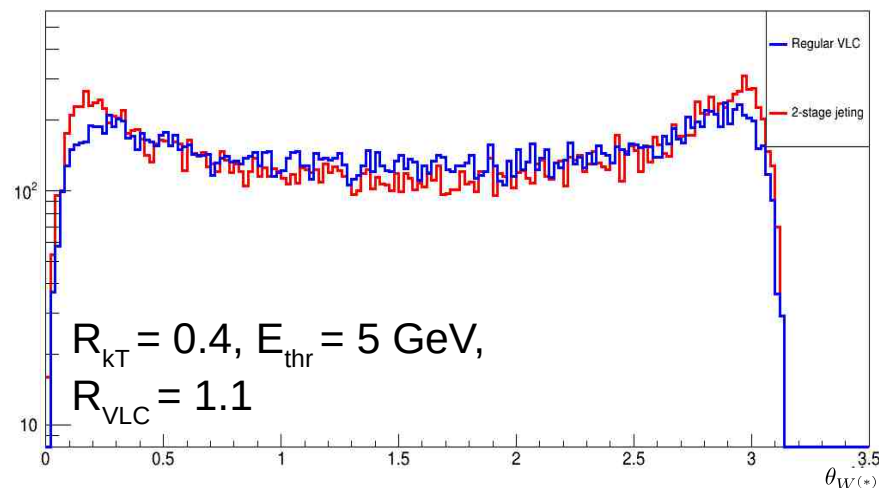
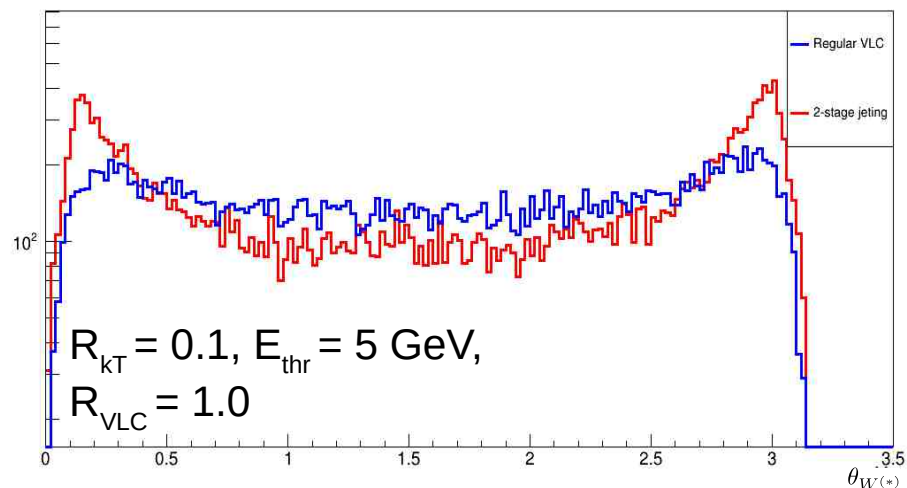
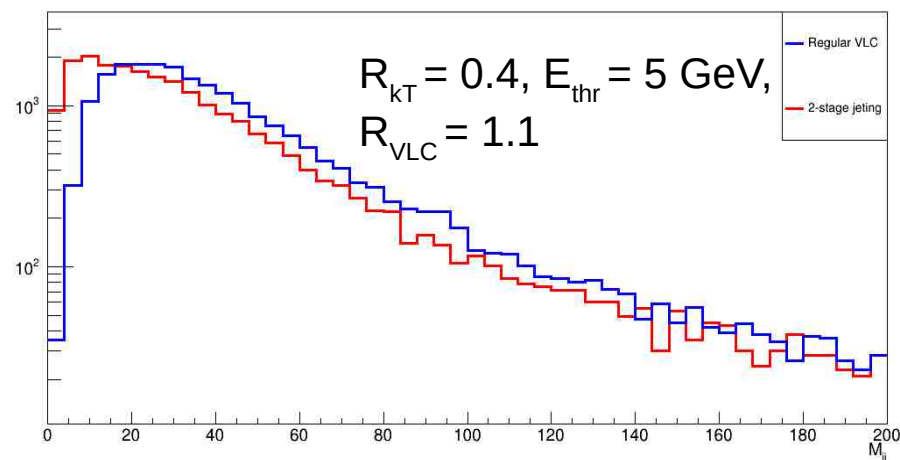
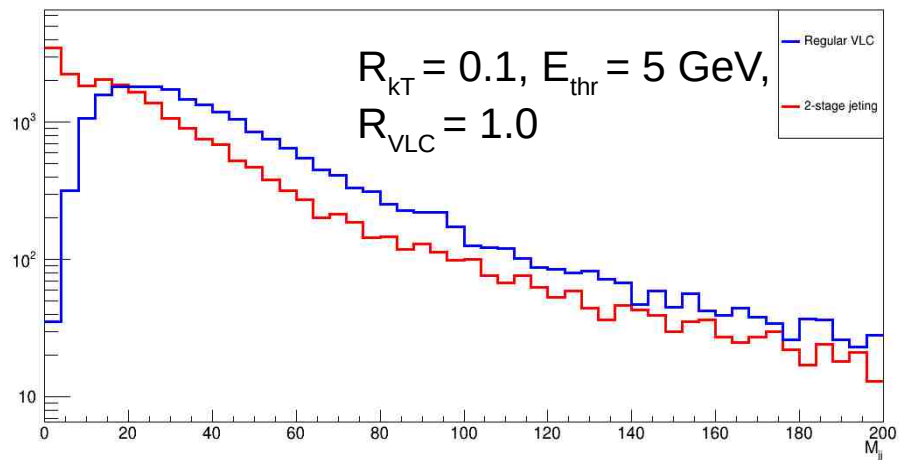
# Full results (fast simulation)

Benchmark point	1.5 TeV		3 TeV		$m_{H^\pm}$ [GeV]
	signif.	$\sigma$ [fb]	signif.	$\sigma$ [fb]	
on-shell $W$					
BP21	21.42	8.192	16.62	4.26603	299.536
BP23	36.07	12.602	22.36	5.67891	190.822
HP1	26.84	7.5919	19.81	4.00834	311.96
HP4	0.53	0.22964	6.89	1.59043	682.54
off-shell $W^*$					
BP18	61.87	11.903	28.87	5.19980	197.403
HP2	5.33	1.49793	10.94	0.79231	565.417
HP3	3.67	0.63347	13.24	1.72873	633.48
HP5	1.93	0.19814	25.47	1.43190	688.437
HP6	0.11	0.037207	13.70	1.07247	723.045
HP7	-	-	13.29	1.00985	818.001
HP8	-	-	7.96	0.69329	943.787
HP9	-	-	11.01	0.607349	987.975
HP10	-	-	2.81	0.43212	998.12
HP11	59.36	7.22539	38.88	3.51379	287.226
HP12	35.72	3.775	23.57	2.09034	332.457
HP13	53.84	5.74048	46.12	3.15121	360.568
HP14	21.14	2.236	14.71	1.40070	381.773
HP15	44.76	4.7676	38.23	2.99062	402.568
HP16	44.33	4.34368	44.46	2.74101	413.464
HP17	16.08	2.44644	21.31	1.42266	440.624
HP18	36.45	3.3074	42.16	2.48253	459.696
HP19	28.64	2.5918	38.92	2.27993	492.329
HP20	17.42	1.3261	29.69	1.54028	543.794

# Influence of pre-clustering, HP17, 1.5 TeV

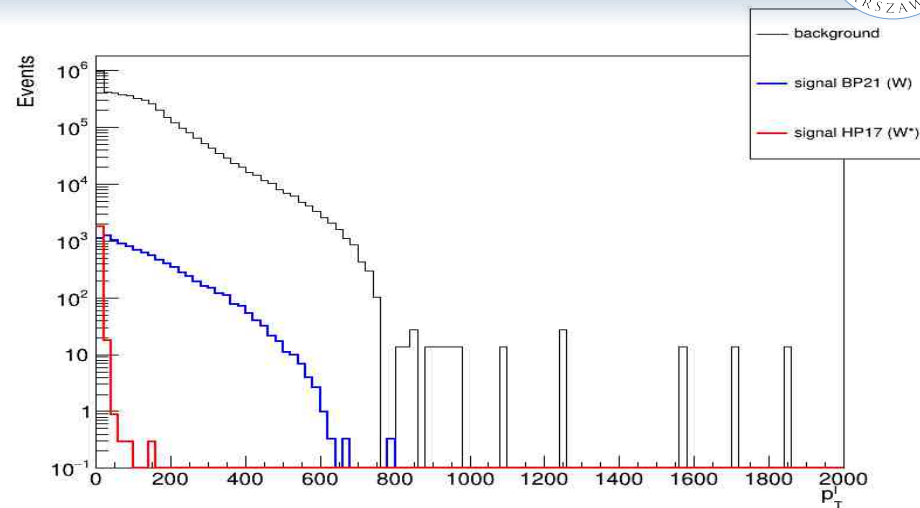
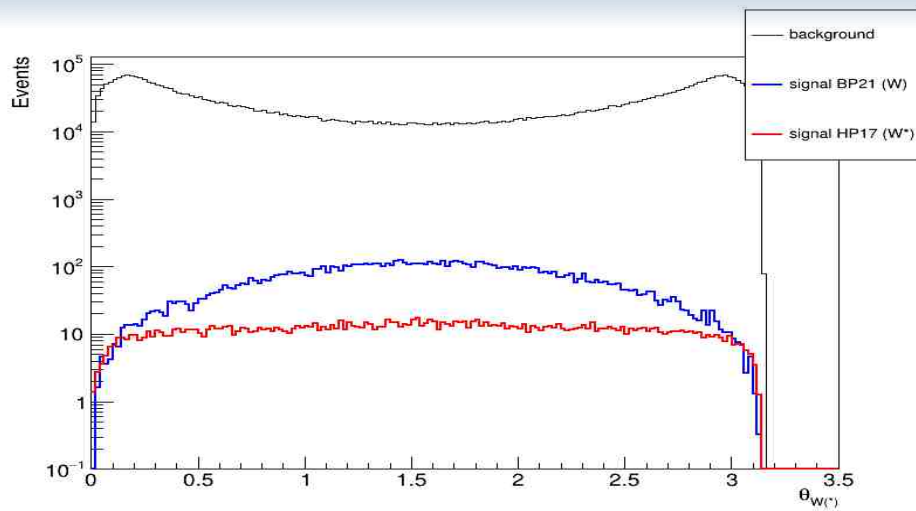


# Influence of pre-clustering, HP17, 3 TeV

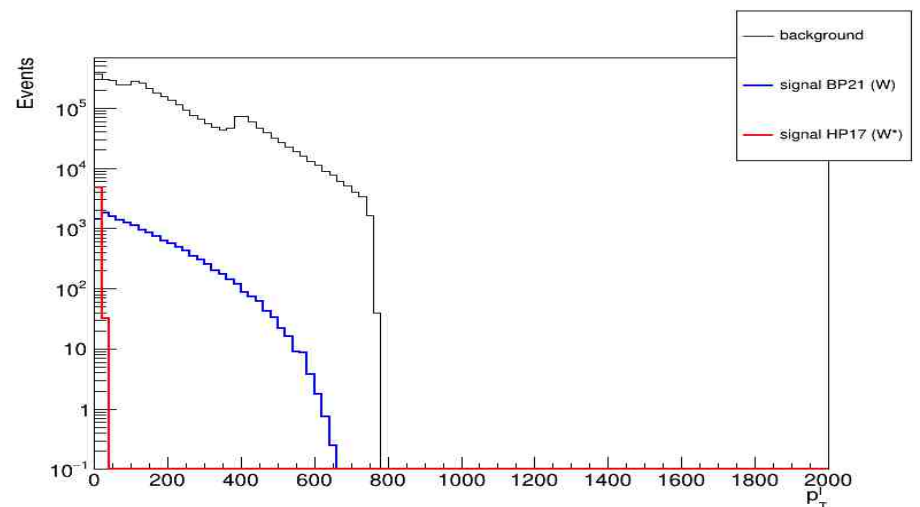
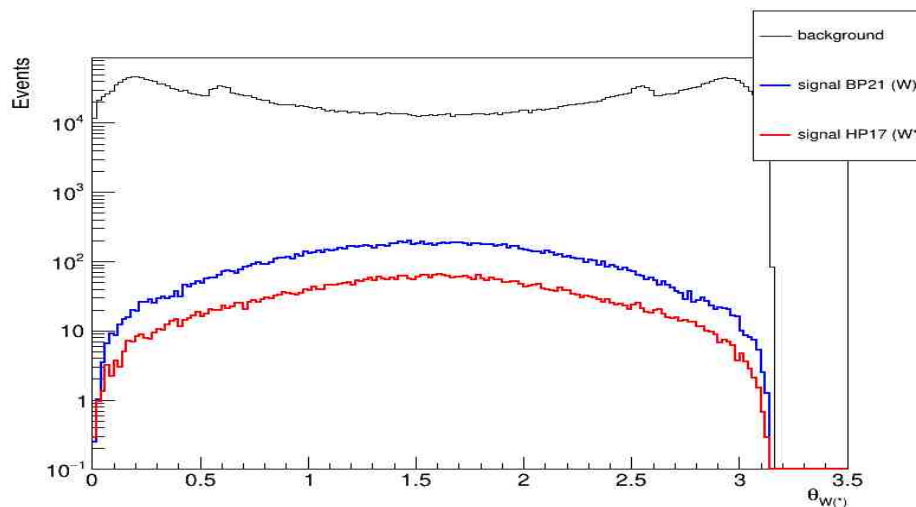


# Kinematic variables distributions, 1.5 TeV

full  
sim.

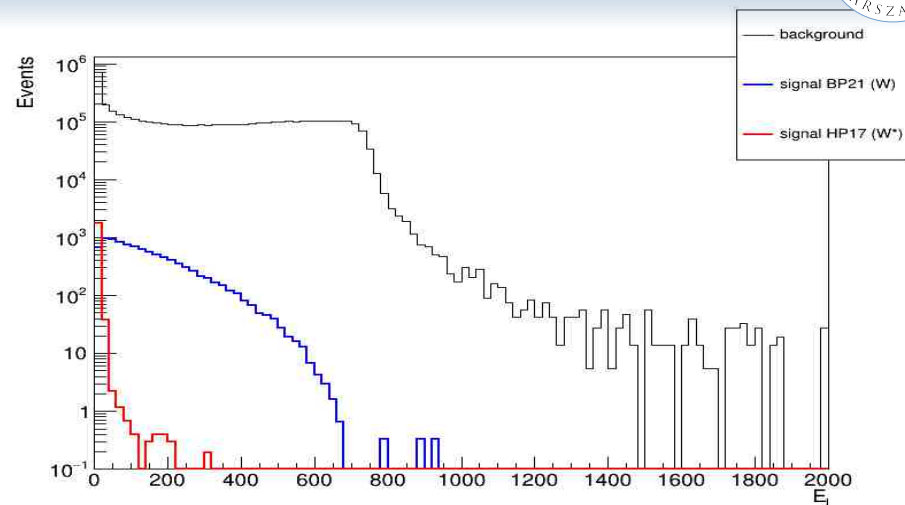
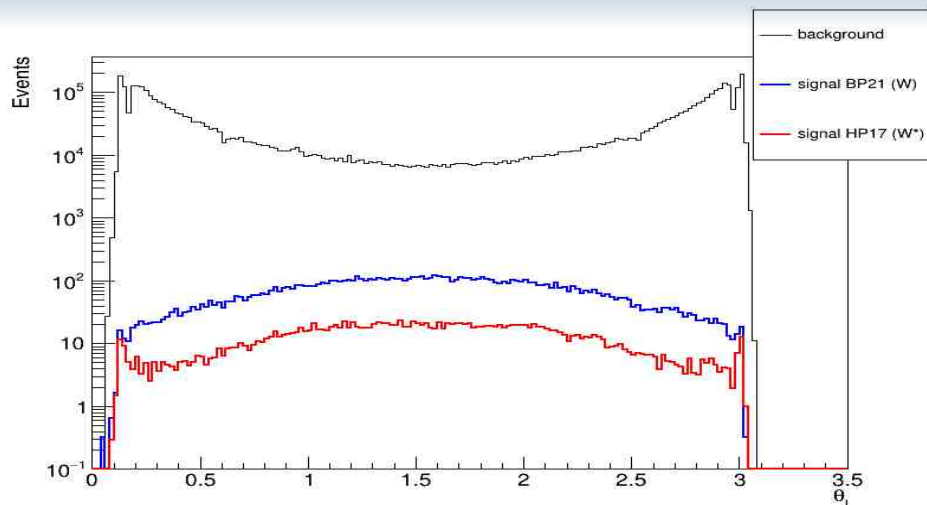


fast  
sim.

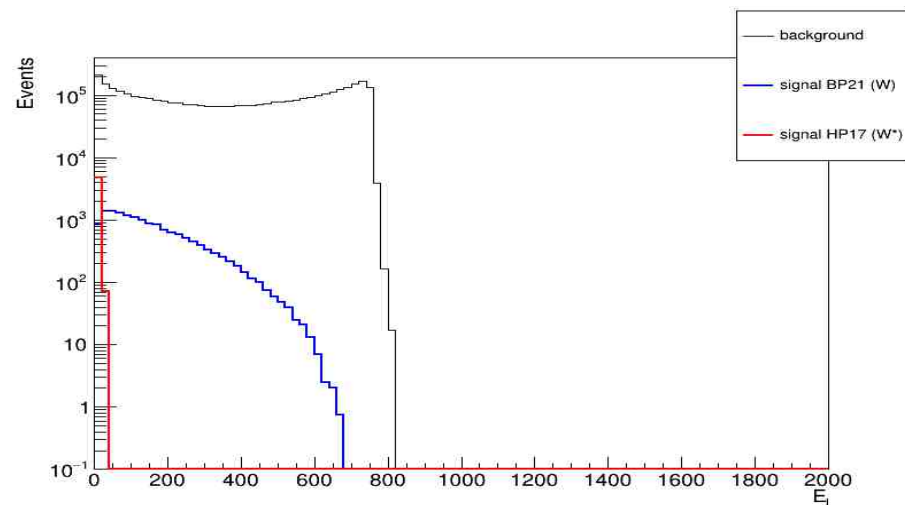
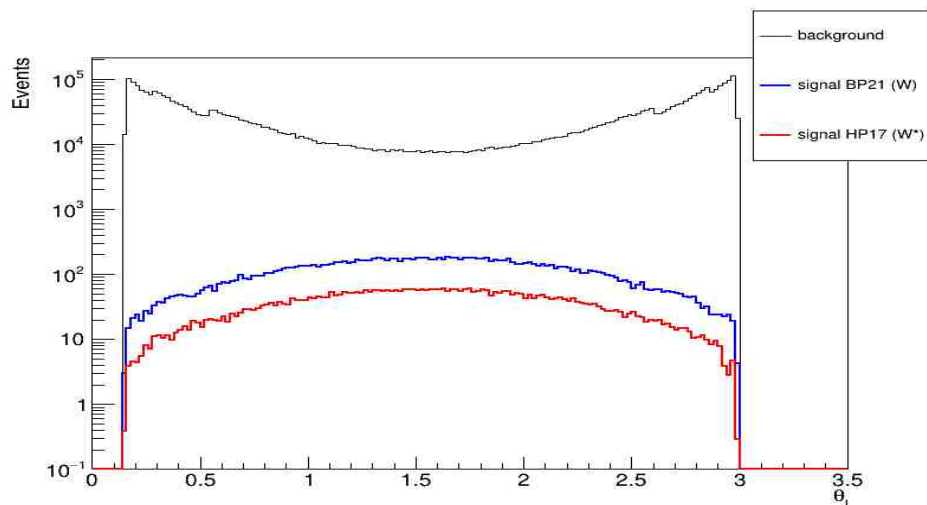


# Kinematic variables distributions, 1.5 TeV

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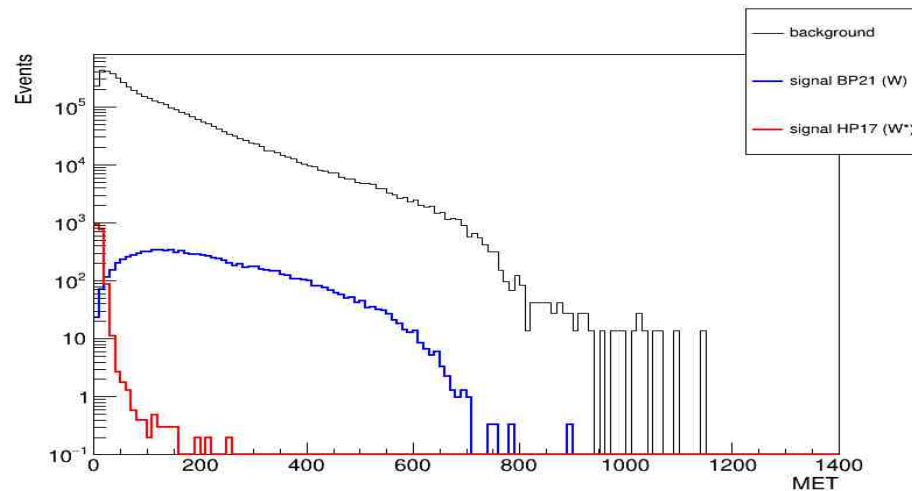
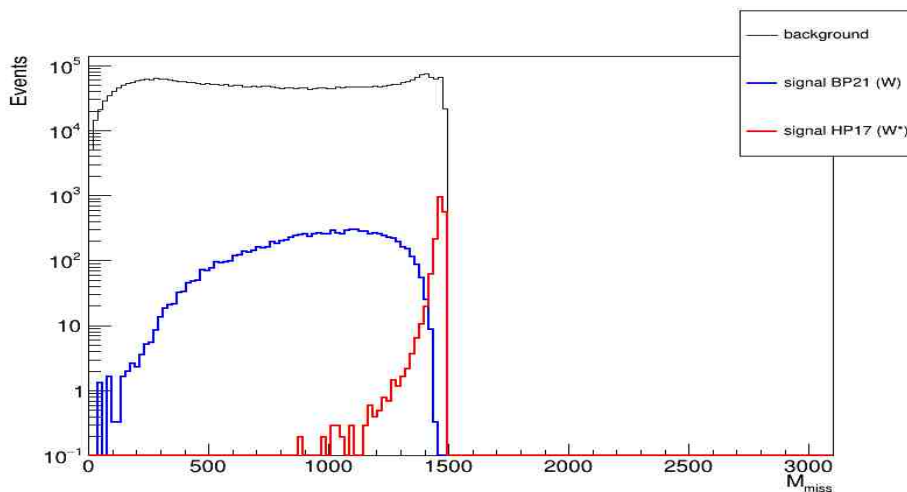


fast  
sim.

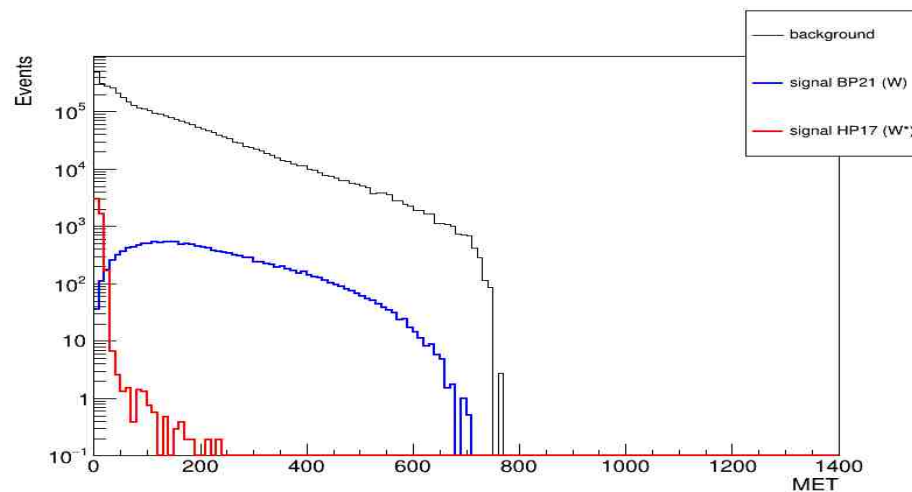
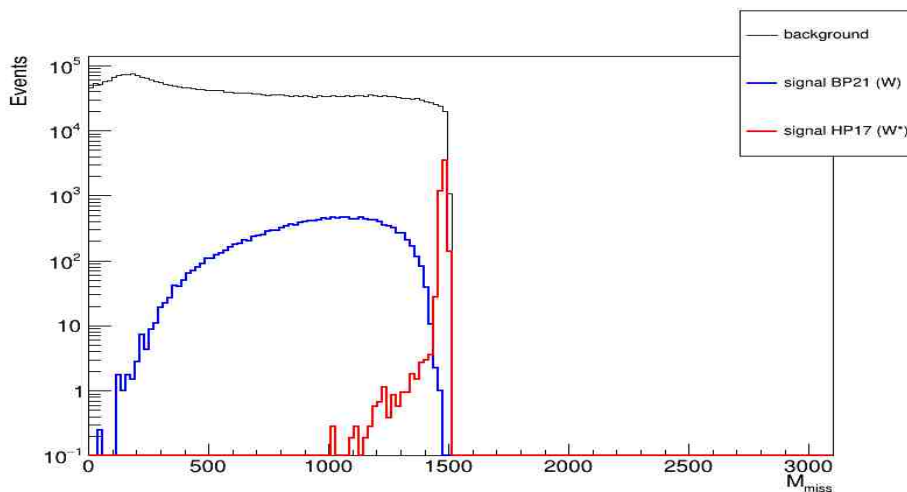


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sim.

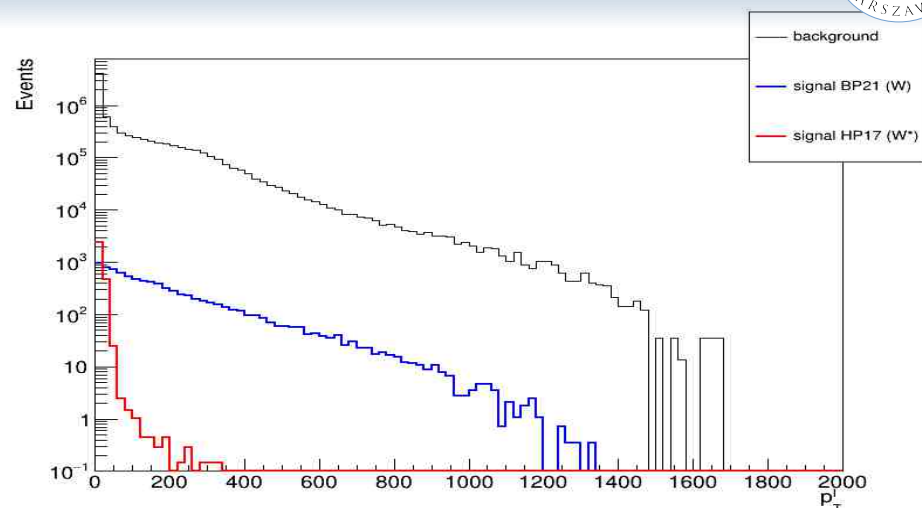
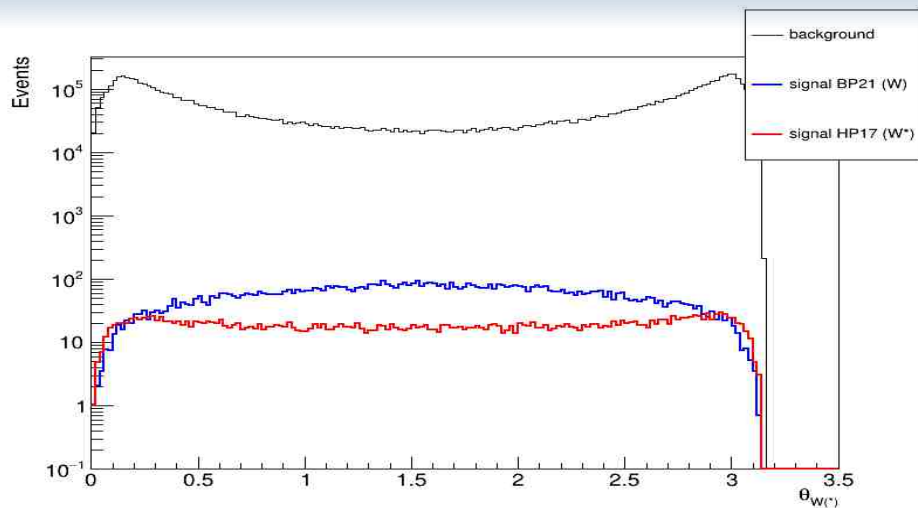


fast  
sim.

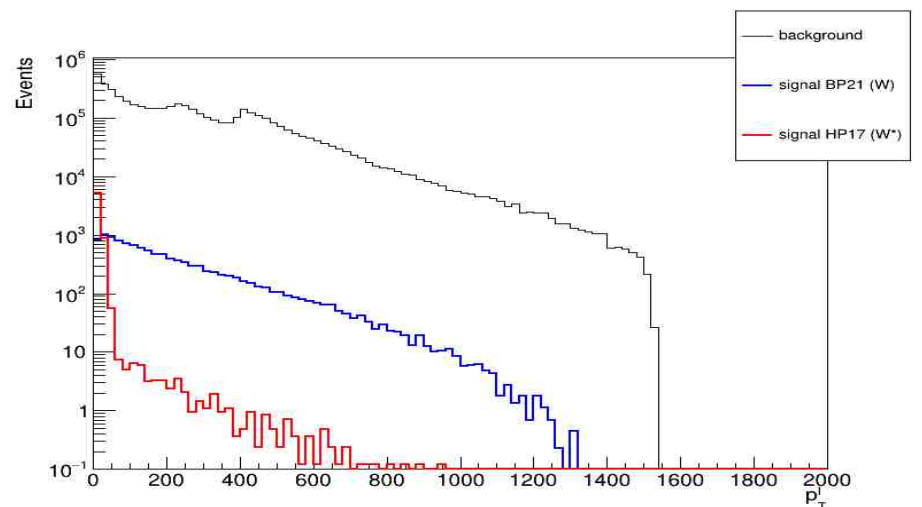
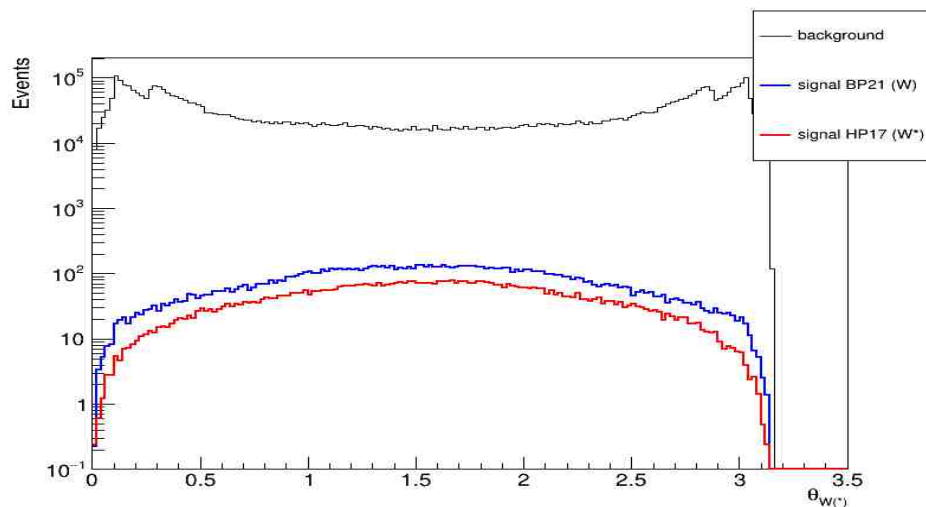


# Kinematic variables distributions, 3 TeV

full  
sim.

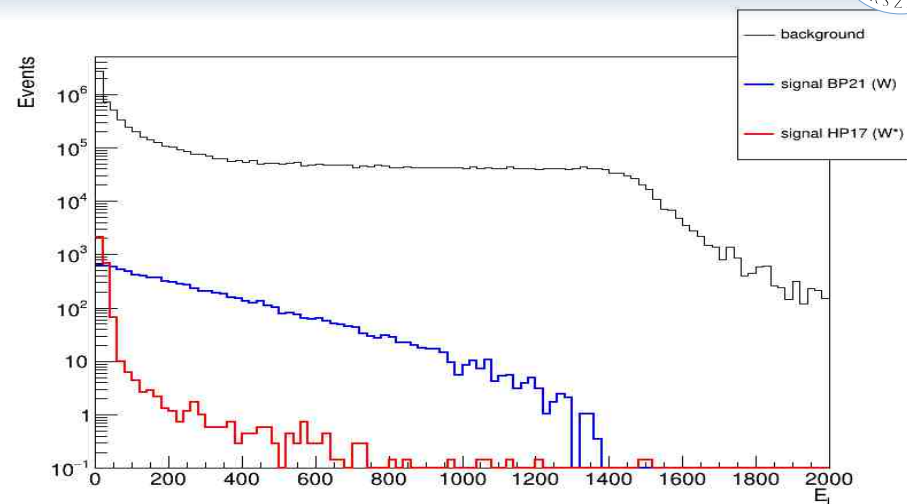
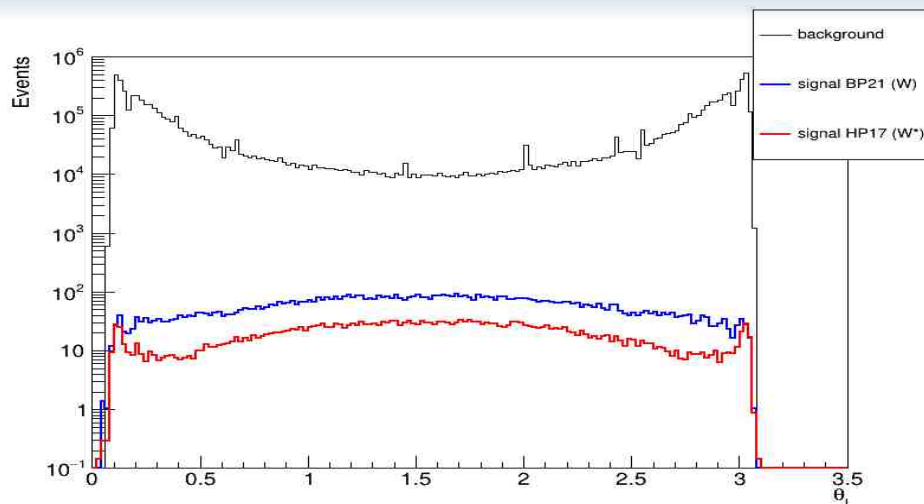


fast  
sim.

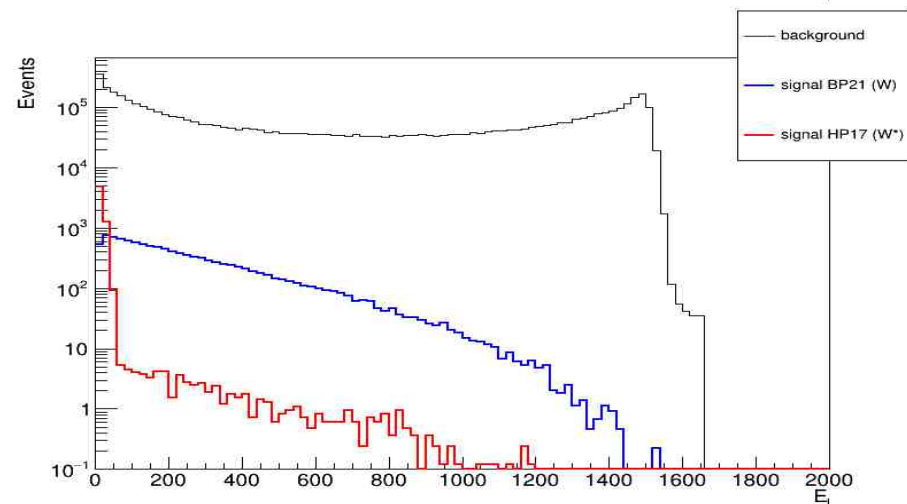
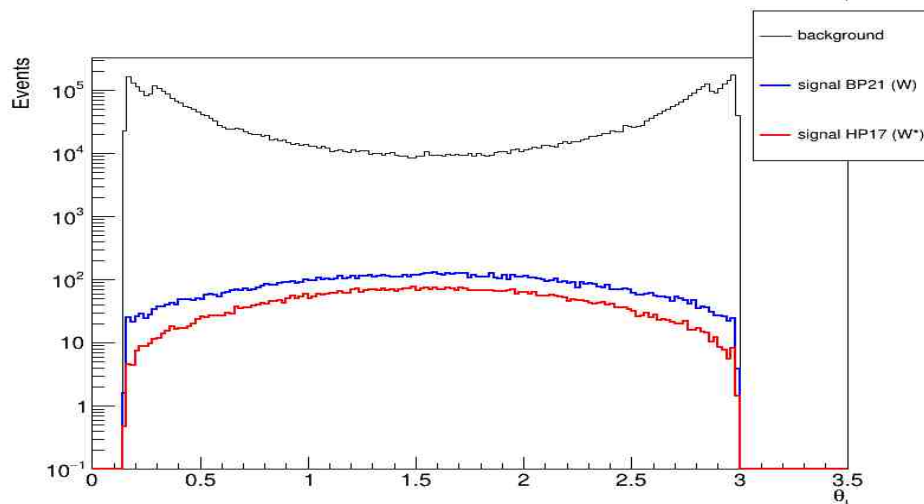


# Kinematic variables distributions, 3 TeV

full  
sim.

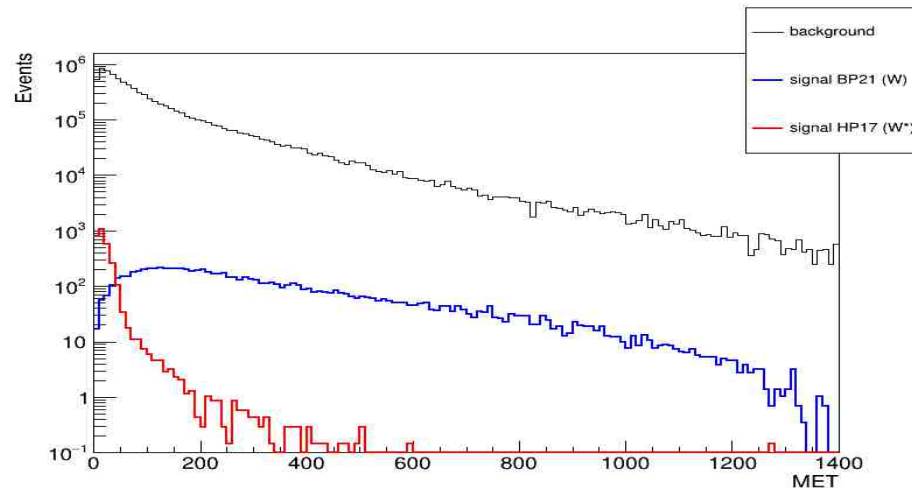
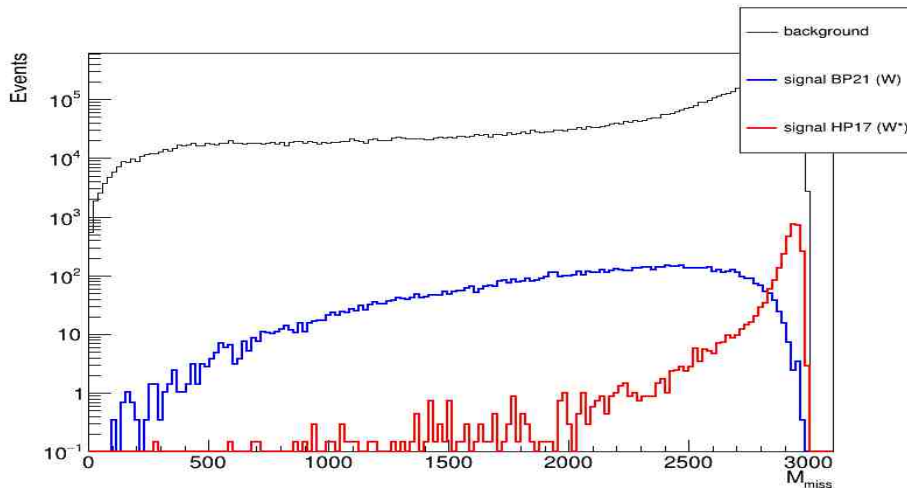


fast  
sim.

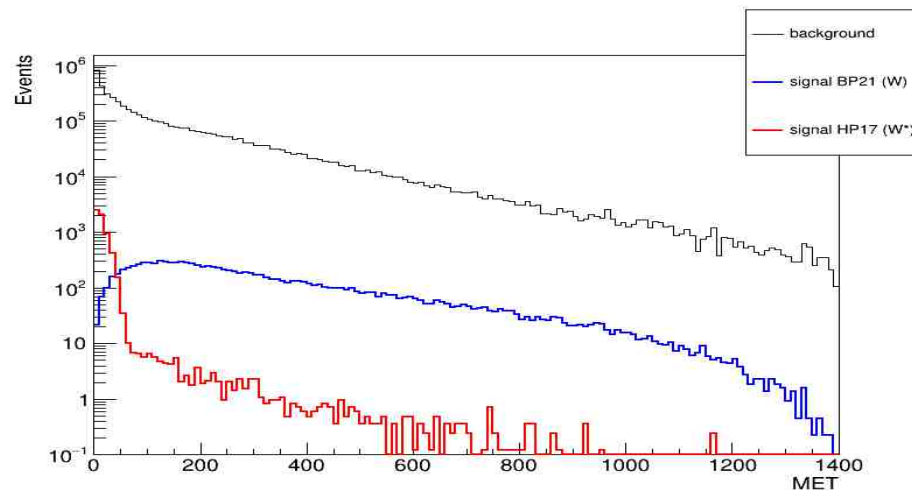
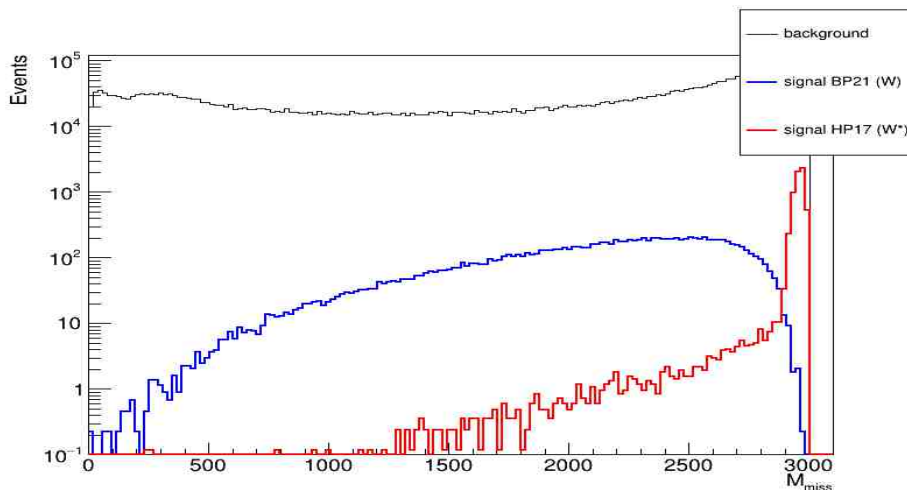


# Kinematic variables distributions, 3 TeV

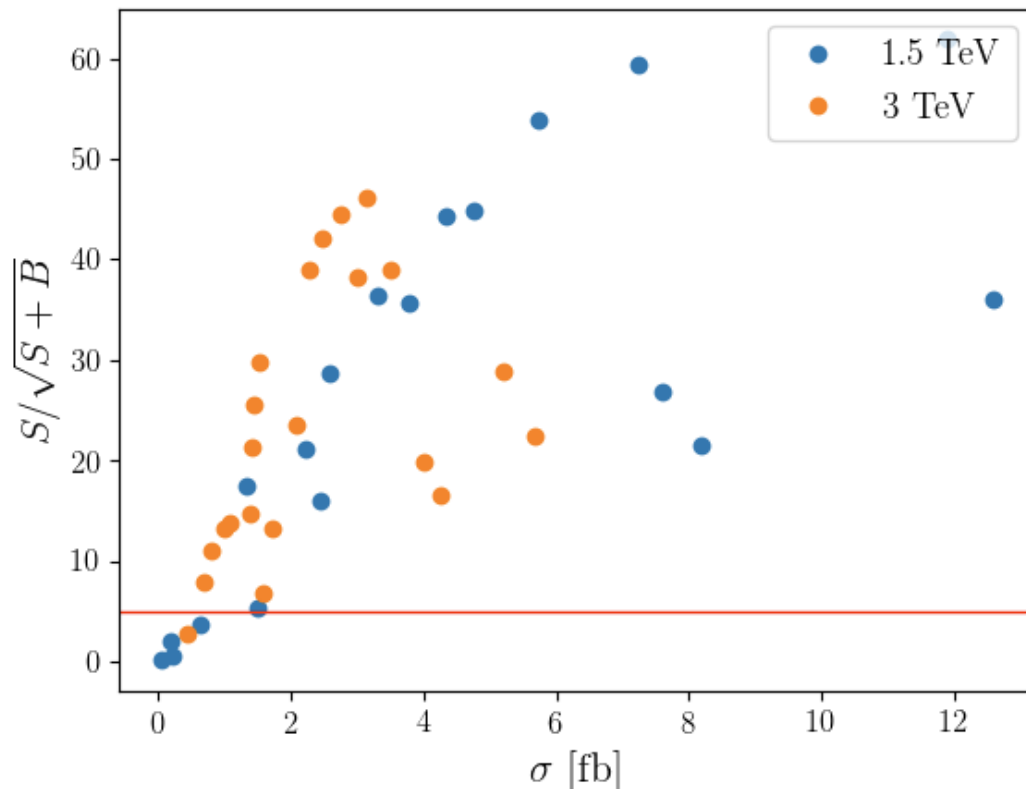
full  
sim.



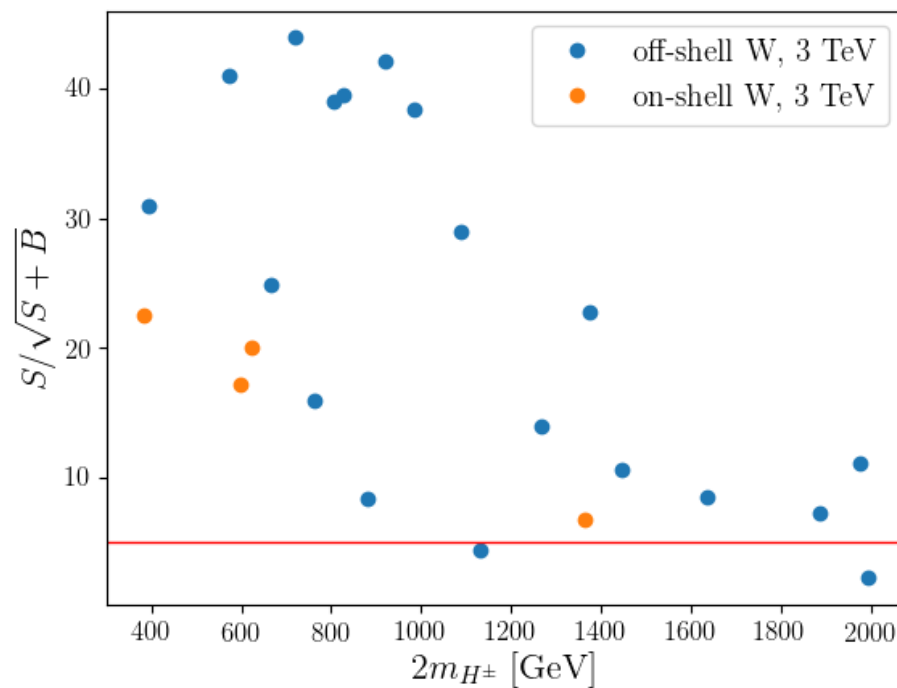
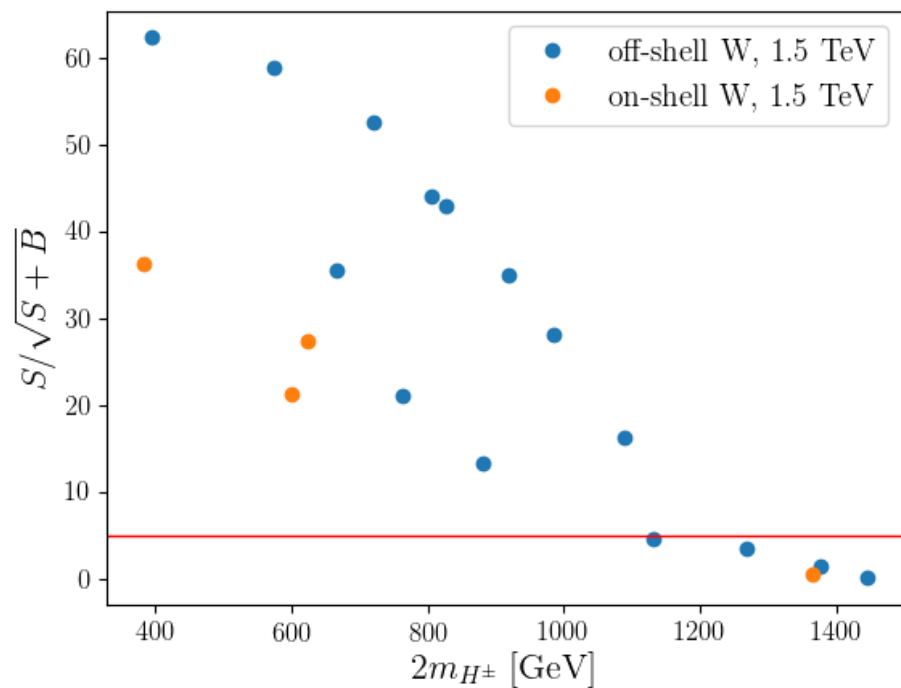
fast  
sim.



# Significance vs. cross section (fast sim.)



# Results (fast sim.)



# Benchmarks

No.	$M_H$	$M_A$	$M_{H^\pm}$	Z on-shell	W on-shell	DM >50%	$\lambda_2$	$\lambda_{345}$	$\Omega_H h^2$
222									
BP1	72.77	107.803	114.639			✓	1.44513	-0.00440723	0.12007
BP2	65	71.525	112.85			✓	0.779115	0.0004	0.070807
BP3	67.07	73.222	96.73			✓	0	0.00738	0.061622
122									
BP4	73.68	100.112	145.728			✓	2.08602	-0.00440723	0.089249
BP6	72.14	109.548	154.761		✓	✓	0.0125664	-0.00234	0.11708
112									
BP7	76.55	134.563	174.367		✓		1.94779	0.0044	0.031402
BP8	70.91	148.664	175.89		✓	✓	0.439823	0.0051	0.124
BP9	56.78	166.22	178.24	✓	✓	✓	0.502655	0.00338	0.081268
BP23	62.69	162.397	190.822	✓	✓	✓	2.63894	0.0056	0.064038
022									
BP10	76.69	154.579	163.045		✓		3.92071	0.0096	0.028141
BP11	98.88	155.037	155.438				1.18124	-0.0628	0.0027369
BP12	58.31	171.148	172.96	✓	✓		0.540354	0.00762	0.0064099
012									
BP13	99.65	138.484	181.321		✓		2.46301	0.0532	0.001255
BP14	71.03	165.604	175.971	✓	✓	✓	0.339292	0.00596	0.11841
BP15	71.03	217.656	218.738	✓	✓	✓	0.766549	0.00214	0.12225
011									
BP16	71.33	203.796	229.092	✓	✓	✓	1.03044	-0.00122	0.12214
002									
BP18	147	194.647	197.403				0.387	-0.018	0.0017718
BP19	165.8	190.082	195.999				2.7675	-0.004	0.0028405
BP20	191.8	198.376	199.721				1.5075	0.008	0.008494
001									
BP21	57.475	288.031	299.536	✓	✓	✓	0.929911	0.00192	0.11946
BP22	71.42	247.224	258.382	✓	✓	✓	1.04301	-0.00406	0.12428

# Benchmarks

No.	$M_H$	$M_A$	$M_{H^\pm}$	$Z$ on-shell	$W$ on-shell	DM >50%	$\lambda_2$	$\lambda_{345}$	$\Omega_H h^2$
HP1	176	291.36	311.96	✓	✓		1.4895	-0.1035	0.00072156
HP2	557	562.316	565.417			✓	4.0455	-0.1385	0.072092
HP3	560	616.32	633.48				3.3795	-0.0895	0.001129
HP4	571	676.534	682.54	✓	✓		1.98	-0.471	0.00056347
HP5	671	688.108	688.437				1.377	-0.1455	0.024471
HP6	713	716.444	723.045				2.88	0.2885	0.035152
HP7	807	813.369	818.001				3.6675	0.299	0.032393
HP8	933	939.968	943.787			✓	2.9745	-0.2435	0.09639
HP9	935	986.22	987.975				2.484	-0.5795	0.0027958
<b>HP10</b>	990	992.36	998.12			✓	3.3345	-0.051	0.12478
HP11	250.5	265.49	287.226				3.90814	-0.150071	0.00535
HP12	286.05	294.617	332.457				3.29239	0.112124	0.00277
HP13	336	353.264	360.568				2.48814	-0.106372	0.00937
HP14	326.55	331.938	381.773				0.0251327	-0.0626727	0.00356
HP15	357.6	399.998	402.568				2.06088	-0.237469	0.00346
HP16	387.75	406.118	413.464				0.816814	-0.208336	0.0116
HP17	430.95	433.226	440.624				3.00336	0.082991	0.0327
HP18	428.25	453.979	459.696				3.87044	-0.281168	0.00858
HP19	467.85	488.604	492.329				4.12177	-0.252036	0.0139
HP20	505.2	516.58	543.794				2.53841	-0.354	0.00887