IDM benchmarks for high energy CLIC

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CLIC Detector & Physics Collaboration Meeting

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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: $H^{\pm}, H, A$

Inert Doublet Model

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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:

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

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

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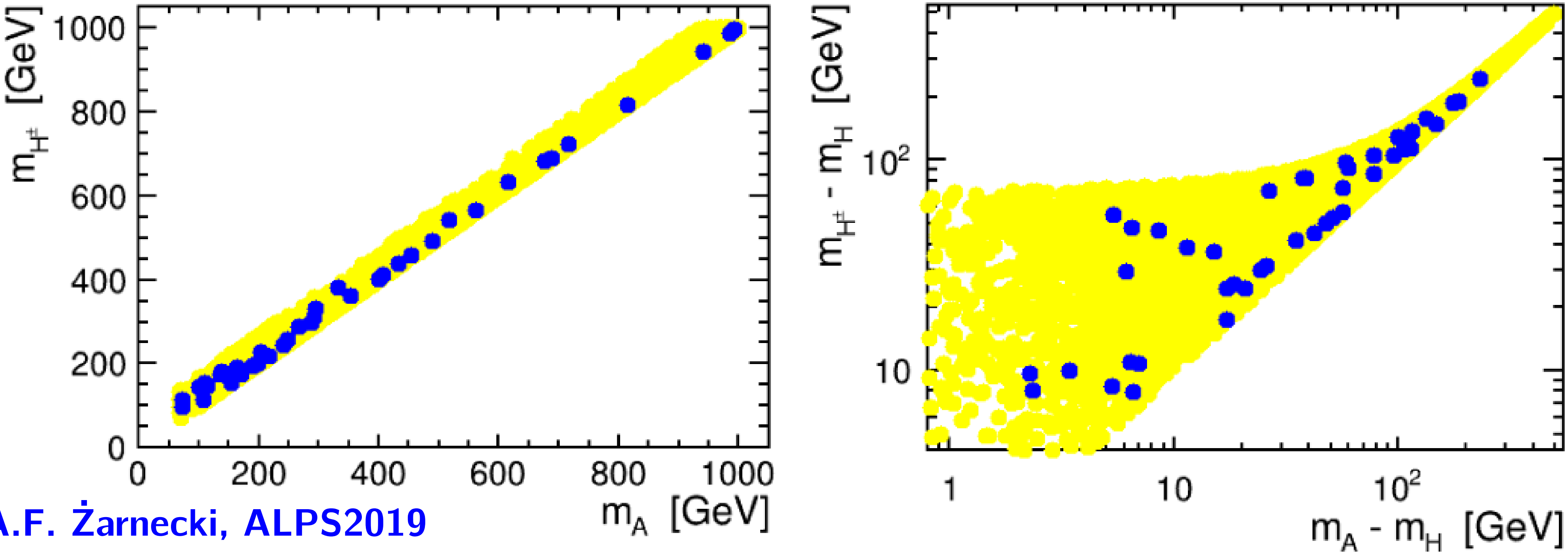
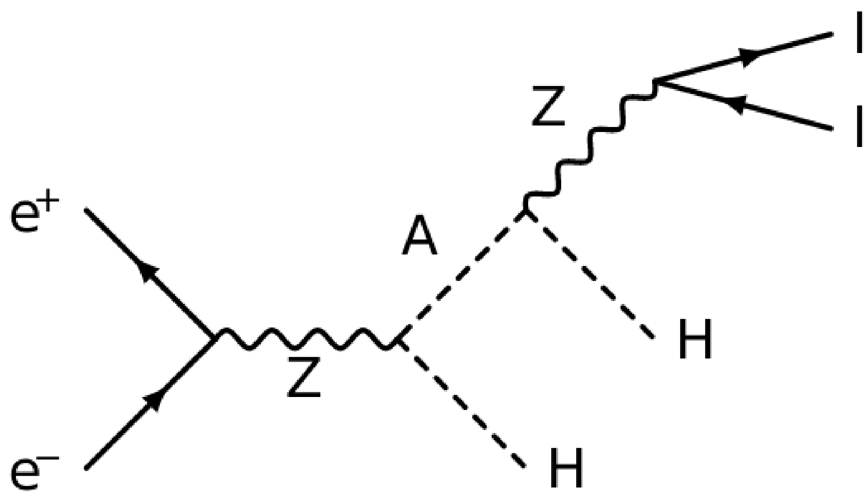
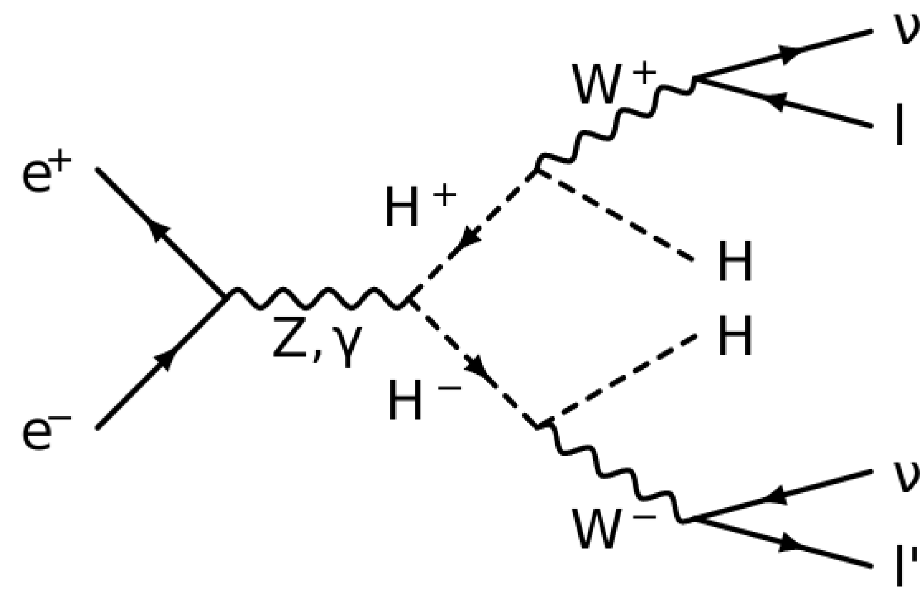


A.F. Żarnecki, ALPS2019

- 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

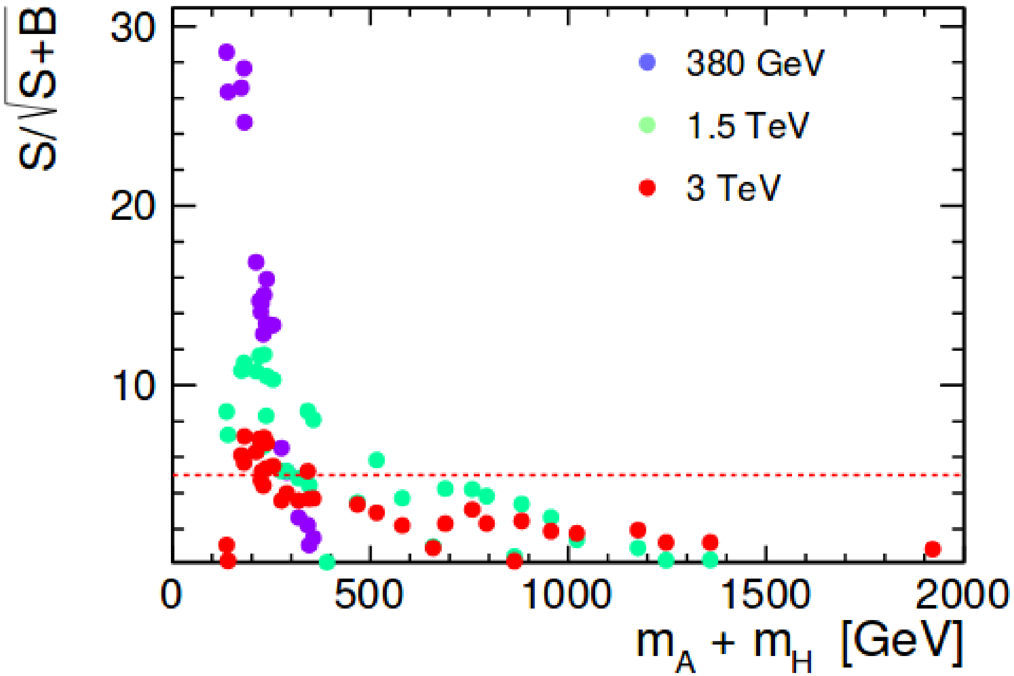
- **Different flavour** leptons
- μe **pair** in the final state

Generator level cuts reflecting detector acceptance

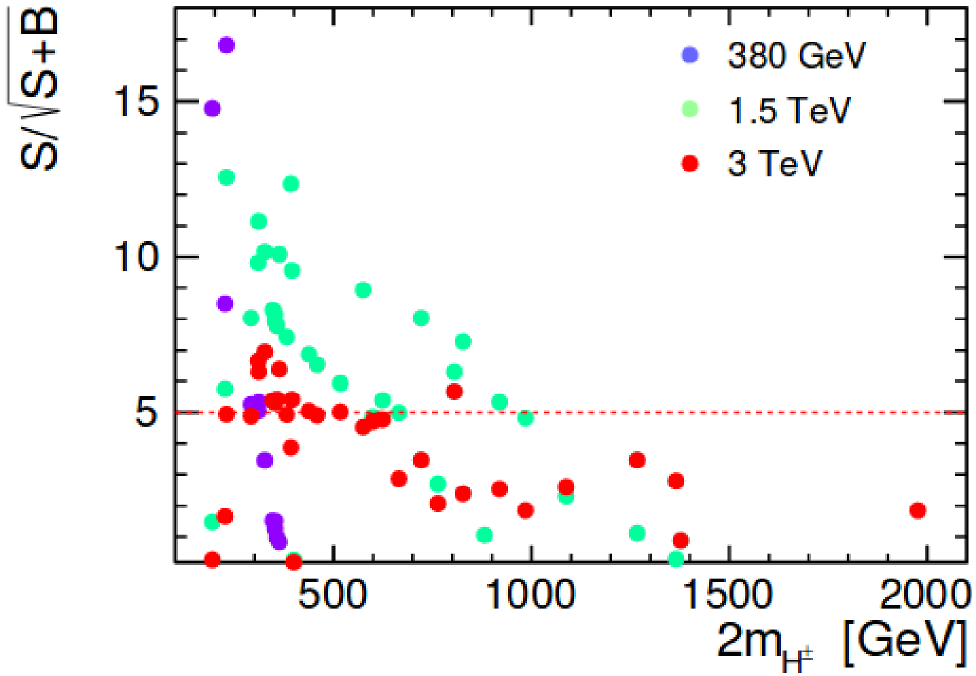
Detector response/efficiency not included

JHEP 1907 (2019) 053, arXiv:1811.06952

$e^+e^- \to HA$ (**$\mu\mu$ pair**)



$e^+e^- \to H^+H^-$ (**μe pair**)



- Many high-mass points below 5σ threshold
- No discovery potential for $m_A + m_H > 550 GeV$,

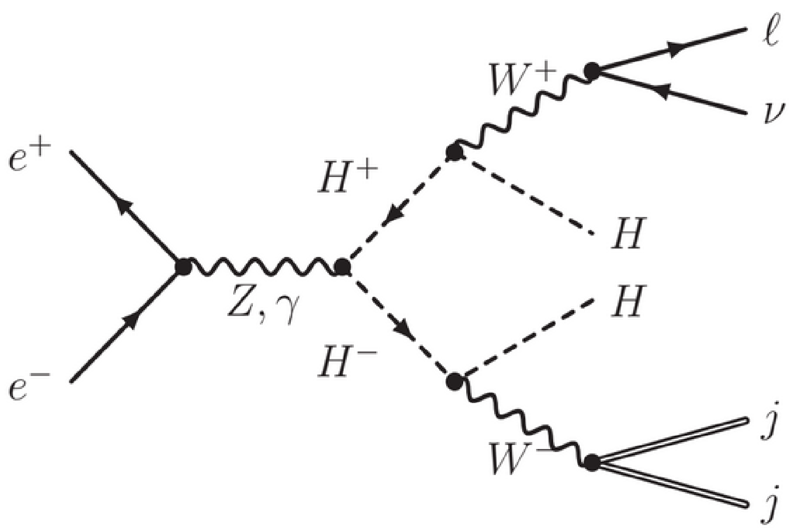
  $m_{H^\pm} > 500 GeV$

$\Longrightarrow$ sensitivity limited by signal statistics

JHEP 1907 (2019) 053, arXiv:1811.06952

Strategy (semi-leptonic)

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



Expected **signature** of the final state:
One lepton, μ or e, and a **pair of jets**

Dominating background:

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

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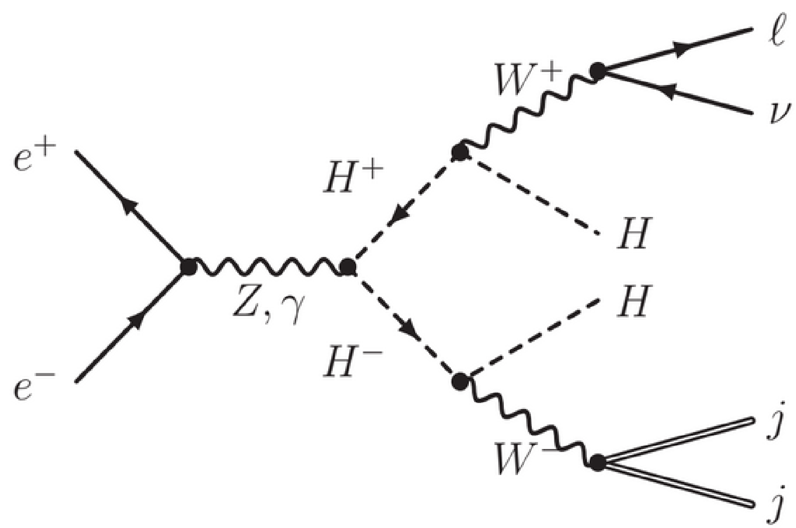

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$qq\ell\nu,\ qq\ell\ell,\ qq\ell\nu\nu\nu,\ qq\ell\nu\ell\nu$

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

Output → **DELPHES** **fast simulation**

Strategy (semi-leptonic)

Reconstruction of:
- jets (VLC algorithm)
- isolated leptons
- isolated photons

} **DELPHES** (CLICdet card)

+ additional jet smearing
(only massless jets smearing in Delphes)

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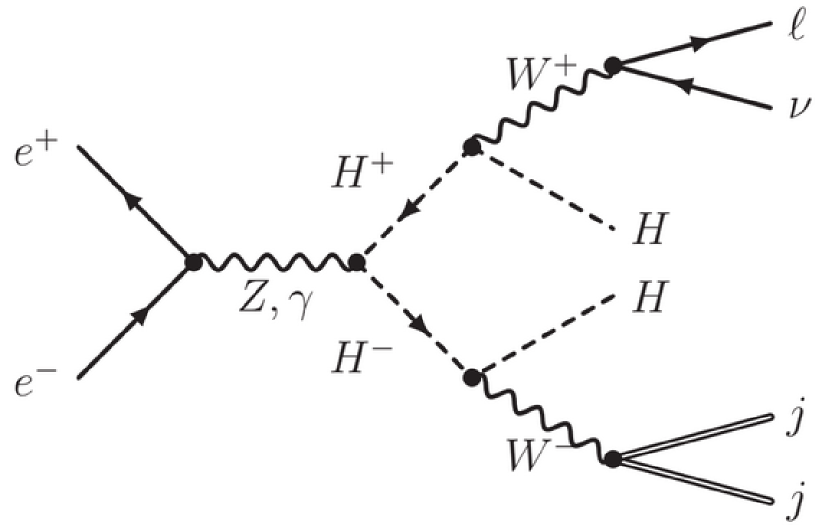
DELPHES (CLICdet card)

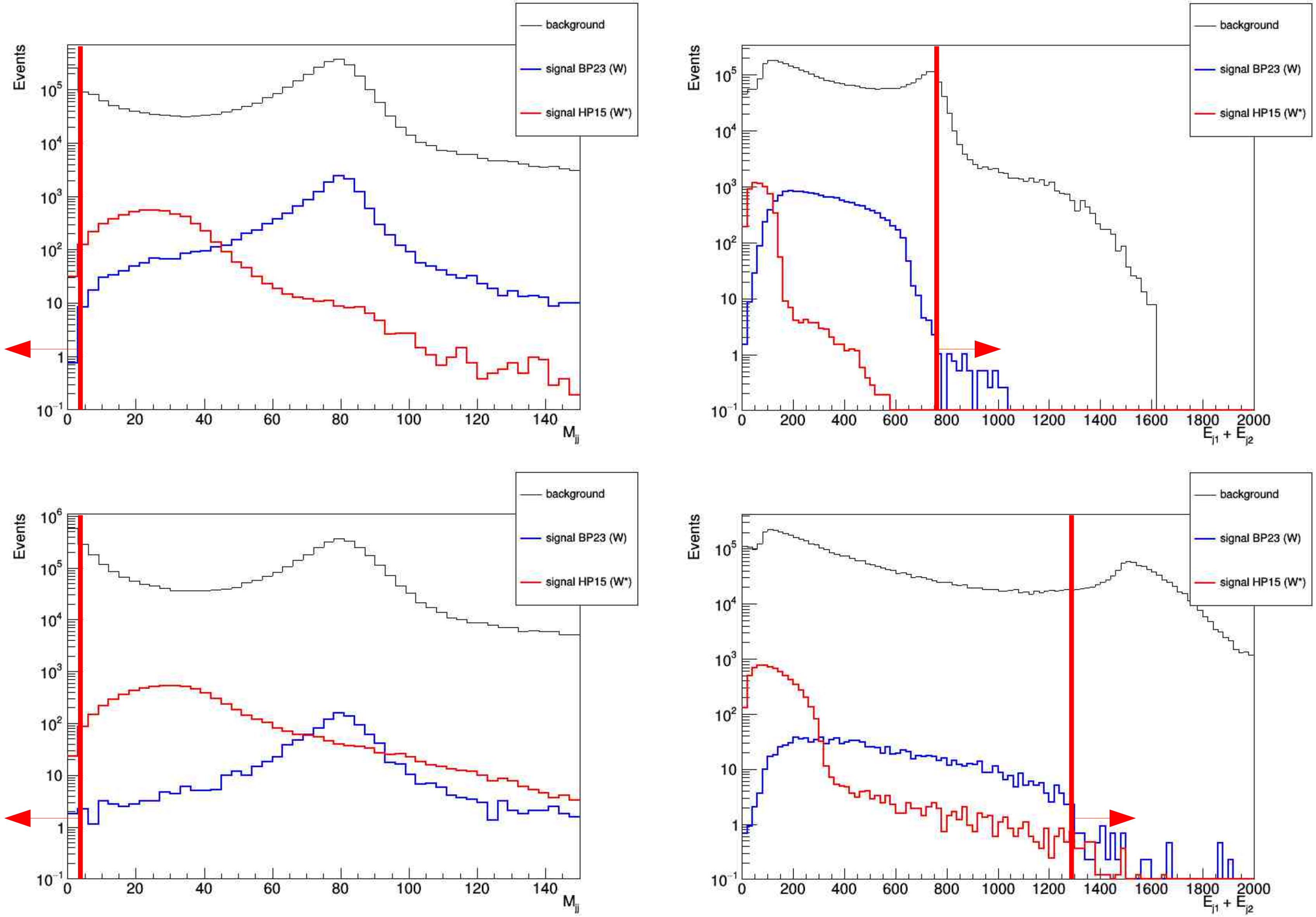


Require:
- exactly **one isolated lepton**
- **no isolated photons** over 10 GeV
- additional energy-flow objects in the detector with less than 20 GeV
- **two** exclusive **jets** (VLC: $\beta = \gamma = 1$, $R = 1.0$ (1.5 TeV), $R = 1.2$ (3 TeV))

Examples of the signal for **on-shell *W* (BP23)** and **off-shell *W** (HP15)**:

1.5 TeV

3 TeV



1.5 TeV

$$M_{jj} > 3\ \mathrm{GeV},\ E_\ell < 600\ \mathrm{GeV},\ p_T^\ell < 550\ \mathrm{GeV}$$
$$M_{miss} > 400\mathrm{GeV}, 0.2 < \theta_W < 2.94, 0.25 < \theta_\ell < 2.89$$

channel	all exp. ev.	exp. ev. after preselec.	eff.
H^+H^- (BP23)	25204	14581	57.9%
H^+H^- (HP15)	9535	5457	57.2%
tot. backg.	35657435	1078272	3.02%
$qq\ell\ell$	5478400	160686	2.93%
$qq\ell\nu$	14109340	832253	5.9%
$qq\ell\nu\ell\nu$	113824	14808	13.01%
$qq\ell\nu\nu\nu$	80295	30770	38.32%
signal/backg. (BP23)	0.0007	0.014	
signal/backg. (HP15)	0.00027	0.0051	

- **Signal to background ratio** improvement

Pre-selection results

3 TeV

$$M_{jj} > 3\,\text{GeV},\; E_\ell < 1000\,\text{GeV},\; p_T^\ell < 800\,\text{GeV}$$
$$0.3 < \theta_W < 2.84, \quad 0.5 < \theta_\ell < 2.64$$

channel	all exp. ev.	exp. ev. after preselec.	eff.
H^+H^- (BP23)	22716	8872	39.1%
H^+H^- (HP15)	11963	6063	50.7%
tot. backg.	74877722	625494	0.84%
$qq\ell\ell$	12877040	78382	0.61%
$qq\ell\nu$	35326320	399470	1.13%
$qq\ell\nu\ell\nu$	317914	30742	9.67%
$qq\ell\nu\nu\nu$	360848	63581	17.62%
signal/backg. (BP23)	0.0003	0.014	
signal/backg. (HP15)	0.00016	0.0097	

- **Signal to background ratio** improvement

BDT, input variables: $M_{jj}, E_{jj}, \theta_{W^\pm},$
$E_\ell, p_T^\ell, \theta_\ell,$
$\mathrm{MET}, M_{miss}, E_{flow}^{\mathrm{sum}},$
$\Delta\theta_{jW^\pm}, \Delta\phi_{jW^\pm}$

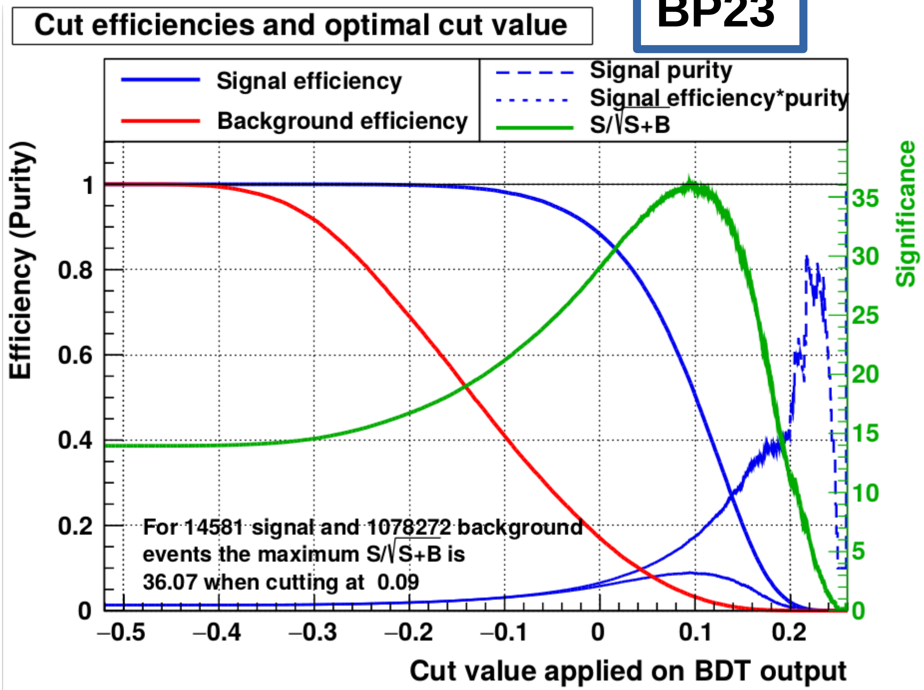
Two BDT's trained:

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

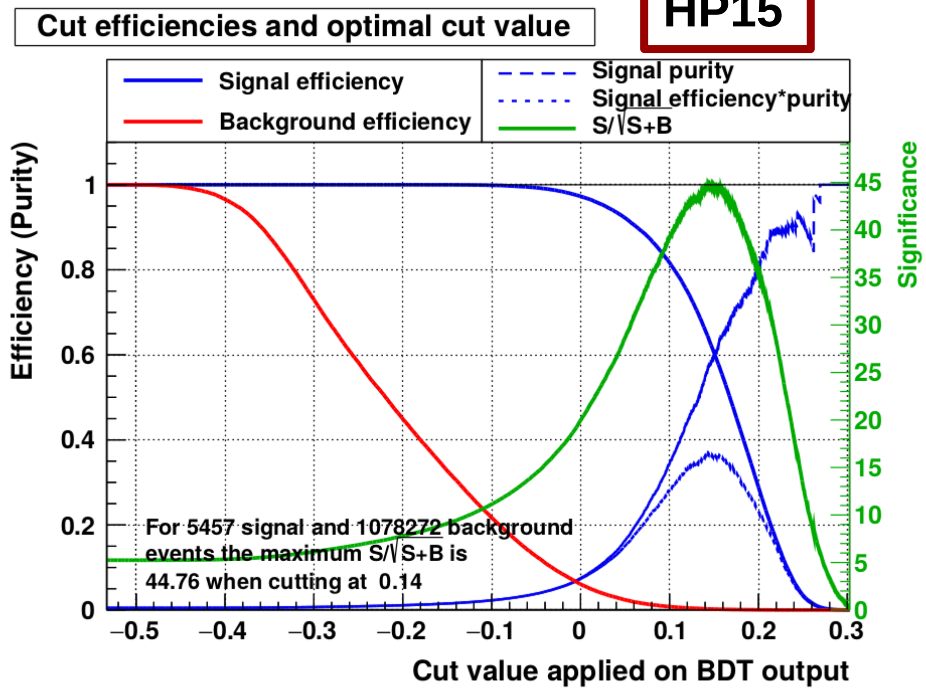
Selection was NOT optimised for particular scenario!

on-shell W | **1.5 TeV** | off-shell W*

BP23



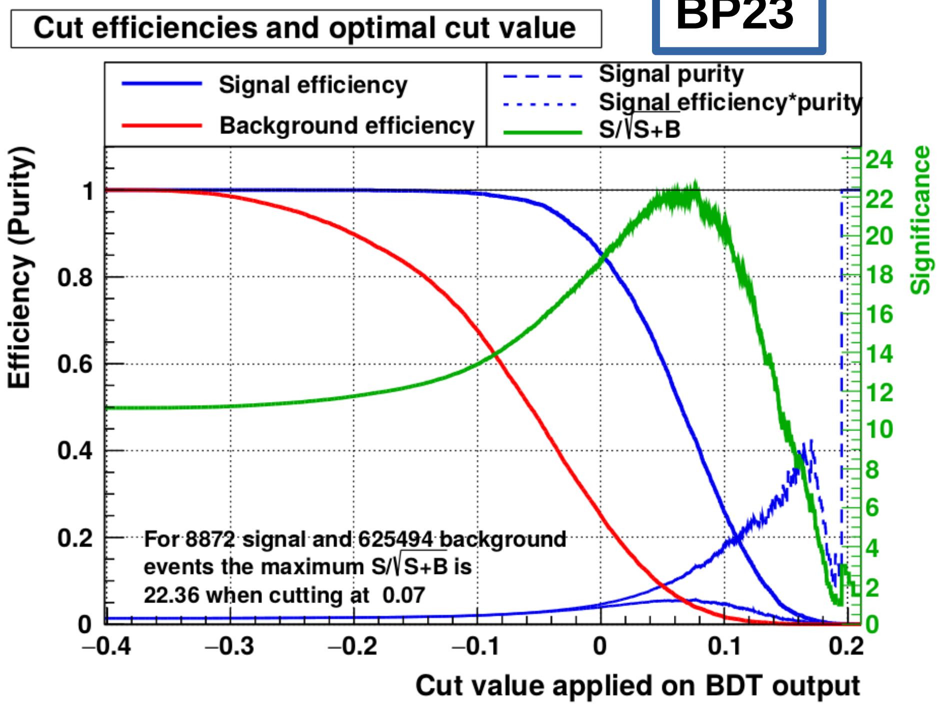
HP15



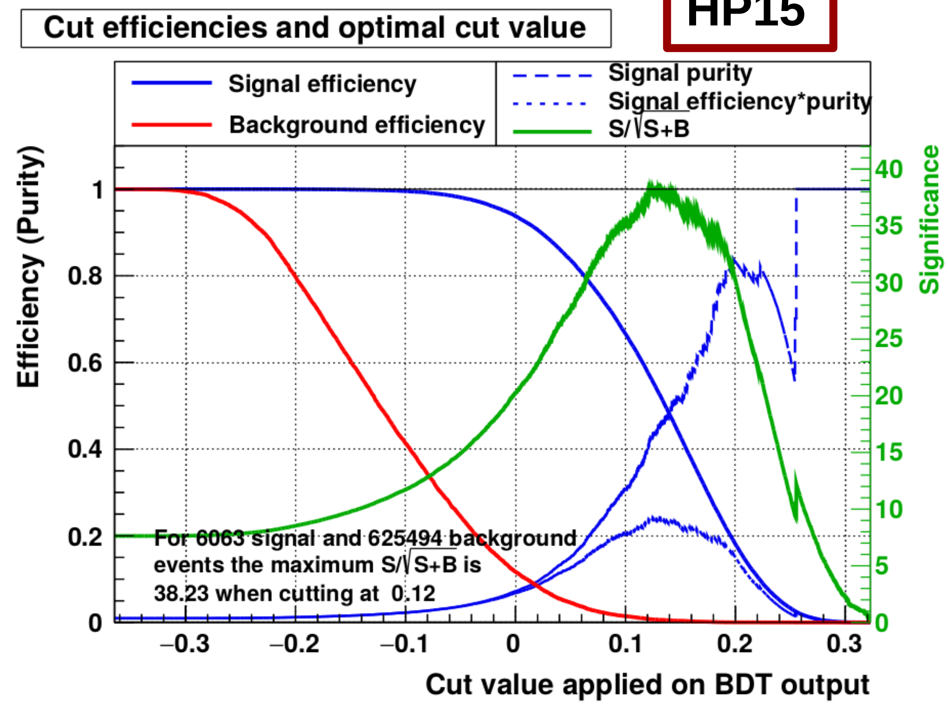
- High signal significance after BDT analysis
- Good signal efficiency after cut on BDT (~25-35%)

on-shell *W* — 3 TeV — off-shell *W**

BP23



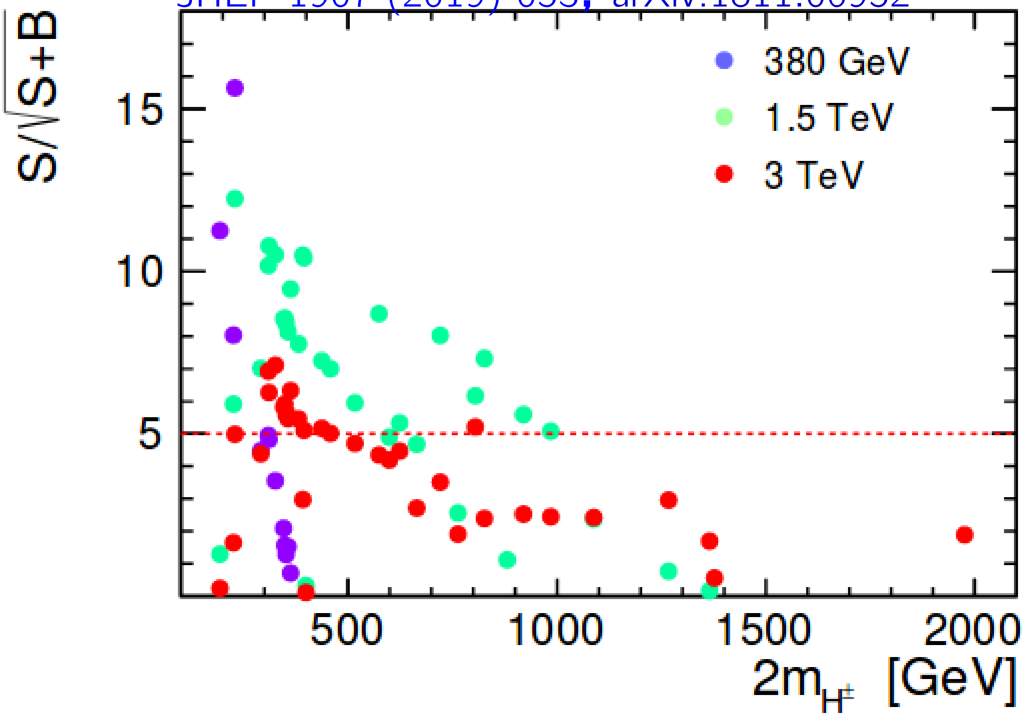
HP15



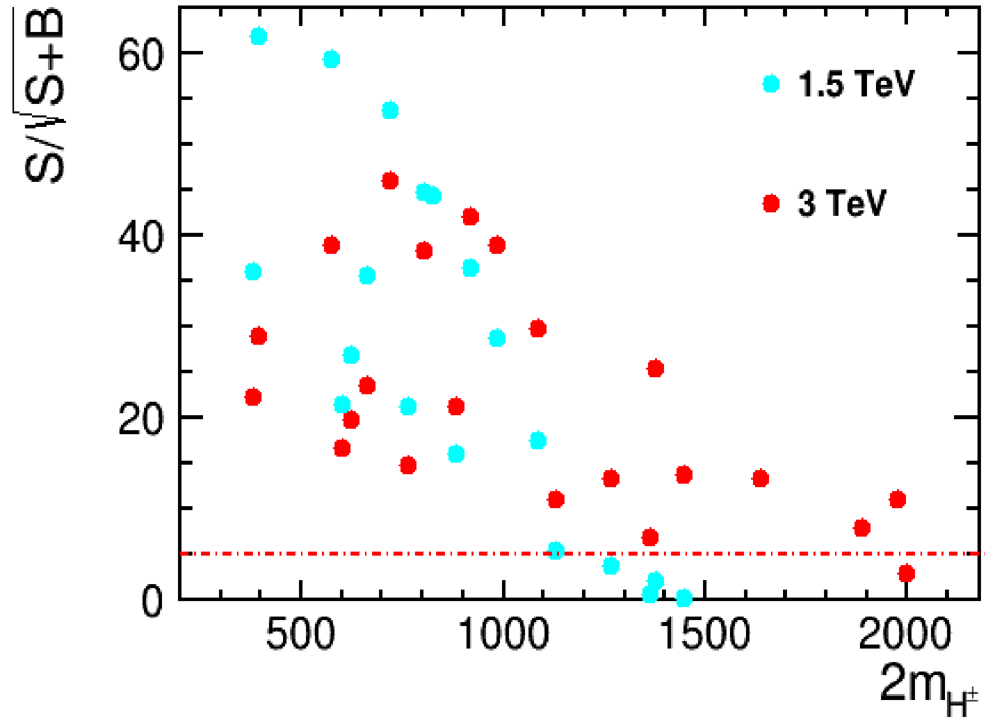
- High signal significance after BDT analysis
- Good signal efficiency after cut on BDT (~20-30%)

Full-leptonic channel results:

JHEP 1907 (2019) 053, arXiv:1811.06952



Semi-leptonic channel results:



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

Summary

- CLIC potential for discovering Inert Doublet Model charged scalars in **semi-leptonic** decay channel studied for **1.5 TeV** and **3 TeV**
- Realistic simulation with **DELPHES** confirms earlier estimates
- Charged IDM scalars pair-production can be observed with high significance up to masses of the order of **1 TeV**
- Influence of the **beam polarisation** still to be studied.

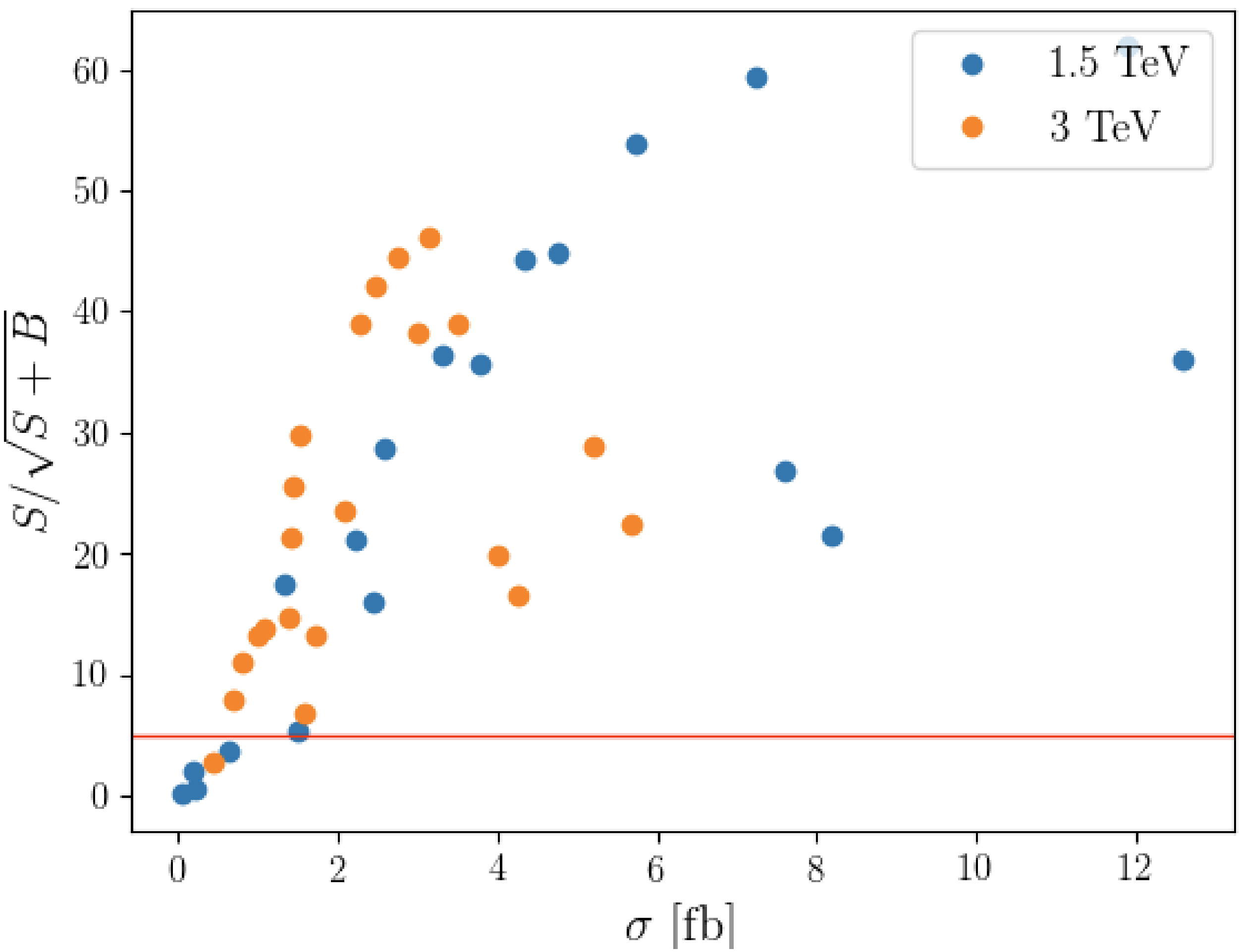
Thank you!

BACKUP

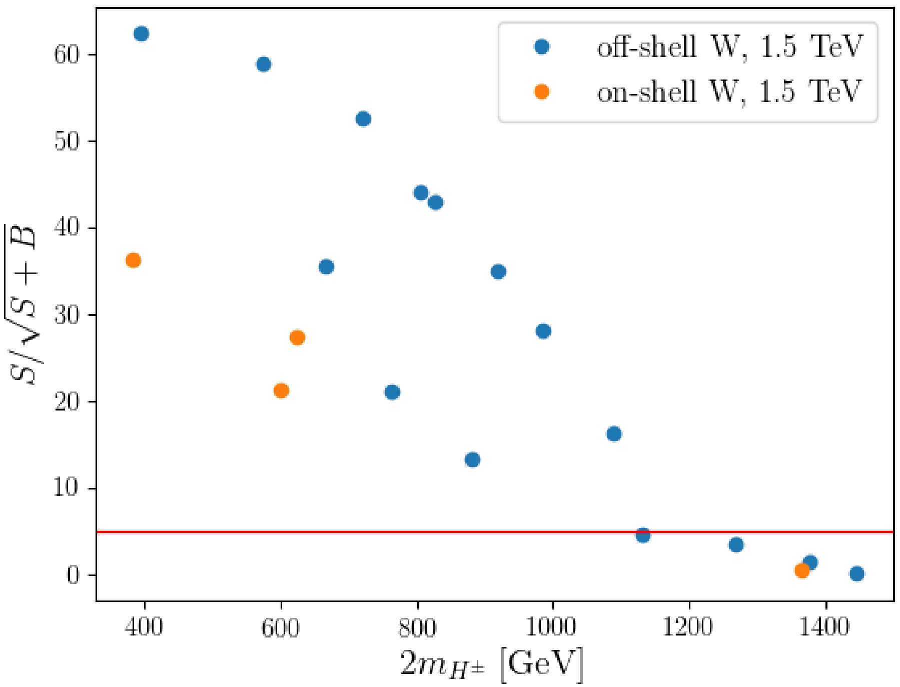
Full results

Benchmark point	1.5 TeV signif.	1.5 TeV σ [fb]	3 TeV signif.	3 TeV σ [fb]	$m_{H^\pm}$ [GeV]
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

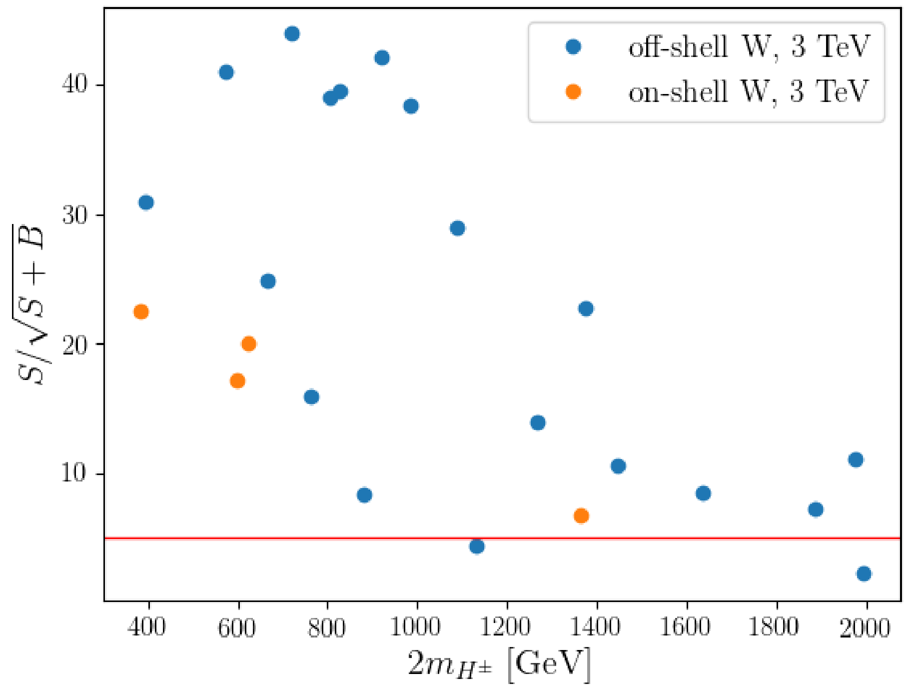
Significance vs. cross section



Results



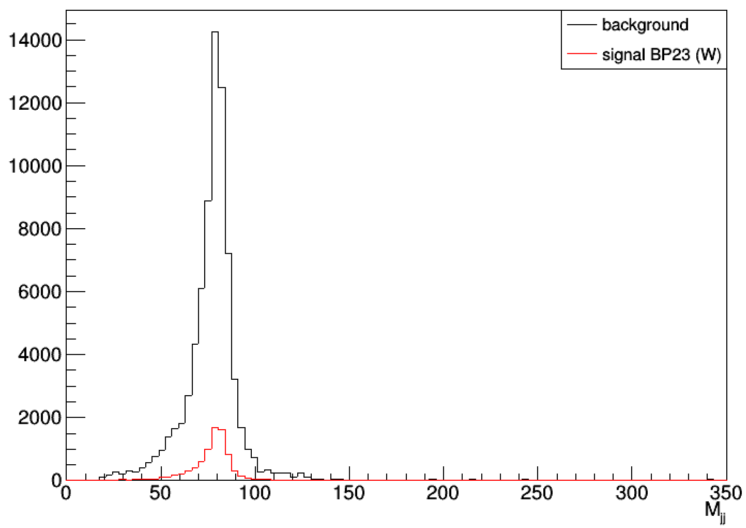
off-shell W, 1.5 TeV
on-shell W, 1.5 TeV
$S/\sqrt{S+B}$
$2m_{H^\pm}$ [GeV]

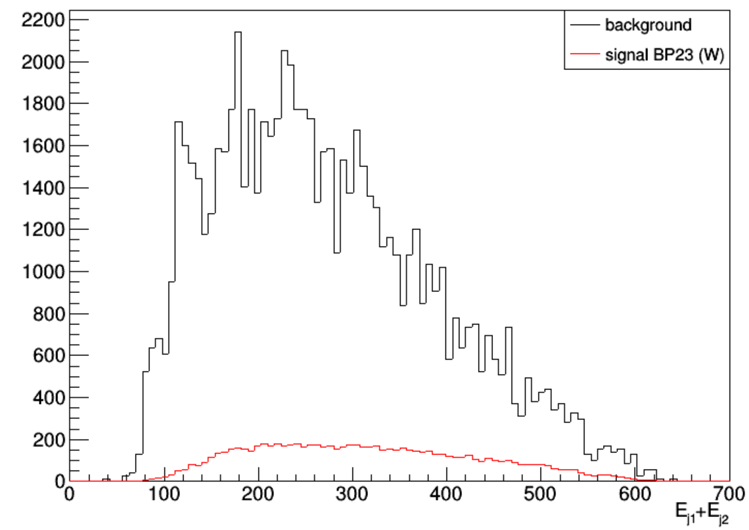


off-shell W, 3 TeV
on-shell W, 3 TeV
$S/\sqrt{S+B}$
$2m_{H^\pm}$ [GeV]

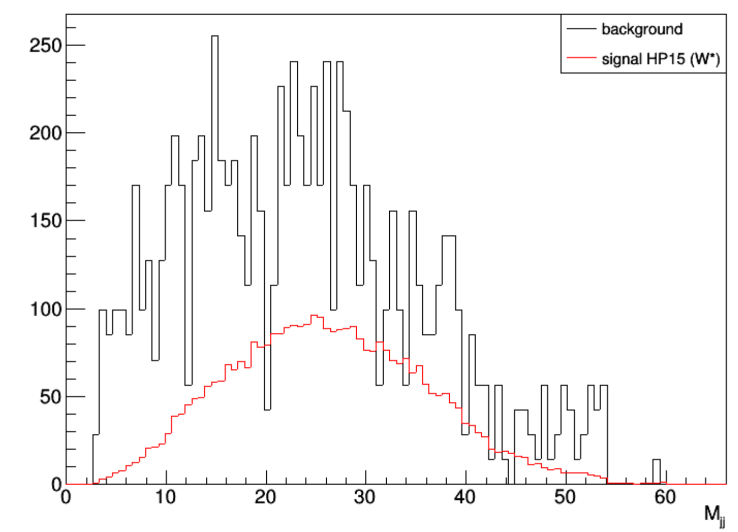
Distributions after cut on BDT at **1.5 TeV**

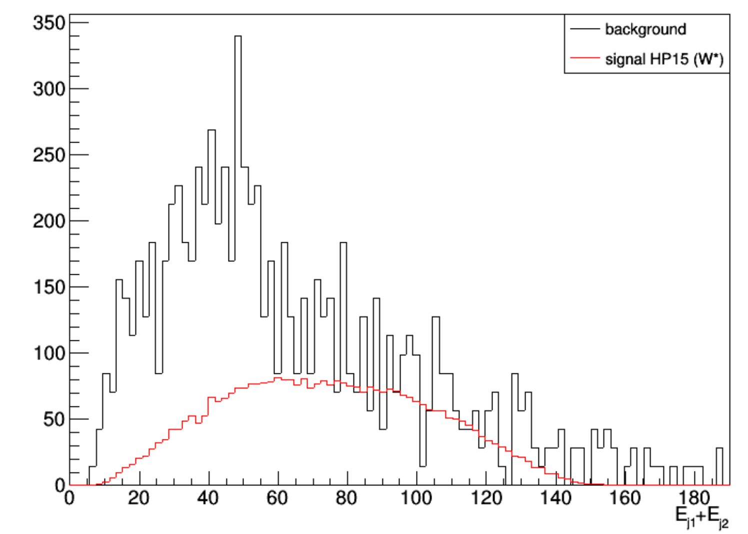
***W* (BP23)**





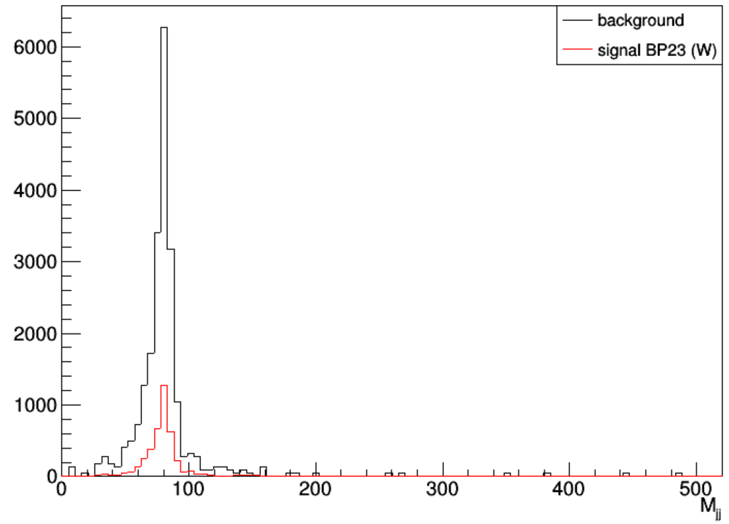
***W** (HP15)**

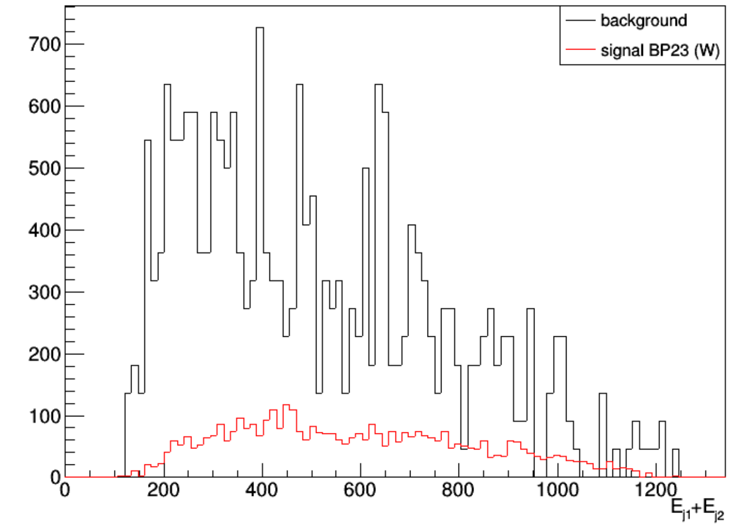




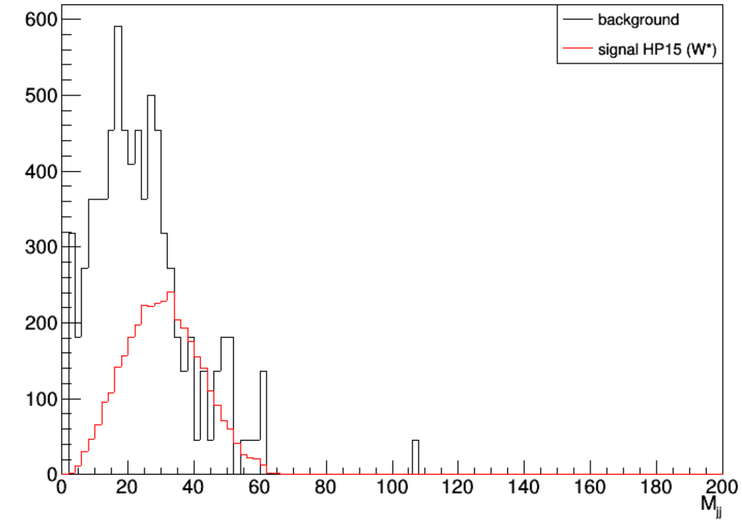
Distributions after cut on BDT at **3 TeV**

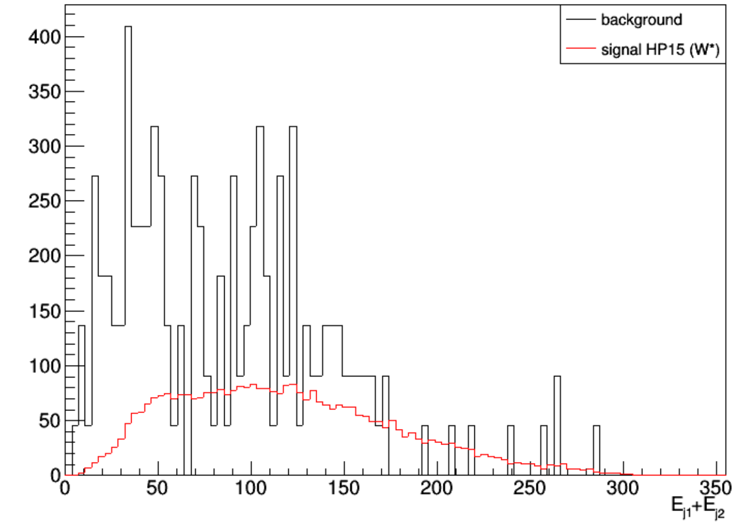
***W* (BP23)**



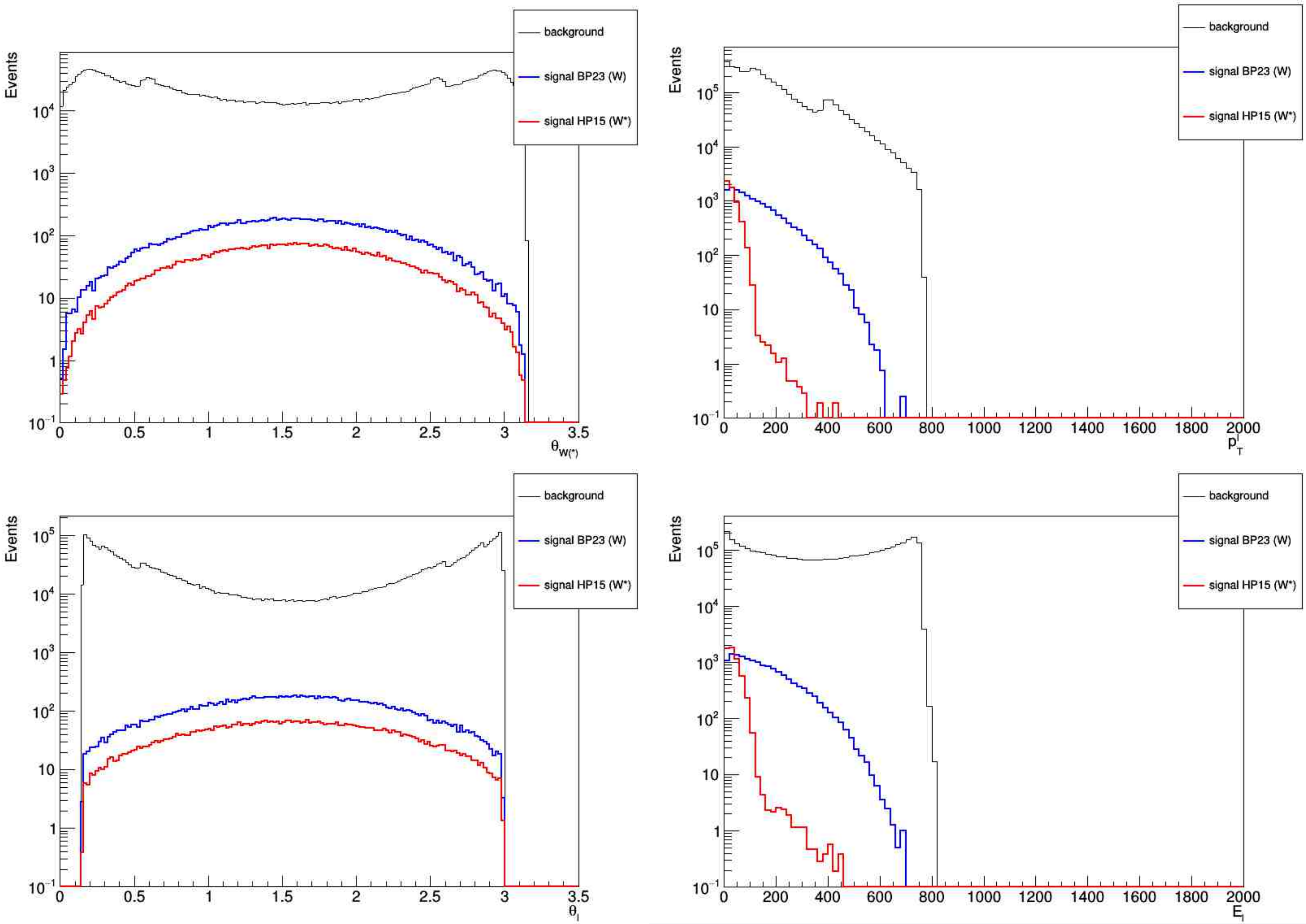


***W** (HP15)**

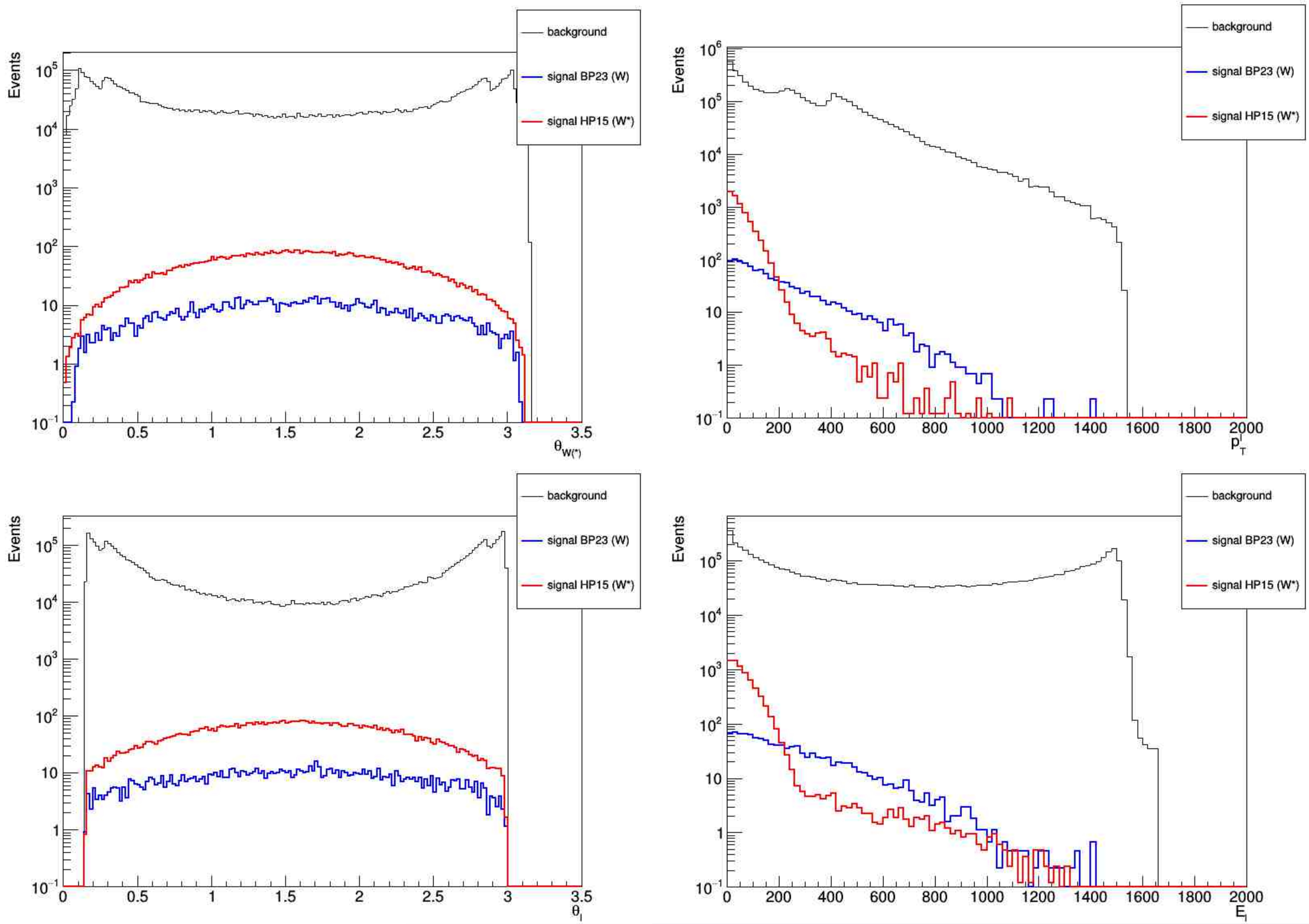




Kinematic variables distributions, 1.5 TeV



Kinematic variables distributions, 3 TeV



Benchmarks

No.	M_H	M_A	$M_{H^\pm}$	Z on-shell	W on-shell	DM >50%	λ_2	λ_{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%	λ_2	λ_{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
HP10	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