ATL-COM-PHYS-2014-283

Searches for long-lived neutral particles decaying into Heavy Flavors in the Hadronic Calorimeter of ATLAS at $\sqrt{s}$ =8 TeV

Abstract: The ATLAS detector at the Large Hadron Collider at CERN is used to search for the decay of a light Higgs to a pair of neutral, long-lived particles in 20.3 fb^{-1} of data collected at a center of mass energy of $\sqrt{s}$ = 8 TeV. This paper reports on a search that requires both long-lived particles to decay to heavy fermions late in the ATLAS Electromagnetic Calorimeter or inside the Hadronic Calorimeter. The resulting event topology is a dijet event with no charged particle tracks pointing at either jet and very little energy in the Electromagnetic Calorimeter as the long-lived particles do not interact with Standard Model particles before their decay. No excess of events is observed for Higgs masses between 100 GeV and 140 GeV and long-lived particle with masses between 10 GeV and 40 GeV. Limits are reported as Higgs boson production times branching ratio as a function of the long-lived particle's proper decay length.

Updates to paper found during management review

https://cds.cern.ch/record/1694731

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MANAGEMENT SIGNOFF TURNS UP A MISSING SYSTEMATIC…

We have a timing cut in our analysis to help reduce the impact from cosmics:

- Jet timing must be between -1 and 5 ns
- We were not applying a systematic.

Comparing MC and Data we smeared the MC's timing value by 0.5 ns, and added a new column to the systematic error table in the paper

- Errors range between 1% and 10% depending on the sample, statistics, etc.

Our limits were re-run with this new systematic error.

Added to the paper (in bold):

- "The \met uncertainty accounts for variations in missing transverse momentum scale and resolution~\cite{met}. **The timing systematic accounts for mismodeling of jet timing between MC and data. Both of these uncertainties** were determined by smearing the associated cut to determine the impact on the acceptance."

Sample m_H, m_{π_v} [GeV]	H σ [%]	JES [%]	Trigger [%]	E_T^{miss} [%]	Time Cut [%]	Total [%]
126, 10	$^{+10.4}_{-10.4}$	$^{+2.2}_{-2.7}$	±1.1	$^{+5.5}_{-2.4}$	$^{+1.6}_{-6.6}$	$^{+16.4}_{-16.7}$
126, 25	$^{+10.4}_{-10.4}$	$^{+1.5}_{-1.6}$	±1.3	$^{+3.1}_{-1.8}$	$^{+0.8}_{-3.3}$	$^{+15.6}_{-15.5}$
126, 40	$^{+10.4}_{-10.4}$	$^{+2.6}_{-6.2}$	±1.1	$^{+7.7}_{-4.6}$	$^{+1.9}_{-5.9}$	$^{+18.2}_{-16.9}$

Sample m_Φ, m_{π_v} [GeV]	Φ σ [%]	JES [%]	Trigger [%]	E_T^{miss} [%]	Time Cut [%]	Total [%]
100, 10	$^{+11.1}_{-10.6}$	$^{+2.3}_{-4.0}$	±0.1	$^{+4.6}_{-3.4}$	$^{+2.7}_{-9.5}$	$^{+16.7}_{-18.5}$
100, 25	$^{+11.1}_{-10.6}$	$^{+5.5}_{-3.7}$	±1.2	$^{+3.4}_{-2.5}$	$^{+1.7}_{-0.7}$	$^{+17.0}_{-15.8}$
140, 10	$^{+10.1}_{-10.3}$	$^{+0.6}_{-1.1}$	±0.5	$^{+4.0}_{-5.6}$	$^{+1.9}_{-6.6}$	$^{+15.6}_{-17.2}$
140, 20	$^{+10.1}_{-10.3}$	$^{+1.2}_{-1.6}$	±1.0	$^{+4.0}_{-3.9}$	$^{+0.4}_{-5.0}$	$^{+15.5}_{-16.2}$
140, 40	$^{+10.1}_{-10.3}$	$^{+1.3}_{-1.6}$	±1.5	$^{+6.3}_{-4.6}$	$^{+1.8}_{-2.4}$	$^{+16.5}_{-15.8}$
300, 50	$^{+9.6}_{-10.0}$	$^{+0.1}_{-0.3}$	±0.3	$^{+9.0}_{-7.4}$	$^{+0.5}_{-3.0}$	$^{+13.9}_{-13.3}$
600, 50	$^{+11.2}_{-10.1}$	$^{+0.0}_{-0.1}$	±0.2	$^{+11.7}_{-11.3}$	$^{+2.2}_{-4.4}$	$^{+17.0}_{-16.2}$
600, 150	$^{+11.2}_{-10.1}$	$^{+0.2}_{-0.2}$	±0.3	$^{+11.5}_{-10.2}$	$^{+2.7}_{-5.3}$	$^{+17.5}_{-15.1}$
900, 50	$^{+12.8}_{-11.5}$	$^{+0.0}_{-0.1}$	±0.1	$^{+12.6}_{-9.7}$	$^{+1.0}_{-3.7}$	$^{+18.5}_{-15.9}$
900, 150	$^{+12.8}_{-11.5}$	$^{+0.2}_{-0.3}$	±0.2	$^{+11.8}_{-10.9}$	$^{+0.9}_{-2.5}$	$^{+18.1}_{-16.3}$

NEW EXTRAPOLATION PROCEEDURE

Extrapolation takes the result at a generated proper lifetime and extrapolates it to a different proper lifetime

While adding the systematic error, we re-examined the extrapolation procedure and discovered an oversight on our part:

- We have both a p_T and timing cut in our analysis.
- Slow particles (low β) would make it into our acceptance region at high proper lifetimes, but would have been out of time…
- The old extrapolation procedure didn't take this into account.
- New procedure uses events and, basically, reweights them by the new ctau profile.

To some extent, our p_T cut reduces the effect

- The jet p_T cut of 40 GeV and 60 GeV meant almost all π_v are $\beta = 1$…
- Effect should get larger for larger $c\tau$ as extrapolation is from samples with "small" generated $c\tau$

NEW LIMITS

Old

Table 4: Ranges of π_v proper decay lengths excluded at 95% CL assuming a 30% and a 10% BR for a $m_H = 126$ GeV.

MC sample m_H, m_{π_v} [GeV]	Excluded range 30% BR $H \to \pi_v \pi_v$ [m]	Excluded range 10% BR $H \to \pi_v \pi_v$ [m]
126, 10	0.10 – 6.61	0.14 – 3.35
126, 25	0.30 – 16.91	0.41 – 8.34
126, 40	0.68 – 20.39	1.06 – 9.11

New

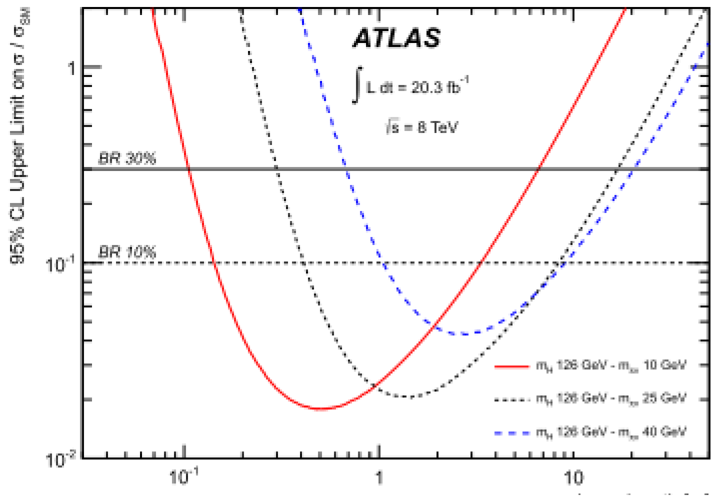
Table 4: Ranges of π_v proper decay lengths excluded at 95% CL assuming a 30% and a 10% BR for a $m_H = 126$ GeV.

MC sample m_H, m_{π_v} [GeV]	Excluded range 30% BR $H \to \pi_v \pi_v$ [m]	Excluded range 10% BR $H \to \pi_v \pi_v$ [m]
126, 10	0.10 – 6.08	0.14 – 3.13
126, 25	0.30 – 14.99	0.41 – 7.57
126, 40	0.68 – 18.50	1.03 – 8.32

Low side limits are basically unchanged...

The high side see a bigger effect…

m_H LIMIT PLOTS



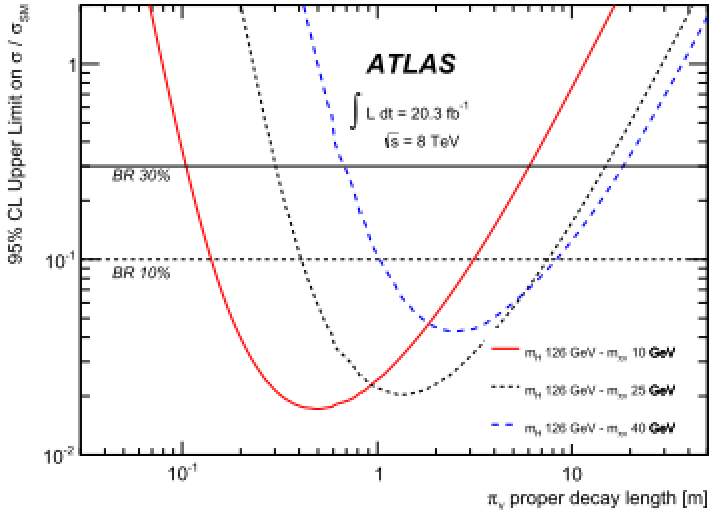
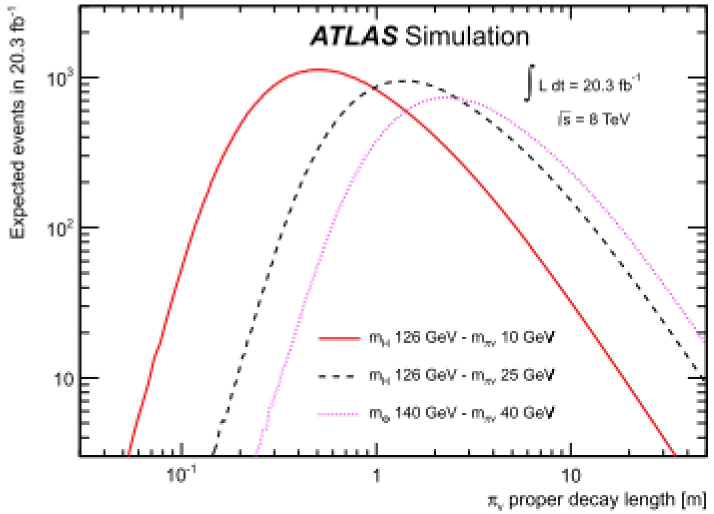


Fig 4a of paper



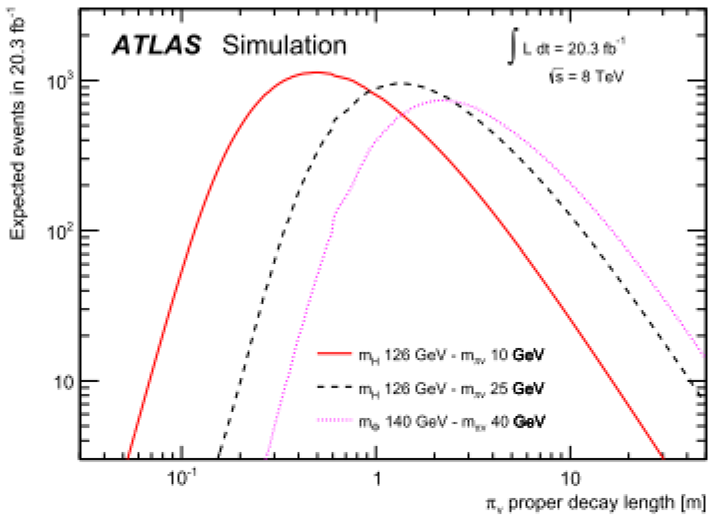


Fig 5 of paper

NON m_H LIMIT PLOTS

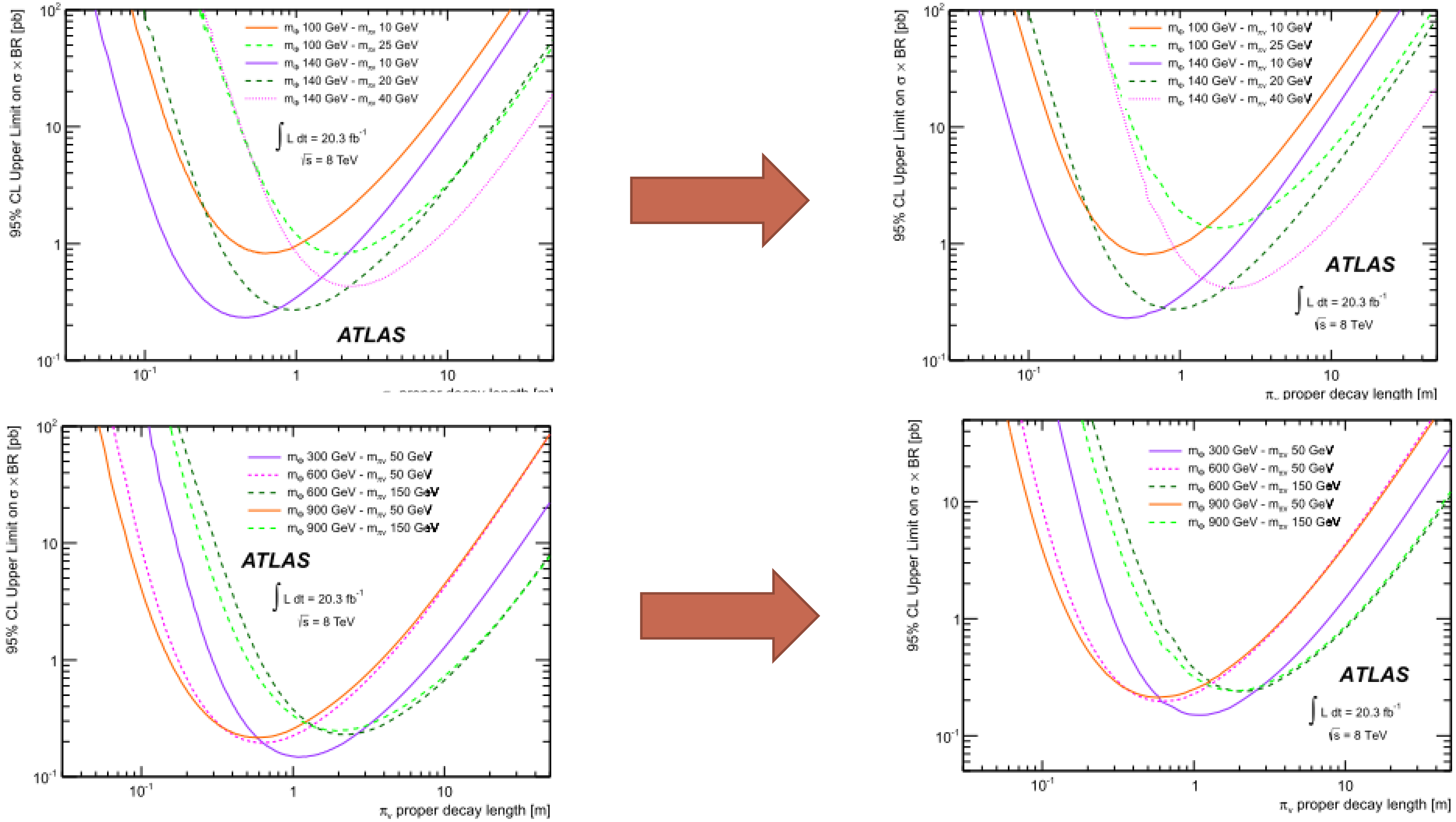


Fig 6 (a,b)

Expected events at $c\tau = 1.5$ m

Table 3: Summary of expected number of signal events, expected background present in the data sample, and the observed number of events in 20.3 fb^{-1}. The error on the signal samples is statistical only, the error on the expected background is statistical $\oplus$ systematic. All results are normalized for a proper decay length of the π_v of 1.5 m. A 100% branching ratio for $\Phi_{hs} \to \pi_v \pi_v$ is assumed.

Sample (m_H, m_{π_v} [GeV])	Expected yields	Global acceptance (%)
126, 10	565 ± 20	0.147 ± 0.005
126, 25	941 ± 37	0.244 ± 0.009
126, 40	353 ± 25	0.092 ± 0.007

Sample (m_H, m_{π_v} [GeV])	Expected yields	Global acceptance (%)
100, 10	460 ± 25	0.076 ± 0.004
100, 25	400 ± 29	0.066 ± 0.005
140, 10	560 ± 18	0.179 ± 0.006
140, 20	961 ± 33	0.307 ± 0.010
140, 40	645 ± 26	0.206 ± 0.008
300, 50	450 ± 9	0.618 ± 0.013
600, 50	36 ± 0.8	0.335 ± 0.009
600, 150	41 ± 1.3	0.387 ± 0.012
900, 50	3 ± 0.2	0.298 ± 0.007
900, 150	5 ± 0.2	0.390 ± 0.014

Table 3: Summary of expected number of signal events, expected background present in the data sample, and the observed number of events in 20.3 fb^{-1}. The error on the signal samples is statistical only, the error on the expected background is statistical $\oplus$ systematic. All results are normalized for a proper decay length of the π_v of 1.5 m. A 100% branching ratio for $\Phi_{hs} \to \pi_v \pi_v$ is assumed.

Sample (m_H, m_{π_v} [GeV])	Expected yields	Global acceptance (%)
126, 10	536 ± 23	0.139 ± 0.006
126, 25	941 ± 44	0.244 ± 0.011
126, 40	365 ± 31	0.095 ± 0.008

Sample (m_H, m_{π_v} [GeV])	Expected yields	Global acceptance (%)
100, 10	440 ± 29	0.073 ± 0.005
100, 25	424 ± 37	0.070 ± 0.006
140, 10	525 ± 20	0.168 ± 0.006
140, 20	900 ± 37	0.287 ± 0.012
140, 40	641 ± 30	0.205 ± 0.010
300, 50	444 ± 11	0.609 ± 0.015
600, 50	35 ± 1	0.330 ± 0.010
600, 150	41 ± 2	0.386 ± 0.015
900, 50	3.5 ± 0.1	0.304 ± 0.011
900, 150	4.6 ± 0.2	0.397 ± 0.016

AUX MATERIAL WITH EXTRAPOLATION DEPENDENT QUANITITIES

sample (m_H, m_{π_v} [GeV])	trigger eff. [%]	offline selection eff. [%]	global acceptance [%]
126, 10	3.19 ± 0.02	4.61 ± 0.16	0.147 ± 0.005
126, 25	4.57 ± 0.04	5.34 ± 0.21	0.244 ± 0.009
126, 40	2.97 ± 0.04	3.10 ± 0.21	0.092 ± 0.007

sample (m_Φ, m_{π_v} [GeV])	trigger eff. [%]	offline selection eff. [%]	global acceptance [%]
100, 10	2.00 ± 0.02	3.80 ± 0.20	0.076 ± 0.004
100, 25	2.07 ± 0.03	3.19 ± 0.23	0.066 ± 0.005
140, 10	3.77 ± 0.02	4.75 ± 0.15	0.179 ± 0.006
140, 20	5.64 ± 0.03	5.44 ± 0.18	0.307 ± 0.010
140, 40	4.85 ± 0.04	4.25 ± 0.17	0.206 ± 0.008
300, 50	14.94 ± 0.06	4.14 ± 0.09	0.618 ± 0.013
600, 50	13.40 ± 0.04	2.50 ± 0.06	0.335 ± 0.009
600, 150	16.73 ± 0.08	2.31 ± 0.08	0.387 ± 0.012
900, 50	12.67 ± 0.04	2.35 ± 0.06	0.298 ± 0.007
900, 150	17.41 ± 0.08	2.24 ± 0.08	0.390 ± 0.014

Table 5: Trigger efficiency, offline selection efficiency and global acceptance (%) for all the signal samples re-scaled to the same proper lifetime of 1.5 m. Trigger efficiency is defined as the number of events passing the trigger divided by the total number of events; offline selection efficiency is defined as the number of events with the two jet topology divided by the number of events passing the trigger; global acceptance is defined as the number of events with the two jet topology divided by the total number of events (trigger efficiency multiplied by the offline selection efficiency).

sample (m_H, m_{π_v} [GeV])	trigger eff. [%]	offline selection eff. [%]	global acceptance [%]
126, 10	3.63 ± 0.10	3.84 ± 0.20	0.139 ± 0.006
126, 25	5.49 ± 0.06	4.45 ± 0.21	0.244 ± 0.011
126, 40	2.81 ± 0.04	3.38 ± 0.29	0.095 ± 0.008

sample (m_Φ, m_{π_v} [GeV])	trigger eff. [%]	offline selection eff. [%]	global acceptance [%]
100, 10	2.72 ± 0.17	2.69 ± 0.24	0.073 ± 0.005
100, 25	2.41 ± 0.04	2.92 ± 0.26	0.070 ± 0.006
140, 10	4.55 ± 0.12	3.69 ± 0.17	0.168 ± 0.006
140, 20	6.66 ± 0.09	4.31 ± 0.19	0.287 ± 0.012
140, 40	4.84 ± 0.05	4.23 ± 0.21	0.205 ± 0.010
300, 50	16.38 ± 0.28	3.71 ± 0.11	0.609 ± 0.015
600, 50	13.42 ± 0.11	2.46 ± 0.08	0.330 ± 0.010
600, 150	16.81 ± 0.11	2.29 ± 0.09	0.386 ± 0.015
900, 50	12.69 ± 0.11	2.39 ± 0.09	0.304 ± 0.011
900, 150	18.44 ± 0.12	2.15 ± 0.09	0.397 ± 0.016

Table 5: Trigger efficiency, offline selection efficiency and global acceptance (%) for all the signal samples re-scaled to the same proper lifetime of 1.5 m. Trigger efficiency is defined as the number of events passing the trigger divided by the total number of events; offline selection efficiency is defined as the number of events with the two jet topology divided by the number of events passing the trigger; global acceptance is defined as the number of events with the two jet topology divided by the total number of events (trigger efficiency multiplied by the offline selection efficiency).

EVENT YIELD TABLES IN AUX MATERIAL

We accidentally normalized the high mass and low mass cut flow tables differently…

- In the low mass tables we reported the number of MC events
- In high mass tables we reweighted this number by pileup.

Everything has been moved to be pileup reweighted.

So the low mass cut-flow tables were updated (see next page).

Event Selection	Events	Events	Events	Events
	m_Φ = 100 GeV m_{π_v} = 10 GeV π_v proper decay length = 450 mm	m_Φ = 100 GeV m_{π_v} = 25 GeV π_v proper decay length = 1250 mm	m_H = 126 GeV m_{π_v} = 10 GeV π_v proper decay length = 350 mm	m_H = 126 GeV m_{π_v} = 25 GeV π_v proper decay length = 900 mm
Processed Events	294697	295399	298899	299600
HV Trigger	8414	5584	15916	12339
Quality Requirements	8110	5347	15270	11788
E_T^{miss} (< 50 GeV)	6276	4207	11157	8961
Requirement on first jet				
jet with timing in (-1; 5) ns	6100	4131	10863	8801
Et > 60 GeV	5976	4054	10738	8681
Log Ratio>1.2	5538	3756	9994	8103
no track pt > 1 GeV	5374	3627	9686	7822
$\lvert\eta\rvert < 2.5$	5374	3627	9686	7822
Requirement on second jet				
jet with timing in (-1; 5) ns	5286	3594	9515	7724
Et > 40 GeV	3952	2521	8091	5995
Log Ratio>1.2	363	200	835	673
no track pt > 1 GeV	305	174	707	575
$\lvert\eta\rvert < 2.5$	303	174	697	573
Two jet topology → **expected at 20.3 fb^{-1}**	**683 ± 37**	**380 ± 28**	**1022 ± 36**	**826 ± 33**
	m_H = 126 GeV m_{π_v} = 40 GeV π_v proper decay length = 1850 mm	m_Φ = 140 GeV m_{π_v} = 10 GeV π_v proper decay length = 275 mm	m_Φ = 140 GeV m_{π_v} = 20 GeV π_v proper decay length = 630 mm	m_Φ = 140 GeV m_{π_v} = 40 GeV π_v proper decay length = 1500 mm
Processed Events	184500	290599	281900	299699
HV Trigger	5547	19390	16193	13051
Quality Requirements	5313	18607	15552	12490
E_T^{miss} (< 50 GeV)	3908	13555	11469	9160
Requirement on first jet				
jet with timing in (-1; 5) ns	3806	13202	11248	8971
Et > 60 GeV	3760	13076	11129	8891
Log Ratio>1.2	3494	12244	10444	8340
no track pt > 1 GeV	3375	11827	10088	8059
$\lvert\eta\rvert < 2.5$	3375	11827	10088	8059
Requirement on second jet				
jet with timing in (-1; 5) ns	3324	11660	9955	7980
Et > 40 GeV	2413	10435	8395	6204
Log Ratio>1.2	219	1069	921	692
no track pt > 1 GeV	179	873	766	565
$\lvert\eta\rvert < 2.5$	179	852	755	557
Two jet topology → **expected at 20.3 fb^{-1}**	**430 ± 30**	**1015 ± 33**	**963 ± 33**	**645 ± 30**

Table 6: Selection flow for the lower mass MC samples. The row labeled *expected* are expected number of events in 20.3 fb^{-1}, including effects due to pile-up re-weighting.

Event Selection	Events	Events	Events	Events
	m_Φ = 100 GeV m_{π_v} = 10 GeV π_v proper decay length = 450 mm	m_Φ = 100 GeV m_{π_v} = 25 GeV π_v proper decay length = 1250 mm	m_H = 126 GeV m_{π_v} = 10 GeV π_v proper decay length = 350 mm	m_H = 126 GeV m_{π_v} = 25 GeV π_v proper decay length = 900 mm
Processed Events	294697	295399	298899	299600
HV Trigger	9310	6185	17748	13596
Quality Requirements	9009	5949	17103	13050
E_T^{miss} (< 50 GeV)	6971	4694	12500	9950
Requirement on first jet				
jet with timing in (-1; 5) ns	6804	4616	12182	9783
Et > 60 GeV	6668	4538	12038	9649
Log Ratio>1.2	6231	4229	11287	9061
no track pt > 1 GeV	6054	4080	10941	8767
$\lvert\eta\rvert < 2.5$	6054	4080	10941	8767
Requirement on second jet				
jet with timing in (-1; 5) ns	5956	4043	10763	8659
Et > 40 GeV	4473	2836	9145	6726
Log Ratio>1.2	402	215	956	760
no track pt > 1 GeV	337	186	804	645
$\lvert\eta\rvert < 2.5$	334	186	794	642
Two jet topology → **expected at 20.3 fb^{-1}**	**683 ± 37**	**380 ± 28**	**1022 ± 36**	**826 ± 33**
	m_H = 126 GeV m_{π_v} = 40 GeV π_v proper decay length = 1850 mm	m_Φ = 140 GeV m_{π_v} = 10 GeV π_v proper decay length = 275 mm	m_Φ = 140 GeV m_{π_v} = 20 GeV π_v proper decay length = 630 mm	m_Φ = 140 GeV m_{π_v} = 40 GeV π_v proper decay length = 1500 mm
Processed Events	184500	290599	281900	299699
HV Trigger	6166	21372	17929	14522
Quality Requirements	5933	20602	17299	13973
E_T^{miss} (< 50 GeV)	4394	15076	12810	10283
Requirement on first jet				
jet with timing in (-1; 5) ns	4281	14704	12590	10080
Et > 60 GeV	4226	14563	12448	9980
Log Ratio>1.2	3953	13729	11768	9423
no track pt > 1 GeV	3815	13246	11365	9104
$\lvert\eta\rvert < 2.5$	3815	13246	11365	9104
Requirement on second jet				
jet with timing in (-1; 5) ns	3760	13059	11211	9018
Et > 40 GeV	2722	11670	9454	7002
Log Ratio>1.2	252	1196	1070	773
no track pt > 1 GeV	206	970	882	624
$\lvert\eta\rvert < 2.5$	206	943	867	617
Two jet topology → **expected at 20.3 fb^{-1}**	**430 ± 30**	**1015 ± 33**	**963 ± 33**	**645 ± 30**

Table 6: Selection flow for the lower mass MC samples. The row labeled *expected* are expected number of events in 20.3 fb^{-1}, including effects due to pile-up re-weighting.