Searches for singly- and doubly-charged Higgs bosons in ATLAS

Yanhui Ma on behalf of the ATLAS Collaboration

2023.11.29

Introduction

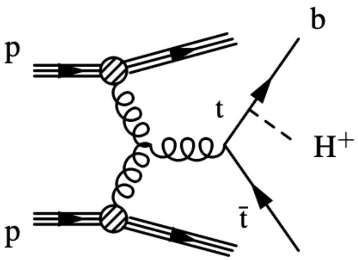
- A neutral scalar particle of mass ~125 GeV discovered at the LHC
  - Confirmed the predicted electroweak symmetry breaking mechanism of the Standard Model (SM)
  - Experimental results are consistent with the SM Higgs boson
- Is there only one Higgs doublet (SM) ? Various Beyond Standard Model (BSM) models predict additional Higgs bosons
  - Minimal extensions of the SM known as two-Higgs-doublet models (2HDMs) predict:

    CP-even h^0 and H^0, CP-odd A^0 Singly-charged H^+ and H^-
  - The other models (such as Left-Right symmetric models, Higgs triplets, etc) predict the existence of $H^{\pm\pm}$
- The discovery of charged Higgs boson would be clear evidence of physics beyond the Standard Model.
- The production and decay modes greatly depend on the mass of the charged Higgs boson

Introduction

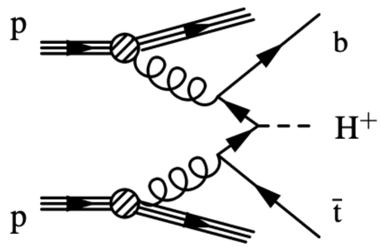
- Three mass categories are commonly used in H± searches:

Light mH± < mt – mb



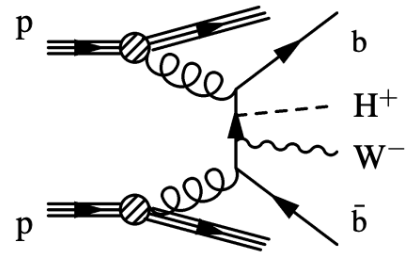
double-resonant t

Heavy mH± > mt - mb



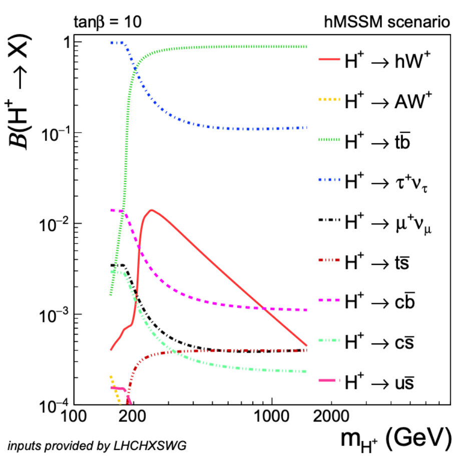
single-resonant t

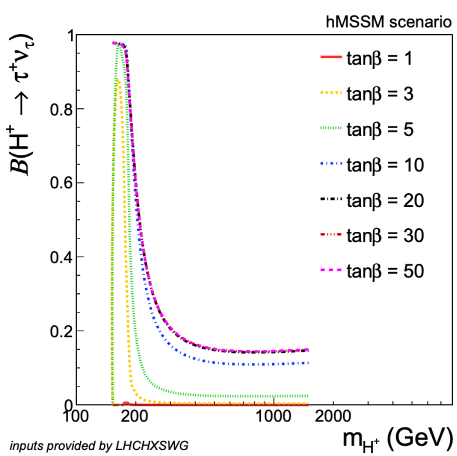
Intermediate mH± ~= mt

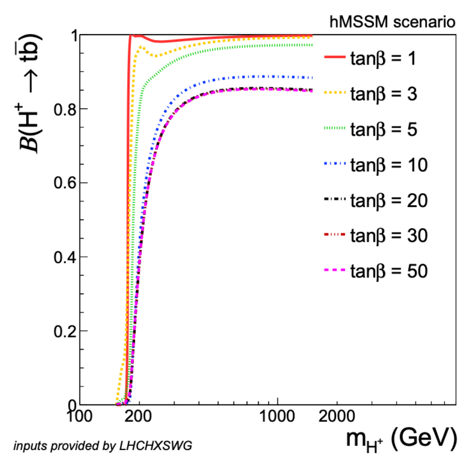


non-resonant t

- Model-dependent H± branching ratios (BRs)
  - For light mH±, the decay H±->tauv usually dominate in a type II 2HDM, with H±-> cs and cb become sizeable at low tanβ.
  - For heavy mH±, the dominate decay is H±->tb, but the branching ratio (BR) for H±->tauv can reach ~15% at large tanβ.







Overview of the Run 2 searches

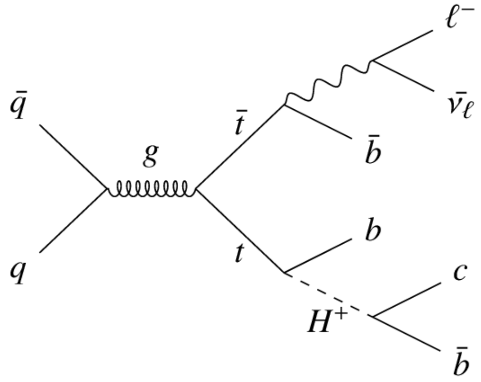
Light Charged Higgs	Intermedinte	Heavy Charged Higgs
$H^{\pm}$ -> cb (139fb^{-1}, arXiv. 2302.11739)		$H^{\pm}$->tb (139fb^{-1}, arXiv.202.10076)
H± -> Wa (139fb^{-1}, arXiv. 2304.14247)		$H^{\pm\pm}/H^{\pm}$ in WW/WZ final state (139fb^{-1}, arXiv.2101.11961)
		$H^{\pm\pm}$ -> multi-lepton (139fb^{-1}, arXiv.2304.14247)
		$H^{\pm}$->WZ->lllv (139fb-1, arXiv.2207.03925)
		VBF $H^{\pm\pm}$/->WW (139fb^{-1}, ATLAS-CONF-2023-023)
$H^{\pm}$> tauμ (36 fb-1, arXiv.1807.07915)		

Covered in this talk!

$H^{\pm}$ -> cb

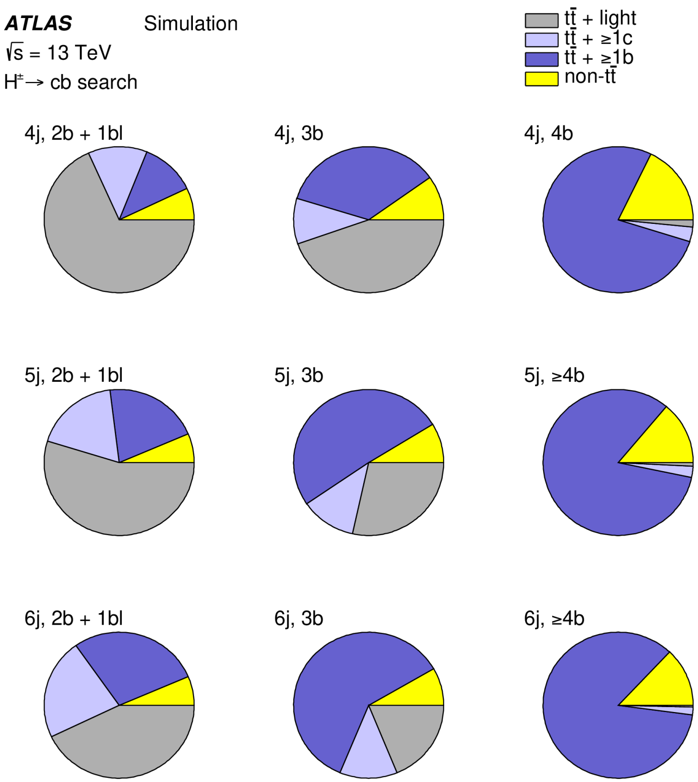
arXiv. 2302.11739

- Search for light charged Higgs (60 GeV < $m_{H^{\pm}}$ < 160 GeV) produced from top decays with ttbar → $WbH^{\pm}b$, using 139 fb^{-1} data at 13 TeV
  - first time for a search in this channel within ATLAS



- Looking for lepton+jets final state (1 lepton (electron or muon), >=4 jets, >=2 b-tagged jets)

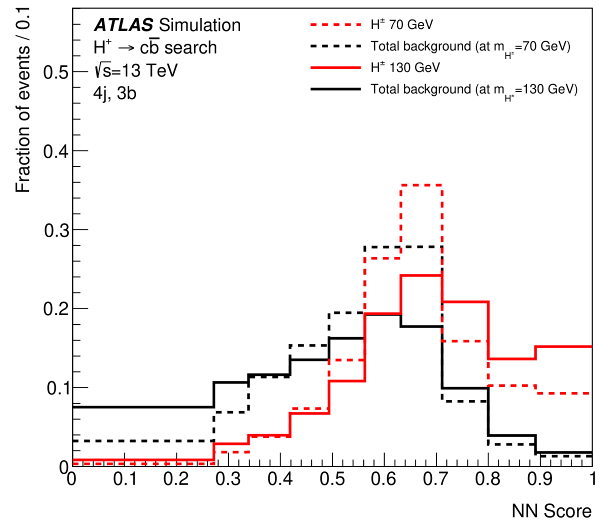
- Event categorization based on the N jets and N b-tagged jets
  - 2b + 1bl (light jet) region: derive data-based corrections to improve modelling of the ttbar
  - (4j, 3b), (5j, 3b) and (6j, 3b) regions: main signal regions
  - (5j, ≥4b) and (6j, ≥4b): ttbar + ≥ 1b background control regions



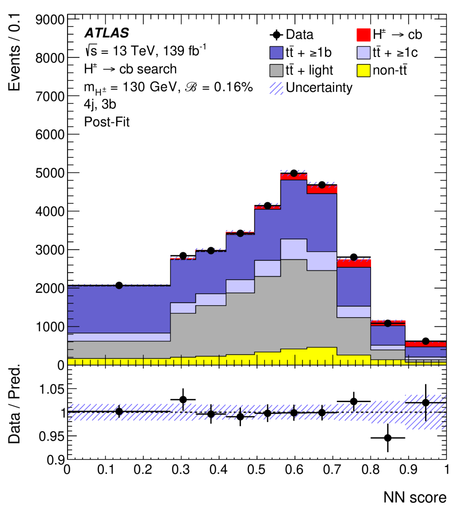
H$^{\pm}$ -> cb

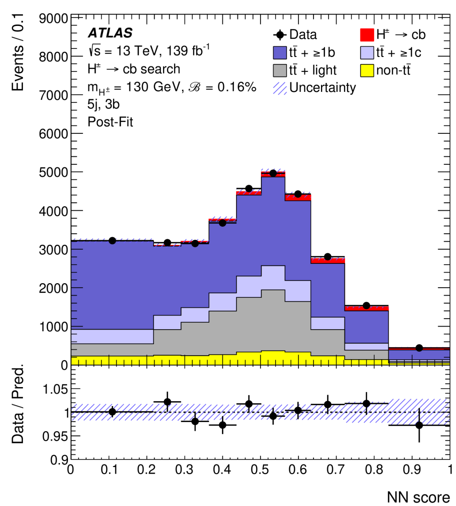
- Building a neural network to separate signal from background.
  - Using only the events in the main SRs (>=4j and >=3b) for the training
  - Input variables carefully selected to maximize the analysis sensitivity

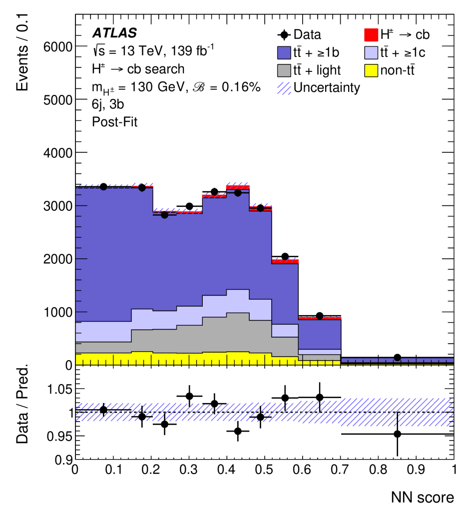
Input variables	Number of variables
p_{T}, η, and ϕ of the first six leading jets	18
b-tagging score of the fourth, fifth, and sixth jets	3
Lepton p_{T}, η, and ϕ	3
Missing transverse energy and its ϕ angle	2
Invariant mass between each of the three leading jets and the fourth jet	3
Total	29



- Fit is performed across regions with >=3b-jets simultaneously



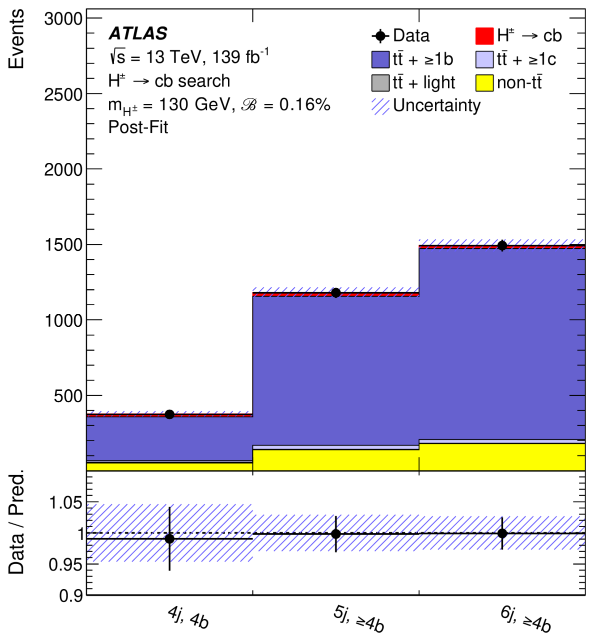


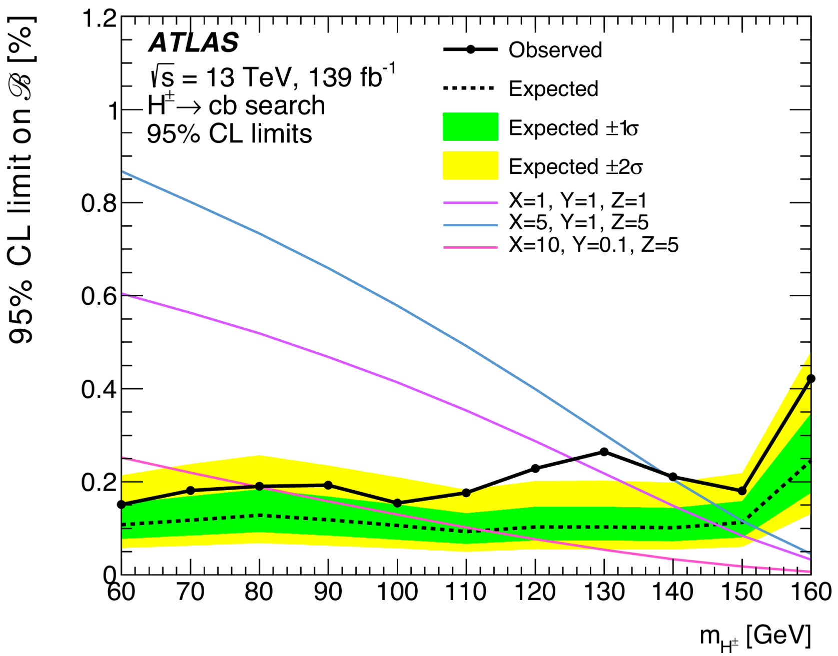


H$^{\pm}$ -> cb

- Observed (Expected) 95% CL upper limits on the branching fraction (B) as a function of mH$^{\pm}$: range from 0.15% (0.09%) up to 0.42% (0.25%) depending on mH$^{\pm}$

  - The largest excess in data is seen at mH$^{\pm}$ = 130 GeV, corresponding to ~3 (2)σ local (global) significance

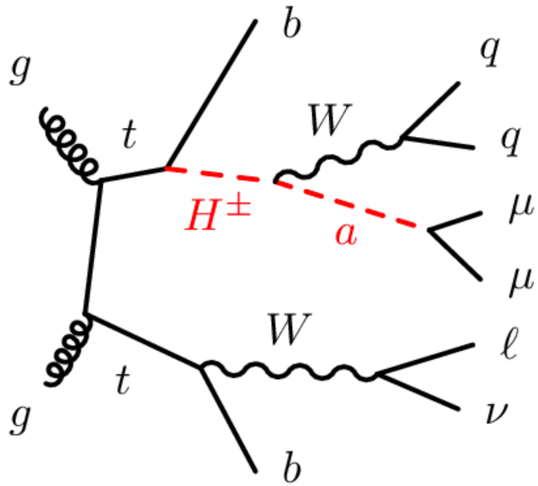




$H^{\pm}$-> Wa , a->mumu

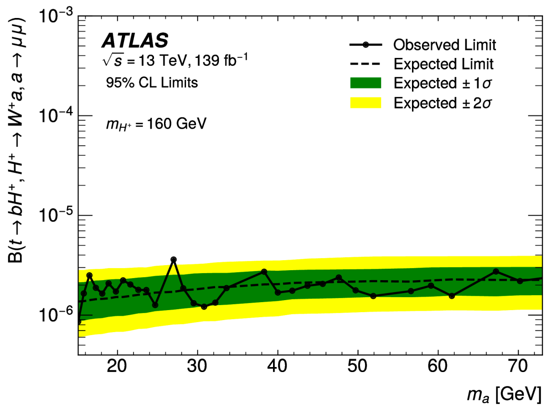
arXiv.2304.14247

- Light scalars have been used to explain Dark Matt (DM) interactions, the excess from the center of our galaxy, are necessary for Electroweak Baryogenesis.

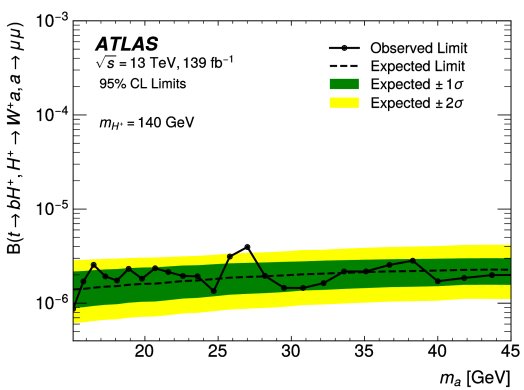


- They are predicted in various BSM theories, such as 2HDM+a, NMSSM, mixing with Higgs bosons, and inheriting Yukawa-like couplings to fermions → large coupling to top quarks

- Focus on the mass ranges 15 GeV < ma < 72 GeV and 120 GeV < mH$^{\pm}$ < 160 GeV.
  - ***Actually a search for a boson but not*** **H$^{\pm}$**
- Final states with 3 leptons (emumu, mumumu)



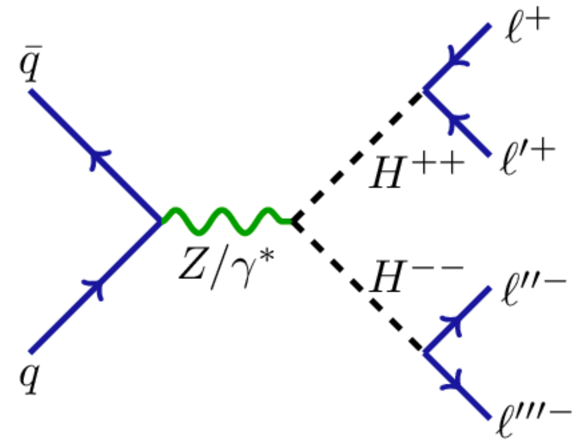
- Set upper limits on the branching ratio in the range at 95% confidence level as a function of ma
  - Excess at 27 GeV 2.4σ local independent of m(H$^{\pm}$)



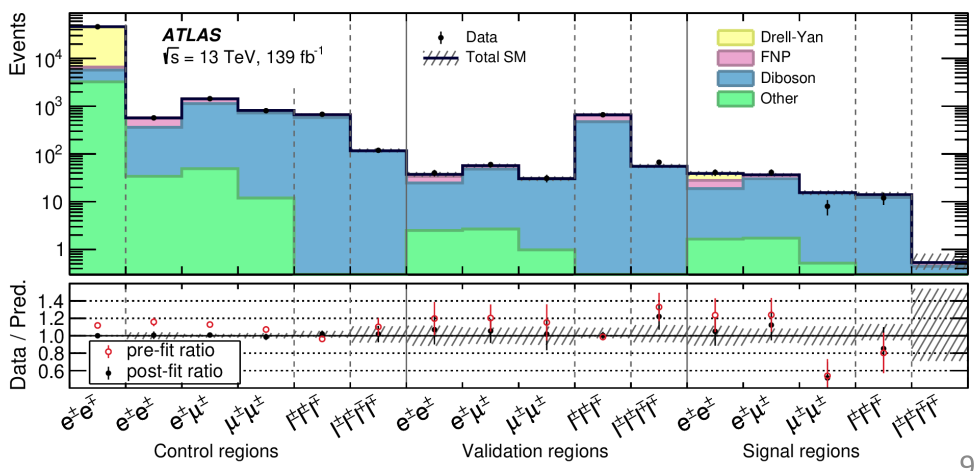
$H^{\pm\pm}$ -> multi-lepton

arXiv.2211.07505

- Search for pair production of doubly charged Higgs with 400 GeV < $mH^{\pm\pm}$ < 1300 GeV using 139 fb^{-1} data at 13 TeV
- Looking for same-charge lepton pairs in final states with two, three or four leptons (electron or muon).
- Signal regions separated by lepton multiplicities (2L, 3L, 4L)

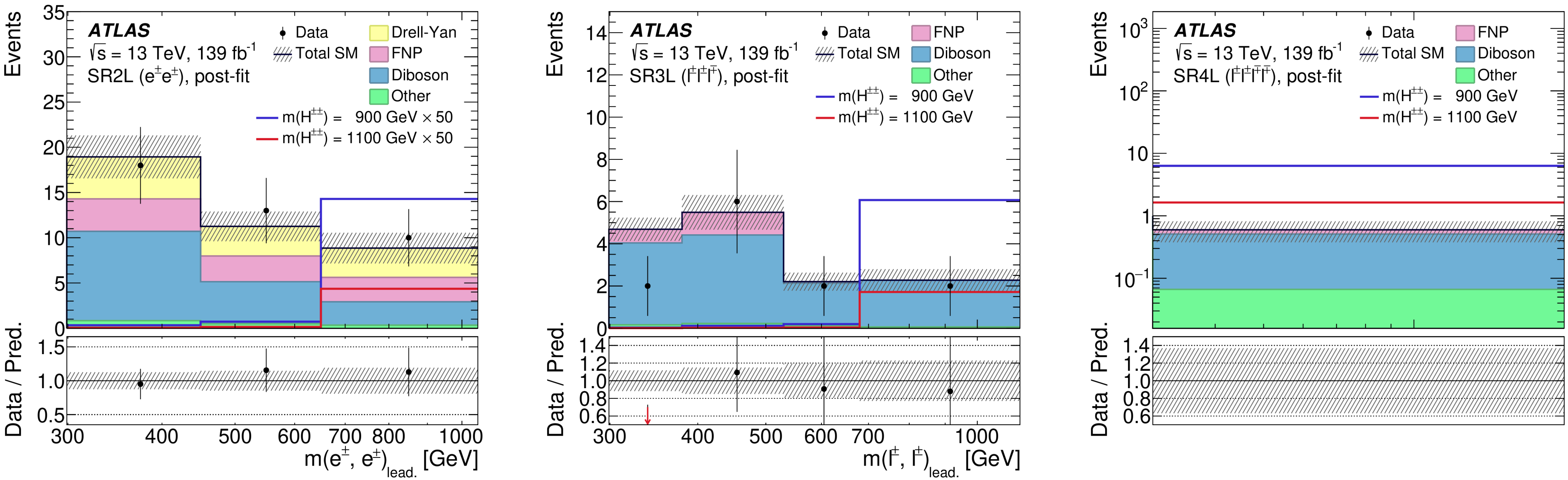


- Main background
  - Irreducible background (mainly from diboson process) -> estimated using MC simulation
  - Reducible background (mainly from events with fake/non-prompt or charge misidentified leptons) -> data driven methods
- Various CRs (VRs) defined to constrain better the main background (validate the background estimation)



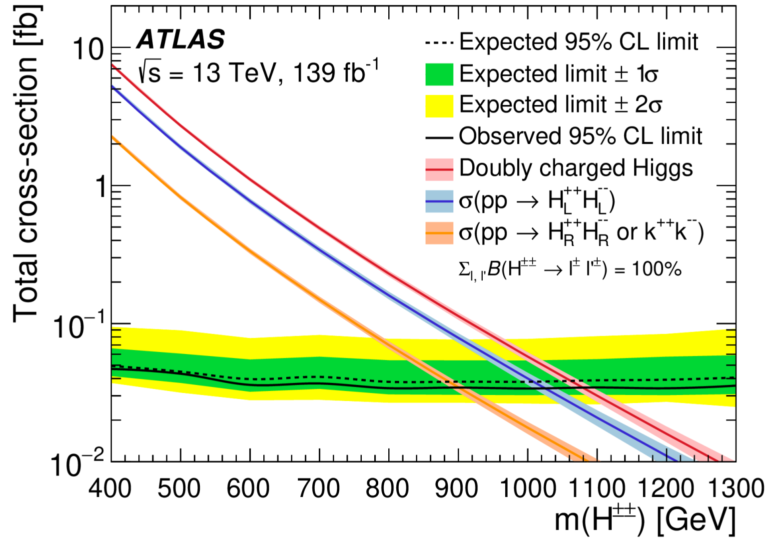
$H^{\pm\pm}$ -> multi-lepton

- Fit observables: m_{ll} in 2L and 3L SRs and CRs; total yields in 4L SRs and CRs
  - The binning is chosen to optimise the expected sensitivity to the signal model, while also keeping low statistical uncertainties in each bin.
  - Drell-Yan and diboson background normalizations are free to float in the fit, and the fitted normalisations are compatible with their SM predictions



$H^{\pm\pm}$ -> multi-lepton

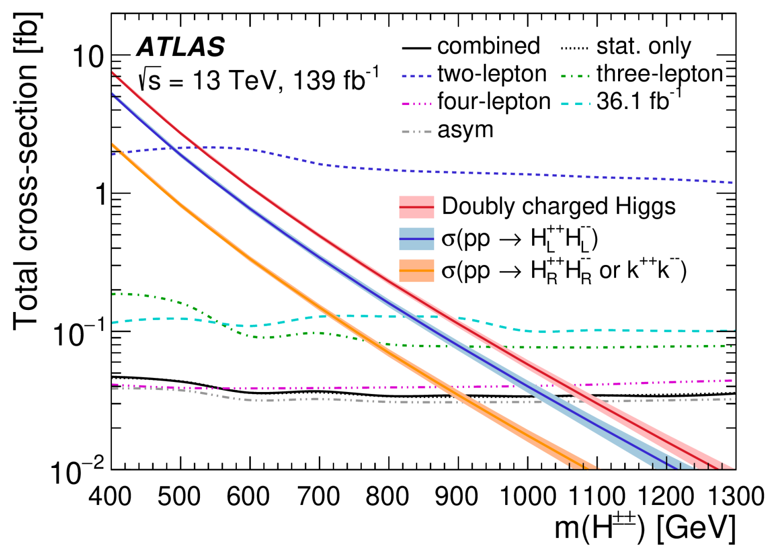
- 95% CL upper limits set on σ, under the assumption of the branching ratios to each of the possible leptonic final states are equal



- No significant excess over SM prediction observed

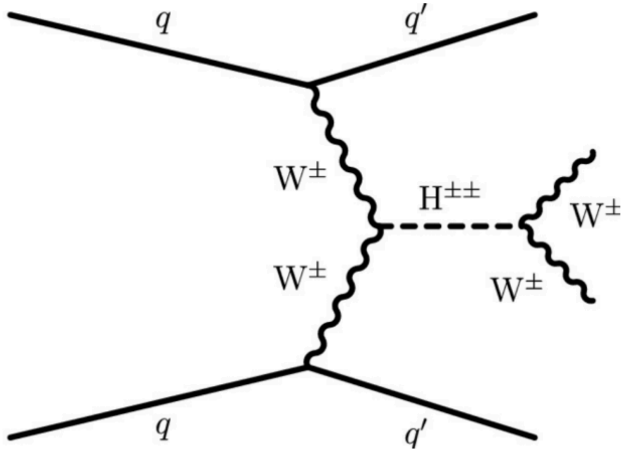
  - $H^{\pm\pm}$ excluded for masses below 1080 GeV, 300 GeV higher than the previous ATLAS measurement (arXiv. 1710.09748) with 36.1fb^{-1} data

- Statistically limited analysis with main sensitivity driven by 4L channel



VBF $H^{\pm\pm}$

- Different models (such as Georgi–Machacek) predict the production of $H^{\pm\pm}$ via Vector Boson Fusion (VBF)



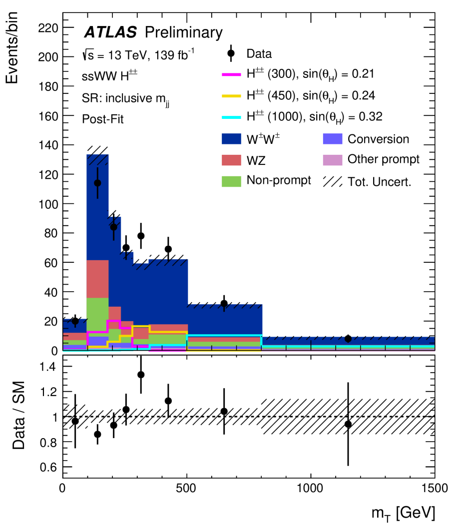
- Search for $H^{\pm\pm}$->WW (200 GeV < $mH^{\pm\pm}$< 3000 GeV) decay in the fully leptonic same sign WW final state (spin-off of SM WWjj production measurement)
  - Request exactly two same charge leptons (e/mu)
  - Request at least two jets with m_{jj} > 500 GeV and $|\Delta Y_{jj}|$ > 2, b-tagged jet veto
- Main backgrounds
  - SM EWK and QCD WWjj, estimated from MC simulation, normalizations freely floating in the fit
  - Backgrounds with fake/non-prompt or charge misidentified leptons -> data driven methods

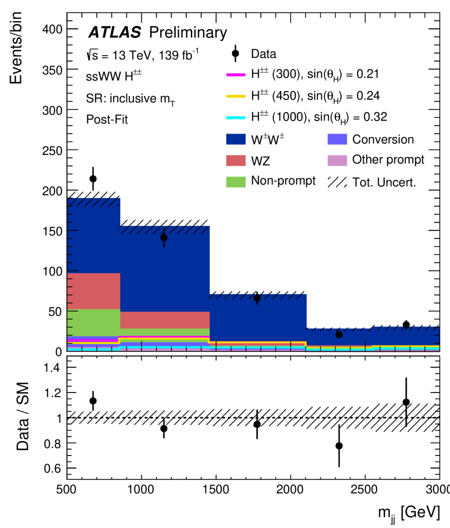
VBF $H^{\pm\pm}$

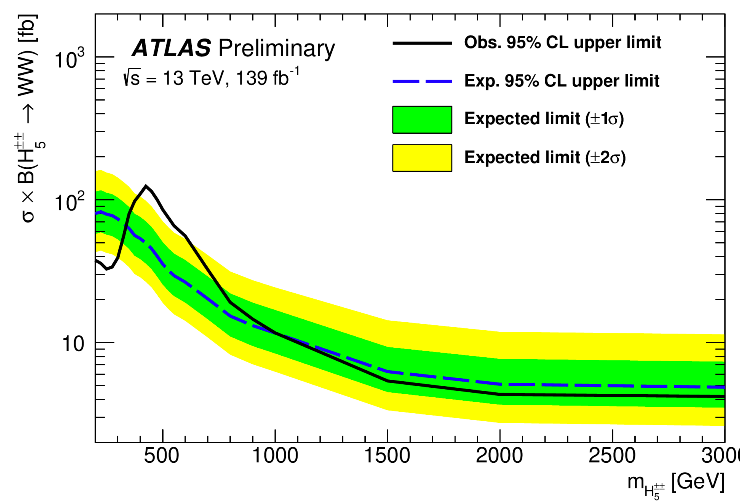
- Transverse mass (m_T) distribution, which provides good discrimination between resonant signal and non resonant background processes, is used as fit observable to extract signal.
  - 2D fit in m_T and m_{jj}

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2},$$

- Upper limits on the product of the cross section and branching fraction of VBF $H^{\pm\pm}$->WW vector are extreacted
  - The largest excess in data is seen at $mH^{\pm\pm}$ = 450 GeV, corresponding to ~3.2 (2.5)σ local (global) significance







Summary

- Presented latest results on searches for $H^{\pm}$ and $H^{\pm\pm}$ at ATLAS, targeting various decay modes, final states and topologies

- No significant deviation from the SM prediction
  - Some local (global) excess at ~3 (2)σ level observed

- Many of the analyses statistical limited. Will profit from more Run 3 data, stay tuned!

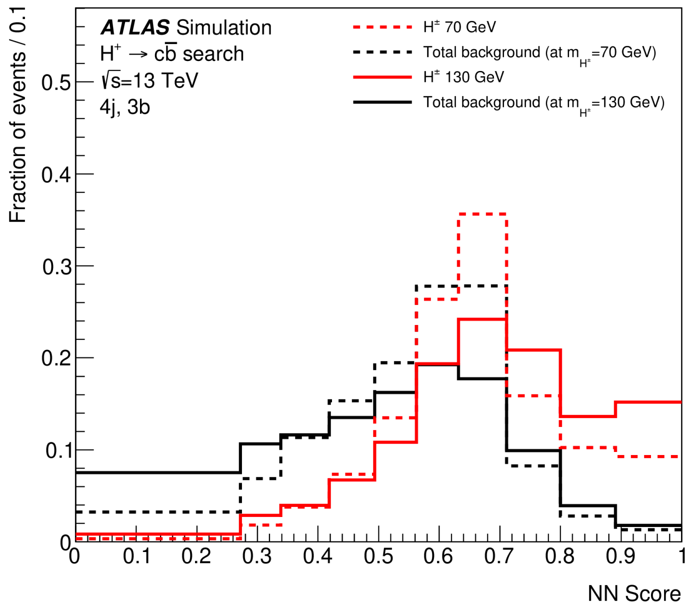
Thanks for your attention

Back Up

H$^{\pm}$ -> cb

N_j \ N_b	**2b + 1bl:** exactly two b-tagged jets (60% OP) plus one loose b- tagged jet (70% OP)	**3b:** exactly three b-tagged jets (60% OP)	**$\geq$4b:** at least four b-tagged jets (60% OP)
4j: exactly four jets	**4j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**4j, 3b** (signal region, 10 bins)	**4j, 4b** ($t\bar{t} + \geq$ 1b background control region and large S/B region, 1 bin)
5j: exactly five jets	**5j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**5j, 3b** (signal region, 10 bins)	**5j,$\geq$ 4b** ($t\bar{t} + \geq$ 1b background control region and large S/B region, 1 bin)
6j: exactly six jets	**6j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**6j, 3b** (signal region, shape correction for the NN discriminant in low S/B bins, 10 bins)	**6j,$\geq$ 4b** ($t\bar{t} + \geq$ 1b background control region, 1 bin)

Regions used to derive $t\bar{t}$ correction **Regions for NN training and fit**

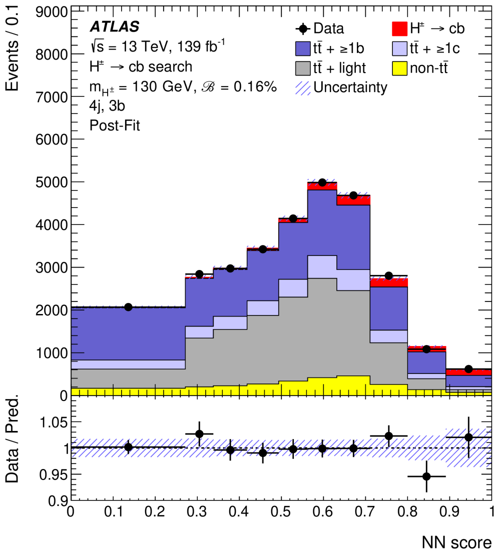


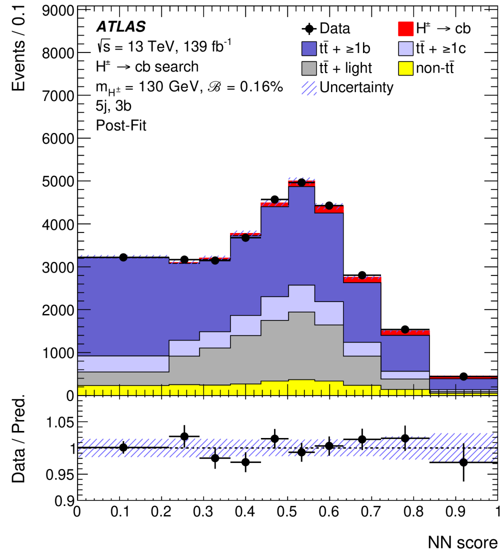
- Summary of analysis regions
- NN score comparison between signal and background

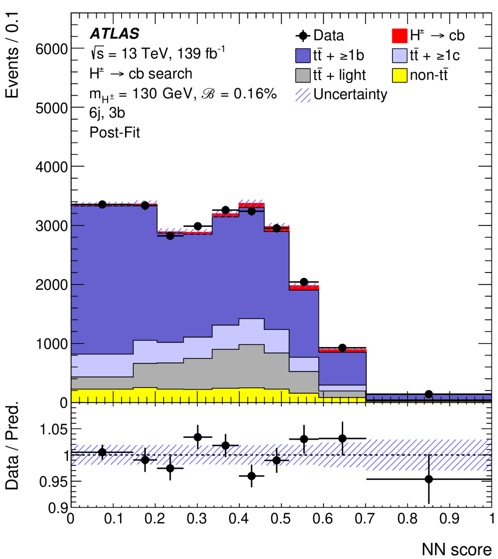
Input variables For NN training	Number of variables
p_T, η, and ϕ of the first six leading jets	18
b-tagging score of the fourth, fifth, and sixth jets	3
Lepton p_T, η, and ϕ	3
Missing transverse energy and its ϕ angle	2
Invariant mass between each of the three leading jets and the fourth jet	3
Total	29

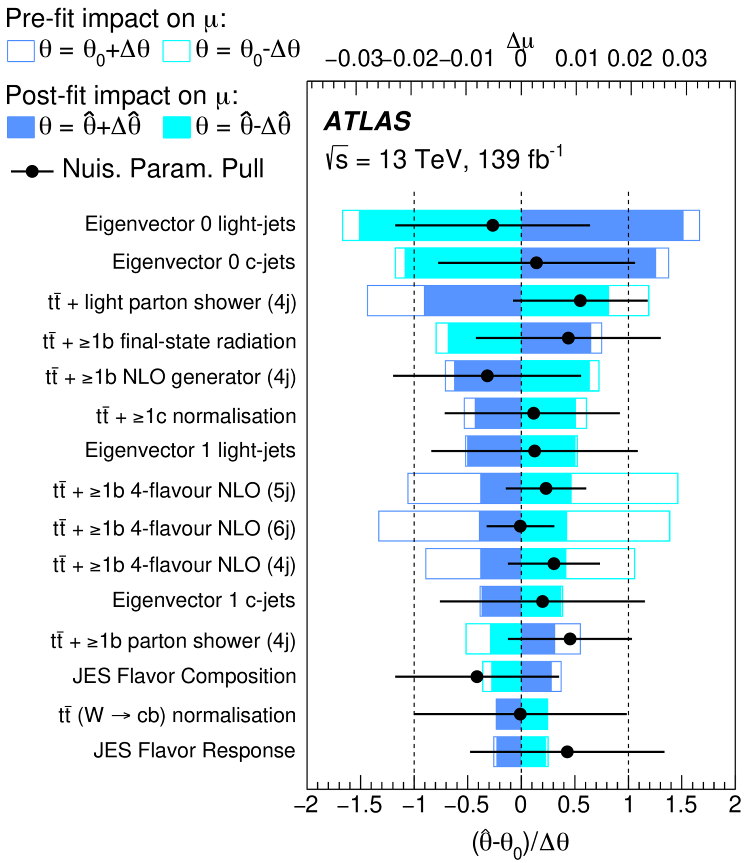
H$^{\pm}$ -> cb

- Post-ft NN score distributions in SRs









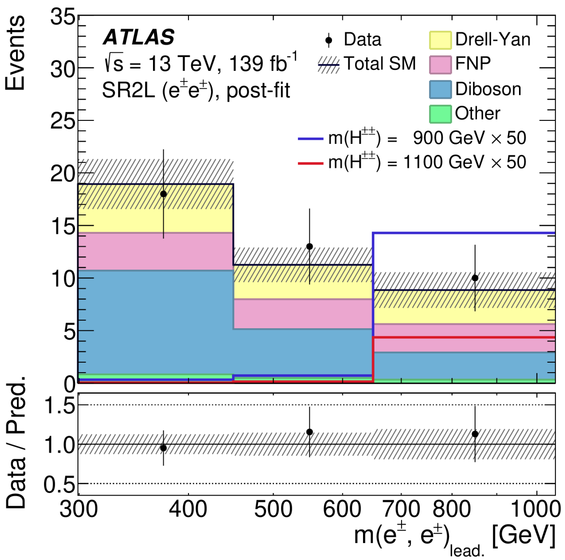
- Ranking of the nuisance parameters

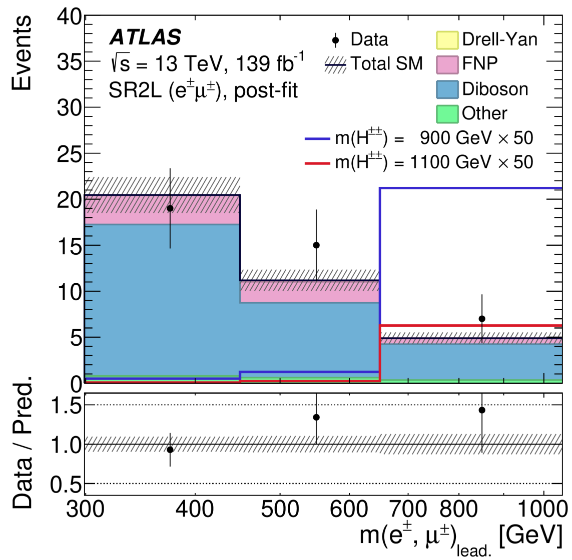
$H^{\pm\pm}$ -> multi-lepton

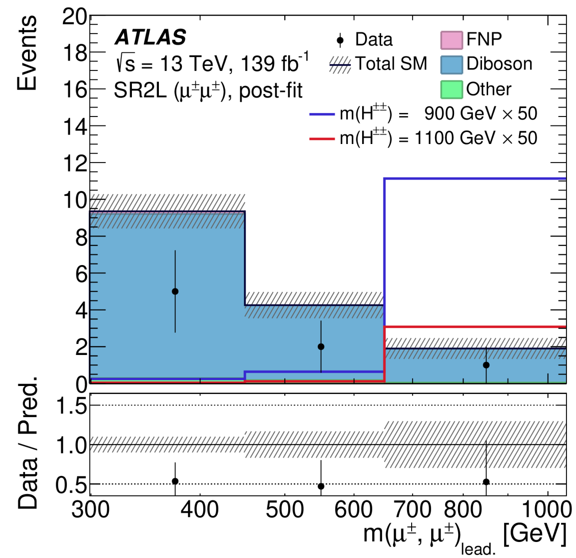
- Summary of analysis regions

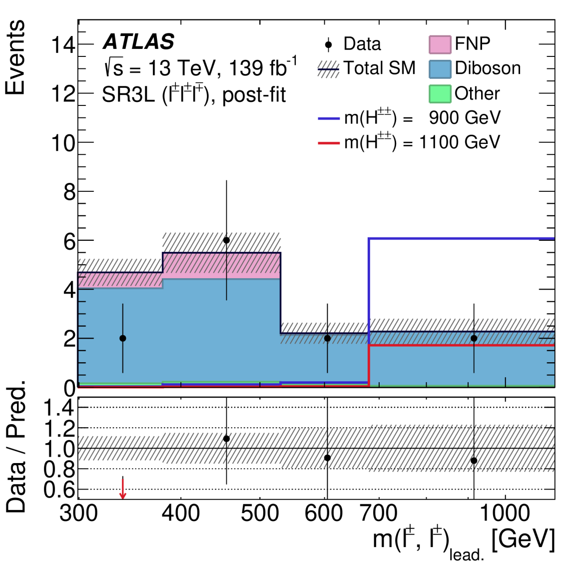
	Control regions				Signal regions			Validation regions		
	DYCR	DBCR2L	DBCR3L	CR4L	SR2L	SR3L	SR4L	VR2L	VR3L	VR4L
Channel	e^+e^-	$e^\pm e^\pm$ $e^\pm\mu^\pm$ $\mu^\pm\mu^\pm$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$e^\pm e^\pm$ $e^\pm\mu^\pm$ $\mu^\pm\mu^\pm$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$e^\pm e^\pm$ $e^\pm\mu^\pm$ $\mu^\pm\mu^\pm$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$
Number of leptons	2	2	3	4	2	3	4	2	3	4
$m(\ell^\pm, \ell'^\mp)_{\text{lead}}$ [GeV]	≥ 300	-	-	-	-	-	-	-	-	-
$m(\ell^\pm, \ell'^\pm)_{\text{lead}}$ [GeV]	-	$[200,\ 300)$	≥ 300	$[100,\ 200)$	≥ 300	≥ 300	≥ 300	≥ 300	$[100,\ 300)$	$[200,\ 300)$
$p_{\text{T}}(\ell^\pm, \ell'^\pm)_{\text{lead}}$ [GeV]	-	-	-	-	≥ 300	≥ 300	-	$[200,\ 300)$	-	-
$\Delta R(\ell^\pm, \ell'^\pm)_{\text{lead}}$	-	-	-	-	< 3.5	-	-	< 3.5	-	-
$\overline{m}$ [GeV]	-	-	-	-	-	-	≥ 300	-	-	-
$E_{\text{T}}^{\text{miss}}$ [GeV]	-	> 30 -	-	-	-	-	-	> 30 -	-	-
$\lvert\eta(\ell, \ell')\rvert$	-	< 3.0 -	-	-	-	-	-	< 3.0 -	-	-
Z-veto	-	-	inverted	-	-	✓	✓	-	✓	-

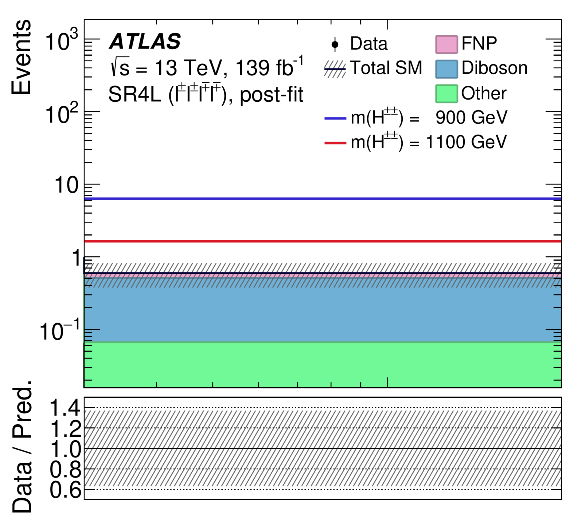
$H^{\pm\pm}$ -> multi-lepton





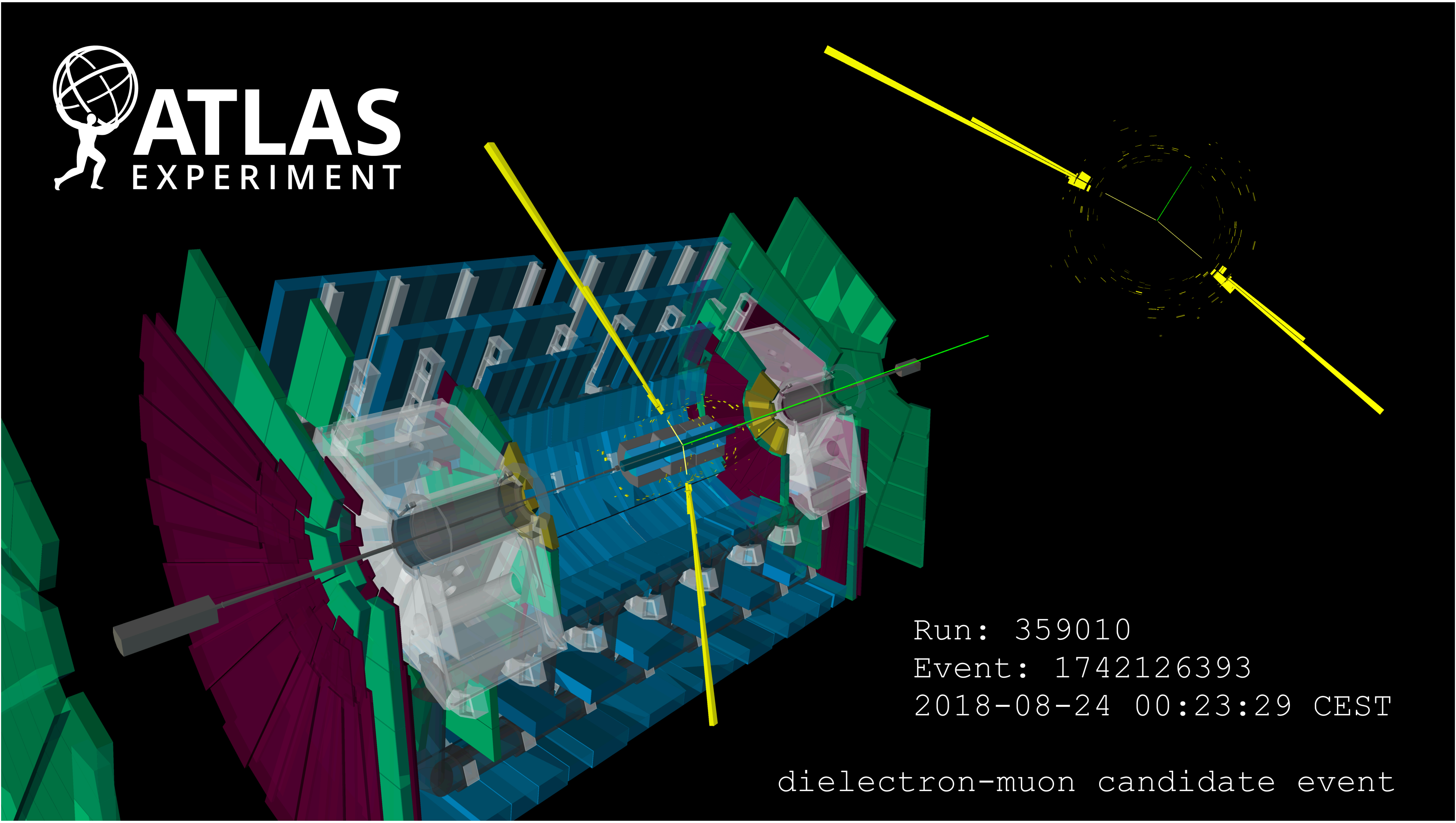






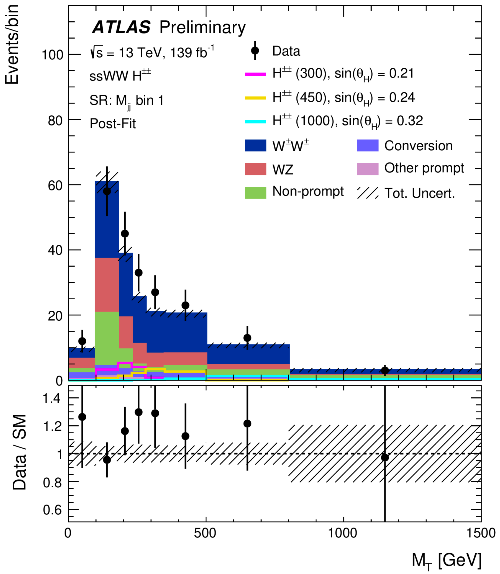
- Post-fit distributions in SRs

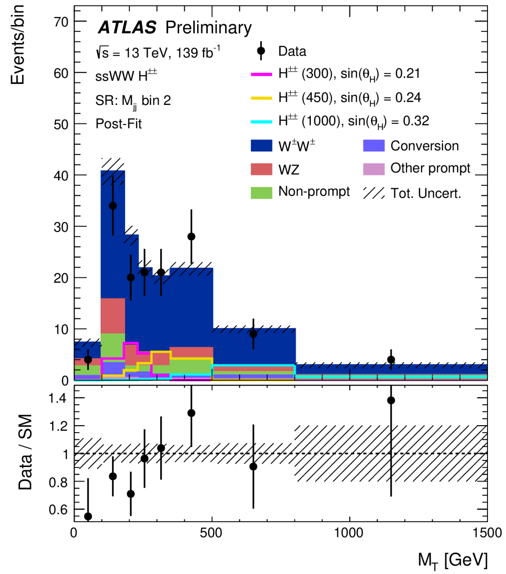
$H^{\pm\pm}$ -> multi-lepton

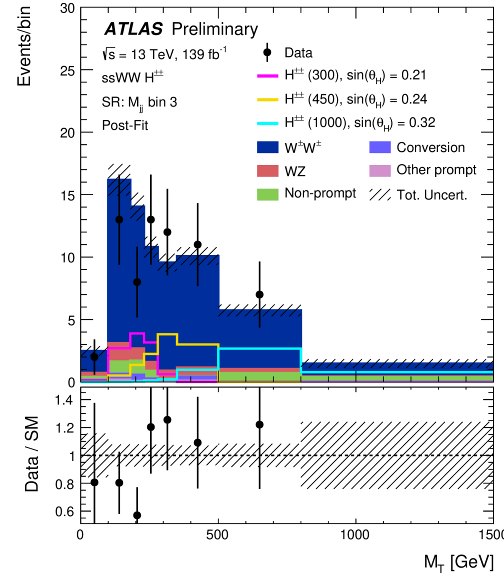


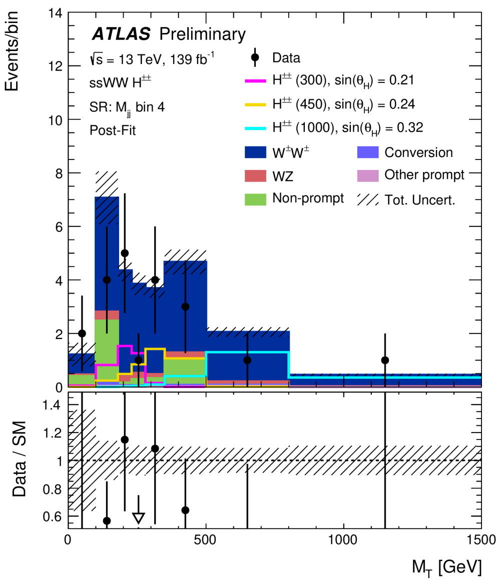
- Display of a candidate pp → $H^{++}H^{--}$ event

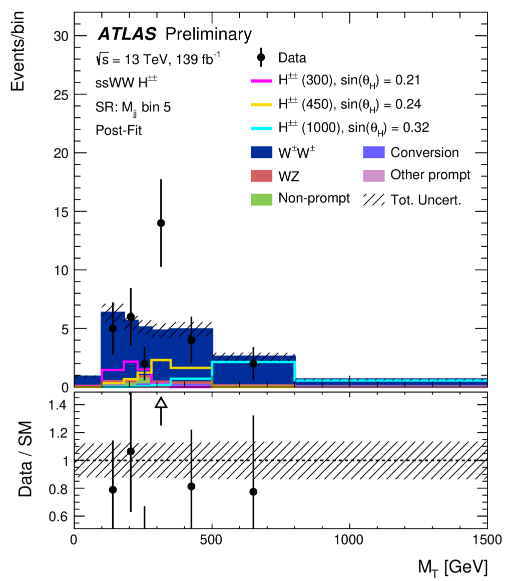
VBF H++











- Post-fit mT distributions in the different mjj bins

Slides to be removed

➢ Now the slides covers 4 analyses as shown below, following the suggestions from HBSM convenors, let me know if you think more results should be covered in the talk, thanks!

- H± -> cb (arXiv. 2302.11739)

- H± -> Wa , a->mumu (arXiv.2304.14247) (not really in search for H+ but light pseudoscalar A, I only mention it very briefly)

- $H^{\pm\pm}$ -> multi-lepton(arXiv.2211.07505)

- VBF $H^{\pm\pm}$ (ATLAS-CONF-2023-023), spin-off the VBS same sign WWjj measurement