DPF PHENO 2024

Search for Charged Higgs through a Reinterpretation of a Dark Mesons search based on 140 fb^{-1} of proton-proton collisions with the ATLAS Detector at the Large Hadron Collider

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The Dark meson search by

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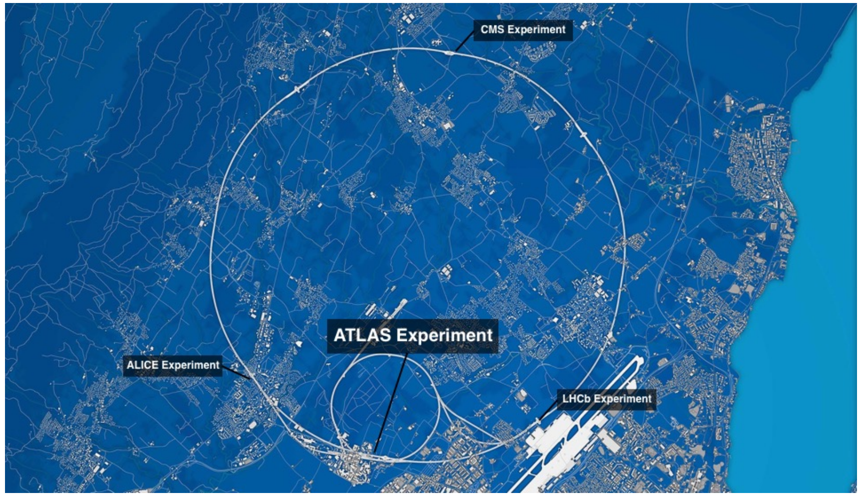
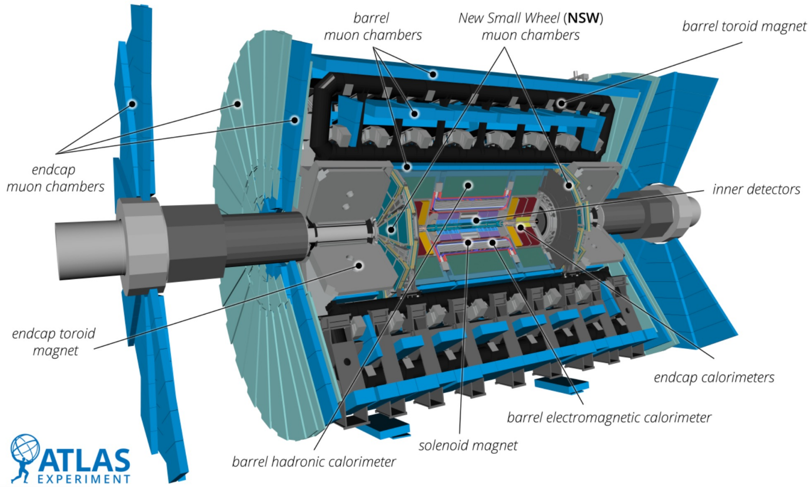
The ATLAS experiment, some background

- The ATLAS experiment is a general-purpose detector located 100m underground that explores fundamental particles and forces using collisions of the two proton beams delivered by the Large Hadron Collider

- Discovery of a neutral Higgs boson of ~125 GeV was announced by the ATLAS and CMS experiment in 2012

- The discovery prompted further discussions about the nature of Higgs boson and possible Higgs boson BSM (Beyond Standard Model)

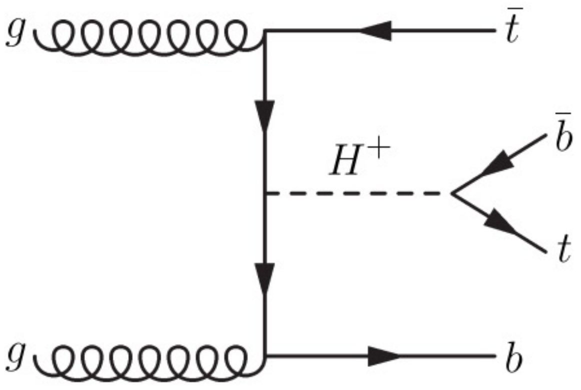




Charged Higgs

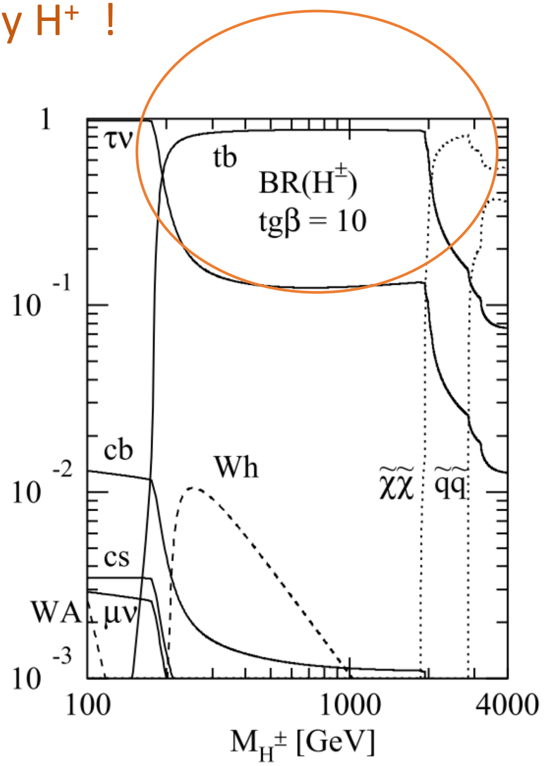
H^+ -> tb^- is the main channel to search for heavy H^+ !

- Charged Higgs bosons (H^+) appear in several extensions to the standard model (SM) when a 2nd doublet or triplet is added to the scalar sector
- Two-Higgs doublet model (2HDM): add one more scalar doublet to the SM and is one of the simplest such models
- Motivated by Higgs sector in MSSM (minimal supersymmetric extension) : hMSSM



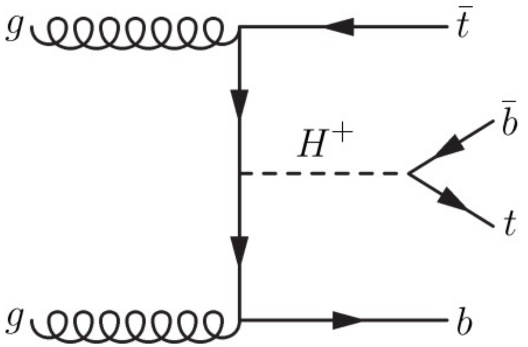
Charged Higgs mass

$\tan\beta = \frac{v2}{v1}$: ratio of the two vacuum expectation values of the two Higgs doublet



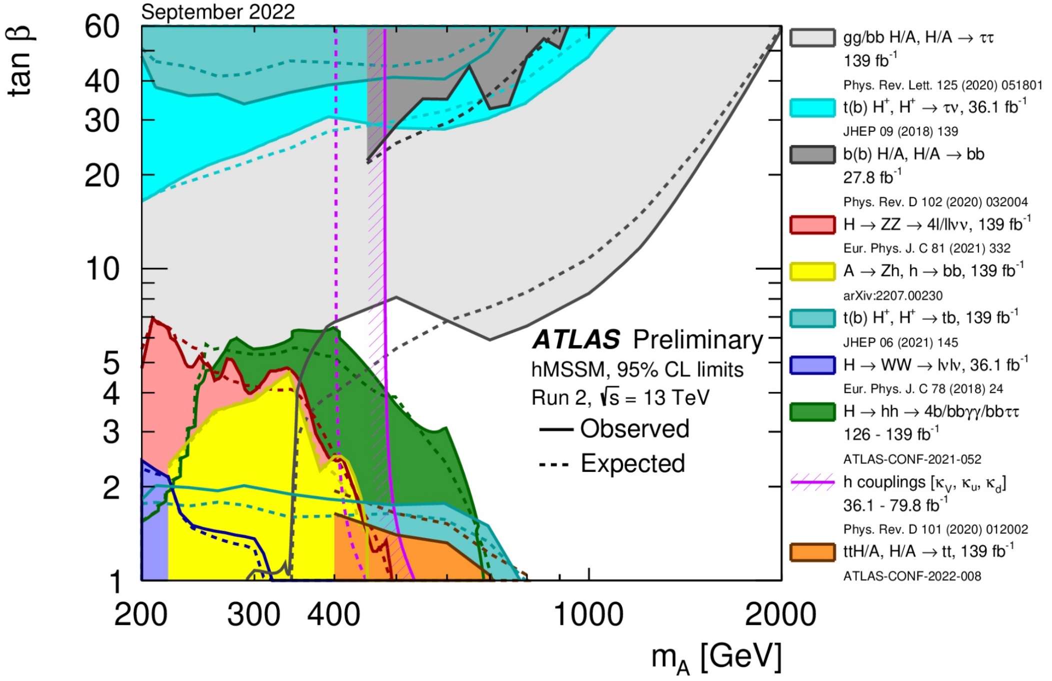
[2] Branching ratios of the charged Higgs boson within the M^{125} h scenario as a function of the charged Higgs mass for tanβ = 10

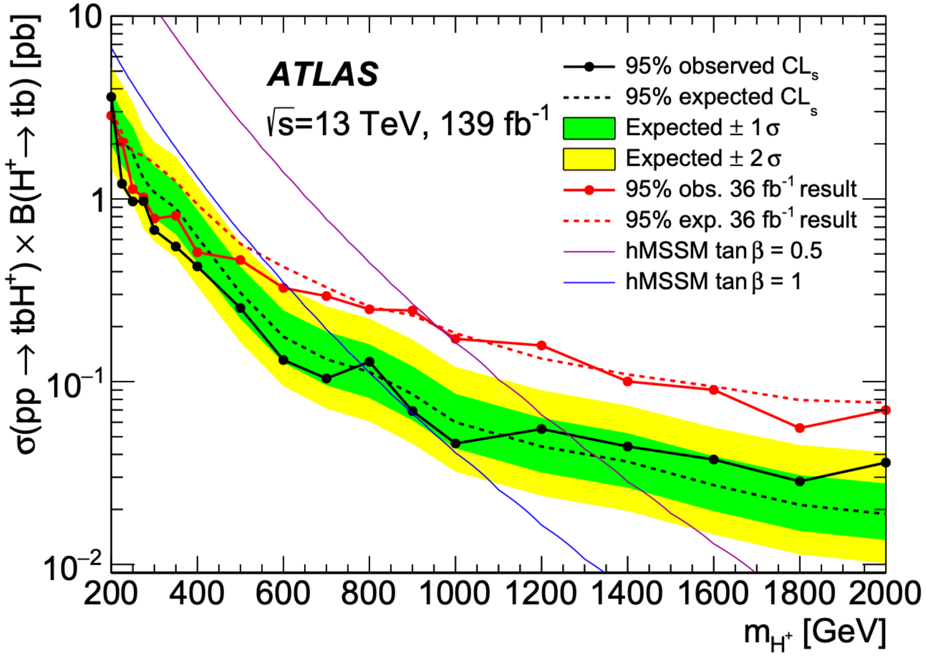
Existing ATLAS searches for H^+



- Sensitivity of H^+ searches has been explored in mass 200-2000 GeV with the full Run 2 dataset

$m_A = m_{H^+}$



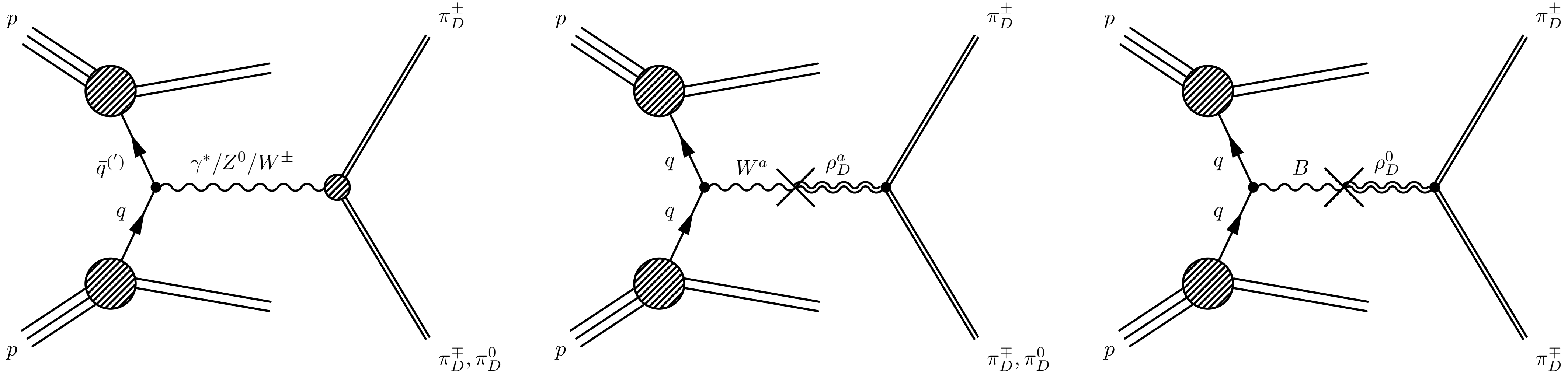


[4]

[1]

ATLAS search for dark mesons

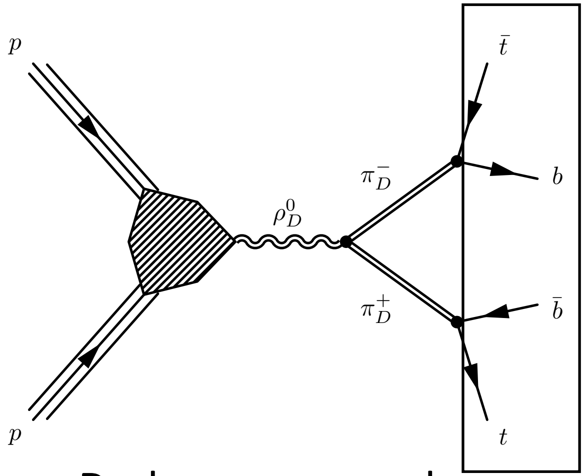
- Dark pions can be pair- produced by Drell-Yan-type production or resonantly produced by an (electrically neutral or charged) dark rho particles;
  - ρ could be produced by kinetic mixing between the dark field and the standard model B or W field (SU(2)$_L$/ SU(2)$_R$)



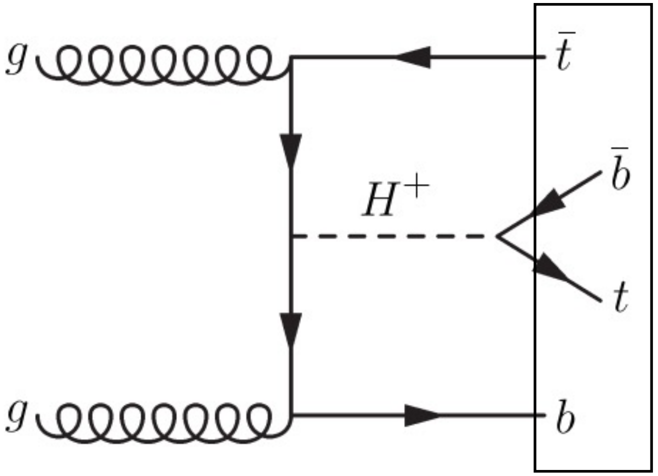
- Focus of the search: SU(2)$_L$ models with no gauge bosons in the final state
- Conference note was published analyzing the above processes: ATLAS-CONF-2023-021

Linking Charged Higgs with dark mesons

- The dark meson search focuses on final state with top and bottom quarks: tttb and ttbb, which subsequently decay to all jets final state (all-hadronic channel); this search could be sensitive to charged Higgs signals
- Final states of the two processes are very similar



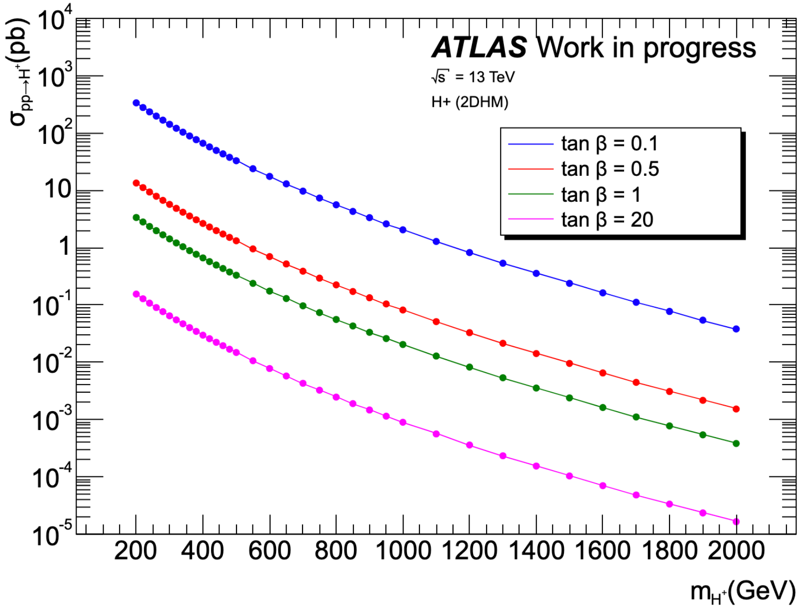
Dark meson search

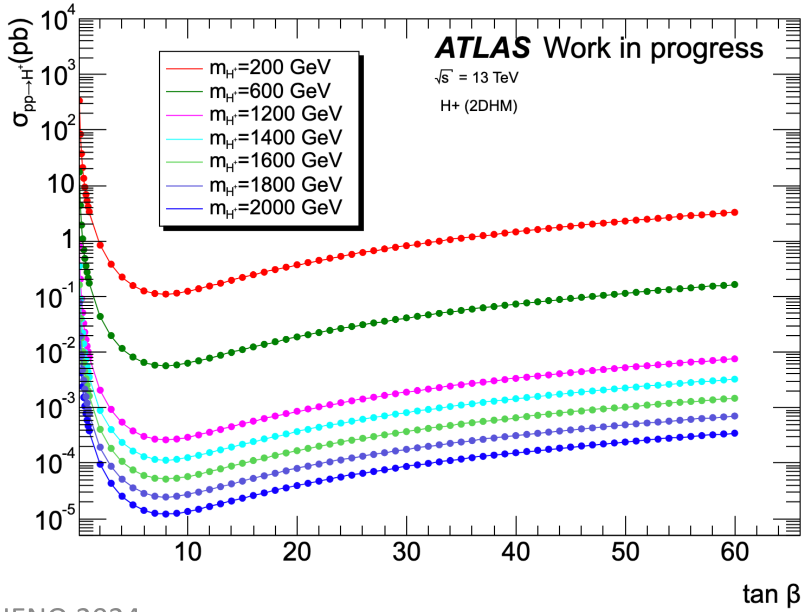


Charged Higgs search

Reinterpretation strategy

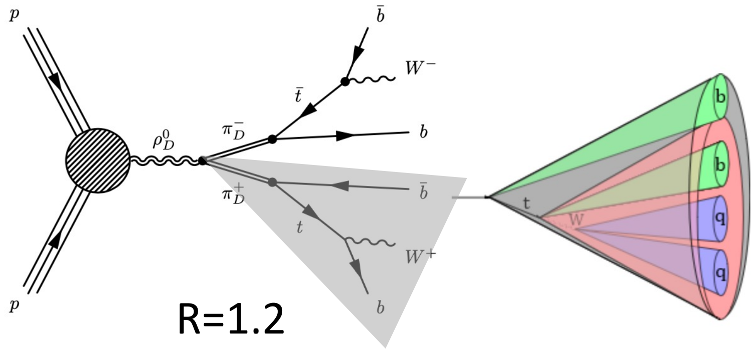
- Signal samples [6] H+ in hMSSM, same as the previous search
- Background samples are the same as used in the dark meson analysis
- 6 mass points of charged Higgs are analyzed in the reinterpretation
    - 600 GeV, 1200 GeV, 1400 GeV, 1600 GeV, 1800 GeV, 2000 GeV
- Heavy charged Higgs NLO cross sections [3] are used to scale events to different tanβ values
    - tanβ = 0.1 is used as a starting point to assess sensitivity





Dark meson all-had channel preselection[5]

Large R jets of Radius 1.2 are re-clustered from radius 0.4 jets



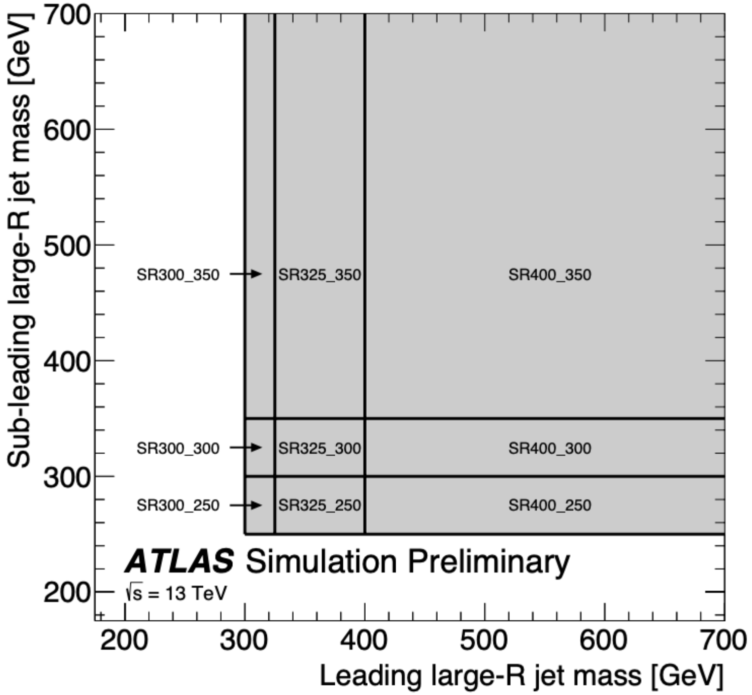
In addition to the generic selections such as good run list, Jet/muon cleaning. etc. Additional criteria are:

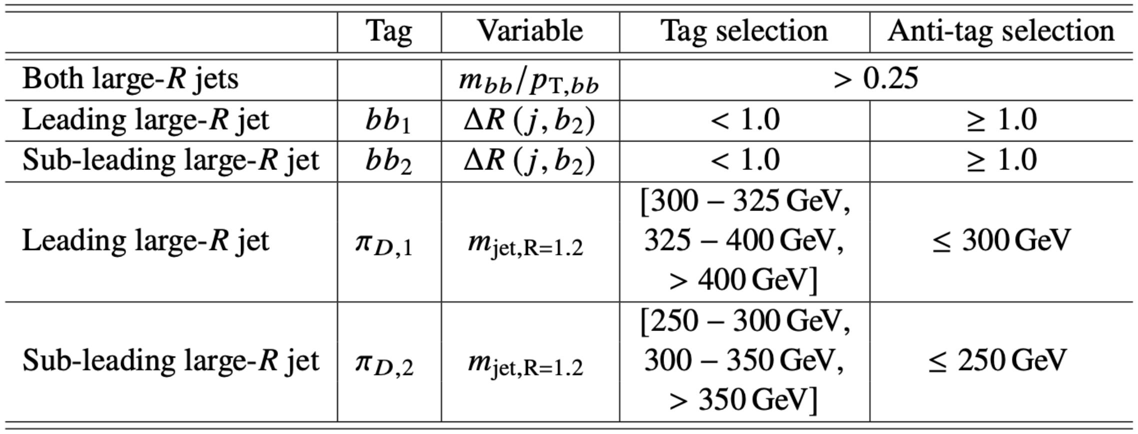
- Zero e/μ
- H_T > 1150 GeV (to avoid region where the H_T trigger is not fully efficient)
- At least 6 jets with p_T > 25 GeV
- At least 3 b-tagged jets
- Leading and sub-leading large R jets to have mass at least 190 GeV

Cut	Preselection
loose ℓ	0
H_T	$>$ 1150 GeV
$p_{T,jet}^6$	$>$ 25 GeV
$\mathrm{N_{b-jets}}$	≥ 3
$m_{\mathrm{jet,R=1.2}}^1$	$>$ 190 GeV
$m_{\mathrm{jet,R=1.2}}^2$	$>$ 190 GeV

DM Signal Region and bkg estimation in all-hadronic channel[5]

- The SR is defined by 4 tags
- There are 9 signal regions defined in terms of leading and sub-leading large R jets mass to improve sensitivity to a range of dark meson signals
- Mutiijet is the main background source for all-hadronic channel and is estimated with Data driven approach with data-MC



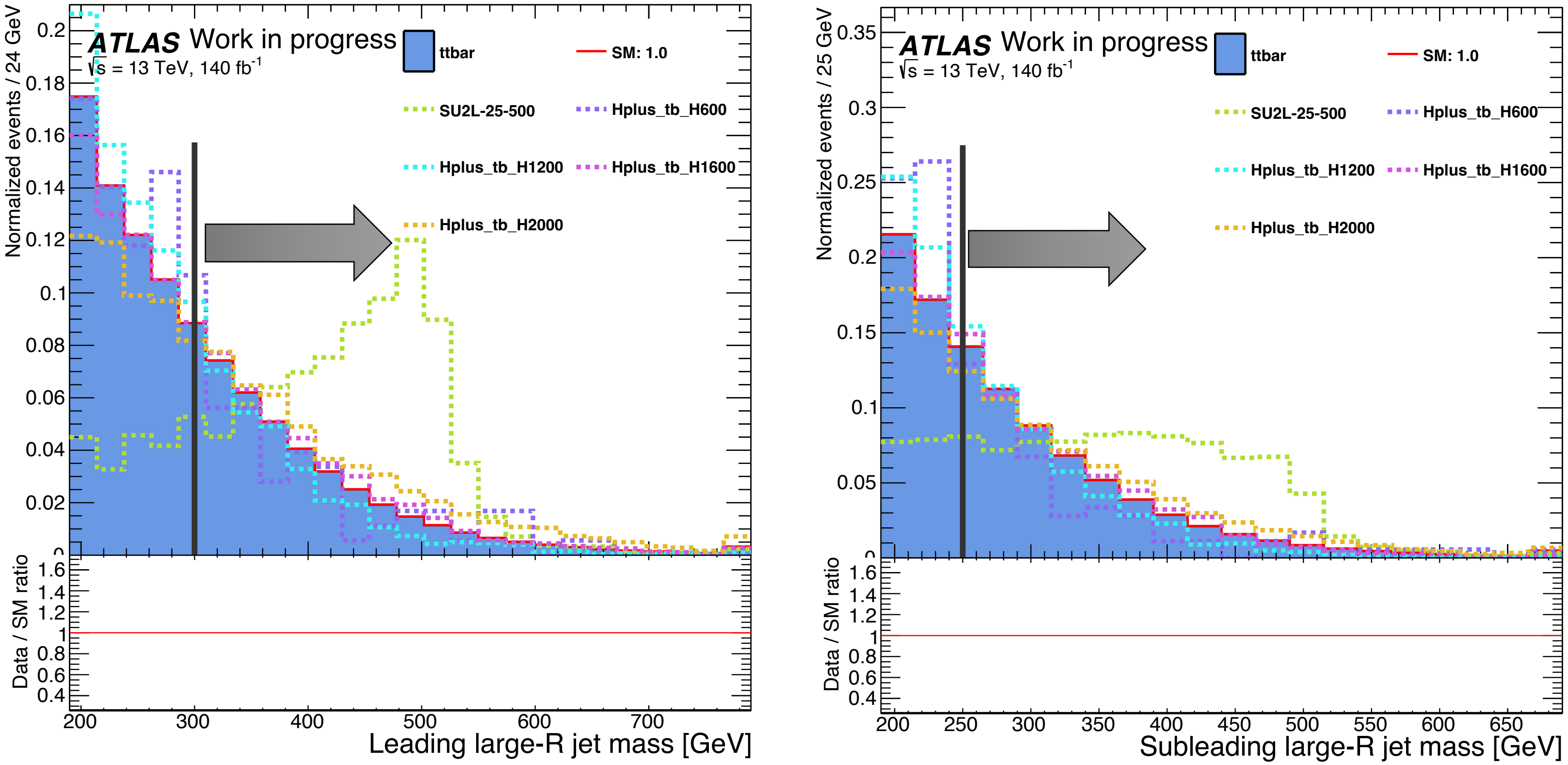


	Tag	Variable	Tag selection	Anti-tag selection
Both large-*R* jets		$m_{bb}/p_{\mathrm{T},bb}$	> 0.25	
Leading large-*R* jet	bb_1	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Sub-leading large-*R* jet	bb_2	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Leading large-*R* jet	$\pi_{D,1}$	$m_{\mathrm{jet,R=1.2}}$	[300 – 325 GeV, 325 – 400 GeV, > 400 GeV]	$\leq$ 300 GeV
Sub-leading large-*R* jet	$\pi_{D,2}$	$m_{\mathrm{jet,R=1.2}}$	[250 – 300 GeV, 300 – 350 GeV, > 350 GeV]	$\leq$ 250 GeV

Large R jet mass distribution (comparing dark meson and H⁺)

- The distributions for the charged Higgs peak at much smaller large R jet mass compared to that of the dark meson signal

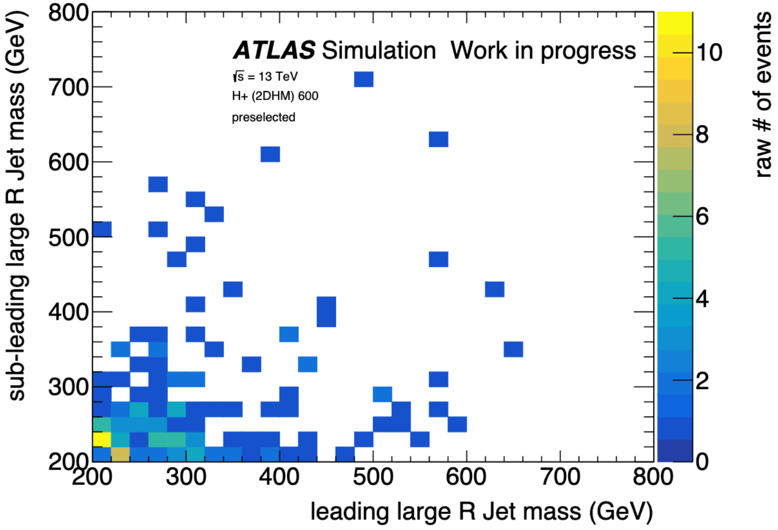
- H^+ signal is more background like in the dark meson analysis [under investigation]



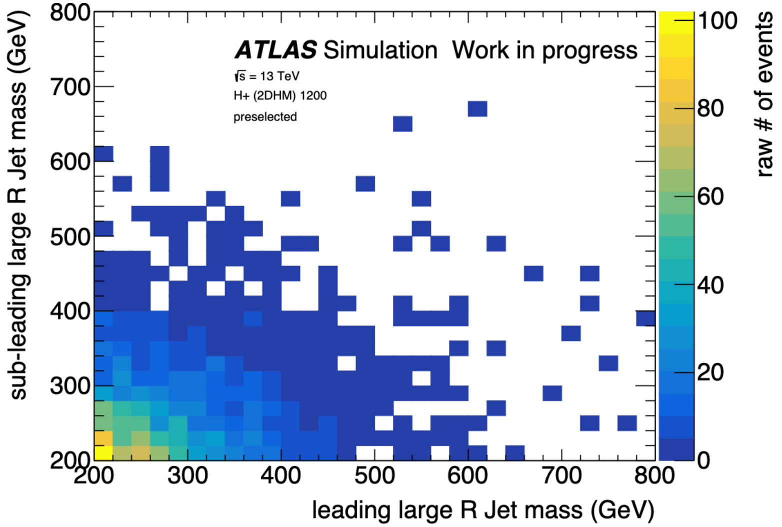
*dominant multijet background not included in the plots here

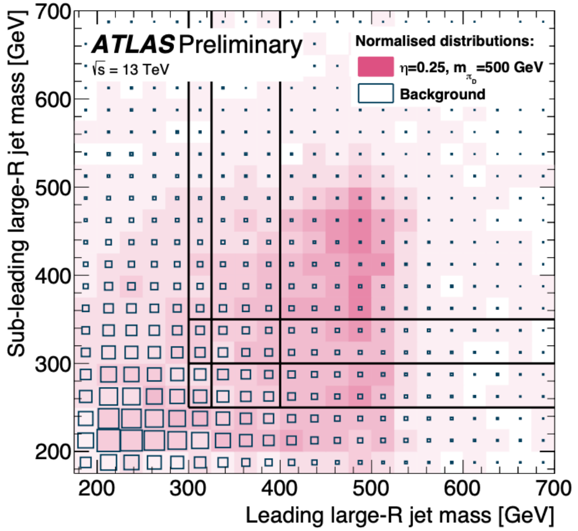
Pre-selected H^+ events in dark meson SR

M_{H+} =600 GeV



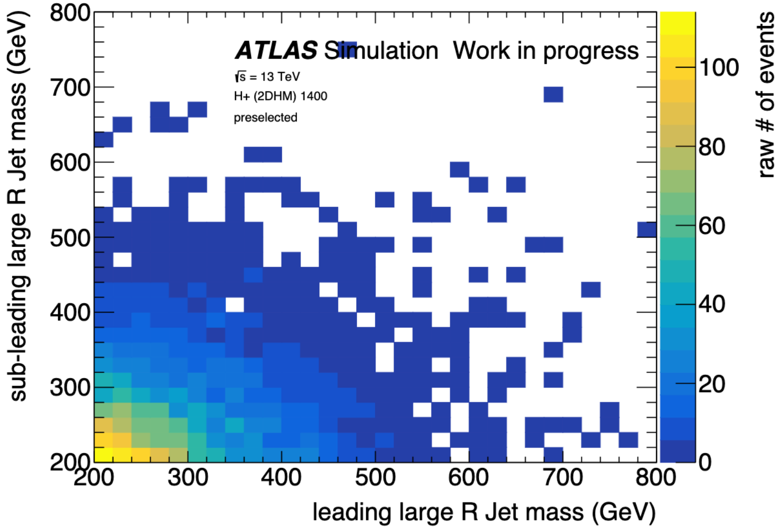
M_{H+} =1200 GeV





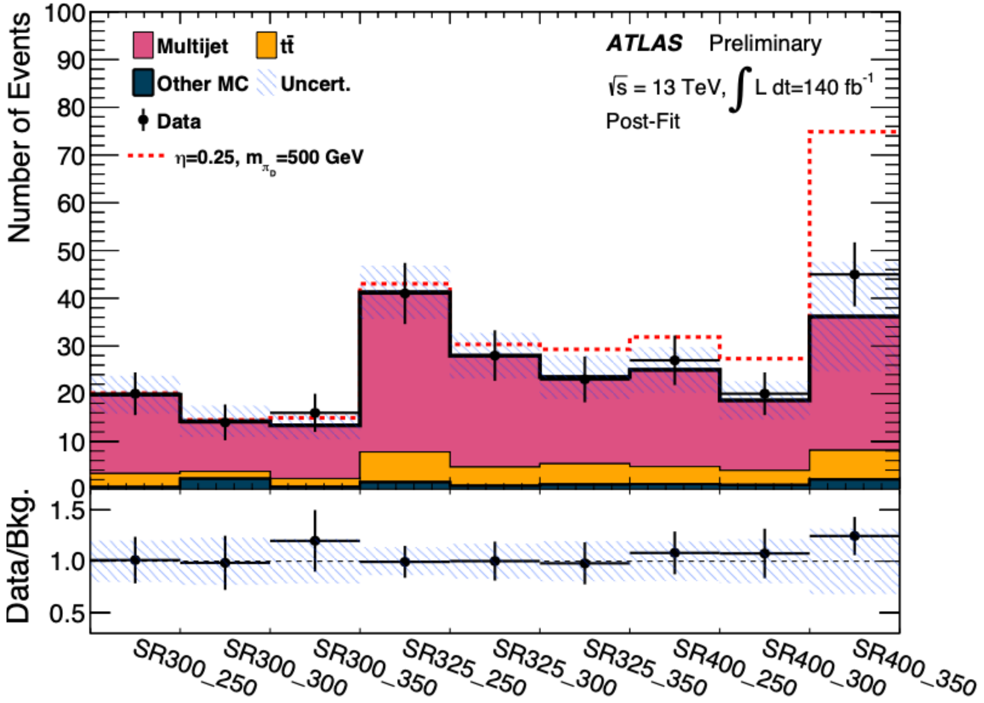
[5]

M_{H+} =1400 GeV

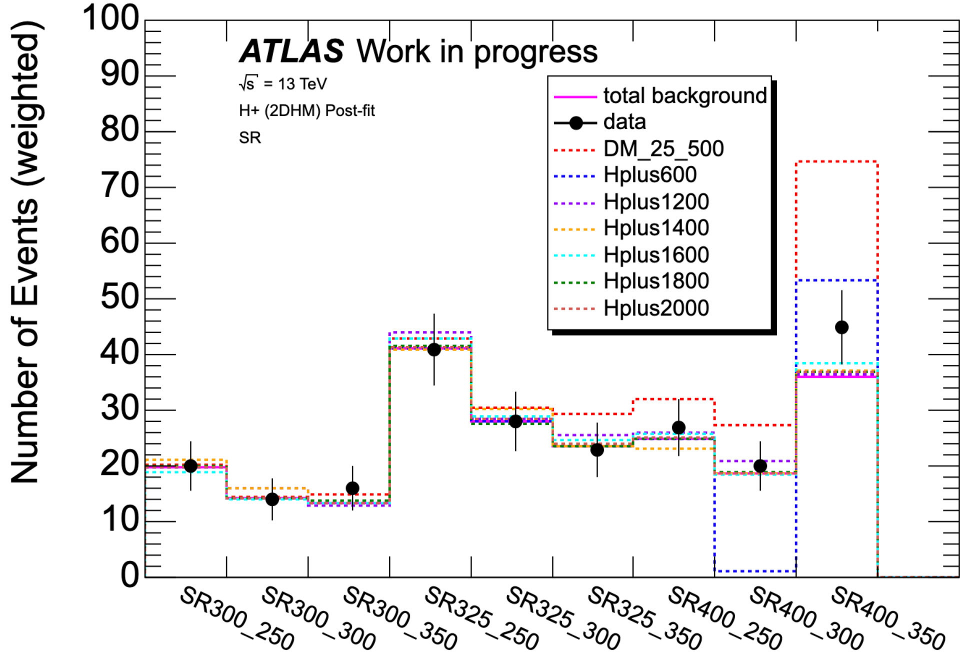


H$^+$ signal in DM all–hadronic Signal regions

ATLAS-CONF-2023-021



Post fit background distributions in all SR bins, η = 0.25, m=500 GeV shows an example dark meson signal



H$^+$ has very small event yield in the 9 signal regions compared to the dark meson signal

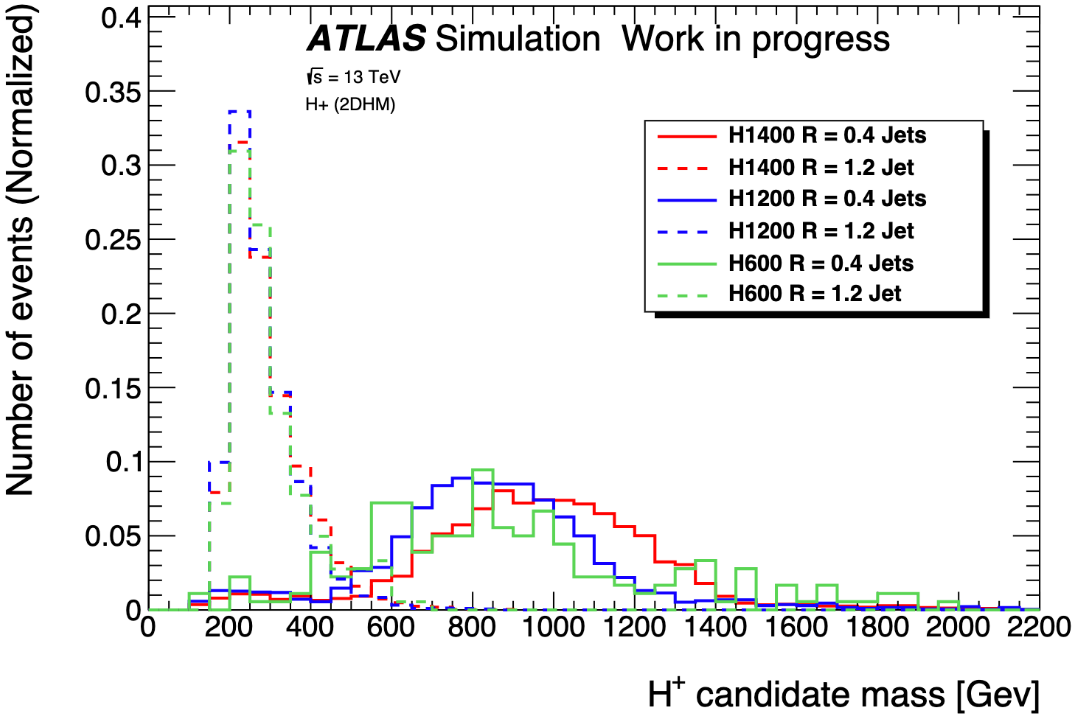
*signals are stacked on top of total background

Reconstructing H^+ mass using R=0.4 jets

- Tried reconstructing H^+ mass using the invariant mass of the two highest p_T jets for M (H^+)= 600, 1200 and 1400 GeV samples

- Reconstruction with smaller jets give mass closer to the true charged Higgs mass

- Changing the H^+ candidate mass reconstruction would require an update of the background estimate and fit



Conclusion and outlook

- A reinterpretation of the dark meson analysis is performed for heavy charged Higgs in 2HDM
- Preliminary results in all-hadronic channel show no net sensitivity towards charged Higgs signals
- To optimize the dark meson search for H+, the method to reconstruct the H^+ might need adjustments
- Explore H^+ search sensitivity with 1-lepton channel of the dark meson search will be the next step

Questions and comments ?

Reference

[1] The ATLAS collaboration., Aad, G., Abbott, B. et al. Search for charged Higgs bosons decaying into a top quark and a bottom quark at s = 13 TeV with the ATLAS detector. J. High Energ. Phys. 2021, 145 (2021). https://doi.org/10.1007/JHEP06(2021)145

[2] Jamie Chang, Fiona Kirk, Margarete Mühlleitner, Michael Spira, Charged Higgs-boson decays into quarks, Nuclear Physics B, Volume 995, 2023, 116330, ISSN 0550-3213, https://doi.org/10.1016/j.nuclphysb.2023.116330.

[3] D. de Florian et al. [LHC Higgs Cross Section Working Group], doi:10.23731/CYRM-2017-002, arXiv:1610.07922 [hep-ph]

[4] ATLAS Collaboration, Summary plots for beyond Standard Model Higgs boson benchmarks for direct and indirect searches, ATL-PHYS-PUB-2022-043

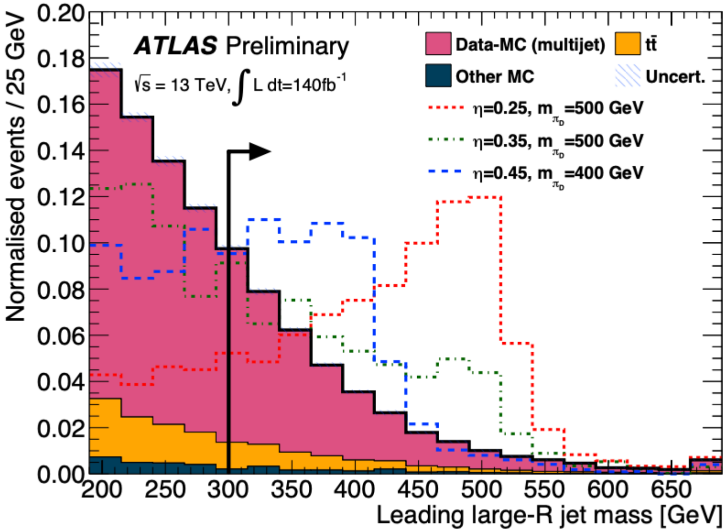
[5] The ATLAS collaboration. Search for dark mesons decaying to top and bottom quarks with the ATLAS detector in 140 fb^{-1} of proton-proton collisions at √s=13, ATLAS-CONF-2023-021

[6] C. Degrande, M. Ubiali, M. Wiesemann and M. Zaro, Heavy charged Higgs boson production at the LHC, JHEP 10 (2015) 145, arXiv: 1507.02549 [hep-ph].

Back up

Multijet background estimation in SR

- An extended ABCD method with 4 discriminating variables is used
- the multijet background is independently estimated for each of the 9 bins in the SR



(a)

S: signal region

Two tag regions DFGHJO are for calculating correlation correction factors

KLMN: 3 tag region are used for validation of the estimate

Leading large-R jet

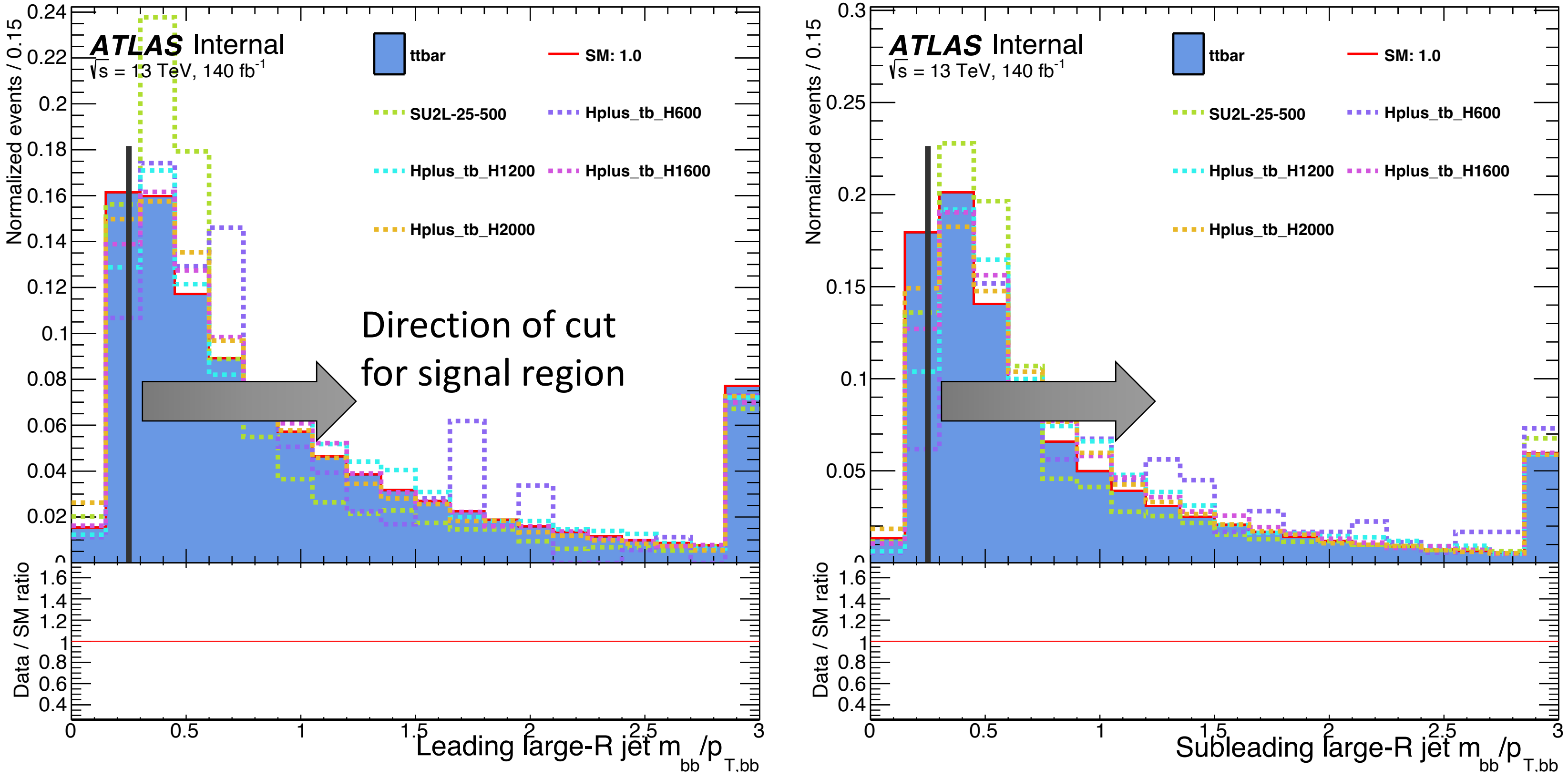
Sub-leading large-R jet

	$\cancel{\pi_D}_{,1}\cancel{bb}_1$	$\pi_{D,1}\cancel{bb}_1$	$\cancel{\pi_D}_{,1}bb_1$	$\pi_{D,1}bb_1$
$\pi_{D,2}bb_2$	J	K	L	S
$\cancel{\pi_D}_{,2}bb_2$	B	D	H	N
$\pi_{D,2}\cancel{bb}_2$	E	F	G	M
$\cancel{\pi_D}_{,2}\cancel{bb}_2$	A	C	I	O

Discriminating variables (comparing dark meson and H^+)

- $m_{bb}/p_{T,bb}$:
- the ratio of mass to p_T for the set of the two closest b-tagged jets to the large-R jet
- It helps suppress multi-jet background
- SU2L-25-500 is the benchmark signal for dark mesons

*Should be ATLAS work in progress



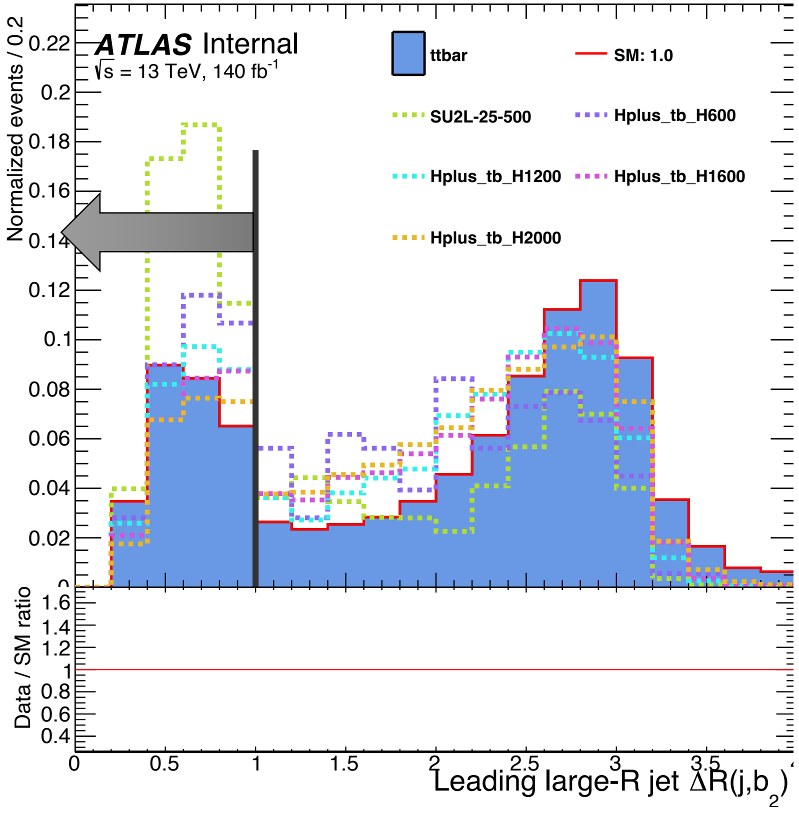
Direction of cut for signal region

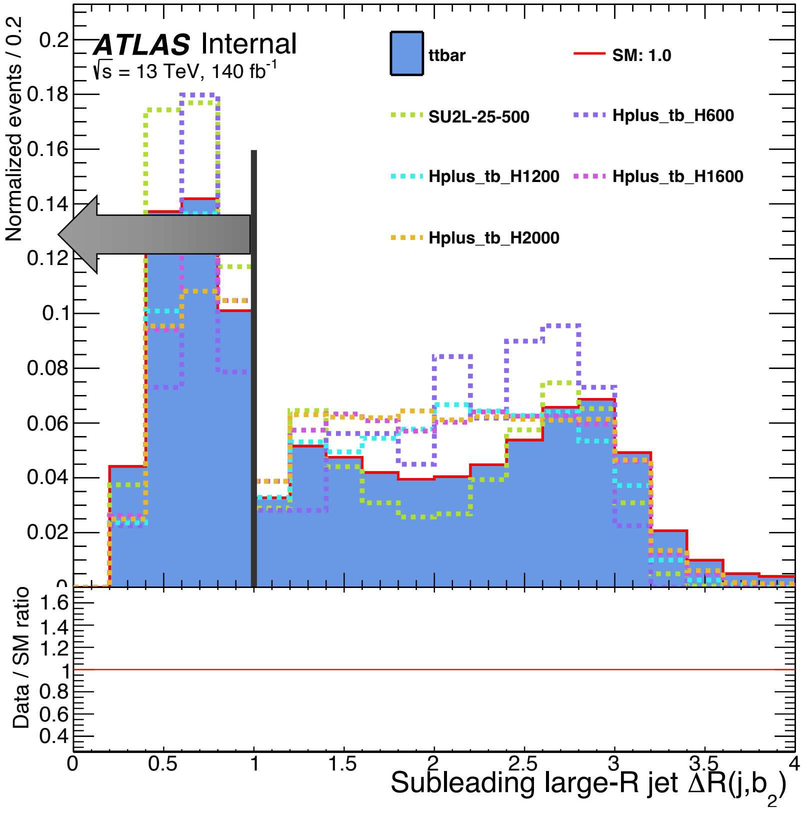
*dominant multijet background not included in the plots here

Discriminating variables (comparing dark meson and H^+)

*Should be ATLAS work in progress

- Δ R (j,b2)
- for a large-R jet is the distance between the 2nd closest b-tagged jet and the large-R jet



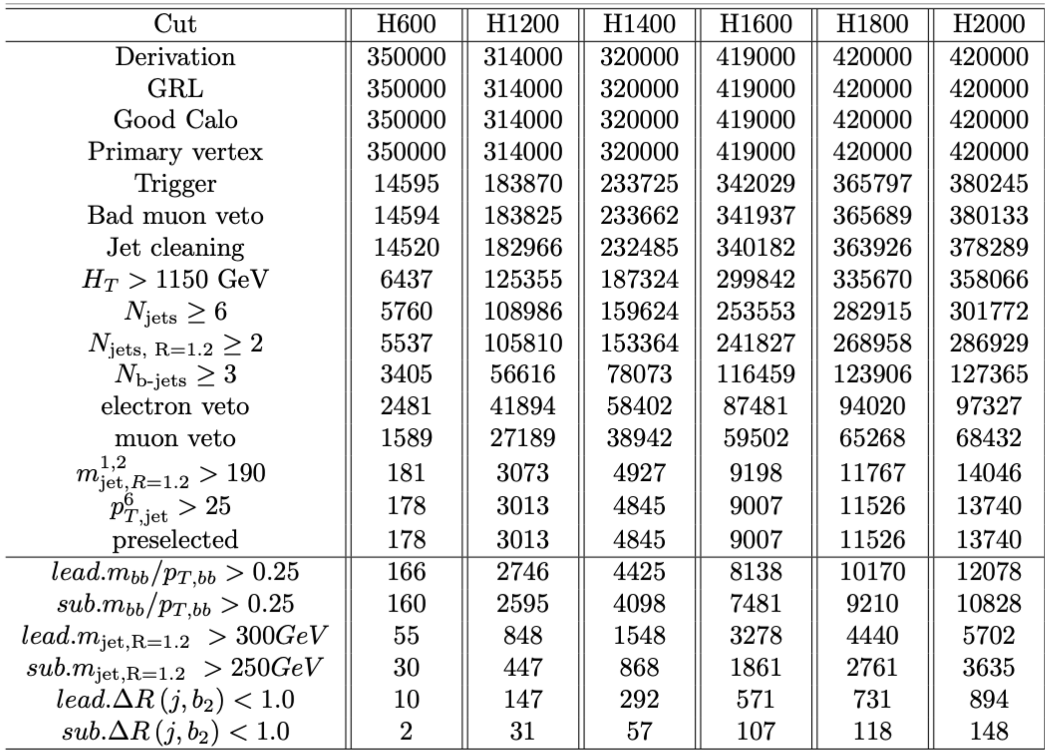


*dominant multijet background not included in the plots here

All hadronic pre and SR selection Cutflow for Charged Higgs

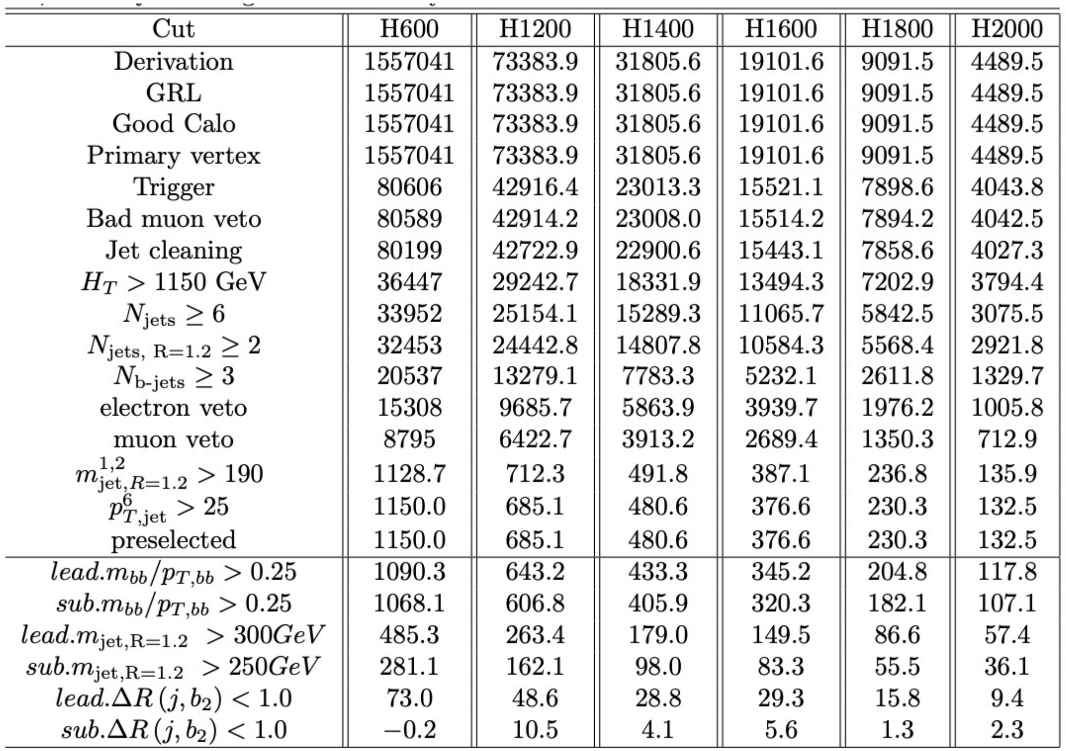
Pre-selection

Signal region selection



Cut	H600	H1200	H1400	H1600	H1800	H2000
Derivation	350000	314000	320000	419000	420000	420000
GRL	350000	314000	320000	419000	420000	420000
Good Calo	350000	314000	320000	419000	420000	420000
Primary vertex	350000	314000	320000	419000	420000	420000
Trigger	14595	183870	233725	342029	365797	380245
Bad muon veto	14594	183825	233662	341937	365689	380133
Jet cleaning	14520	182966	232485	340182	363926	378289
$H_T > 1150$ GeV	6437	125355	187324	299842	335670	358066
$N_{\text{jets}} \geq 6$	5760	108986	159624	253553	282915	301772
$N_{\text{jets, R=1.2}} \geq 2$	5537	105810	153364	241827	268958	286929
$N_{\text{b-jets}} \geq 3$	3405	56616	78073	116459	123906	127365
electron veto	2481	41894	58402	87481	94020	97327
muon veto	1589	27189	38942	59502	65268	68432
$m^{1,2}_{\text{jet},R=1.2} > 190$	181	3073	4927	9198	11767	14046
$p^{6}_{T,\text{jet}} > 25$	178	3013	4845	9007	11526	13740
preselected	178	3013	4845	9007	11526	13740
$lead.m_{bb}/p_{T,bb} > 0.25$	166	2746	4425	8138	10170	12078
$sub.m_{bb}/p_{T,bb} > 0.25$	160	2595	4098	7481	9210	10828
$lead.m_{\text{jet,R=1.2}} > 300GeV$	55	848	1548	3278	4440	5702
$sub.m_{\text{jet,R=1.2}} > 250GeV$	30	447	868	1861	2761	3635
$lead.\Delta R\,(j, b_2) < 1.0$	10	147	292	571	731	894
$sub.\Delta R\,(j, b_2) < 1.0$	2	31	57	107	118	148

Raw event counts

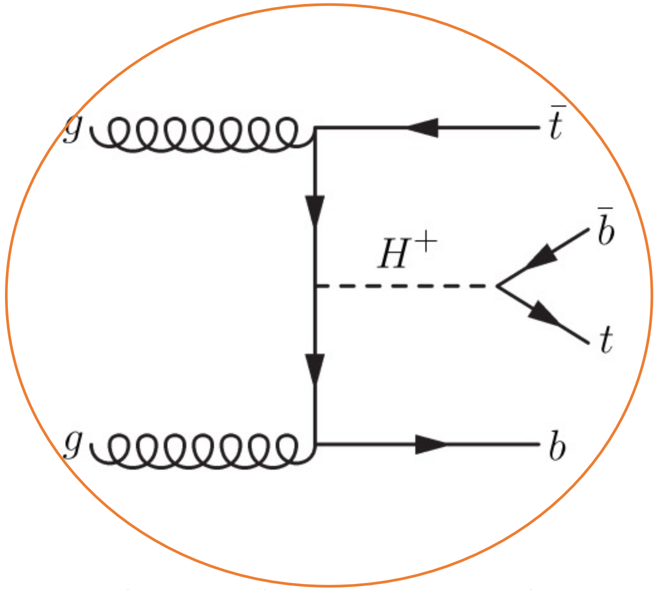


Cut	H600	H1200	H1400	H1600	H1800	H2000
Derivation	1557041	73383.9	31805.6	19101.6	9091.5	4489.5
GRL	1557041	73383.9	31805.6	19101.6	9091.5	4489.5
Good Calo	1557041	73383.9	31805.6	19101.6	9091.5	4489.5
Primary vertex	1557041	73383.9	31805.6	19101.6	9091.5	4489.5
Trigger	80606	42916.4	23013.3	15521.1	7898.6	4043.8
Bad muon veto	80589	42914.2	23008.0	15514.2	7894.2	4042.5
Jet cleaning	80199	42722.9	22900.6	15443.1	7858.6	4027.3
$H_T > 1150$ GeV	36447	29242.7	18331.9	13494.3	7202.9	3794.4
$N_{\text{jets}} \geq 6$	33952	25154.1	15289.3	11065.7	5842.5	3075.5
$N_{\text{jets, R=1.2}} \geq 2$	32453	24442.8	14807.8	10584.3	5568.4	2921.8
$N_{\text{b-jets}} \geq 3$	20537	13279.1	7783.3	5232.1	2611.8	1329.7
electron veto	15308	9685.7	5863.9	3939.7	1976.2	1005.8
muon veto	8795	6422.7	3913.2	2689.4	1350.3	712.9
$m^{1,2}_{\text{jet},R=1.2} > 190$	1128.7	712.3	491.8	387.1	236.8	135.9
$p^{6}_{T,\text{jet}} > 25$	1150.0	685.1	480.6	376.6	230.3	132.5
preselected	1150.0	685.1	480.6	376.6	230.3	132.5
$lead.m_{bb}/p_{T,bb} > 0.25$	1090.3	643.2	433.3	345.2	204.8	117.8
$sub.m_{bb}/p_{T,bb} > 0.25$	1068.1	606.8	405.9	320.3	182.1	107.1
$lead.m_{\text{jet,R=1.2}} > 300GeV$	485.3	263.4	179.0	149.5	86.6	57.4
$sub.m_{\text{jet,R=1.2}} > 250GeV$	281.1	162.1	98.0	83.3	55.5	36.1
$lead.\Delta R\,(j, b_2) < 1.0$	73.0	48.6	28.8	29.3	15.8	9.4
$sub.\Delta R\,(j, b_2) < 1.0$	−0.2	10.5	4.1	5.6	1.3	2.3

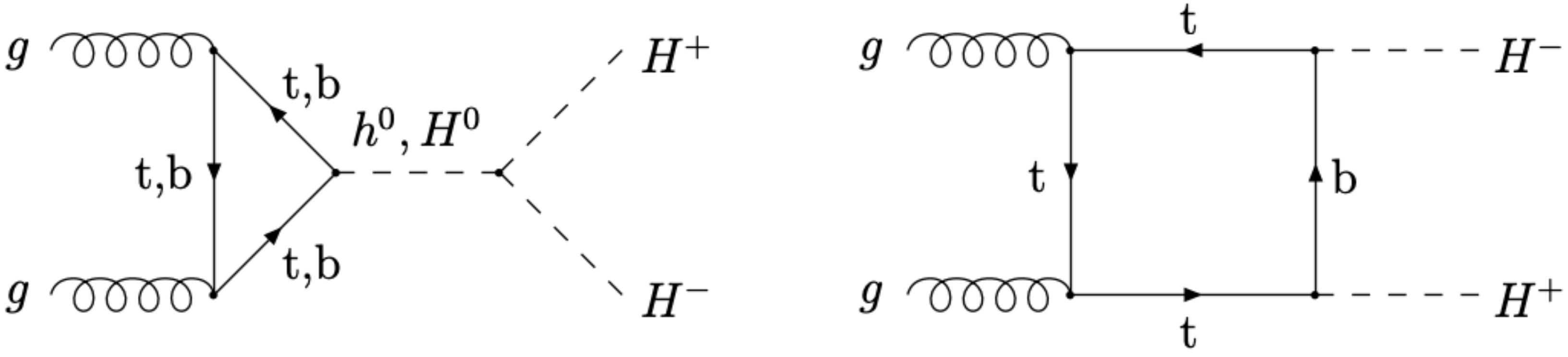
Weighted event counts

Charged Higgs-production mode

- Single production and pair production of charged Higgs
- The dark meson search could be recycled to search for both



Leading order Feynman diagram for the production a single heavy Higgs



The s-channel Triangle and box diagrams contributing to gg->H^+ H^-

Charged Higgs coupling to t and b

- The Yukawa coupling of the charged Higgs to the top and an anti-bottom quark is given by

$$g_{t\bar{b}H^-} = \sqrt{2}\left(\frac{m_t}{v}P_R\cot\beta + \frac{m_b}{v}P_L\tan\beta\right)$$

  - v is the Higgs vacuum expectation value
  - $\tan\beta = \frac{v2}{v1}$, is the ratio of the two vacuum expectation values v2 and v1 of the two Higgs doublet

Exclusion limits of dark meson analysis in all-had channel

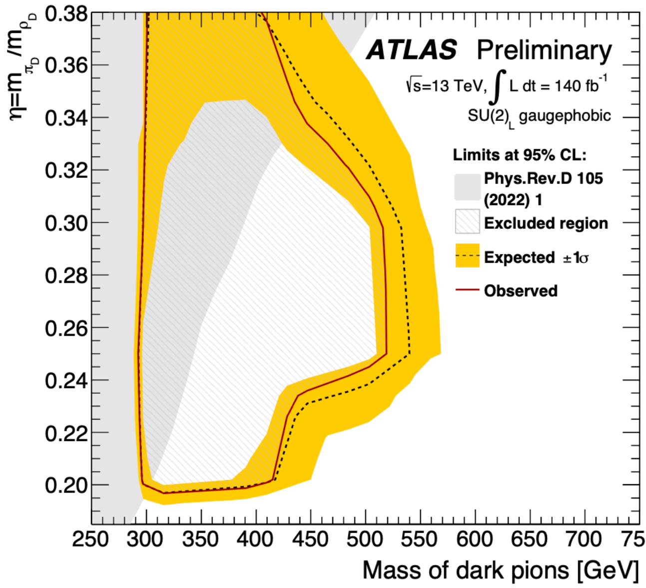


Figure 8: Observed (red solid line) and expected (black dashed line) exclusion contours at 95% CL in the η–m_{π_D} plane for $SU(2)_L$ signal models. Masses that are within the contours are excluded. An uncertainty band (yellow) corresponding to the $\pm1\sigma$ variation on the expected limit is also indicated. The grey area indicates the phase space previously excluded through re-interpretation of other collider searches presented in Ref. [2].

Table 21: Event yields in all nine all-hadronic signal regions with three example signal points at the full 140 fb^{-1} integrated luminosity. The quoted uncertainties contain statistical and systematical components. The name of the signal regions indicate the lower mass boundary on the leading large-R jet in GeV followed by the sub-leading large-R jet lower mass boundary.

	SR300_250	SR300_300	SR300_350	SR325_250	SR325_300
$t\bar{t}$	3.09 ± 2.13	1.71 ± 1.01	1.78 ± 0.73	6.83 ± 3.98	4.27 ± 2.22
V+jets	0.00 ± 0.00	2.00 ± 1.83	0.28 ± 0.29	0.72 ± 0.94	0.13 ± 0.24
Single top	0.12 ± 0.14	0.00 ± 0.03	0.00 ± 0.00	0.36 ± 0.22	0.12 ± 0.17
$t\bar{t} + X$	0.30 ± 0.07	0.22 ± 0.06	0.17 ± 0.05	0.35 ± 0.10	0.44 ± 0.14
Multiboson	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
QCD	15.86 ± 8.67	11.62 ± 6.95	9.04 ± 3.76	35.24 ± 12.05	25.27 ± 11.10
Total background	19.38 ± 8.82	15.55 ± 7.20	11.26 ± 3.66	43.49 ± 11.52	30.24 ± 10.75
$\eta = 0.25$, $m_{\pi_D} = 500$ GeV	0.36 ± 0.25	0.30 ± 0.23	1.59 ± 0.54	1.80 ± 0.45	2.38 ± 0.55
$\eta = 0.35$, $m_{\pi_D} = 500$ GeV	2.77 ± 1.46	0.35 ± 0.36	1.47 ± 1.06	4.44 ± 1.81	4.36 ± 1.77
$\eta = 0.45$, $m_{\pi_D} = 400$ GeV	2.57 ± 1.39	3.09 ± 1.63	0.40 ± 0.90	5.87 ± 1.90	8.97 ± 2.56
Data	20	14	16	41	28

	SR325_350	SR400_250	SR400_300	SR400_350
$t\bar{t}$	4.64 ± 2.24	3.87 ± 1.89	3.41 ± 2.91	6.61 ± 4.28
V+jets	0.19 ± 0.34	0.72 ± 0.90	0.00 ± 0.28	1.18 ± 0.76
Single top	0.28 ± 0.25	0.00 ± 0.00	0.47 ± 0.26	0.11 ± 0.11
$t\bar{t} + X$	0.50 ± 0.09	0.34 ± 0.08	0.40 ± 0.10	0.73 ± 0.13
Multiboson	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
QCD	27.34 ± 12.38	18.75 ± 8.69	15.40 ± 6.32	26.40 ± 13.10
Total background	32.95 ± 11.94	23.68 ± 8.39	19.68 ± 6.10	35.03 ± 12.32
$\eta = 0.25$, $m_{\pi_D} = 500$ GeV	5.82 ± 1.09	6.90 ± 1.01	8.76 ± 1.40	38.74 ± 3.59
$\eta = 0.35$, $m_{\pi_D} = 500$ GeV	5.48 ± 2.03	4.91 ± 1.82	6.99 ± 2.19	12.78 ± 2.82
$\eta = 0.45$, $m_{\pi_D} = 400$ GeV	10.16 ± 2.54	1.47 ± 0.82	5.50 ± 2.59	3.59 ± 1.50
Data	23	27	20	45