A search for non-standard Higgs bosons with the ATLAS experiment

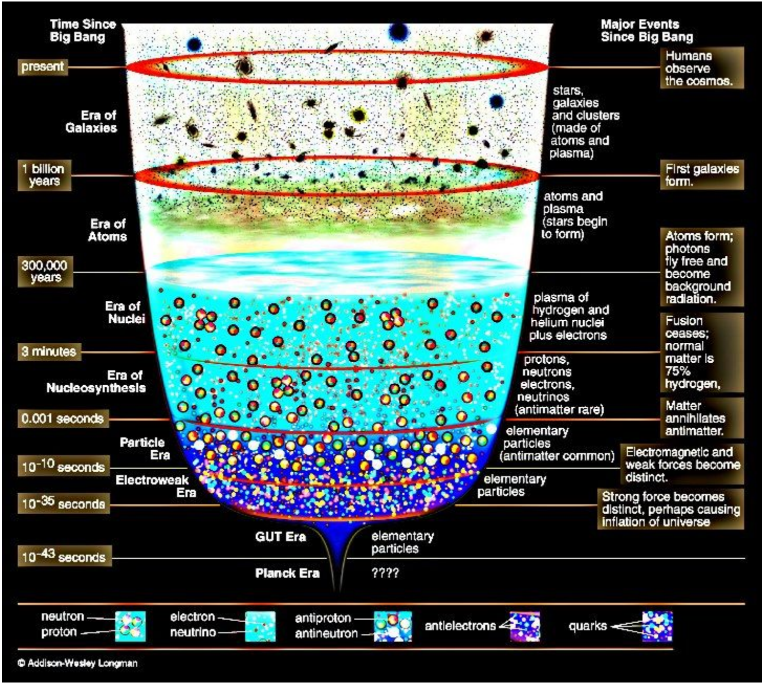
Otilia Ducu

CERN, IFIN-HH

May 17, 2021

Meeting agenda

- Paper on arxiv here (submitted to JHEP)



Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
Era of Galaxies
stars, galaxies and clusters (made of atoms and plasma)
1 billion years
First galaxies form.
Era of Atoms
atoms and plasma (stars begin to form)
300,000 years
Atoms form; photons fly free and become background radiation.
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
3 minutes
Fusion ceases; normal matter is 75% hydrogen,
Era of Nucleosynthesis
protons, neutrons electrons, neutrinos (antimatter rare)
0.001 seconds
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10-10 seconds
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10-35 seconds
Strong force becomes distinct, perhaps causing inflation of universe
GUT Era
elementary particles
10-43 seconds
Planck Era
????
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks
© Addison-Wesley Longman

Standard Model (SM) of particle physics

- SM describes the fundamental structure of matter using an elegant series of equations

→ Describes how everything we observe in the universe is made from a few basic blocks called fundamental particles, governed by four forces

→ All fundamental particles predicted by SM were observed, and the measured probabilities to produce them (∼ cross-section), alone or in combination, agree with theoretical calculation

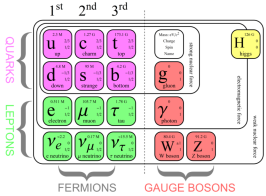


figure from [here](#)

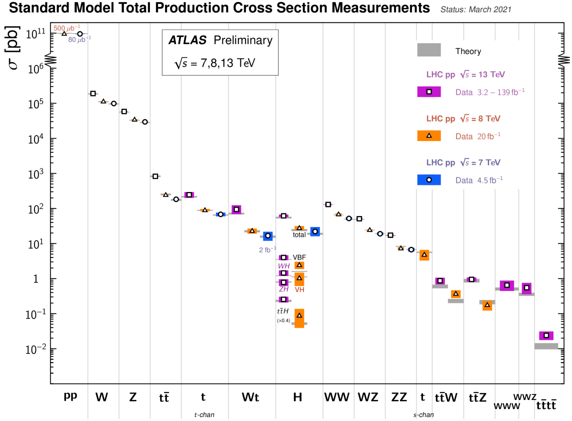
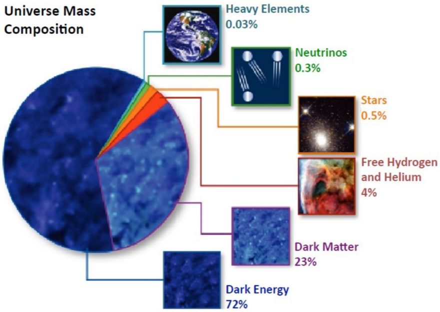


figure from [here](#)

Problems of the Standard Model

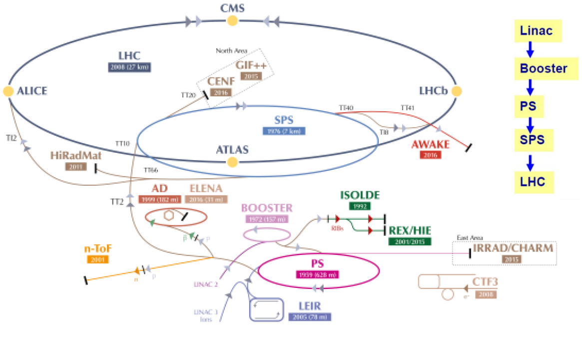
It is well known that the SM is not complete, and there are clear evidences of new physics:

- No successful description of gravity as a (renormalizable) QFT
- Hierarchy problem
- Number of fermion generations
- Absence of CP violation by strong interactions
- Neutrino masses ($\neq 0$) and oscillations
- The existence of Dark Matter
- The matter-antimatter asymmetry in the Universe
- Etc.



Such problems the ATLAS (CMS, etc) collaboration @CERN aims to address

Large Hadron Collider (VIDEO)



H⁻ (hydrogen anions) p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

- *Linac2 accelerates negative hydrogen ions to 50 MeV; the ions are stripped of their two e^- during injection from Linac4 into the PS Booster to leave only protons*; Turned off for the last time on 12/11/2018
- *PS Booster accelerates p to 1.4 GeV for injection into the PS*
- *PS accelerator operates at up to 26 GeV*
- *SPS operates at up to 450 GeV*

ATLAS (VIDEO, VIDEO)

- ATLAS (A Toroidal LHC ApparatuS), a general-purpose detector:

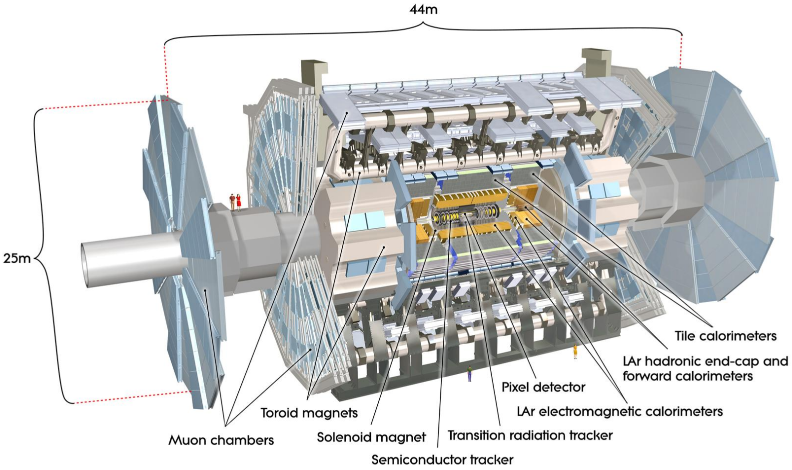
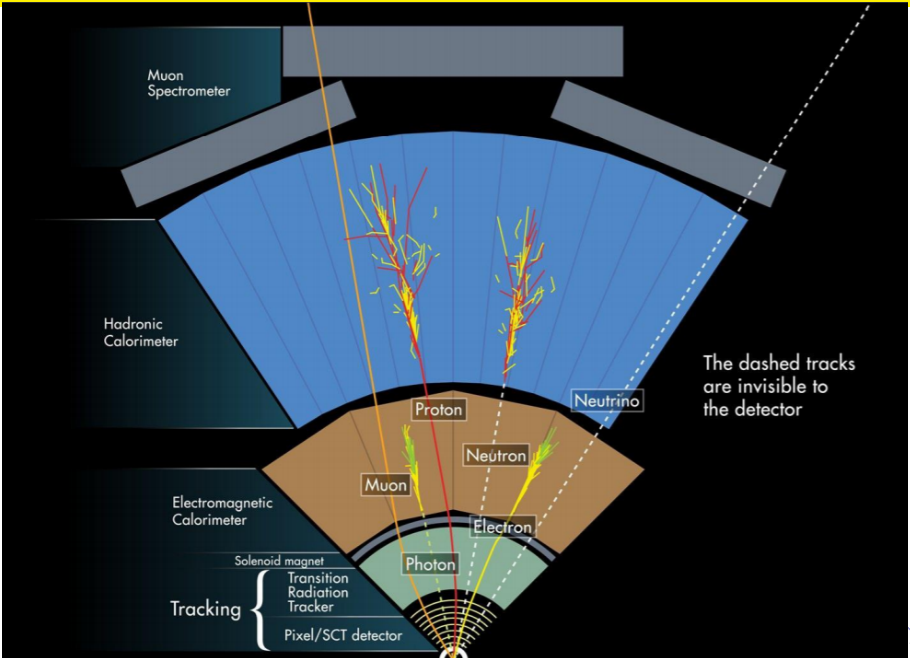


Image from opendata.atlas.cern

Particle detection in ATLAS



ATLAS DATA

LHC performance in Run-1:

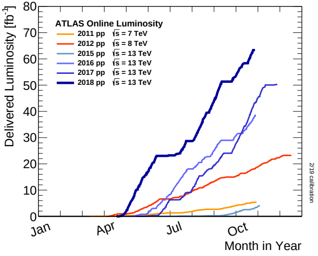
- First pp collisions at LHC occurred in November 2009, at $\sqrt{s} = 900$ GeV
- In April 2010 the collisions started at $\sqrt{s} = 7$ TeV, and by the end of 2011 the integrated luminosity was of 4.7 fb^{-1}
- The last Run-1 data-taking started in May 2012 at $\sqrt{s} = 8$ TeV, and an integrated luminosity of 23 fb^{-1} was collected

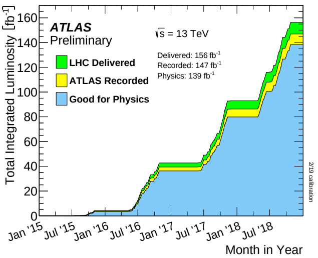
LHC performance in Run-2:

- On June 3rd 2015, the LHC started the collisions at $\sqrt{s} = 13$ TeV

$\rightarrow$ and at the end of Run-2 (in 2018) 139 fb^{-1} were collected for physics studies

- Today, I will presents a search for non-standard Higgs bosons with 139 fb^{-1} of pp data





Signal model

Type-II Seesaw doublet-triplet-Higgs-Model (DTHM, Phys. Rev. D84(2011)095005)

- Extends the scalar sector of the SM with a scalar triplet, Δ

$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + Tr(D_\mu \Delta)^\dagger (D^\mu \Delta) - V(H,\Delta) + \mathcal{L}_{\rm Yukawa}$$

The covariant derivatives:

$$D_\mu H = \partial_\mu H + igT^a W_\mu^a H + i\frac{g'}{2} B_\mu H$$

$$D_\mu \Delta = \partial_\mu \Delta + ig[T^a W_\mu^a, \Delta] + ig'\frac{Y_\Delta}{2} B_\mu \Delta$$

$(W_\mu^a,\ g)$, and $(B_\mu,\ g')$ ⇨ the $SU(2)_L$ and $U(1)_Y$ gauge fields and couplings

The Higgs potential:

$$V(H,\Delta) = -m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + M_\Delta^2 Tr(\Delta^\dagger \Delta) + [\mu(H^T i\sigma^2 \Delta^\dagger H) + \text{h.c.}]$$
$$+\lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr\Delta^\dagger \Delta)^2 + \lambda_3 Tr(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H$$

$\mathcal{L}_{\rm Yukawa}$ ⇨ contains all the Yukawa sector of the SM plus one extra Yukawa term that leads after EWSB to (Majorana) mass terms for the neutrinos

- EWSB achieved by requiring the neutral components of the SM Higgs and Δ to acquire vacuum expectation values, ν_d and ν_t (with $\nu_t > 0$)
- After EWSB: $H^{\pm\pm}$, $H^\pm$, A^0 (CP odd), H^0 (CP even), h^0 (SM Higgs) scalar bosons

  + mass terms for neutrinos proportional to ν_t

Constraints from experimental measurements

Constraints from electroweak precision measurements:

- In the SM (at tree level) $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$
- In the DTHM one can write $M_W^2 = \frac{g^2(\nu_d^2+2\nu_t^2)}{4}$ and $M_Z^2 = \frac{g^2(\nu_d^2+4\nu_t^2)}{4\cos^2\theta_W}$

  thus $\rho = \frac{\nu_d^2+2\nu_t^2}{\nu_d^2+4\nu_t^2} \neq 1$, and actually at tree level $\rho < 1$

→ Interested only in the $\nu_d \ggg \nu_t$ limit, thus one can rewrite ρ as:

$\rho \simeq 1 - 2\frac{\nu_t^2}{\nu_d^2} = 1 + \delta\rho$, with $\delta\rho = -2\frac{\nu_t^2}{\nu_d^2} < 0$ and $\sqrt{\nu_d^2 + 2\nu_t^2} = 246$ GeV

- From the latest EW precision measurements $\rho_0 = 1.0004 \pm 0.00048$ (2σ level)
- Now one can place an upper bound on ν_t of 2.5 GeV

Additional contraints

1) Absence of tachyonic modes: lower and upper bounds on μ

→ Amended by taking into account the existing exclusion limits on the Higgs boson masses

$$\mu > 0\,,\ \mu_- < \mu < \mu_+$$

$$\mu_- = ((\lambda_1+\lambda_4)^2 - \lambda(\lambda_2+\lambda_3))\,\frac{2\sqrt{2}}{\lambda}\frac{v_t^3}{v_d^2} + \mathcal{O}(v_t^4)$$

$$\mu_+ = \frac{\lambda}{4\sqrt{2}}\frac{v_d^2}{v_t} + \sqrt{2}(\lambda_1+\lambda_4)v_t + \mathcal{O}(v_t^2)$$

$$\mu = \frac{\sqrt{2}v_t}{v_d^2+4v_t^2}.m_A^2$$

$$\mu_{\rm min} = \max\begin{bmatrix} \dfrac{\sqrt{2}\,v_t}{v_d^2+4v_t^2}\,(m_A^2)_{\rm exp}, \\ \dfrac{\lambda_4 v_t}{2\sqrt{2}} + \dfrac{\sqrt{2}\,v_t}{v_d^2+2v_t^2}\,(m_{H^\pm}^2)_{\rm exp}, \\ \dfrac{\lambda_4 v_t}{\sqrt{2}} + \sqrt{2}\dfrac{\lambda_3 v_t^3}{v_d^2} + \dfrac{\sqrt{2}\,v_t}{v_d^2}\,(m_{H^{\pm\pm}}^2)_{\rm exp} \end{bmatrix}$$

$$\mu_{\rm max} \sim \mathcal{O}(M_{\rm GUT})$$

(could be)

→ $\mu_{\rm max}$ can be used to condition the maximally allowed values of m_{A^0}, m_{H^0}, $m_{H^{\pm\pm}}$, $m_{H^\pm}$

- If values of $\mu \leq 1$ TeV, the BSM Higgs bosons might be accessible at the LHC

Additional constraints (cont'd)

2) The vacuum structure + potential stability constraints

- Make sure the EW vacuum is a minimum and not a saddle point or a local maximum
- Some of these "bad" configurations are already excluded when:

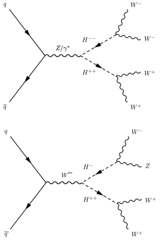
→ e.g considering the experimental mass limits on the SM Higgs

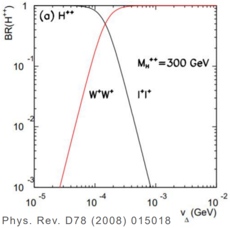
3) The potential must be bounded from below

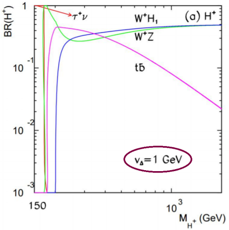
4) Unitarity constraints

- All these constraints help to choose allowed values for the other model parameters
  - → To be able to select some charged Higgs production modes

Considered scenarios







Two production modes explored, $\nu_t = 0.1$ GeV (such low ν_t values studied only by this team):

1) Pair production: only $H^{\pm\pm}$ and SM h^0 in the observable range

→ Only $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ considered, with a BR of $\sim 100\%$ (middle plot)

→ $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ suppressed with increasing ν_t

- Scenario extensively studied by ATLAS & CMS, excluding $m_{H^{\pm\pm}}$ up to 870 GeV

2) Associated production: $m_{H^{\pm}} \approx m_{H^{\pm\pm}}$ (5 GeV difference)

- Only $H^{\pm} \rightarrow W^{\pm}Z$ considered, with a BR of $\sim 60\%$ (left-hand side plot)
- New with respect to 36 fb^{-1} version of the analysis

- $pp \rightarrow W^{\pm *}W^{\pm *} \rightarrow H^{\pm\pm}$ proportional with ν_t, thus negligible
  - VBF production mode studied by CMS ($H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$, ν_t of a few tens of GeV)

Production cross-sections

- The model parameters used for the $H^{\pm\pm}$ $H^{\pm}$ associated production:

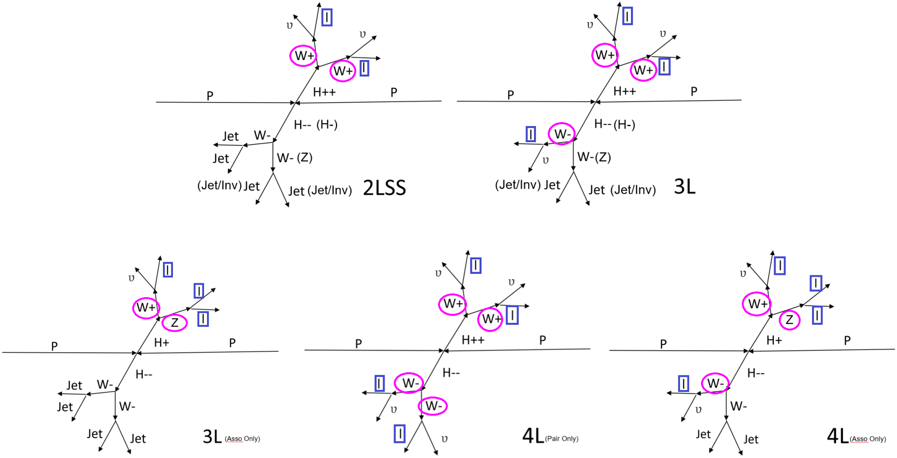
H^{++}	μ	$\sin\alpha$	λ_0	λ_1	λ_2	λ_3	λ_4
200	0.0875	0.00085	0.52307	0.57271	1.40845	0.23625	-0.08383
250	0.1359	0.00038	0.51669	1.40310	1.84833	-0.2507	-0.14354
300	0.1986	0.00064	0.52167	1.16310	1.99467	-0.9168	-0.16540
350	0.2819	0.00055	0.51652	1.67939	1.86355	-1.0817	-0.06053
400	0.3550	0.00062	0.51925	1.82309	1.66474	1.19800	-0.26601
450	0.4422	0.00066	0.52353	1.99415	-0.4973	1.61944	-0.43840
500	0.5683	0.00071	0.52047	1.67672	1.47220	0.71157	-0.22528
550	0.6755	0.00074	0.52175	1.71884	0.43733	1.79197	-0.44375
600	0.8571	0.00069	0.52261	1.93299	0.54575	-0.4439	0.22486

- The NLO cross-sections (BR of the charged Higgs bosons to $W^{\pm}W^{\pm}$ or $W^{\pm}Z$ included):

$m_{H^{\pm\pm}}$ [GeV]	200	300	350	400	500	600
$m_{H^{\pm}}$ [GeV]	400	400	700	700	700	700
$\mathcal{B}(H^{\pm\pm} \to W^{\pm}W^{\pm})$ [%]	100	100	100	100	100	100
Cross section [fb] ($H^{\pm\pm}$ pair production)	81.0	16.5	8.7	4.9	1.8	0.7

$m_{H^{\pm\pm}}$ [GeV]	200	220	300	400	450	500	550	600
$m_{H^{\pm}}$ [GeV]	196	215	295	395	445	496	545	602
$\mathcal{B}(H^{\pm\pm} \to W^{\pm}W^{\pm})$ [%]	100	100	100	100	100	100	100	100
$\mathcal{B}(H^{\pm} \to W^{\pm}Z)$ [%]	58.8	44.3	37.3	44.7	45.9	45.7	48.4	50.8
Cross section [fb] ($H^{\pm\pm}H^{\mp}$ associated production)	88.7	44.5	9.5	3.0	1.9	1.2	0.8	0.5

Selected final states

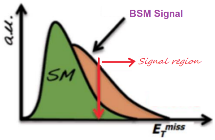


- Two same-sign leptons, three or four leptons final states
  - → Quite low Standard Model background

Strategy to look for this BSM signal

All searches for non-standard Higgs bosons (or other new physics) have some common points:

- Signal regions (SRs): regions targeting specific the signal models
  - → Defined to have the best discovery potential in the selected models
  - → For one model, several SRs can be defined, to cover each region of the phase-space (low, intermediate and high mass difference between the sparticles)
  - → In Run2: exploiting more new variables and using machine learning techniques



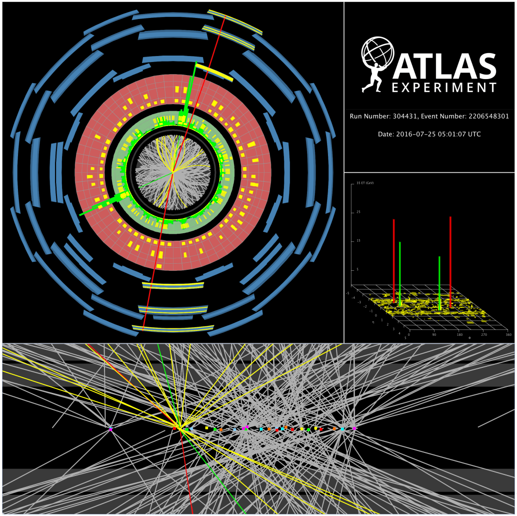
- Background (bkg): identify → understand → estimate as precise as possible → validate
  - → Standard Model (SM) bkg, or Detector bkg
  - → Estimated from Monte Carlo (MC) simulations, or using data control regions (CRs), or with data-based techniques, as appropriate
  - → In Run 2: an increased use of data-based bkg estimates to avoid dependence on MC
- Statistical interpretation: test the compatibility between data and bkg estimation in SRs
- In case of no excess:
  - → Set model dependent / independent exclusion limits

Object definition

Following the various CP groups recommendations (details in back-up)

- Only electrons and muons, no taus (for candidates leptons $p_T > 10$ GeV)

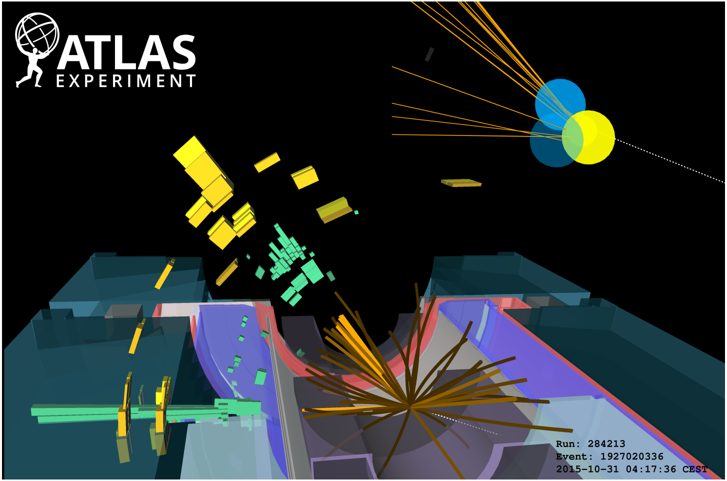
→ Three signal lepton categories: loose (L), loose and minimally-isolated (L*) and tight (T)



Object definition

Following the various CP groups recommendations (details in back-up)

- No b-tagged jets in the events (very powerful against $t\bar{t}$ bkg)



Event selection

Trigger selection

- Lowest unprescaled single lepton triggers (list in back-up)

Event preselection (SC = same-charge, SFOC = same-flavor opposite-charge)

- Three channels classified according to the number of leptons $2\ell^{sc}$, 3ℓ and 4ℓ in the event

→ $2\ell^{sc}$ channel divided in ee, $e\mu$ and $\mu\mu$ sub-channels

→ 3ℓ divided in two sub-channels, depending on the nr. of SFOC pairs (SFOC0 and SFOC1,2)

Selection criteria	$2\ell^{sc}$	3ℓ	4ℓ
Trigger	At least one tight lepton with $p_T^\ell > 30$ GeV that fulfils the requirements of single-lepton triggers		
N_ℓ (type L)	=2	=3	=4
N_ℓ (type L*)	–	–	=4
N_ℓ (type T)	=2	≥2 ($\ell_{1,2}$)	≥1
$\lvert\sum Q_\ell\rvert$	2	1	2 or 0
Lepton p_T	$p_T^{\ell_1,\ell_2} > 30, 20$ GeV	$p_T^{\ell_0,\ell_1,\ell_2} > 10, 20, 20$ GeV	$p_T^{\ell_1,\ell_2,\ell_3,\ell_4} > 10$ GeV
E_T^{miss}	> 70 GeV	> 30 GeV	> 30 GeV
N_{jets}	≥ 3	≥ 2	–
b-jet veto	$N_{b\text{-jet}} = 0$		
Low SFOC $m_{\ell\ell}$ veto	–	$m_{\ell\ell}^{oc} > 15$ GeV	
Z boson decays veto	$\lvert m_{ee}^{sc} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell\ell}^{oc} - m_Z\rvert > 10$ GeV	

Signal regions (SRs)

- Optimization done per analysis sub-channel, per $H^{\pm\pm}$ mass point

$\rightarrow$ Final SRs harmonized to have the same selection per analysis channel

Charged Higgs boson mass	$m_{H^{\pm\pm}}$ = 200 GeV, $m_{H^{\pm}}$ = 196 GeV	$m_{H^{\pm\pm}}$ = 300 GeV, $m_{H^{\pm}}$ = 295 GeV	$m_{H^{\pm\pm}}$ = 400 GeV, $m_{H^{\pm}}$ = 395 GeV	$m_{H^{\pm\pm}}$ = 500 GeV or 600 GeV, $m_{H^{\pm}}$ = 496 GeV or 602 GeV
Selection criteria	$2\ell^{sc}$ channel			
m_{jets} [GeV]	[100, 450]	[100, 500]	[300, 700]	[400, 1000]
S [rad.]	<0.3	<0.6	<0.6	<0.9
$\Delta R_{\ell^{\pm}\ell^{\pm}}$ [rad.]	<1.9	<2.1	<2.2	<2.4
$\Delta\phi_{\ell\ell,E_{\text{T}}^{\text{miss}}}$ [rad.]	<0.7	<0.9	<1.0	<1.0
$m_{x\ell}$ [GeV]	[40, 150]	[90, 240]	[130, 340]	[130, 400]
$E_{\text{T}}^{\text{miss}}$ [GeV]	>100	>130	>170	>200
Selection criteria	3ℓ channel			
$\Delta R_{\ell^{\pm}\ell^{\pm}}$ [rad.]	[0.2, 1.7]	[0.0, 2.1]	[0.2, 2.5]	[0.3, 2.8]
$m_{x\ell}$ [GeV]	>160	>190	>240	>310
$E_{\text{T}}^{\text{miss}}$ [GeV]	>30	>55	>80	>90
$\Delta R_{\ell\text{jet}}$ [rad.]	[0.1, 1.5]	[0.1, 2.0]	[0.1,2.3]	[0.5, 2.3]
$p_{\text{T}}^{\text{leading jet}}$ [GeV]	>40	>70	>100	>95
Selection criteria	4ℓ channel			
$m_{x\ell}$ [GeV]	>230	>270	>360	>440
$E_{\text{T}}^{\text{miss}}$ [GeV]	>60	>60	>60	>60
$p_{\text{T}}^{\ell_1}$ [GeV]	>65	>80	>110	>130
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\text{min}}$ [rad.]	[0.2, 1.2]	[0.2, 2.0]	[0.5, 2.4]	[0.6, 2.4]
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\text{max}}$ [rad.]	[0.3, 2.0]	[0.5, 2.6]	[0.4, 3.1]	[0.6, 3.1]

Background types

Two main background categories:

1) SM background: leptons from prompt leptonic decays of W and Z bosons

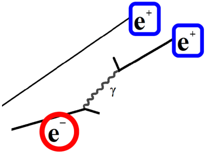
→ Estimated with MC simulations normalised to the SM cross sections

→ WZ normalisation corrected using data, with a dedicated control region

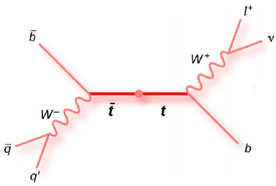
2) Detector background: (a) electron charge-flip and (b) fake/non-prompt leptons

→ Electron charge-flip bkg significantly reduced with the ECIDS (BDT) tool

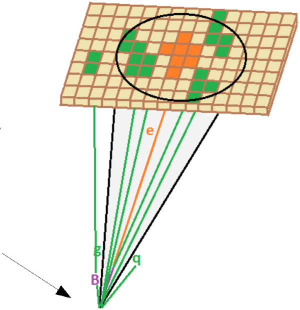
→ Fake/NP leptons greatly reduced with the non-prompt lepton veto (PLV tool)



a)



b)



WZ BACKGROUND

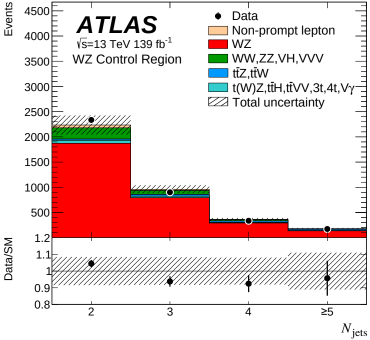
WZ is the main SM background contribution in the $2\ell^{sc}$ and 3ℓ signal regions

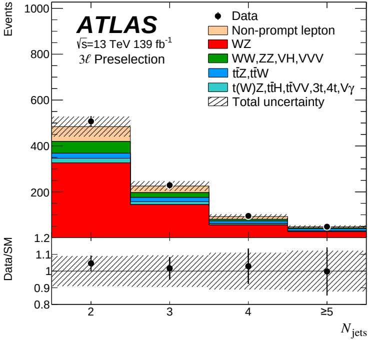
- Not great moddeling of the $N_{jets} > 1$ distribution seen in many analyses, including this one

- Mismodeling corrected with a normalization factor, applied to *WZ* events with $N_{jets} > 1$

$\rightarrow$ derived in a linear fit to the N_{jets} ratio between data (- non-WZ bkg) and WZ contribution

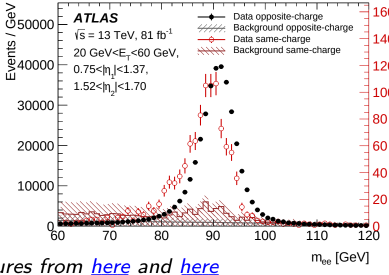
$\rightarrow$ Normalization factor $\rightarrow 0.83 \pm 0.07$ (stat. + syst.)

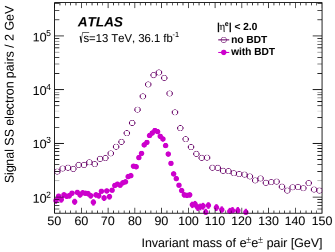




Charge-flip background

Significant only for electrons, only in the $2\ell^{sc}$ region (ee and $e\mu$ sub-channels)





Figures from here and here

- Estimated by reweighting opposite-charge (OC) data events with this ratio:

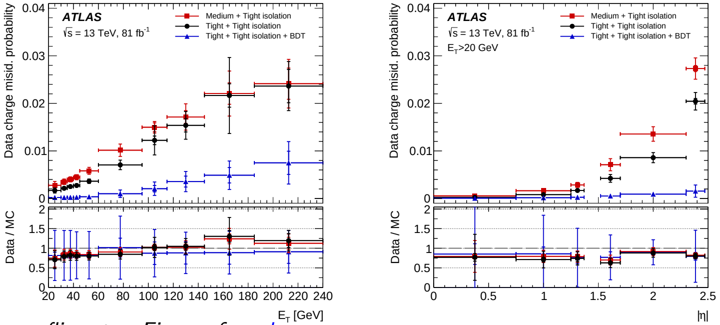
  $r = (\varepsilon_1 + \varepsilon_2)/(1 - \varepsilon_1 - \varepsilon_2)$

→ ε_i the probability of i electron to have a wrong charge (= 0 for muons)

- Probabilities measured using a LLH-based method

→ Applied on $Z \to ee$ events, in data (80 GeV $< m_{\ell\ell} <$ 100 GeV)

Charge-flip probability



Typical charge flip rates; Figures from here

Several sources of uncertainties considered:

- Statistical unc. from Likelihood fit (because of limited stat. in the measurement region)

→ 2%-26%, depending on the [η, p_T] bin

- Background subtraction uncertainties: vary the $m_{\ell\ell}$ cut; approximately 3%
- Uncertainty of the method: accounts for the differences in the charge flip rate between the different sources ($t\bar{t}$, V+jets and $W^{\pm}W^{\mp}$); approximately 10%
- FSR: include it or not in the truth rate computation, less than 1%

Fake/NP lepton background in the $2\ell^{SC}$ SRs

Performed using the well known Fake Factor method

- Fake/NP leptons can be estimated in a region R using an extrapolation (fake) factor, θ

$$N^{\mathrm{fake},R}_{e\mu} = \theta^{2\ell^{SC}}_{e} \times (N^{\mathrm{Data}} - N^{\mathrm{Prompt}} - N^{\mathrm{Charge-flip}})^{R}_{\mu\not{e}} + \theta^{2\ell^{SC}}_{\mu} \times (N^{\mathrm{Data}} - N^{\mathrm{Prompt}} - N^{\mathrm{Charge-flip}})^{R}_{e\not{\mu}} ,$$

$$N^{\mathrm{fake},R}_{ee,\ \mu\mu} = \theta^{2\ell^{SC}}_{e,\mu} \times (N^{\mathrm{Data}} - N^{\mathrm{Prompt}} - N^{\mathrm{Charge-flip}})^{R}_{e\not{e},\ \mu\not{\mu}} .$$

$\not{e}$ and $\not{\mu}$ are leptons passing the loose signal requirements, but failing the tight ones

- The fake factors are measured in dedicated CRs, enriched in fake/NP leptons

→ For $2\ell^{sc}$ channel, the CR is defined as the $2\ell^{sc}$ preselection region, but with $E_T^{miss} < 70$ GeV

→ Electron (muon) fake factor measured with SC electron (muon) pairs: $\theta^{2\ell^{sc}}_{\ell} = \frac{N_{\ell\ell}}{N_{\ell\not{\ell}}}$

→ Measurement in three p_T bins; main assumptions:

Nume $2\ell^{sc}$ pairs: leading lepton = prompt, sub-leading lepton = fake/NP
Deno $\ell\not{\ell}$ pairs: ℓ = prompt, $\not{\ell}$ = fake/NP

Fake/NP leptons in $2\ell^{SC}$ SRs (cont'd)

Measured fake factors and the assigned uncertainties:

p_T region	Fake Factor $\pm$ stat uncertainty
Electrons:	
< 40 GeV	0.03 ± 0.01
> 60 GeV	0.16 ± 0.05
Muons:	
< 40 GeV	0.03 ± 0.01
> 60 GeV	0.09 ± 0.02

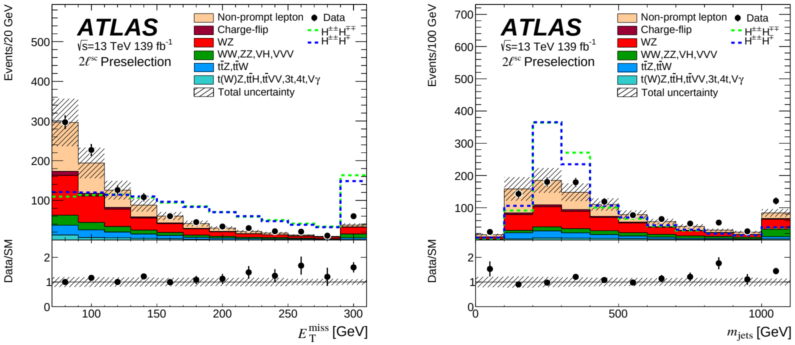
Where the sources of uncertainties are coming from:

- SM processes (around 20%) and electron charge-flip (15%) bkg subtraction
- Variation of the fake factor with E_T^{miss} or by applying a different selection to vary the fraction of jets containing heavy-flavour hadrons; 20% (10%) for electrons (muons)
- Truth level studies to evaluate how many times the fake/NP lepton is actually the one with the highest lepton pT and not the one with the second highest pT, as assumed;

$\rightarrow$ dominant when $p_T > 60$ GeV, where it reaches 45% (80%) for electrons (muons)

Total unc. = all above sources, treated as uncorrelated, combined

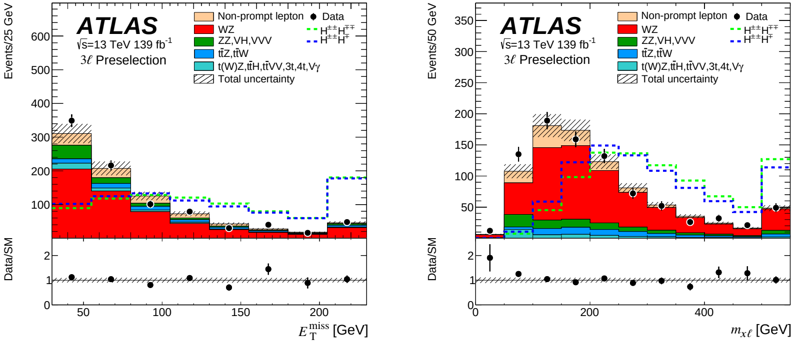
Fair agreement at preselection level (fake/NP leptons a dominant source)



- *Stat. unc. and all sources of syst. unc. on the background estimation*

Fake/NP leptons in 3ℓ SRs

- Estimated using the same method as in the $2\ell^{sc}$ channel
- Fair agreement at preselection level (fake/NP leptons non-negligible source of bkg)



- *Stat. unc. and all sources of syst. unc. on the background estimation*

FAKE/NP LEPTON BACKGROUND IN THE 4ℓ SRs

Not enough statistic to use the Fake Factor method in the 4ℓ channel

- Instead, use the yields predicted by the MC but corrected with dedicated scale factors (SFs)
- SFs measured in dedicated control regions:

Sample	Z+jets-enriched region	$t\bar{t}$-enriched region
N_ℓ (type L*)	=3	=3
$\lvert\sum Q_\ell\rvert$	1	1
N_{jets}	1 or 2	1 or 2
$p_{\text{T}}^{\text{jet}}$	> 25 GeV	> 30 (25) GeV
Z-window	$\lvert m_{\ell\ell}^{\text{oc}} - m_Z\rvert < 10$ GeV	No same-flavour opposite-charge ℓ pair
$E_{\text{T}}^{\text{miss}}$	< 50 GeV	–
m_{T}	< 50 GeV	–

→ Ele. SFs measured for light- (LF) and heavy-flavor fake/NP sources, in Z-CR and Top-CR

→ Muon SFs measured for heavy-flavor (HF) fake/NP sources in Top-CR

- Three scale factors λ^e_{HF}, λ^e_{LF} and λ^μ_{HF} are obtained from:

$$N^e_{\text{data}|X} - N^e_{\text{prompt}|X} = \lambda^e_{\text{HF}} N^e_{\text{HF}|X} + \lambda^e_{\text{LF}} N^e_{\text{LF}|X} \ , \quad (1)$$

$$N^\mu_{\text{data}|X} - N^\mu_{\text{prompt}|X} - N^\mu_{\text{LF}|X} = \lambda^\mu_{\text{HF}} N^\mu_{\text{HF}|X} \ . \quad (2)$$

X = Z-CR for electrons, or Top-CR for electrons and muons

FAKE/NP LEPTONS IN 4ℓ SRS (CONT'D)

Final scale factors and uncertainties:

- $\lambda^{e}_{HF} = 0.98 \pm 0.18$ (stat) $\pm$ 0.06 (syst)
- $\lambda^{e}_{LF} = 1.34 \pm 0.17$ (stat) $\pm$ 0.20 (syst)
- $\lambda^{\mu}_{HF} = 0.94 \pm 0.04$ (stat) $\pm$ 0.04 (syst)

Where the considered sources of uncertainties are obtained from:

- Alternative 3ℓ CRs, where the jet multiplicity and the lepton p_T threshold are varied

→ Accounts for the differences in the SFs when changing the composition of the fake/NP leptons (CRs to SRs extrapolation)

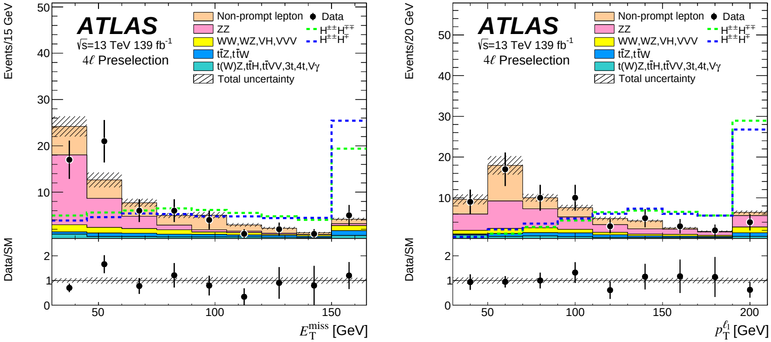
- Unc. on the prompt lepton subtraction

→ Dominant contributions found to be from the variation of the renormalisation and factorisation scales and PDFs

- Final syst. unc. combine all the sources mentioned, treated as fully uncorrelated

Fake/NP leptons in 4ℓ SRs (cont'd)

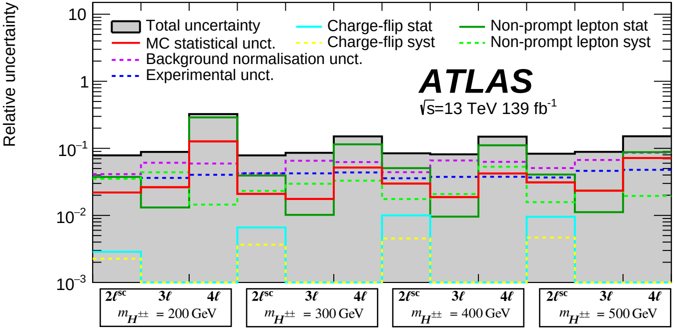
Fair agreement at preselection level (fake/NP leptons a non-negligible source of bkg)



- *Stat. unc. and all sources of syst. unc. on the background estimation*

Exp and theory uncertainties

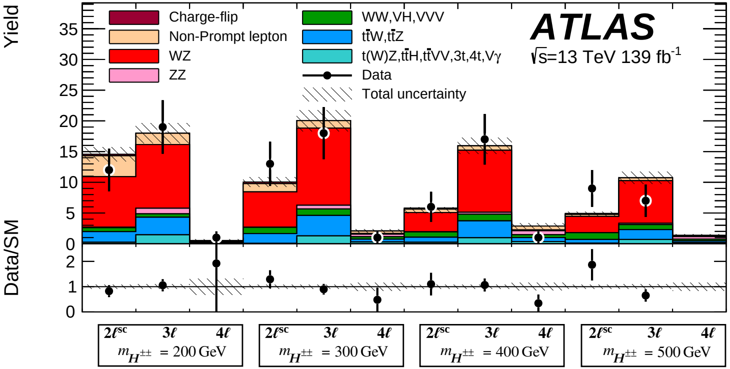
All sources of experimental and theory uncertainties considered



- The uncertainties range from 10% to 30%
- The uncertainties associated to the charge-flip background small in all SRs
- Dominant sources: stat uncertainties in the fake/NP estimate and the theory uncertainties

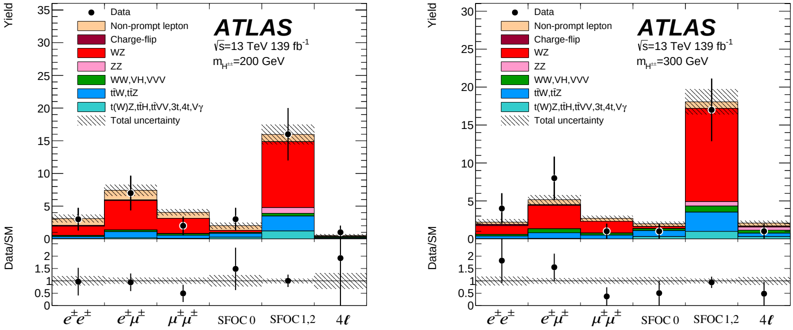
→ An exception is is $m_{H^{\pm\pm}} = 300$ GeV $2\ell^{sc}$ SR, where most sources of unc. are of similar size

Results in the SRs

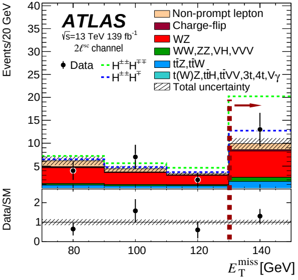


- No significant excess in any of the signal regions...

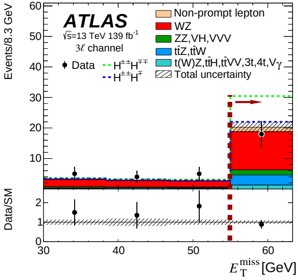
Results in the SRs – per channel



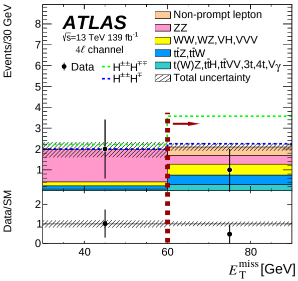
- Interesting to see the composition in each channel, per SR



ATLAS
√s=13 TeV 139 fb-1
2ℓsc channel
Data
H±±H∓∓
H±±H∓
Non-prompt lepton
Charge-flip
WZ
WW,ZZ,VH,VVV
tt̄Z,tt̄W
t(W)Z,tt̄H,tt̄VV,3t,4t,Vγ
Total uncertainty
Events/20 GeV
Data/SM
E_T^miss [GeV]



ATLAS
√s=13 TeV 139 fb-1
3ℓ channel
Data
H±±H∓∓
H±±H∓
Non-prompt lepton
WZ
ZZ,VH,VVV
tt̄Z,tt̄W
t(W)Z,tt̄H,tt̄VV,3t,4t,Vγ
Total uncertainty
Events/8.3 GeV
Data/SM
E_T^miss [GeV]

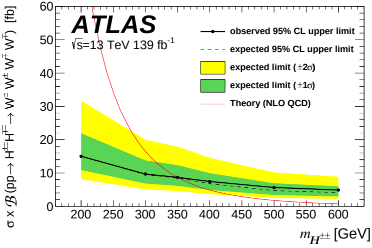


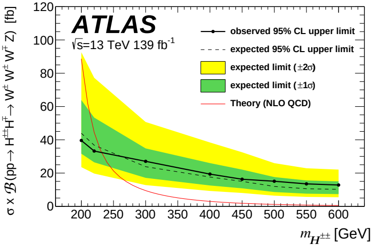
ATLAS
√s=13 TeV 139 fb-1
4ℓ channel
Data
H±±H∓∓
H±±H∓
Non-prompt lepton
ZZ
WW,WZ,VH,VVV
tt̄Z,tt̄W
t(W)Z,tt̄H,tt̄VV,3t,4t,Vγ
Total uncertainty
Events/30 GeV
Data/SM
E_T^miss [GeV]

The limits

Observed and expected upper limits:

- For the charged Higgs pair production and associated production cross-section times branching fraction (95% CL)
- Obtained from the combination of $2\ell^{sc}$, 3ℓ and 4ℓ SRs



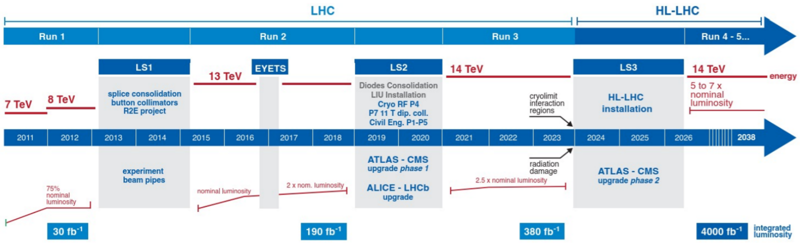


- Charged Higgs boson masses excluded up to 350 GeV for the pair production mode and up to 230 GeV for the associated production mode

Discussion

139 fb^{-1} version of the analyis finished! what's next?

- Prepare the Run-3 analysis:
  - (Re-)Discuss with our theorist colleague the signal model
  - → Do we want to consider more decay modes for the non-standard Higgs bosons?
  - Maybe include more channels to increase the analysis sensitivity?
  - → E.g look at the 1-lepton (and even 0-leptons) channels
  - See if we can make improvements in event selection & object definitions



Thank you!

MC background samples

Table 2: Summary of the event generators, parton shower models, and PDF sets used for the simulation of the background event samples. The notation V is used to refer to an electroweak gauge boson W or Z/γ^*. In the final column, 'default' refers the to default parameter set provided with the event generator.

Process	Generator	ME accuracy	PDF	Parton shower and hadronisation	Parameter set
$VV, V\gamma$	Sherpa	NLO (0-1j) + LO (2-3j)	NNPDF3.0nnlo	Sherpa	default
VV-EW jj	Sherpa	LO	NNPDF3.0nnlo	Sherpa	default
VVV	Sherpa	NLO(0j) + LO (1-2j)	NNPDF3.0nnlo	Sherpa	default
V+jets	Sherpa	NLO (0-2j) + LO (3-4j)	NNPDF3.0nnlo	Sherpa	default
VH	Pythia 8	LO	NNPDF2.3lo	Pythia 8	A14
$t\bar{t}H$	Powheg-Box v2	NLO	NNPDF3.0nlo	Pythia 8	A14
$t\bar{t}V, tWZ, tZ$	MadGraph5_aMC@NLO	NLO	NNPDF3.0nlo	Pythia 8	A14
$t\bar{t}, tW$	Powheg-Box v2	NLO	NNPDF3.0nnlo	Pythia 8	A14
$t\bar{t}t\bar{t}, t\bar{t}t\ \ t\bar{t}WW, t\bar{t}WZ$	MadGraph5_aMC@NLO	NLO	NNPDF3.1nlo	Pythia 8	A14

Trigger selection

2015	2016-2018
HLT_e26_lhmedium_L1EM20VH	HLT_e26_lhtight_nod0_ivarloose
HLT_e60_lhmedium	HLT_e60_lhmedium_nod0
HLT_e120_lhloose	HLT_e140_lhloose_nod0
HLT_mu20_iloose_L1MU15	HLT_mu26_ivarmedium
HLT_mu50	HLT_mu50

Object definition

Following the various CP groups recommendations

- Only electrons and muons, no taus (for candidates leptons $p_T > 10$ GeV)

$\rightarrow$ Three signal lepton categories: loose (L), loose and minimally-isolated (L*) and tight (T)

	Electrons				Muons			
	Candidate	L	L*	T	Candidate	L	L*	T
$\lvert z_0 \sin\theta \rvert$	< 0.5 mm				< 0.5 mm			
$\lvert d_0 \rvert / \sigma(d_0)$	< 5				< 3			
Identification	Loose			Tight	Medium			
Isolation	No		Loose	Yes	No		FixedCutLoose	Yes
Non-prompt-lepton veto	No			Yes	No			Yes
Electron charge-flip veto	No	Yes			N/A			

- Pflow jets with $p_T > 20$ GeV and $|\eta| < 2.5$ (anti-k_{T}, $\Delta R = 0.4$)

$\rightarrow$ Pile-up jets removed with the jet vertex tagger

- For b-jets using DL1r tagger, 70% WP
- E_T^{miss} computed using as input: candidate leptons and calibrated jets before any selection
- Overlap removal applied: standard WP for electrons, pt-dependent WP for muons

MC background samples

In addition to $E_{\mathrm{T}}^{\mathrm{miss}}$ the following variables are used to define SRs:

- The invariant mass of all selected leptons in the event, $m_{x\ell}$, where x can be 2, 3 or 4 corresponding to the $2\ell^{\mathrm{sc}}$, 3ℓ or 4ℓ channels.
- The invariant mass of all jets in the event, m_{jets}. When there are more than four jets in the event, only the leading four jets are used. This variable is only used for the $2\ell^{\mathrm{sc}}$ channel.
- The distance in η–ϕ between two same-charge leptons, $\Delta R_{\ell^{\pm}\ell^{\pm}}$. It is used for the $2\ell^{\mathrm{sc}}$ and 3ℓ channels. In the 4ℓ channel, two such variables can be calculated per event, $\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{min}}$ and $\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{max}}$, denoting the minimum and maximum values, respectively.
- The transverse momentum of the highest-p_{T} jet, $p_{\mathrm{T}}^{\mathrm{leading\ jet}}$. This variable is used in the 3ℓ channel.
- The transverse momentum of the highest-p_{T} lepton, $p_{\mathrm{T}}^{\ell_1}$. This variable is used in the 4ℓ channel.
- The azimuthal distance between the dilepton system and $E_{\mathrm{T}}^{\mathrm{miss}}$, $\Delta\phi_{\ell\ell,E_{\mathrm{T}}^{\mathrm{miss}}}$. It is only used in the $2\ell^{\mathrm{sc}}$ channel.
- The smallest distance in η–ϕ between any lepton and its closest jet, $\Delta R_{\ell\mathrm{jet}}$. This variable is used in the 3ℓ channel.