Searches for new phenomena in leptonic final states using the ATLAS detector

Lake Louise Winter Institute 2018

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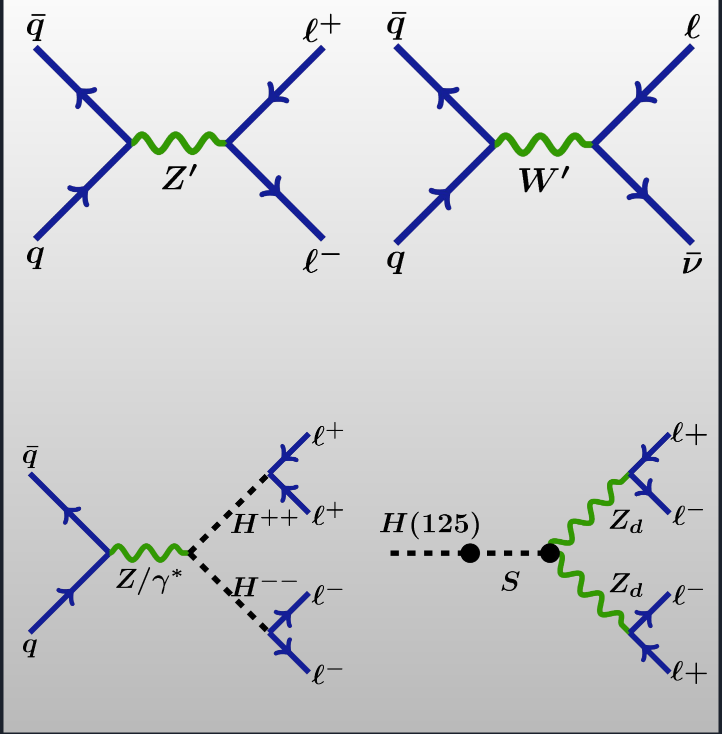
Introduction

- Resonances decaying to leptons are very common in various BSM theories:
  - Grand Unification Theory,
  - Sequential Standard Model,
  - Left-Right Symmetric Model,
  - Two-Higgs-doublet model,
  - Higgs triplet, dark sector extensions, ...
- Final states with leptons have lower backgrounds and can be efficiently triggered.
- The detector resolution allows a good mass measurement of BSM resonances decaying to *e* or *μ*.
- The talk covers only electrons and muons.
- **"ℓ" represents *e* or *μ* in this presentation.**



Presented results

Search for a new heavy gauge-boson resonance decaying into **a lepton** and missing transverse momentum in 36 fb^{-1} of *pp* collisions at $\sqrt{s}$ = 13 TeV with the ATLAS experiment [EXOT-2016-06]	$W' \rightarrow \ell\nu$
Search for new high-mass phenomena in the **dilepton final state** using 36 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13 TeV with the ATLAS detector [EXOT-2016-05]	$Z' \rightarrow \ell^{\pm}\ell^{\mp}$
Search for doubly charged Higgs boson production in **multi-lepton final states** with the ATLAS detector using proton–proton collisions at $\sqrt{s}$ = 13 TeV [EXOT-2016-07]	$pp \rightarrow H^{++}H^{--} \rightarrow \ell^{+}\ell^{+}\ell^{-}\ell^{-}$
Search for Higgs decays to beyond the standard model light gauge bosons in **four-lepton events** with the ATLAS detector $\sqrt{s}$ = 13 TeV [EXOT-2016-22]	$H(125) \rightarrow XX \rightarrow 4\ell$

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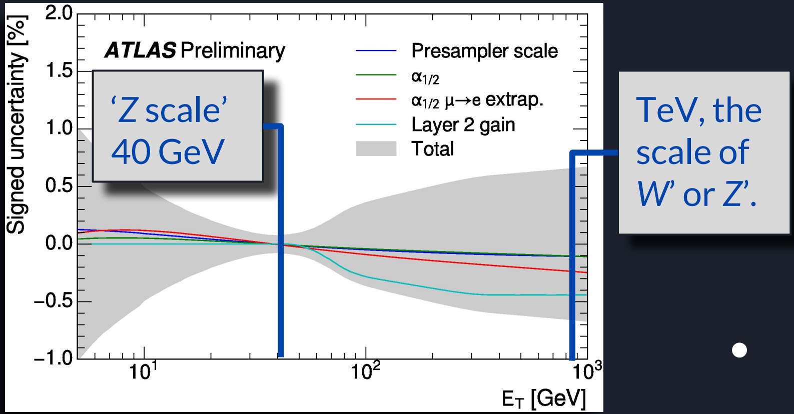
Search for doubly charged Higgs boson production in **multi-lepton final states** with the ATLAS detector u … 3 TeV [EXOT-2016-07] **Submitted on 18 Dec 2017**	$pp \to H^{++}H^{--} \to \ell^{+}\ell^{+}\ell^{-}\ell^{-}$
Search for Higgs decays to beyond the standard model light gauge bosons in **four-lepton even** … [EXOT-2016-22] **Submitted on 9 Feb 2018**	$H(125) \to XX \to 4\ell$

Experimental challenges

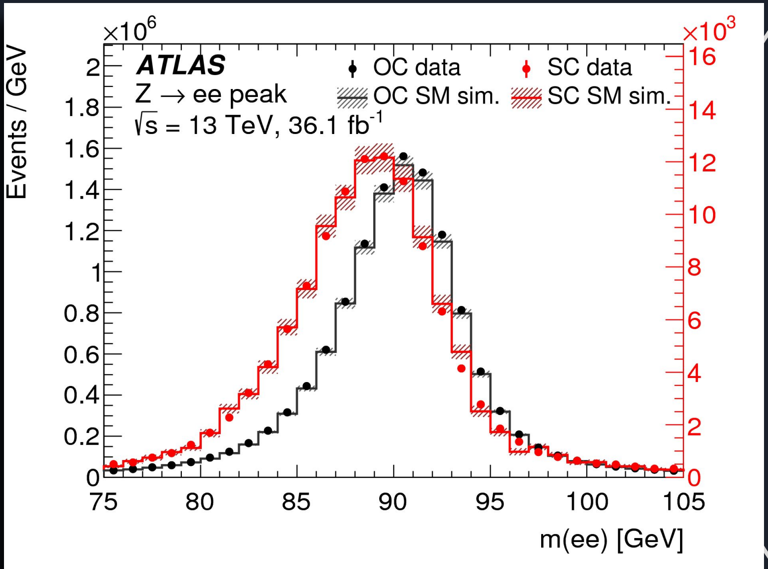


Electron energy scale uncertainty

- All analyses with leptons in final states have a common set of hurdles. Among them are:
  - Mismeasurement of the electron charge.
  - Fake and non-prompt leptons (mis)identified as prompt leptons.
  - The *Z* peak is the highest known point of reference we can use for lepton calibration. We extrapolate our calibration from the *Z* scale to TeV scales (example plot on the left).
- In this talk, I will cover the experimental techniques used to tackle these issues in more detail (than usual).

[ATL-PHYS-PUB-2016-015]

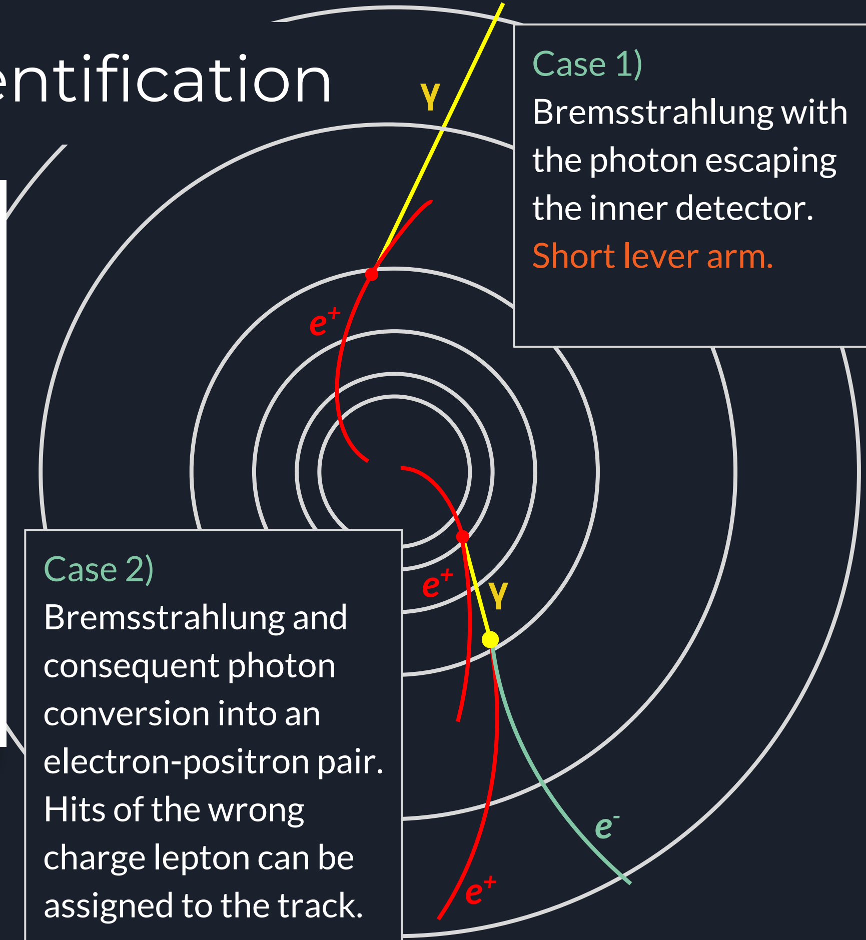
Electron charge misidentification



At typical energies (p_T < 1 TeV) charge misID is caused predominantly by bremsstrahlung.

The probability is about 1% at the Z peak.

[EXOT-2016-07]

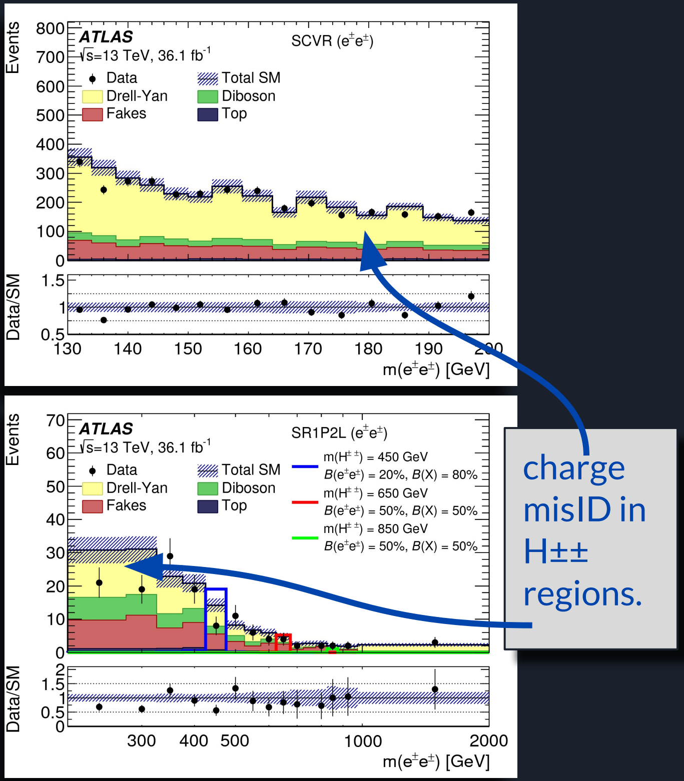


Case 1)
Bremsstrahlung with the photon escaping the inner detector.
Short lever arm.

Case 2)
Bremsstrahlung and consequent photon conversion into an electron-positron pair. Hits of the wrong charge lepton can be assigned to the track.

Electron charge misidentification

- Consequences of charge misidentification:
  - potential loss of signal efficiency
    e.g.: $Z' \rightarrow e^{+}e^{-} \rightarrow e^{+}e^{+}$
    - solved by not requiring opposite charge for the di-lepton system.
  - Charge misID is a major background source in particular for the same-charge dilepton signature. Mostly affects the $H^{++}H^{--}$ search.
- In analyses with a large charge misidentification background, data-driven techniques are used to estimate it. Complexities involved in simulating the process cause a deviation of the MC prediction from the data.
- In the $H^{++}H^{--}$ search, charge misID probabilities are measured both in data and MC. Scale-factors are derived and applied on the MC to compensate for the differences.



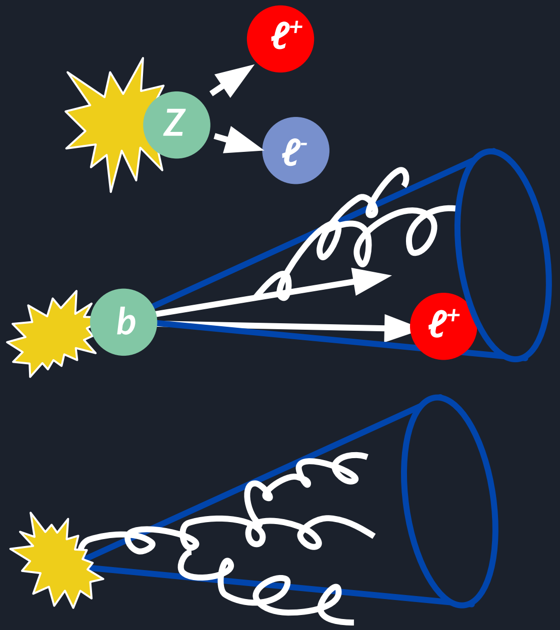
[EXOT-2016-07]

Fake and non-prompt leptons (collectively called "fakes")

prompt: leptons directly produced in the hard interaction ($Z \to \ell\ell$, $W \to \ell\nu$, $t \to \ell\nu b$).
Likely well isolated.

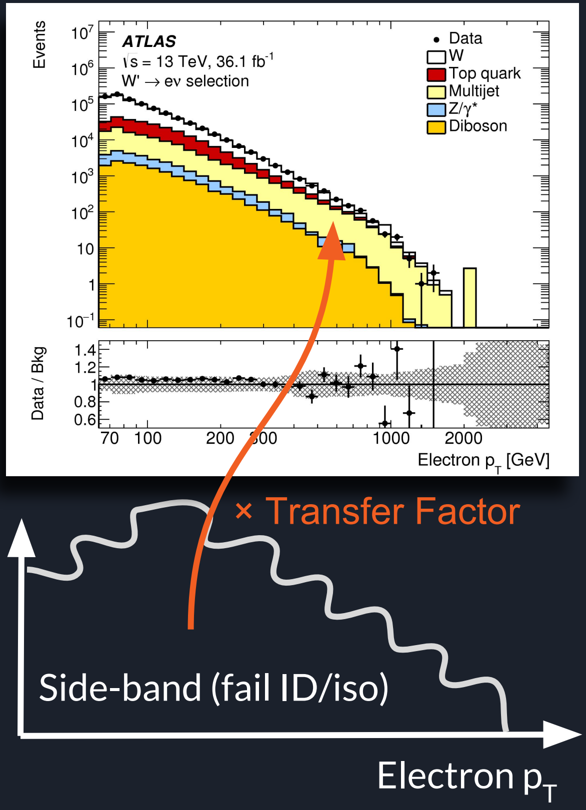
non-prompt: everything else; e.g.:
meson decays, photon conversions (FSR, π^0).
Not well isolated, displaced.

fake: any non-lepton object identified as a lepton by the reconstruction software; e.g.:
light jets (u, d, g initiated).
Not well isolated.



Estimation of the fake background

- The simulation of hadronization (jet production) has large uncertainties.
  - Very commonly, a data-driven approach is used.
- The most evolved data-driven techniques are the “matrix method” and the “fake factor method”.
  - These are mathematically analogous methods with small differences under the hood.
  - **Used in *W’*, *Z’*, and *H*$^{++}$ searches.**
- Side-band regions in data are designed by requiring at least one of the leptons to fail the analysis requirement (identification, isolation, $\sigma(d_0)$).
- Transfer factors, measured from the data are used to predict (extrapolate) the number of fakes in the signal region.



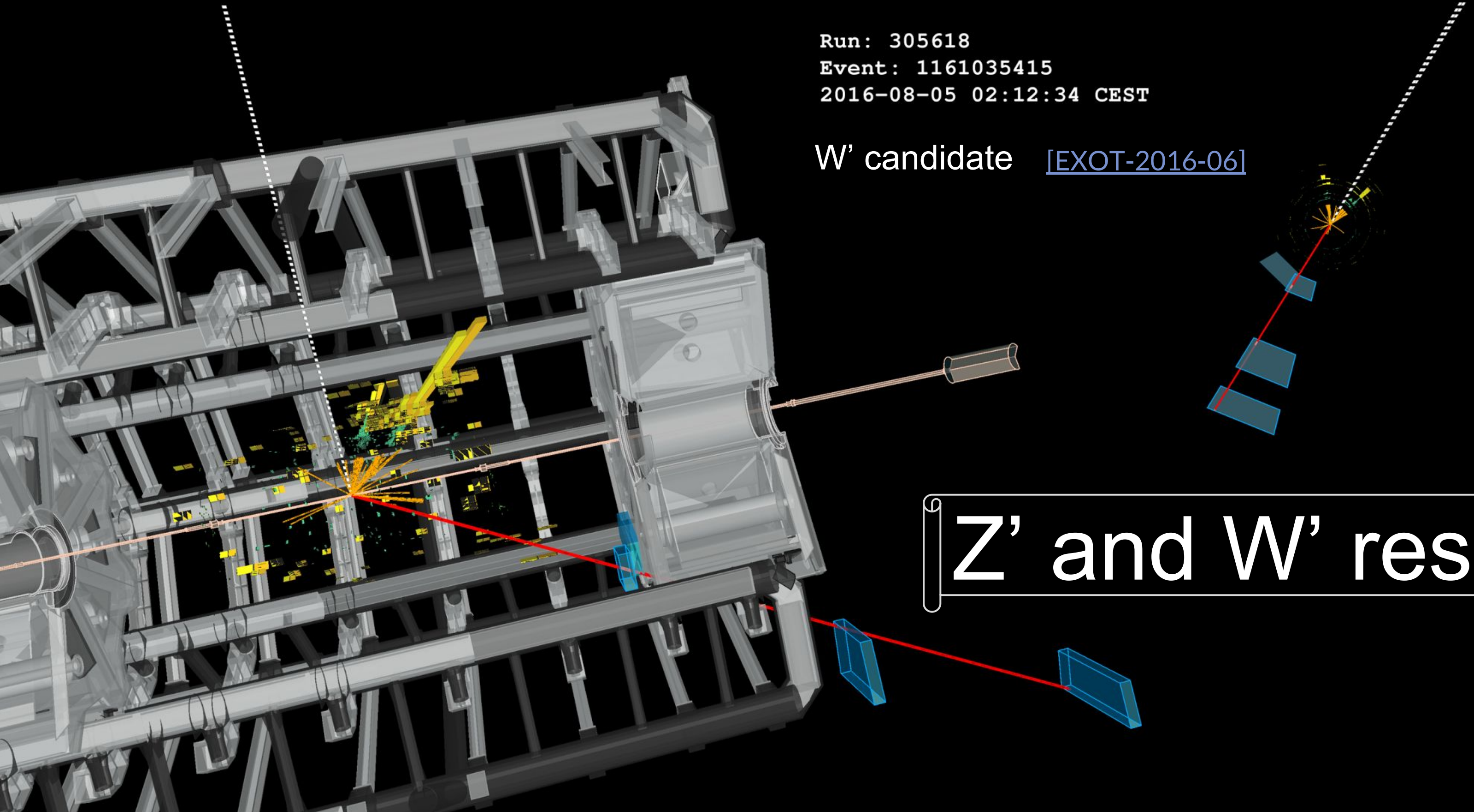
[EXOT-2016-06]

Z’ and W’ results

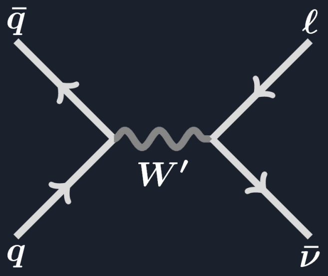
ATLAS
EXPERIMENT

Run: 305618
Event: 1161035415
2016-08-05 02:12:34 CEST

W’ candidate [EXOT-2016-06]



W' in the Sequential Standard Model

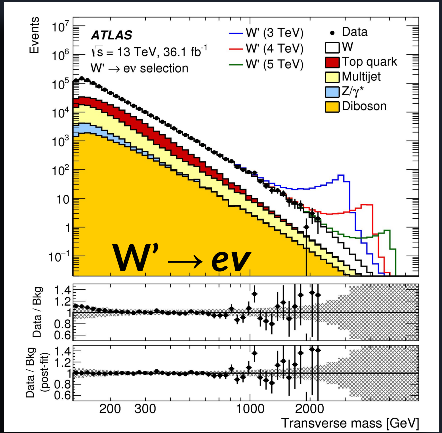


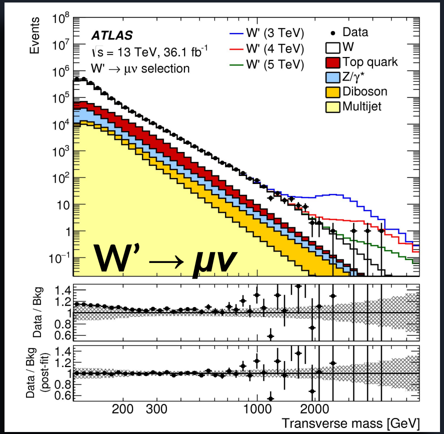
- Events are selected by requiring exactly one high-p_T, isolated lepton and large missing transverse momentum.
- Transverse mass is used as the discriminating variable $m_T = \sqrt{(2 p_T E_T (1 - \cos(\phi_{l\nu})))}$
- Irreducible background estimated with MC and the background due to fake leptons estimated with the Matrix Method.

Dominant SM MC:

Powheg
CT10 PDF
W → eν

k-factors:
NNLO QCD
NLO EWK



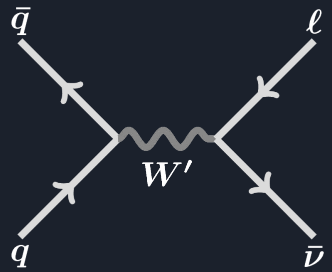


Largest experimental uncertainties In the expected number of SM events at high m_T (~4 TeV):

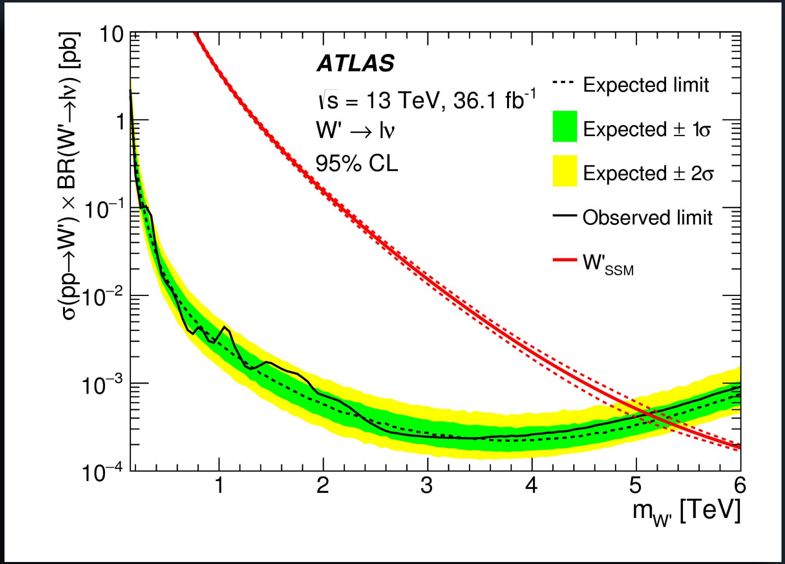
fake electron background (70%)
muon reconstruction (7%)
muon resolution (9%)
electron resolution (3%)

[EXOT-2016-06]

Results of the *W'* search

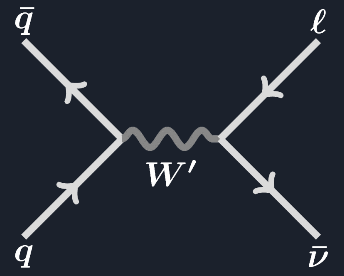


- No significant deviation from the SM in the transverse mass spectrum observed.
- Masses for W'_{SSM} up to 5.1 TeV are excluded at 95% CL.
- The limit is dominated by the electron channel due to a better resolution of lepton energy at high transverse momenta.

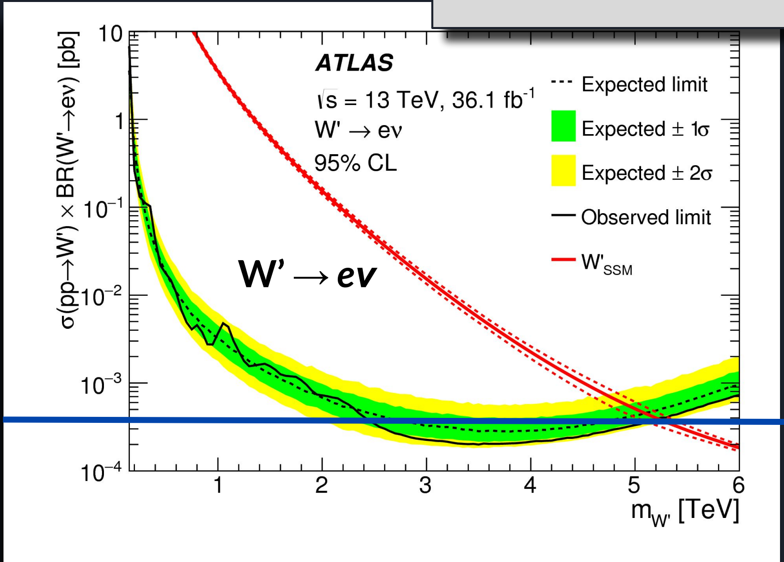


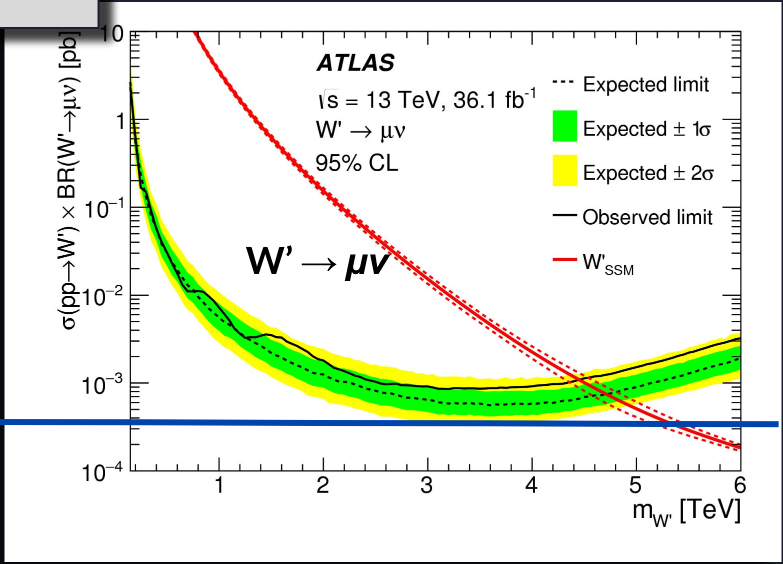
[EXOT-2016-06]

Results of the *W'* search



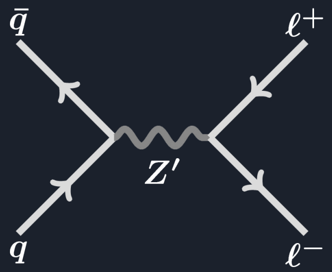
Combined: 5.1 TeV
Electron channel: 5.2 TeV
Muon channel: 4.5 TeV





[EXOT-2016-06]

Z' measurement

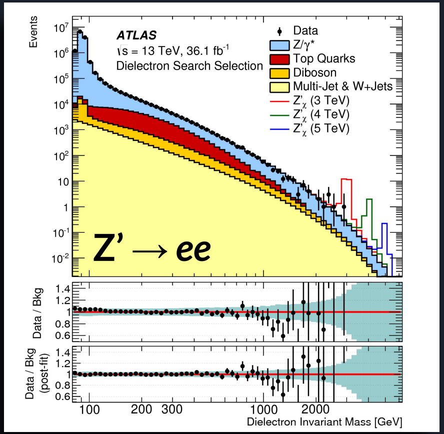


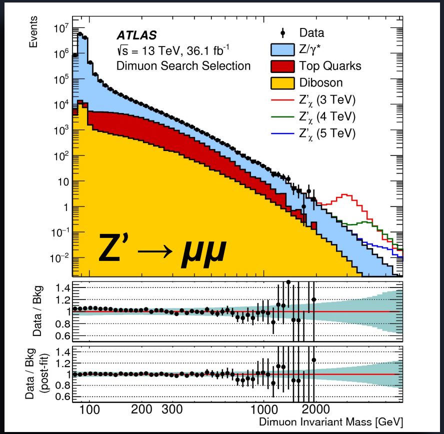
- Events are selected by requiring at least one pair of same-flavour, isolated lepton candidates with p_T > 30 GeV (**no opposite-charge requirement**).
- Invariant mass of the lepton pair is used as the discriminating variable.
- Irreducible background estimated with MC and the background due to fake leptons estimated with the Matrix Method (fakes are negligible in the muon channel).

Dominant SM MC:

Powheg
CT10 PDF
Z → ee

k-factors:
NNLO QCD
NLO EWK



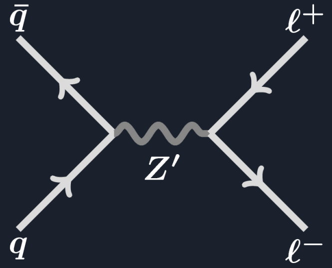


Largest experimental uncertainties
In the expected number of SM
events at high masses (~4 TeV):

fake electron background (130%)
muon reconstruction (17%)
electron isolation (9.7%)
lepton resolution (6%)

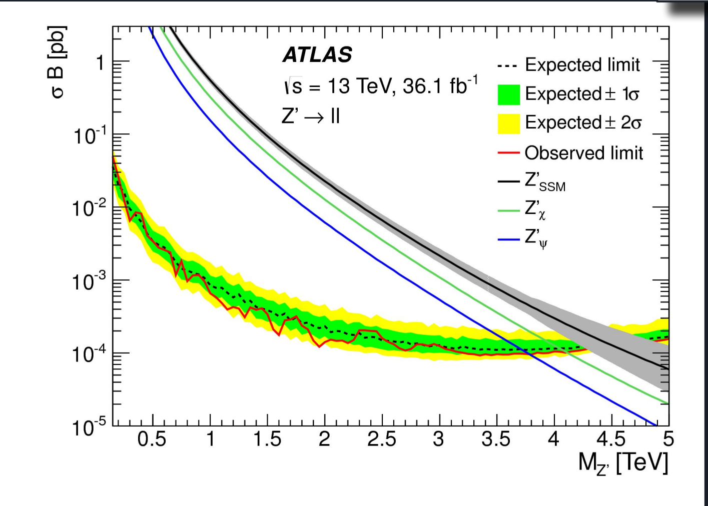
[EXOT-2016-05]

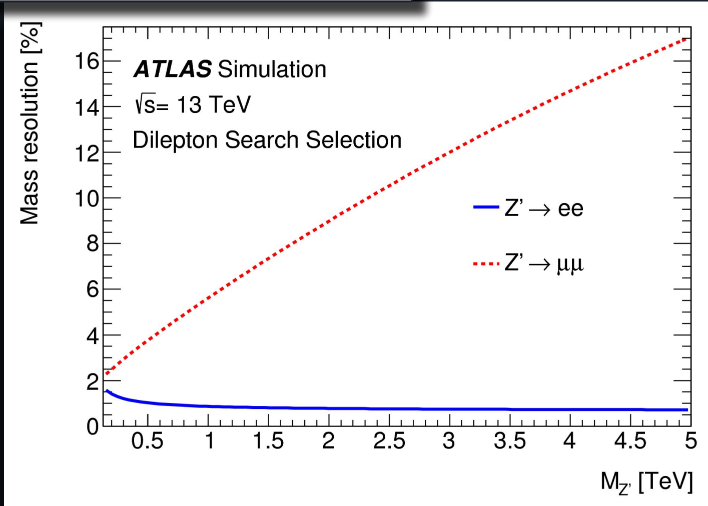
Results of the *Z'* search



- Sequential Standard Model and E_6 GUT: $Z'(\theta_{E6}) = Z'_\psi \cos(\theta_{E6}) + Z'_\chi \sin(\theta_{E6})$
  - *Z'* decay width:
    - *Z'*(SSM) : 3.0% of mass
    - $Z'\psi$: 0.5% of mass
    - $Z'\chi$: 1.2% of mass

SSM Z'
Combined: 4.5 TeV
Electron channel: 4.3 TeV
Muon channel: 4.0 TeV

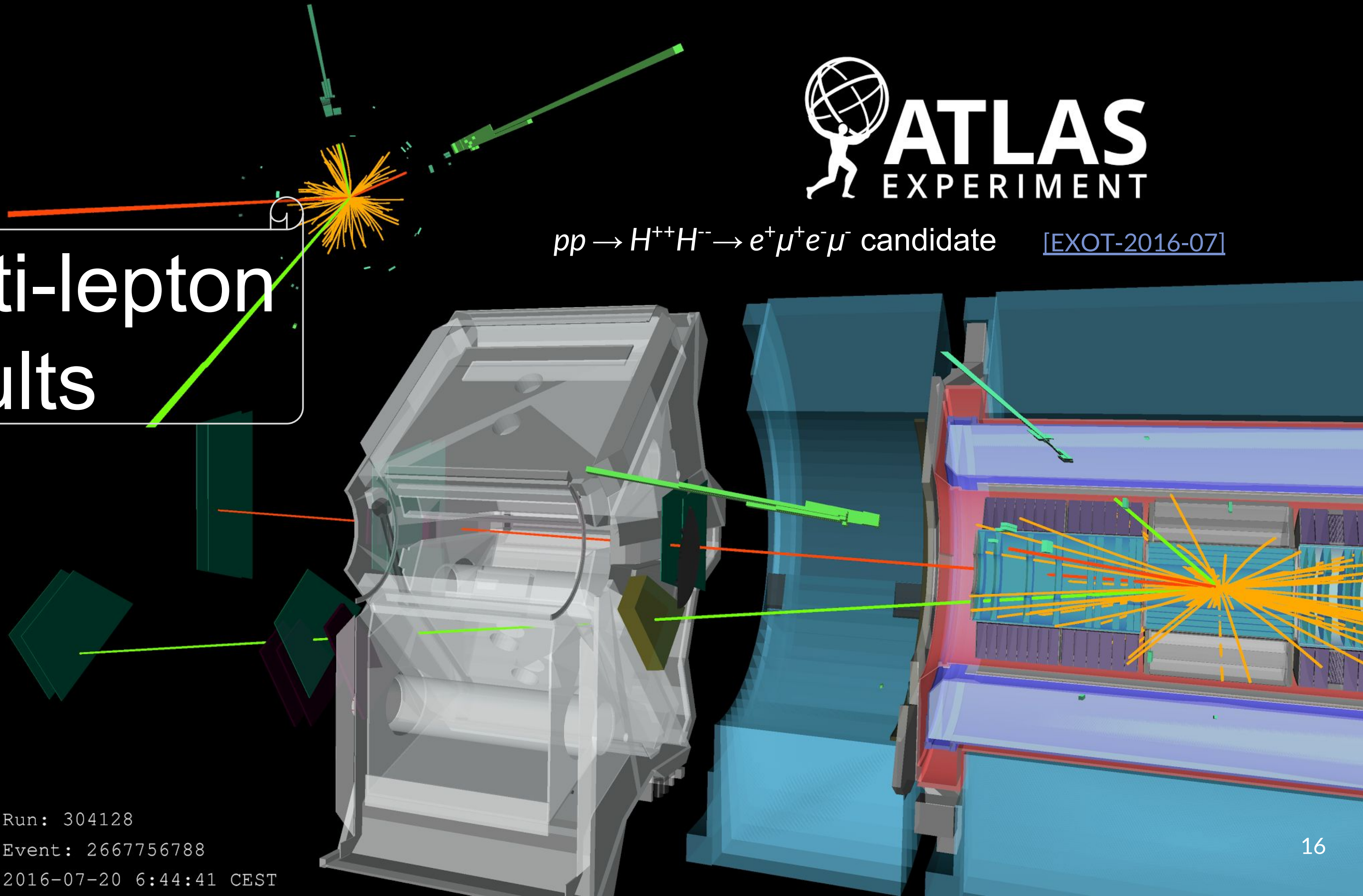




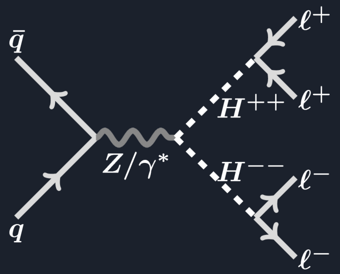
[EXOT-2016-05]

Multi-lepton results

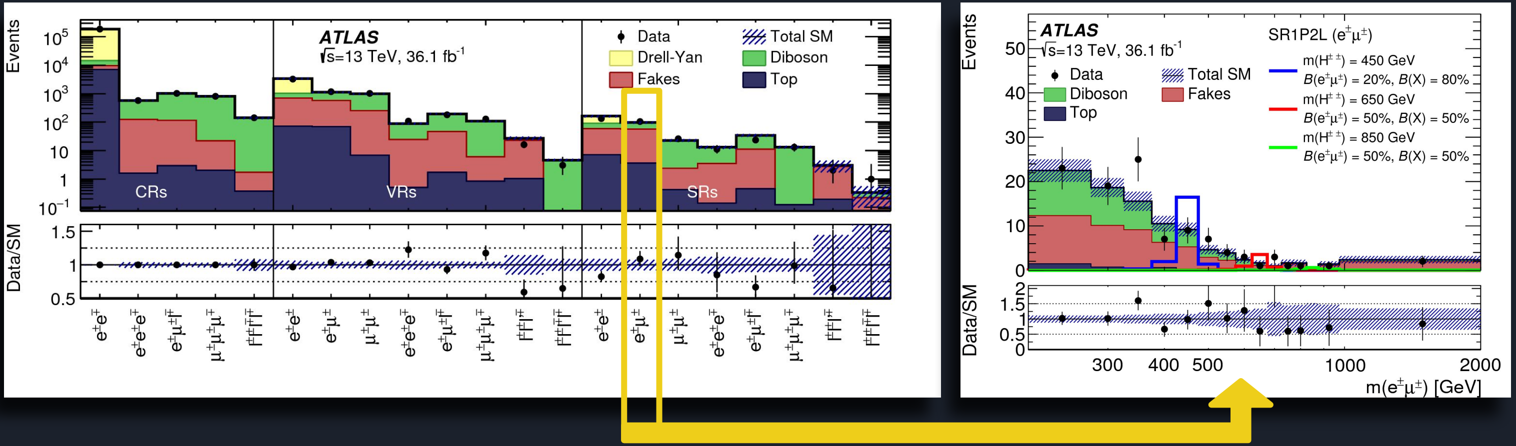
$pp \to H^{++}H^{--} \to e^{+}\mu^{+}e^{-}\mu^{-}$ candidate [EXOT-2016-07]



Doubly Charged Higgs

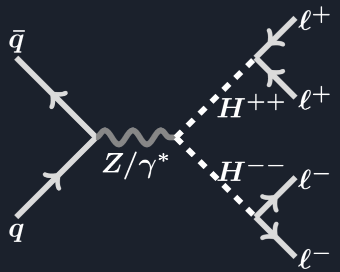


- Dedicated 2, 3, and 4, lepton final states to catch as much as possible signal events in case some signal leptons are not reconstructed.
- The invariant mass of the same-charge lepton pair is fitted in all two and three lepton regions and the average mass is fitted in the four lepton region.
- Dominant experimental uncertainties: fake lepton and charge mis-identification background estimation.



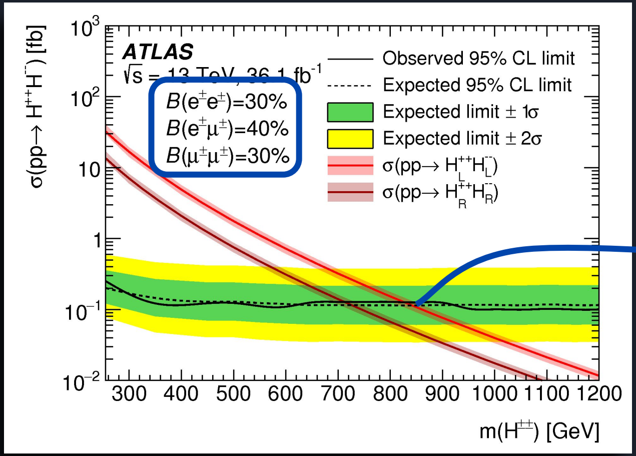
[EXOT-2016-07]

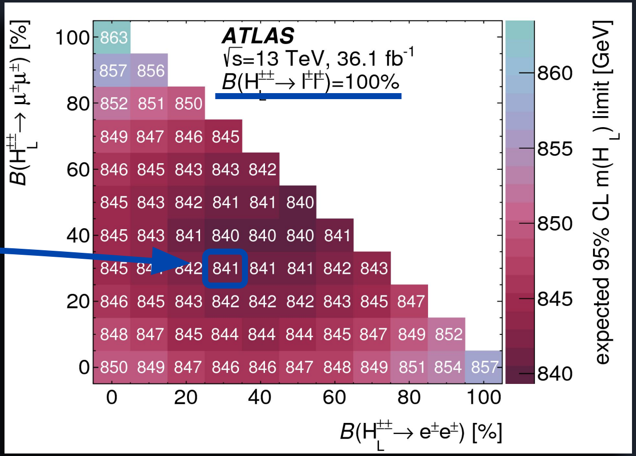
Lower limit on $m(H^{\pm\pm})$ at 95% CL



Free parameters:
$B(H^{\pm\pm} \rightarrow e^{\pm}e^{\pm})$ +
$B(H^{\pm\pm} \rightarrow e^{\pm}\mu^{\pm})$ +
$B(H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}) = B(H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm})$

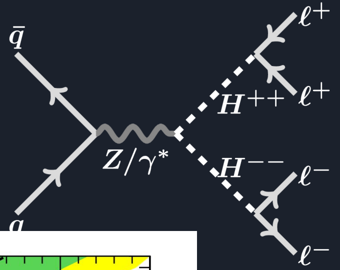
- The mass limit is derived for all combinations of the partial branching ratios.



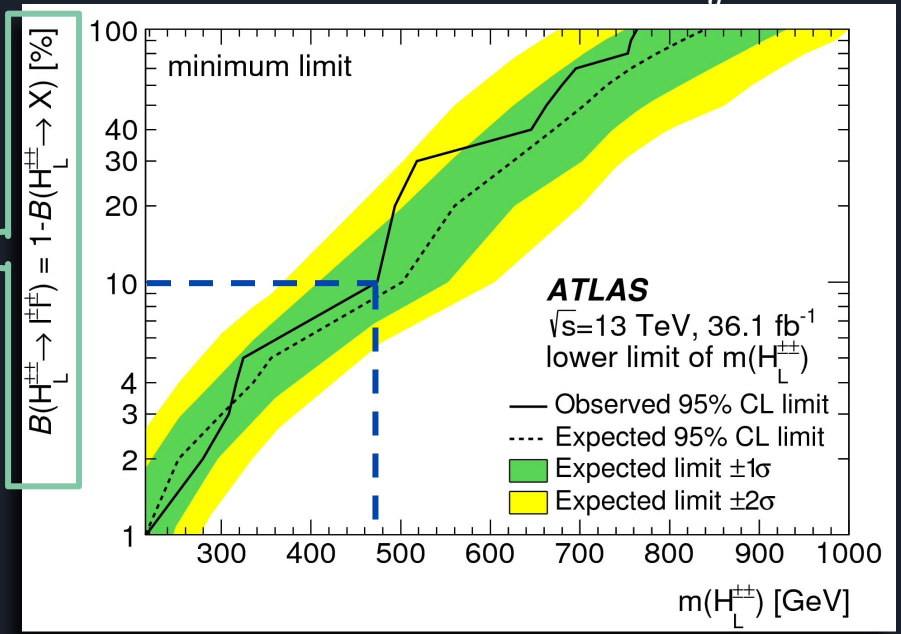


[EXOT-2016-07]

Lower limit on m($H^{\pm\pm}$) at 95% CL



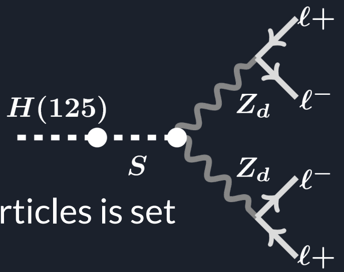
Free parameters:
$B(H^{\pm\pm} \to e^{\pm}e^{\pm})$ +
$B(H^{\pm\pm} \to e^{\pm}\mu^{\pm})$ +
$B(H^{\pm\pm} \to \mu^{\pm}\mu^{\pm})$ +
= $B(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm})$



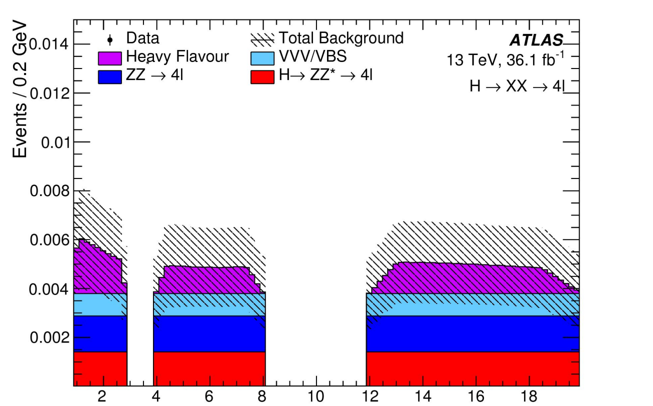
- The muon channel is the most powerful, however, the differences are small.
- The limit can be compactly presented as a function of $B(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm})$.

[EXOT-2016-07]

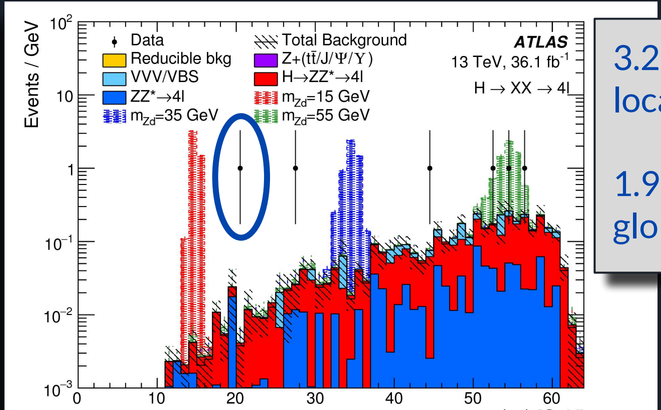
Higgs decays to BSM light bosons



- Motivation: upper bound on the Higgs boson decay branching ratio to BSM particles is set at 0.34 at 95% CL. [1606.02266]
- Analysis is split into three optimized regions targeting different processes:
  - $H(125) \to ZX \to 4\ell$, $2\ell 2e$ and $2\ell 2\mu$
  - $H(125) \to XX \to 4\ell$, 15 GeV < m(X) < 60 GeV, $4e$, $2e2\mu$, and 4μ
  - $H(125) \to XX \to 4\ell$, 1 GeV < m(X) < 15 GeV, 4μ



low-mass selection



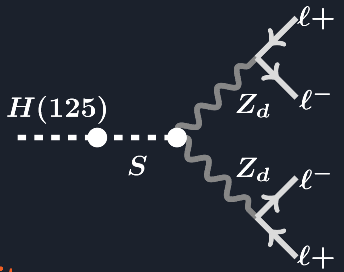
high-mass selection

3.2 σ local p_0

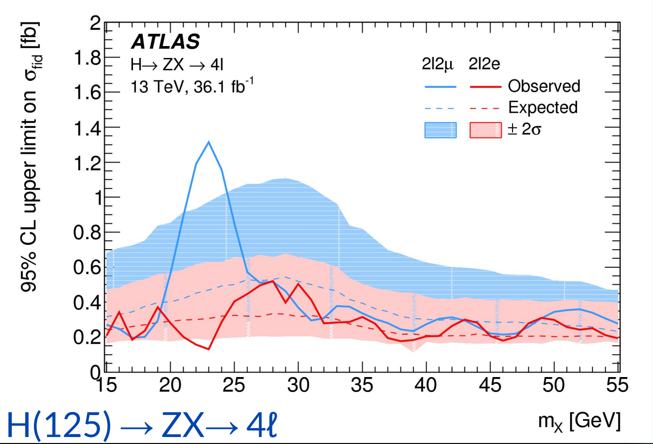
1.9 σ global p_0

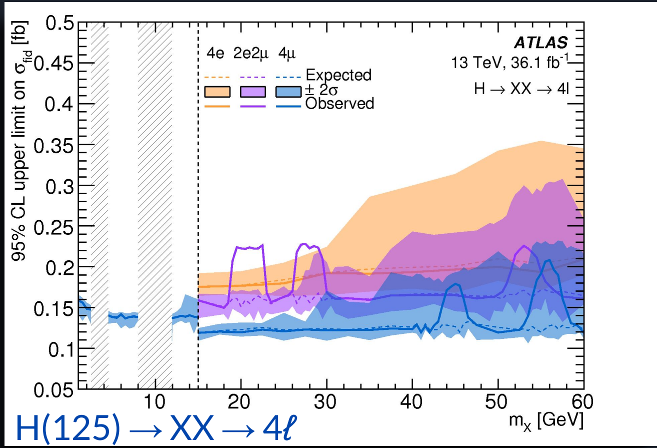
[EXOT-2016-22]

Results of the H → BSM → 4ℓ search



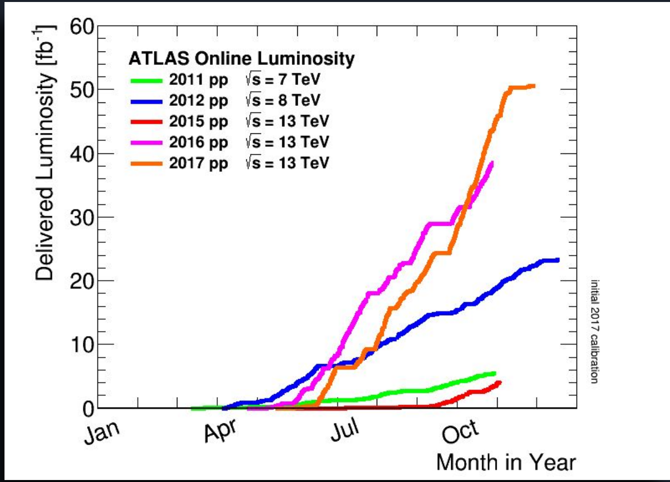
- Fiducial phase-space are defined (see the note) to give model independent limits.
- Derived upper limits are applicable to any models of 125 GeV Higgs-boson decays to four leptons via two intermediate, on-shell, narrow, promptly-decaying bosons.





[EXOT-2016-22]

Summary

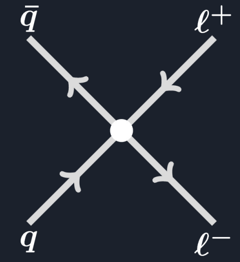


More data coming soon, stay tuned :)

- Final states with leptons are very well understood despite the experimental challenges.
- Presented searches cover energy scales from 1 GeV to a few TeV.
- Final states include both opposite-charge and same-charge lepton pairs in two, three, and four lepton signal regions.
- Numerous BSM models are tested in these regions and the most stringent constraints are set.

Backup

Contact interactions: $qq \rightarrow \ell^+\ell^-$

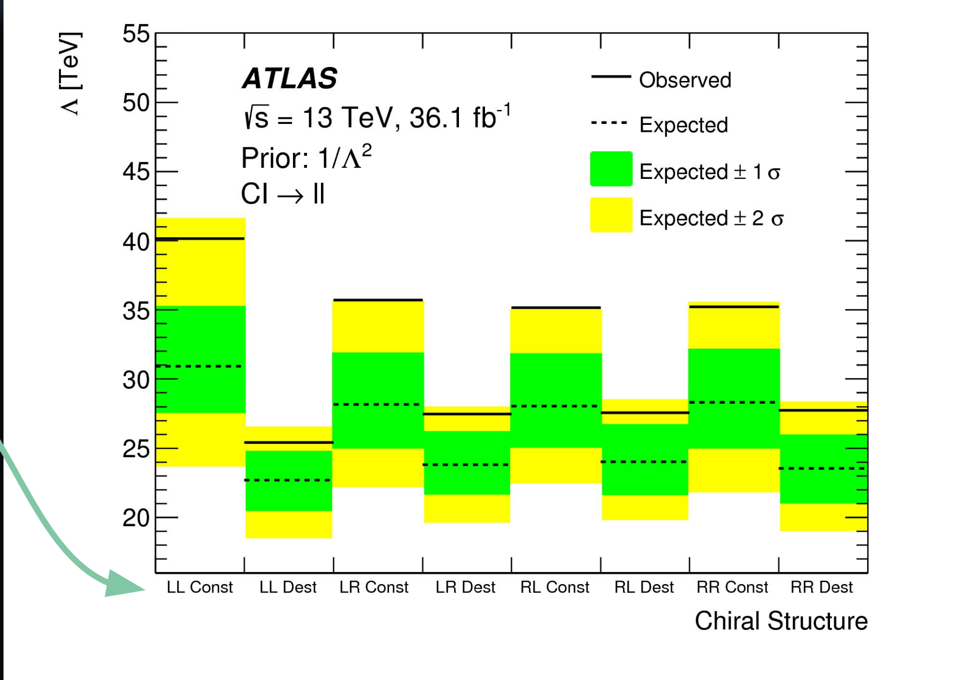


$\mathcal{L} \pm= g^2/\Lambda^2 (q\gamma^\mu q)(\ell\gamma_\mu \ell)$

Quark chirality Lepton chirality

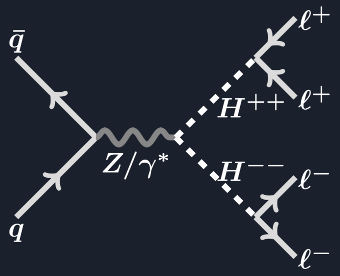
(L|R) (L|R) (Const | Dest)

Constructive (+) or destructive (-) term



[EXOT-2016-05]

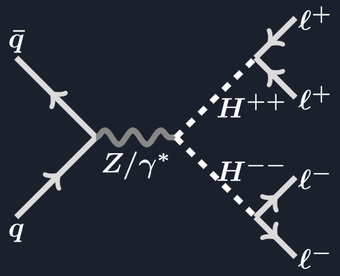
Doubly Charged Higgs
MC samples



Physics process	Event generator	ME PDF set	Cross-section normalisation	Parton shower	Parton shower tune
Signal					
$H^{\pm\pm}$	Pythia 8.186 [34]	NNPDF2.3NLO [35]	NLO (see Table 2)	Pythia 8.186	A14 [36]
Drell–Yan					
$Z/\gamma^* \to ee/\tau\tau$	Powheg-Box v2 [37,38,39]	CT10 [40]	NNLO [41]	Pythia 8.186	AZNLO [42]
Top					
$t\bar{t}$	Powheg-Box v2	NNPDF3.0NLO [43]	NNLO [44]	Pythia 8.186	A14
Single top	Powheg-Box v2	CT10	NLO [45]	Pythia 6.428 [46]	Perugia 2012 [47]
$t\bar{t}W$, $t\bar{t}Z/\gamma^*$	MG5_aMC@NLO 2.2.2 [48]	NNPDF2.3NLO	NLO [49]	Pythia 8.186	A14
$t\bar{t}H$	MG5_aMC@NLO 2.3.2	NNPDF2.3NLO	NLO [49]	Pythia 8.186	A14
Diboson					
ZZ, WZ	Sherpa 2.2.1 [50]	NNPDF3.0NLO	NLO	Sherpa	Sherpa default
Other (inc. $W^\pm W^\pm$)	Sherpa 2.1.1	CT10	NLO	Sherpa	Sherpa default
Diboson Sys.					
ZZ, WZ	Powheg-Box v2	CT10NLO	NLO	Pythia 8.186	AZNLO

[EXOT-2016-07]

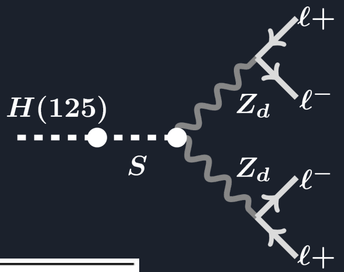
Doubly Charged Higgs
Event selection



Channel \ Region	Control Regions			Validation Regions			Signal Regions		
	OCCR	DBCR	4LCR	SCVR	3LVR	4LVR	1P2L	1P3L	2P4L
Electron channel	$e^\pm e^\mp$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$	
Mixed channel	-	$e^\pm \mu^\pm \ell^\mp$	$\ell^\pm \ell^\pm$ $\ell^\mp \ell^\mp$	$e^\pm \mu^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$\ell^\pm \ell^\pm$ $\ell^\mp \ell^\mp$	$e^\pm \mu^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$\ell^\pm \ell^\pm$ $\ell^\mp \ell^\mp$
Muon channel	-	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$	
$m(e^\pm e^\pm)$ [GeV]	$[130, 2000]$	$[90, 200)$		$[130, 200)$	$[90, 200)$		$[200, \infty)$	$[200, \infty)$	
$m(\ell^\pm \ell^\pm)$ [GeV]	-	$[90, 200)$	$[60, 150)$	$[130, 200)$	$[90, 200)$	$[150, 200)$	$[200, \infty)$	$[200, \infty)$	$[200, \infty)$
$m(\mu^\pm \mu^\pm)$ [GeV]	-	$[60, 200)$		$[60, 200)$	$[60, 200)$		$[200, \infty)$	$[200, \infty)$	
b-jet veto	✓	✓	✓	✓	✓	✓	✓	✓	✓
Z veto	-	inverted	-	-	✓	-	-	✓	✓
$\Delta R(\ell^\pm, \ell^\pm) < 3.5$	-	-	-	-	-	-	✓	✓	-
$p_{\mathrm{T}}(\ell^\pm \ell^\pm) > 100$ GeV	-	-	-	-	-	-	✓	✓	-
$\sum \lvert p_{\mathrm{T}}(\ell) \rvert > 300$ GeV	-	-	-	-	-	-	✓	✓	-
$\Delta M/\bar{M}$ requirement	-	-	-	-	-	-	-	-	✓

[EXOT-2016-07]

Higgs decays to BSM light bosons
Event Selection

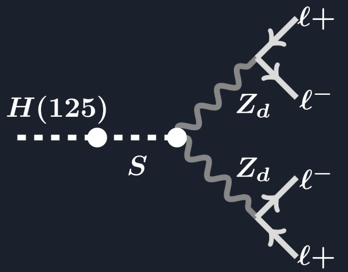


<table>
<tr><th rowspan="2">Object</th><th rowspan="2">$H \to ZZ_d \to 4\ell$</th><th colspan="2">$H \to XX \to 4\ell$</th></tr>
<tr><th>High Mass selection</th><th>Low Mass selection</th></tr>
<tr><td rowspan="3">QUADRUPLET SELECTION</td><td colspan="3">- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons
- Three leading-p_T leptons satisfy $p_T > 20$ GeV, 15 GeV, 10 GeV.
- At least three muons are required to be reconstructed by combining ID and MS tracks in the 4μ channel.</td></tr>
<tr><td rowspan="2">- Select best quadruplet (per channel) to be the one with the (sub)leading dilepton mass (second) closest the Z mass
- Leading di-lepton mass requirement: $50\ GeV < m_{12} < 106\ GeV$

- Sub-leading di-lepton mass requirement: $12\ GeV < m_{34} < 115\ GeV$
- $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same (different) flavour leptons in the quadruplet
- Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} <$ 5 GeV</td><td colspan="2">- Leptons in the quadruplet responsible for firing at least one trigger</td></tr>
<tr><td>- $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same (different) flavour leptons in the quadruplet</td><td></td></tr>
<tr><td>QUADRUPLET RANKING</td><td>- Select quadruplet with the highest expected signal rate, in the order: 4μ, $2e2\mu$, $2\mu2e$, $4e$</td><td colspan="2">- Select quadruplet with smallest $\Delta m_{\ell\ell} = |m_{12} - m_{34}|$</td></tr>
<tr><td rowspan="2">EVENT SELECTION</td><td rowspan="2">- $115\ GeV < m_{4\ell} < 130\ GeV$</td><td colspan="2">- Reject event if:
$(m_{J/\Psi} - 0.25\ GeV) < m_{12,34,14,23} < (m_{\Psi(2S)} + 0.30\ GeV)$
$(m_{\Upsilon(1S)} - 0.70\ GeV) < m_{12,34,14,23} < (m_{\Upsilon(3S)} + 0.75\ GeV)$
- $m_{34}/m_{12} > 0.85$</td></tr>
<tr><td>- $115\ GeV < m_{4\ell} < 130\ GeV$
- $10\ GeV < m_{12,34} < 64$ GeV
- $5\ GeV < m_{14,32} < 75$ GeV for $4e$ and 4μ channels</td><td>- $120\ GeV < m_{4\ell} < 130\ GeV$
- $0.88\ GeV < m_{12,34} < 15$ GeV
- No restriction on alternative pairing</td></tr>
</table>

[EXOT-2016-22]

Higgs decays to BSM light bosons
Fiducial definitions



	$H \to XX \to 4\ell$		$H \to ZZ_d \to 4\ell$
Object	**High Mass Fiducial** **(for** $15\ GeV < m_X < 60\ GeV$**)**	**Low Mass Fiducial** **(for** $1\ GeV < m_X < 15\ GeV$**)**	**High Mass Fiducial** **(for** $15\ GeV < m_{Z_d} < 55\ GeV$**)**
Electrons	Dressed with prompt photons within $\Delta R = 0.1$ $p_T > 7\ GeV$ $\lvert\eta\rvert < 2.5$		
Muons	Dressed with prompt photons within $\Delta R = 0.1$ $p_T > 5\ GeV$ $\lvert\eta\rvert < 2.7$		
Quadruplet	Three leading-p_T leptons satisfy $p_T > 20$ GeV, 15 GeV, 10 GeV		
	Reject event if either of: $(m_{J/\psi} - 0.25\ GeV) < m_{12,34,14,23} < (m_{\psi(2S)} + 0.30\ GeV)$ $(m_{\Upsilon(1S)} - 0.70\ GeV) < m_{12,34,14,23} < (m_{\Upsilon(3S)} + 0.75\ GeV)$		$50\ GeV < m_{12} < 106$ GeV $12\ GeV < m_{34} < 115$ GeV $\Delta R > 0.1$ (0.2) between SF (OF) leptons $m_{12,34,14,23} > 5$ GeV $115\ GeV < m_{4\ell} < 130$ GeV
	$m_{34}/m_{12} > 0.85$		
	$10\ GeV < m_{12,34} < 64$ GeV $\Delta R > 0.1$ (0.2) between SF (DF) leptons $5\ GeV < m_{32,14} < 75\ GeV$ if $4e$ or 4μ	$0.88\ GeV < m_{12,34} < 20\ GeV$	

[EXOT-2016-22]