technische universität
dortmund

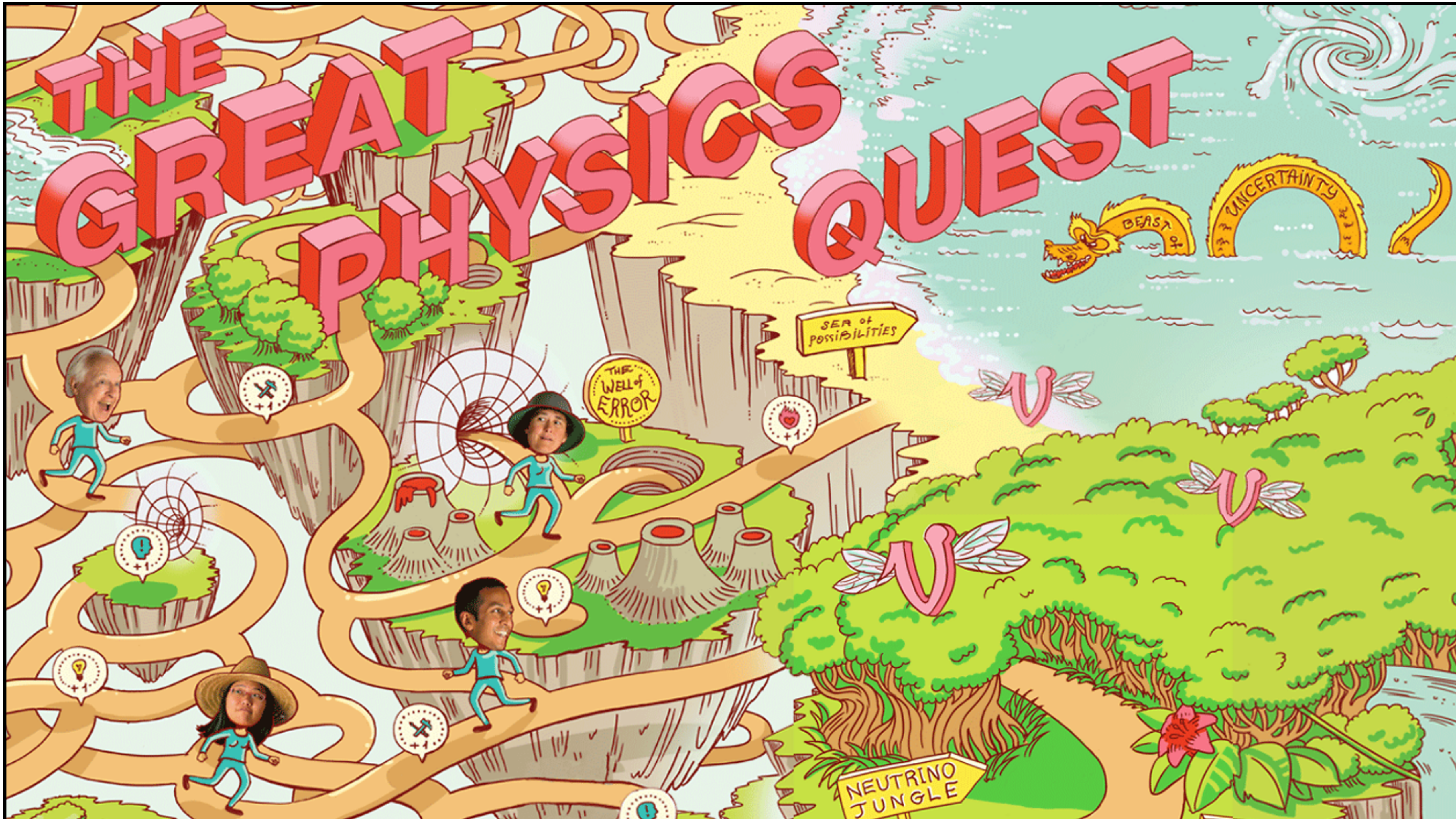
“Search for doubly charged Higgs bosons with the ATLAS detector”

Giulia Ucchielli
on behalf of the ATLAS Collaboration

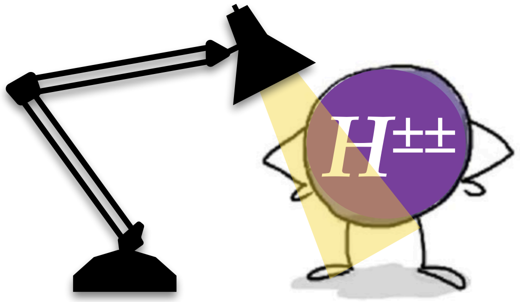
Charged 2018, Uppsala 27/09/2018

Outline:

- *why doubly charged Higgs bosons?*
- *searches for doubly charged Higgs bosons in ATLAS @ 13 TeV*



Theory:



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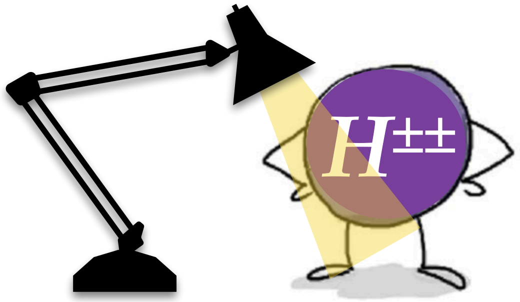

- Left-Right symmetric models (LRSM) [1]

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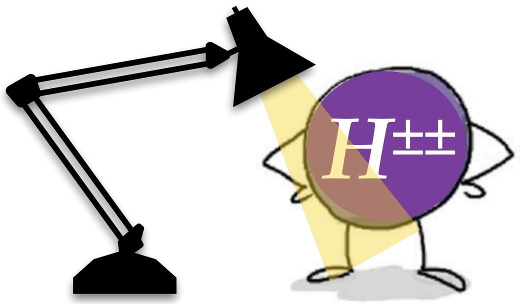

- Left-Right symmetric models (LRSM) [1]
- Higgs triplets (HTM) [2,3]

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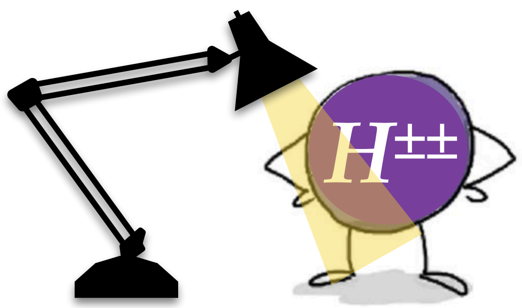

- Left-Right symmetric models (LRSM) [1]
- Higgs triplets (HTM) [2,3]
- Zee-Babu models [4,5]

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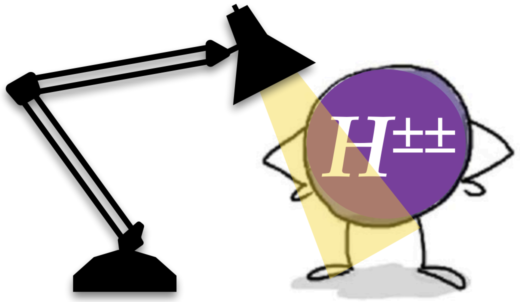

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- Georgi–Machacek [6]

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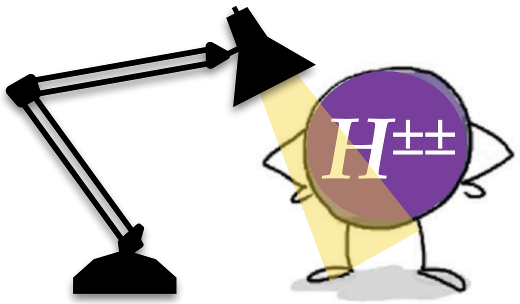

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Why?

✤ ***Restoring parity symmetry in weak interactions*** at higher energy (LRSM)

✤ ***Explain light neutrino masses*** through Type I/II See-Saw mechanism

↪ *Phenomenology: new particle* $\boldsymbol{H^{\pm\pm}}$

left and right-handed in LRSM or letf-handed only in Higgs triplets

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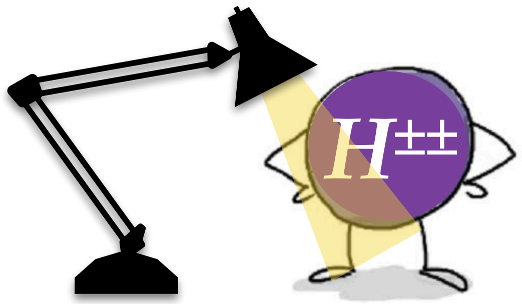

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✤ *Explain light neutrino masses* through Type I/II See-Saw mechanism

↪ *Phenomenology: new particle* ***H***$^{\pm\pm}$

left and right-handed in LRSM or letf-handed only in Higgs triplets

✤ Both L and R triplets acquire a ***v.e.v*** **≠ 0**, constraint by precise measurements of *W* and *Z* boson masses:

$$\rho = \frac{M^2_{W_L}}{\cos^2\theta_W M^2_Z} \sim \frac{1+2v_L^2/v^2}{1+4v_L^2/v^2}$$

➔ if ϱ = 1.0004 ±0.003 ➜ **v_L < 1 GeV**

✤ In LRSM, three possible choices for *v.e.v*:

- ✤ **$v_L = v_R$** ➜ unwanted because we need to break the symmetry ✘
- ✤ **$v_L \sim 0$** ➜ wanted to preserve ϱ =1: ✔
- ✤ **$v_R = 0$** ➜ discarded because of the two above ✘

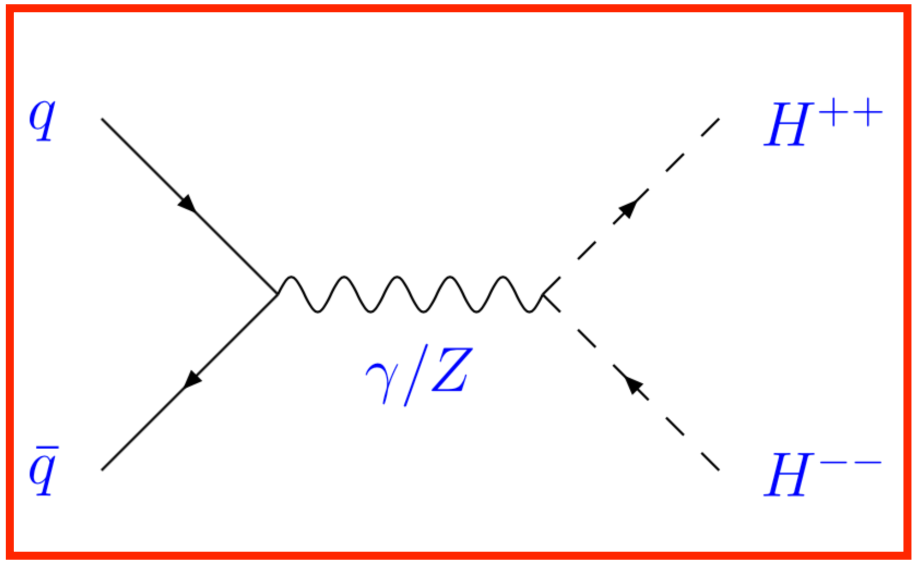
$$v_L \propto \frac{v^2}{v_R}$$

➜ **$v_R \sim$ TeV**

$H^{\pm\pm}$ production and decay:

Production..

Main production at LHC



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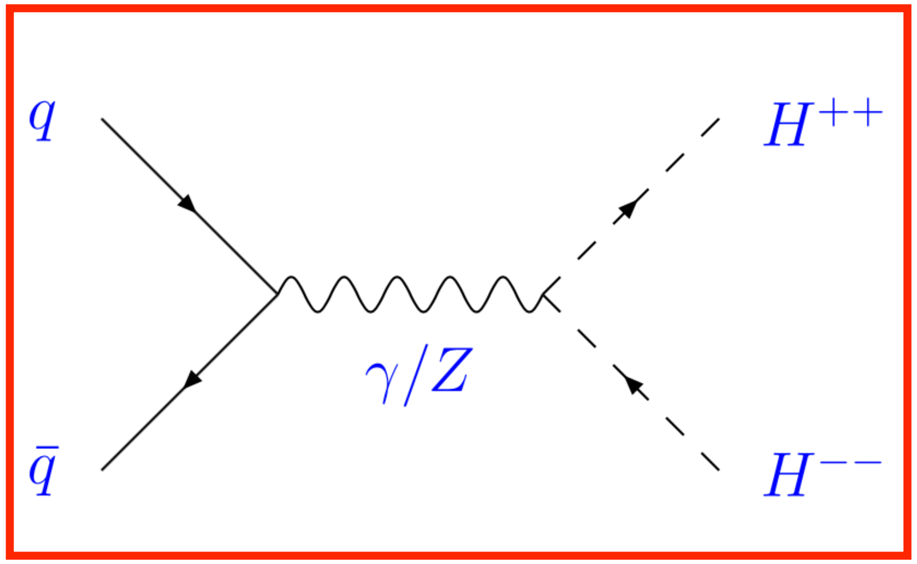
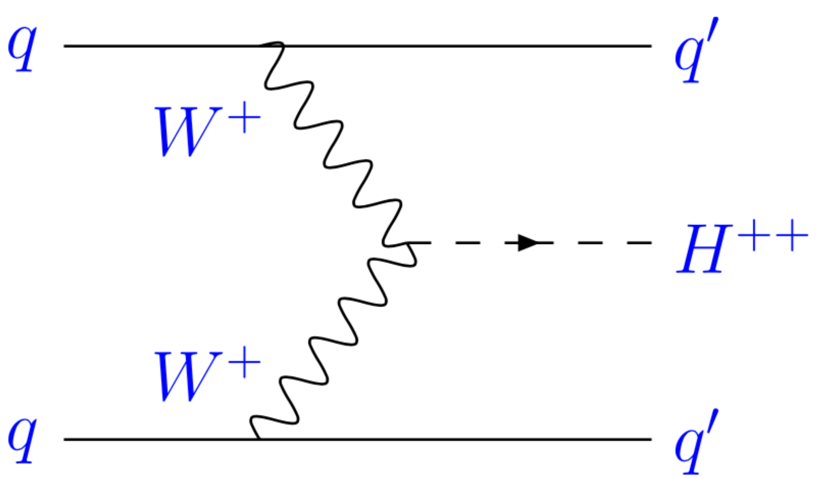


Proportional to *v.e.v*: negligible



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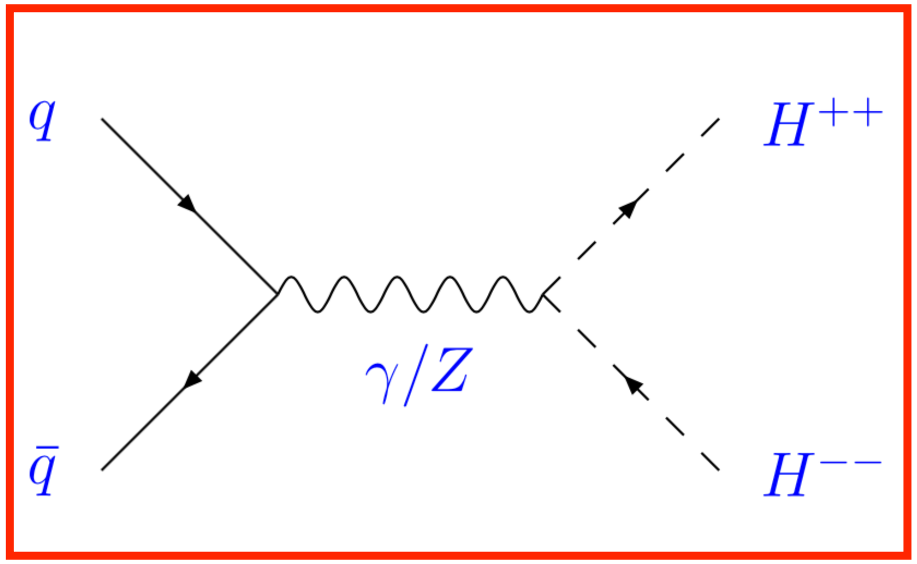

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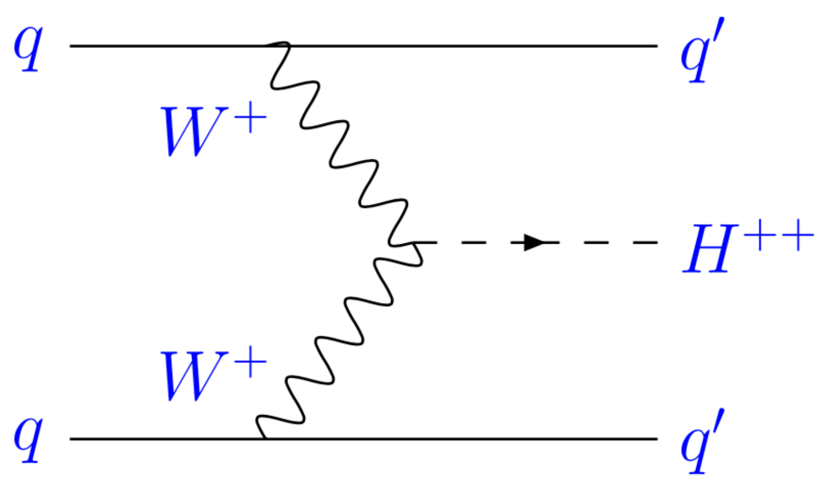
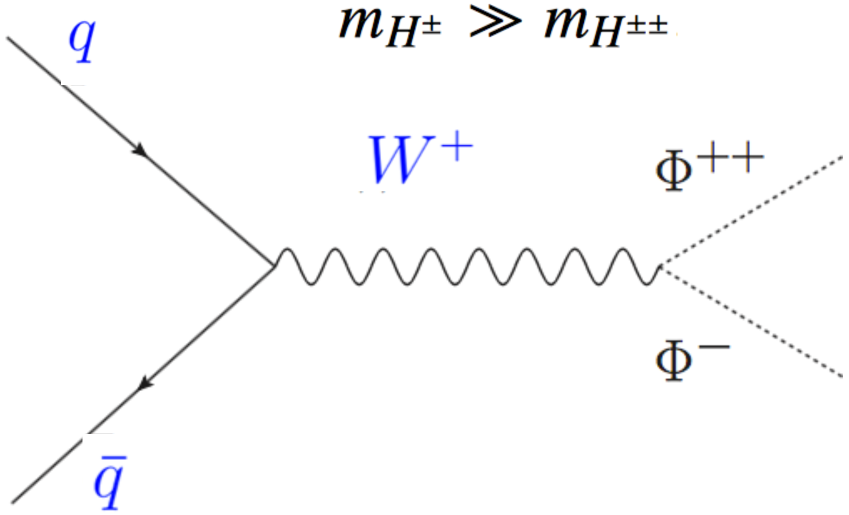


Suppressed in the scenario:

$m_{H^{\pm}} \gg m_{H^{\pm\pm}}$



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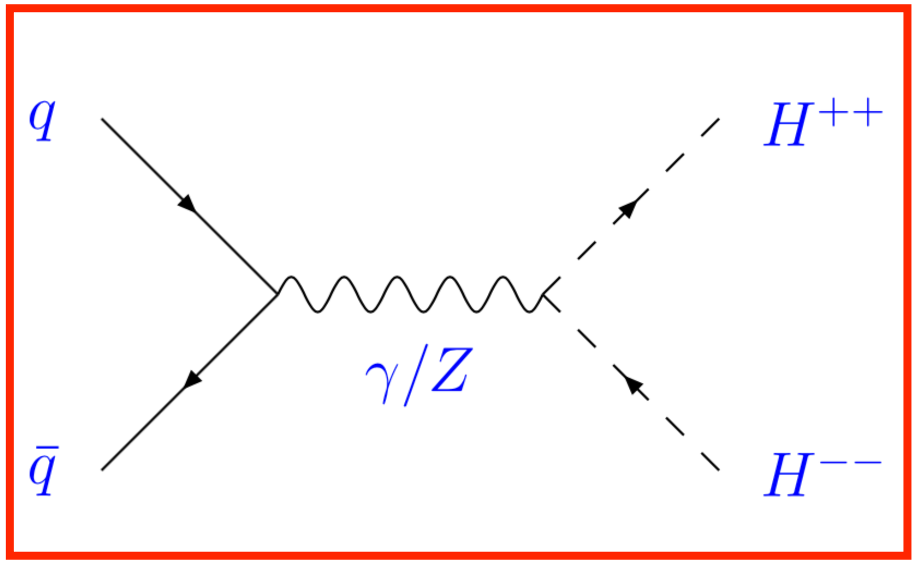

- dominant in LRSM and HTM
- only production mode considered here and in ATLAS searches @ 7 TeV [Eur.Phys.J. C72 (2012) 2244] and @ 8 TeV [JHEP 03 (2015) 041]

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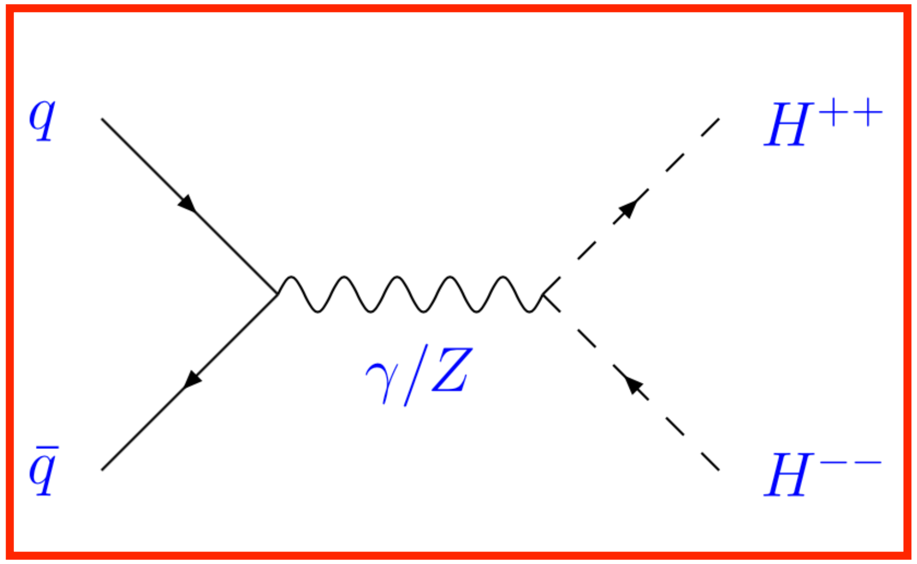

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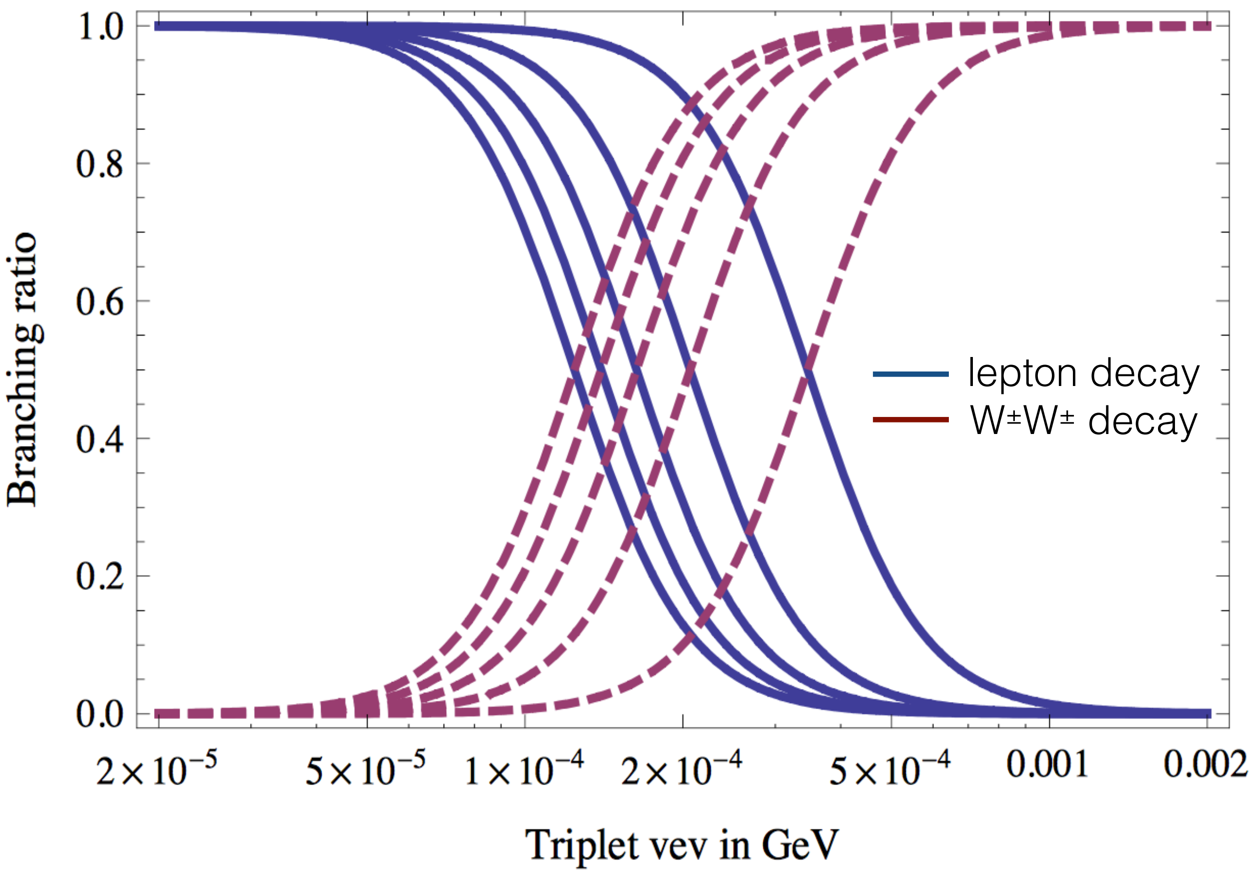


To leptons:

$$\Gamma(H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}) = \frac{(1+\delta_{OF})}{16\pi} h^2_{\ell\ell'} m(H^{\pm\pm})$$

- Coupling to leptons not determined by lepton mass
- **Lepton number violating** decays are **allowed**.

To bosons:

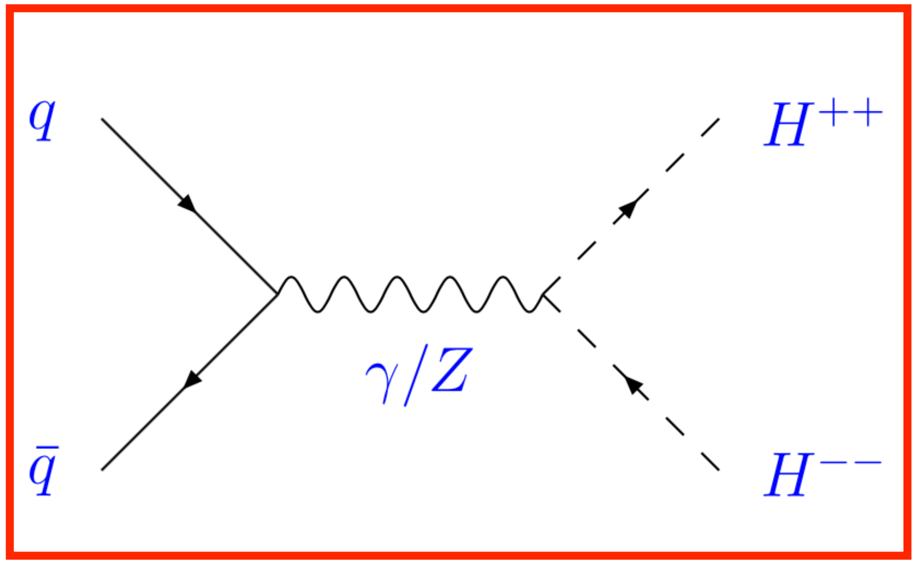
$$\Gamma(H^{\pm\pm} \to W^{\pm}W^{\pm}) = \frac{g^4 v_t^2}{32\pi} \times f(m_{H^{\pm\pm}}, m_W)$$

- Depends on *v.e.v* parameter
- Dominant mode for *v.e.v* >0.1 MeV

$H^{\pm\pm}$ production and decay:

Production..

Main production at LHC



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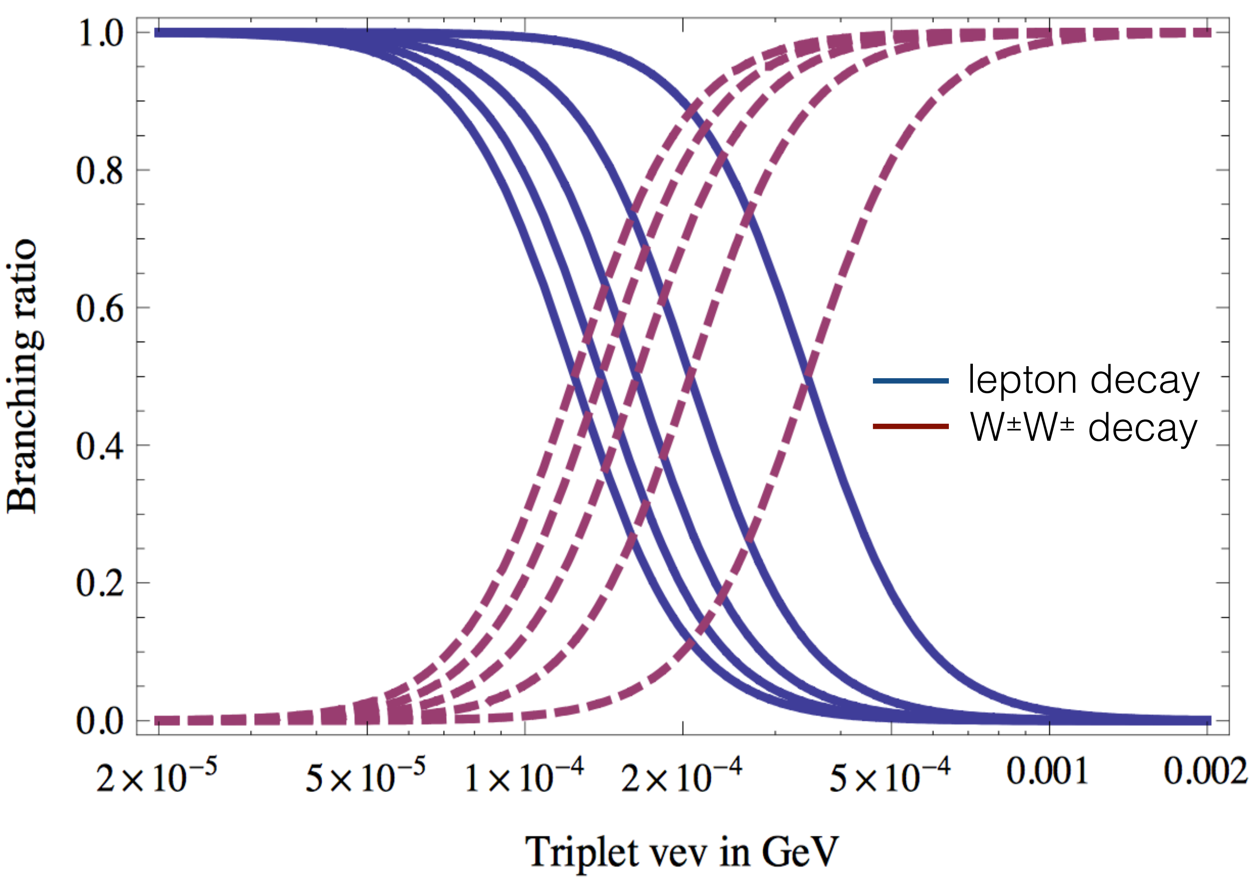

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- Coupling to leptons not determined by lepton mass
- **Lepton number violating** decays are **allowed**.

- only **light leptons (e,μ)**, either from $H^{\pm\pm}$ or from $W^{\pm}W^{\pm}$ decays, considered here

To bosons:

$$\Gamma(H^{\pm\pm} \to W^{\pm}W^{\pm}) = \frac{g^4 v_t^2}{32\pi} \times f(m_{H^{\pm\pm}}, m_W)$$

- Depends on *v.e.v* parameter
- Dominant mode for *v.e.v* >0.1 MeV

$H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ - analysis signal regions:

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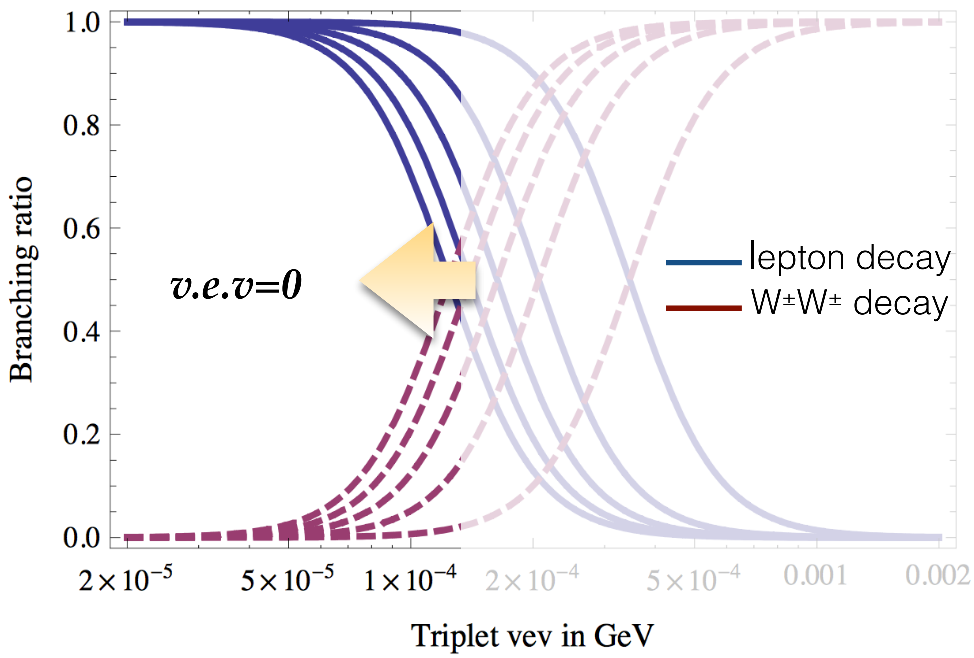

P: #pair
L: #leptons

Channel \ Region	Signal Regions 1P2L	1P3L	2P4L
Electron channel	$e^{\pm}e^{\pm}$	$e^{\pm}e^{\pm}e^{\mp}$	
Mixed channel	$e^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell'^{\mp}$	$\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$
Muon channel	$\mu^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$	
$m(e^{\pm}e^{\pm})$ [GeV]	$[200, \infty)$	$[200, \infty)$	
$m(\ell^{\pm}\ell^{\pm})$ [GeV]	$[200, \infty)$	$[200, \infty)$	$[200, \infty)$
$m(\mu^{\pm}\mu^{\pm})$ [GeV]	$[200, \infty)$	$[200, \infty)$	
b-jet veto	✓	✓	✓
Z veto	-	✓	✓
$\Delta R(\ell^{\pm}, \ell^{\pm}) < 3.5$	✓	✓	-
$p_{\mathrm{T}}(\ell^{\pm}\ell^{\pm}) > 100$ GeV	✓	✓	-
$\sum \lvert p_{\mathrm{T}}(\ell) \rvert > 300$ GeV	✓	✓	-
$\Delta M/\bar{M}$ requirement	-	-	✓
A x ε	9.1%		

- *clean signature:* 2,3,4 light leptons
- masses *200-1300 GeV*
- no explicit requirement on jet multiplicity

Signal region optimization based on signal topology:

- same-sign leptons with ΔR (< 3.5)
- *high transverse momentum of the same-sign pair* (>100 GeV)
- mass equality in a pair (ΔM/M)

- Major backgrounds:
  electron charge misidentification, *VV* production, misreconstructed objects *faking* prompt leptons

$H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ - analysis signal regions:

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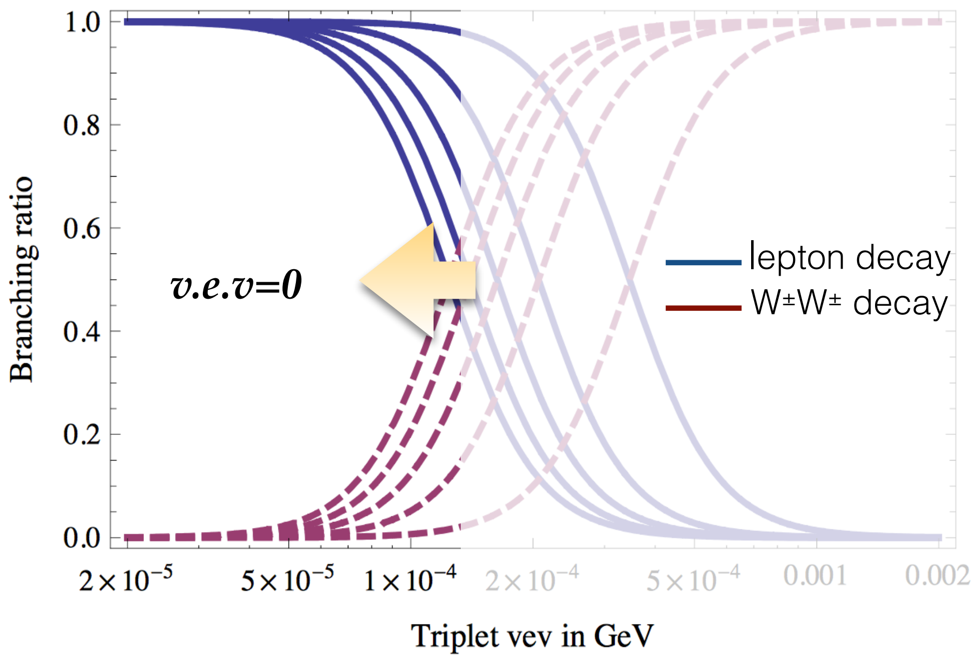

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$\sum \lvert p_{\mathrm{T}}(\ell) \rvert > 300$ GeV	✓	✓	-
$\Delta M/\bar{M}$ requirement	-	-	✓
A x ε	9.1%	33.7%	

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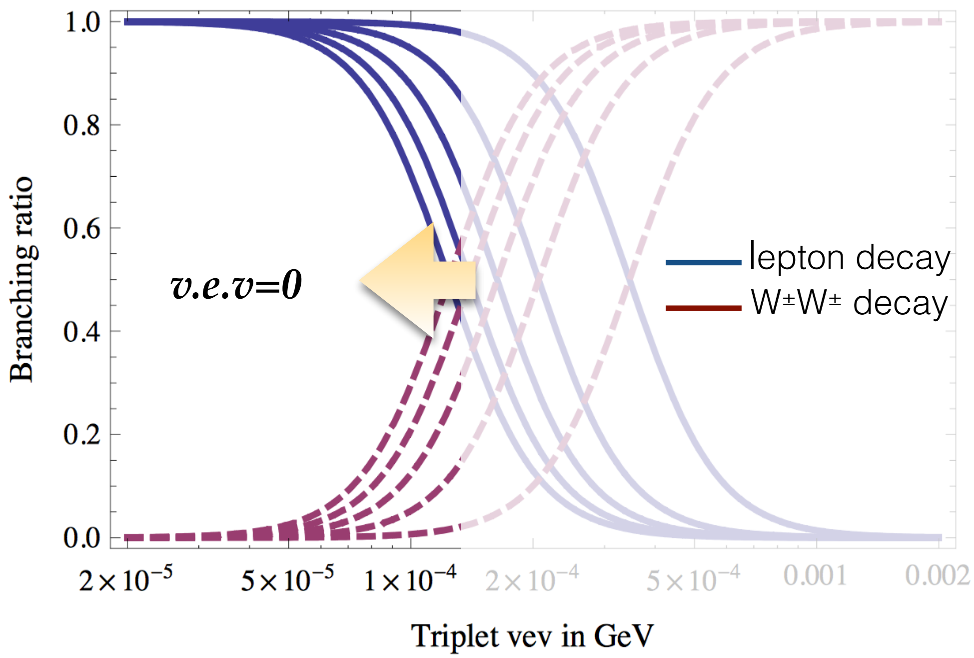

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$p_{\mathrm{T}}(\ell^{\pm}\ell^{\pm}) > 100$ GeV	✓	✓	-
$\sum \lvert p_{\mathrm{T}}(\ell) \rvert > 300$ GeV	✓	✓	-
$\Delta M/\bar{M}$ requirement	-	-	✓
A x ε	9.1%	33.7%	57.2%

- *clean signature:* 2,3,4 light leptons
- masses *200-1300 GeV*
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Signal region optimization based on signal topology:

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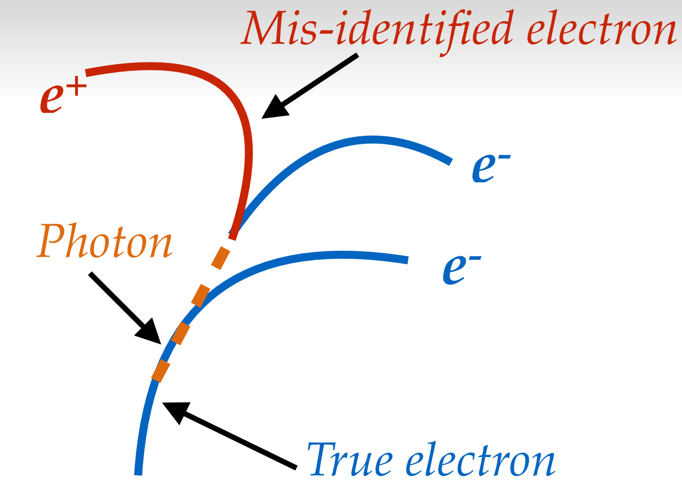
$H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ - electron charge misidentification:



Mainly due to:

- *bremsstrahlung:* $e^{\pm} \rightarrow e^{\pm}\gamma \rightarrow e^{\pm}e^{\pm}e^{\mp}$: wrong calo-track matching
- *stiff tracks:* high-p_T electrons less bent by magnetic field

Muon charge mis-ID negligible (<1%) up to p_T~ 4 TeV

Data-driven method in Z peak:

Select $Z \rightarrow ee$ events with:

- $|m_{SC(ee)} - m_Z| < 15.8$ GeV
- $|m_{OC(ee)} - m_Z| < 14$ GeV

and two sideband regions:

- $15.8 \text{ GeV} < |m_{SC(ee)} - m_Z| < 31.6$ GeV
- $14 \text{ GeV} < |m_{SC(ee)} - m_Z| < 18$ GeV

$$\lambda = N^{ij}(P_i(1-P_j) + P_j(1-P_i))$$

$$f(N_{SS}^{ij};\lambda) = \frac{\lambda^{N_{SS}^{ij}} e^{-\lambda}}{N_{SS}^{ij}!}$$

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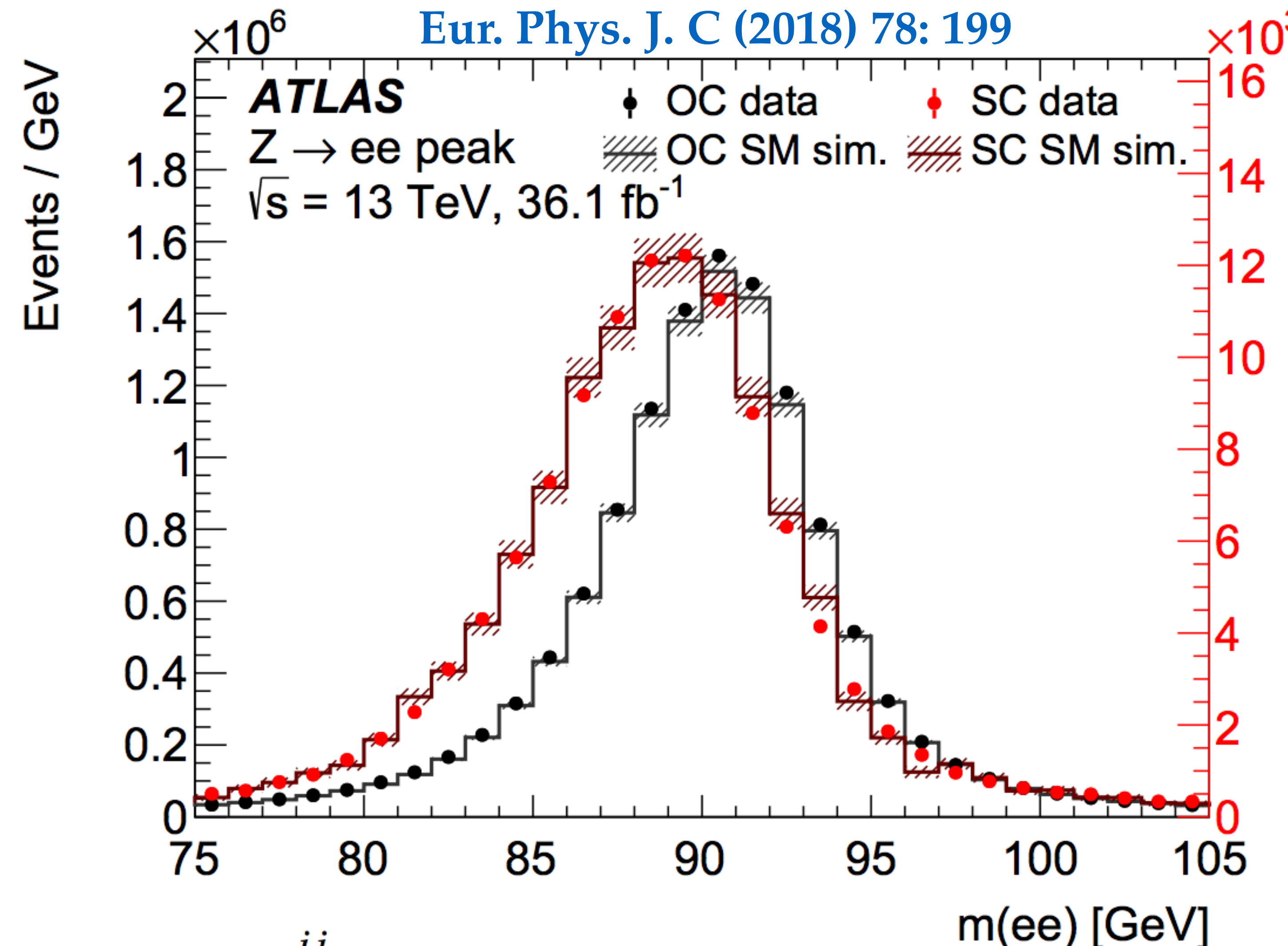
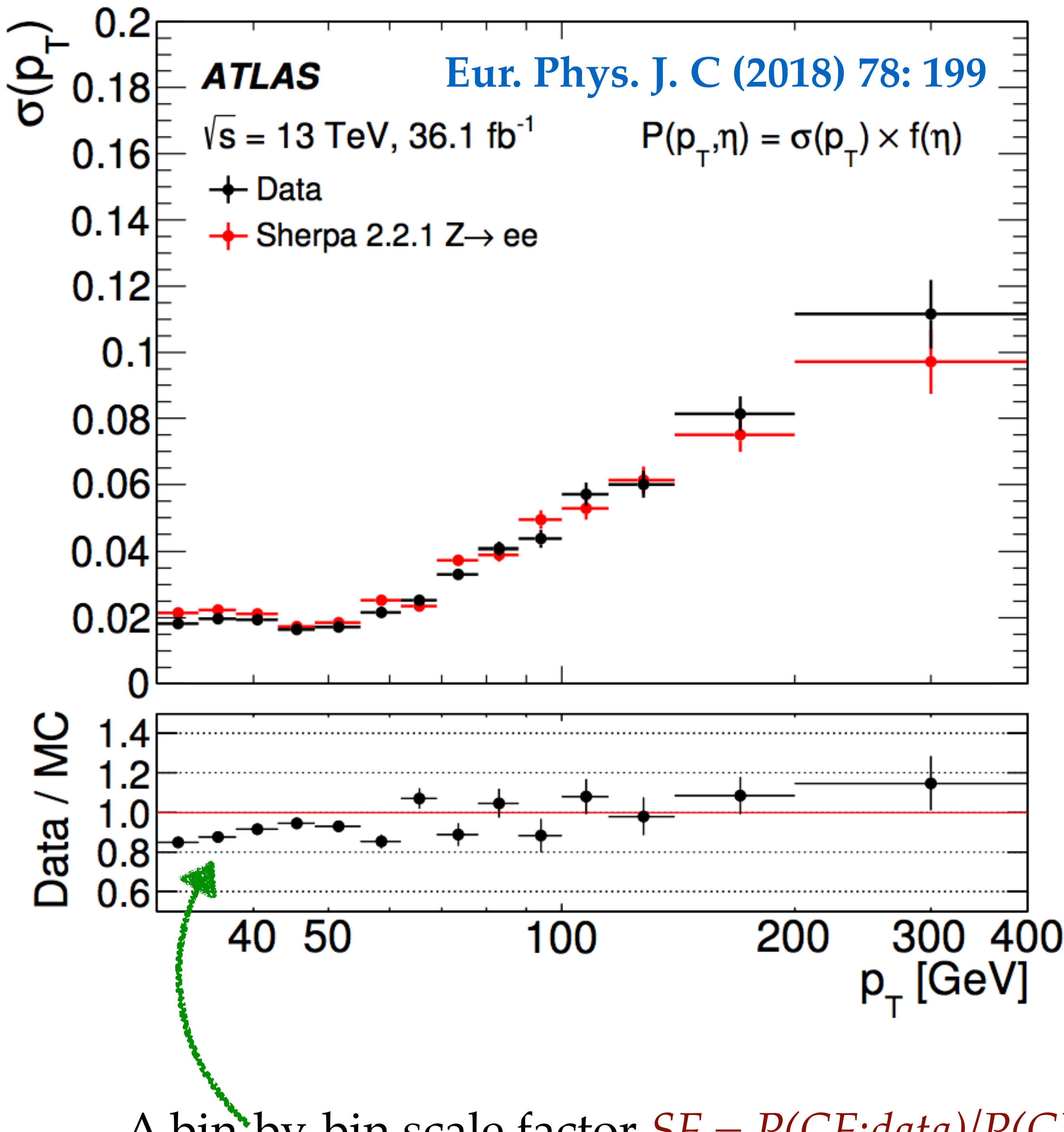


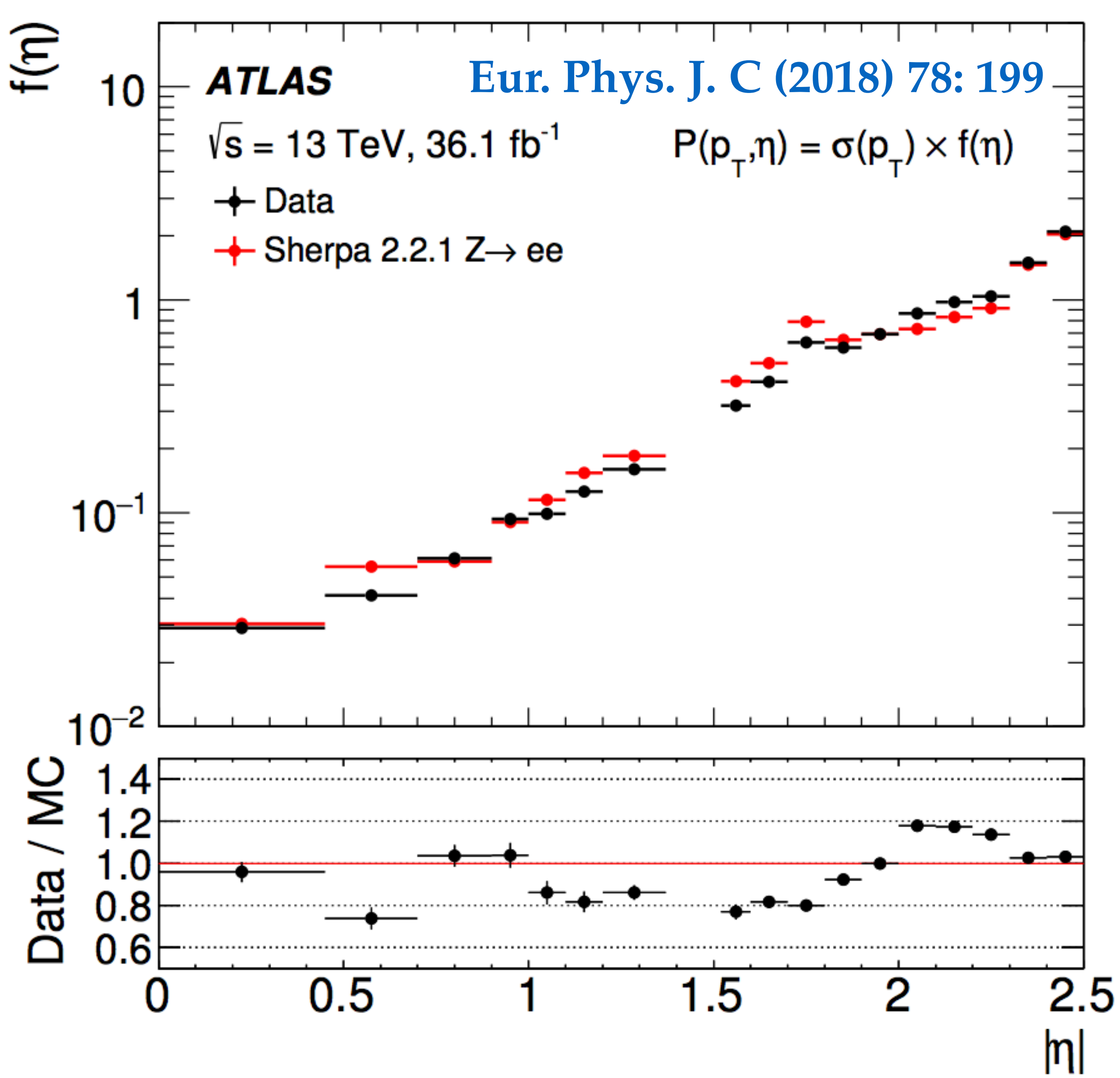
$$-\log L(\boldsymbol{P}|\boldsymbol{N}_{\mathrm{SC}},\boldsymbol{N}) = \sum_{i,j} \log(N^{ij}(P_i(1-P_j) + P_j(1-P_i)))N_{\mathrm{SC}}^{ij} - N^{ij}(P_i(1-P_j) + P_j(1-P_i))$$

→ *extracted from the fit*

$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ - electron charge misidentification - II:

$P(p_T, \eta) = \sigma(p_T)\times f(\eta)$





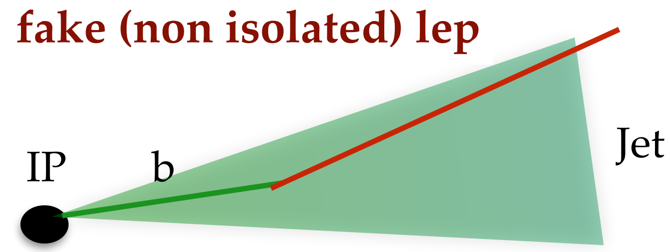
A bin-by-bin scale factor *SF = P(CF;data)/P(CF;MC)* and an *anti-SF = [1-P(CF;data)]/[1-P(CF;MC)]* are respectively applied to MC electrons with correct or incorrect charge.

Uncertainties: statistics of the data / MC sample 10%-20% on rates across p_T, η bins.

$H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ - *fake* lepton background:

Fake leptons

- in-flight decays of mesons inside jets
- mis-identified jets
- initial/final state radiation conversions



Design control regions enriched in fake leptons:

Selection for fake-enriched regions	
Muon channel	Electron channel
Single-muon trigger	Single-electron trigger
b-jet veto	b-jet veto
One muon and one jet	One electron
$p_{\mathrm{T}}(\mathrm{jet}) > 35$ GeV	Number of tight electrons < 2
$\Delta\phi(\mu, \mathrm{jet}) > 2.7$	$m(ee) \notin [71.2, 111.2]$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}} < 40$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} < 25$ GeV

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$$N^{\mathrm{fake}} = \sum_{i=1}^{N_{\mathrm{SB}}^{\mathrm{data}}} (-1)^{N_{L,i}+1} \prod_{l=1}^{N_{L,i}} F_l - \sum_{i=1}^{N_{\mathrm{SB}}^{\mathrm{MC}}} (-1)^{N_{L,i}+1} \prod_{l=1}^{N_{L,i}} F_l$$

Uncertainties:

- *fake composition*: varying nominal fake-enriched kinematic definition.
- *theory*: residual component from prompt leptons subtracted to avoid double counting.
  change MC normalization up/down when subtracting from data.

Uncertainty varies between 10%-20% depending on lepton p_{T}.

$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ - analysis signal regions:

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Channel \ Region	Control Regions			Validation Regions		
	OCCR	DBCR	4LCR	SCVR	3LVR	4LVR
Electron channel	$e^{\pm}e^{\mp}$	$e^{\pm}e^{\pm}e^{\mp}$		$e^{\pm}e^{\pm}$	$e^{\pm}e^{\pm}e^{\mp}$	
Mixed channel	-	$e^{\pm}\mu^{\pm}\ell^{\mp}$	$\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$	$e^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell'^{\mp}$	$\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$
Muon channel	-	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$		$\mu^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$	
$m(e^{\pm}e^{\pm})$ [GeV]	$[130, 2000]$	$[90, 200)$		$[130, 200)$	$[90, 200)$	
$m(\ell^{\pm}\ell^{\pm})$ [GeV]	-	$[90, 200)$	$[60, 150)$	$[130, 200)$	$[90, 200)$	$[150, 200)$
$m(\mu^{\pm}\mu^{\pm})$ [GeV]	-	$[60, 200)$		$[60, 200)$	$[60, 200)$	
b-jet veto	✓	✓	✓	✓	✓	✓
Z veto	-	inverted	-	-	✓	-

used for Drell-Yan normalization

$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ - analysis signal regions:

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Channel \ Region	Control Regions			Validation Regions		
	OSCR	*DBCR*	*4LCR*	SCVR	3LVR	4LVR
Electron channel	$e^{\pm}e^{\mp}$	$e^{\pm}e^{\pm}e^{\mp}$		$e^{\pm}e^{\pm}$	$e^{\pm}e^{\pm}e^{\mp}$	
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Muon channel	-	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$		$\mu^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$	
$m(e^{\pm}e^{\pm})$ [GeV]	$[130, 2000]$	$[90, 200)$		$[130, 200)$	$[90, 200)$	
$m(\ell^{\pm}\ell^{\pm})$ [GeV]	-	$[90, 200)$	$[60, 150)$	$[130, 200)$	$[90, 200)$	$[150, 200)$
$m(\mu^{\pm}\mu^{\pm})$ [GeV]	-	$[60, 200)$		$[60, 200)$	$[60, 200)$	
b-jet veto	✓	✓	✓	✓	✓	✓
Z veto	-	inverted	-	-	✓	-

used for diboson normalization

$H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ - analysis signal regions:

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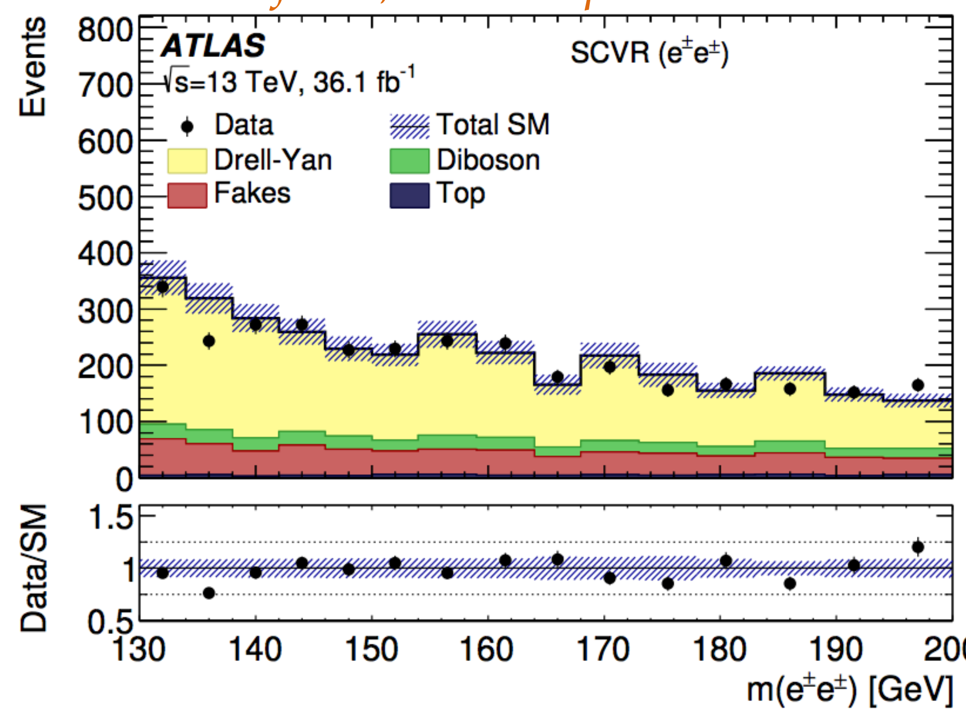
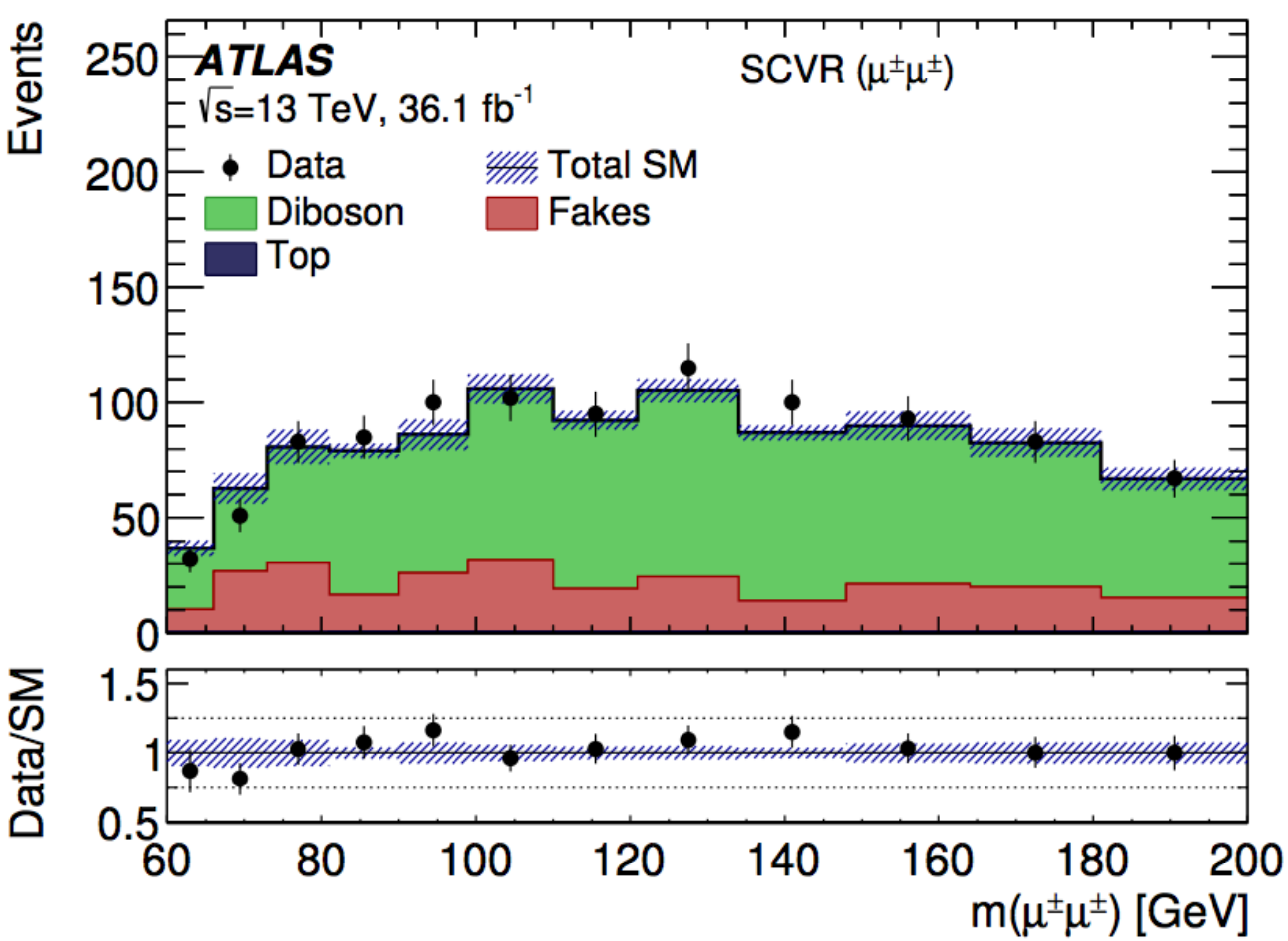
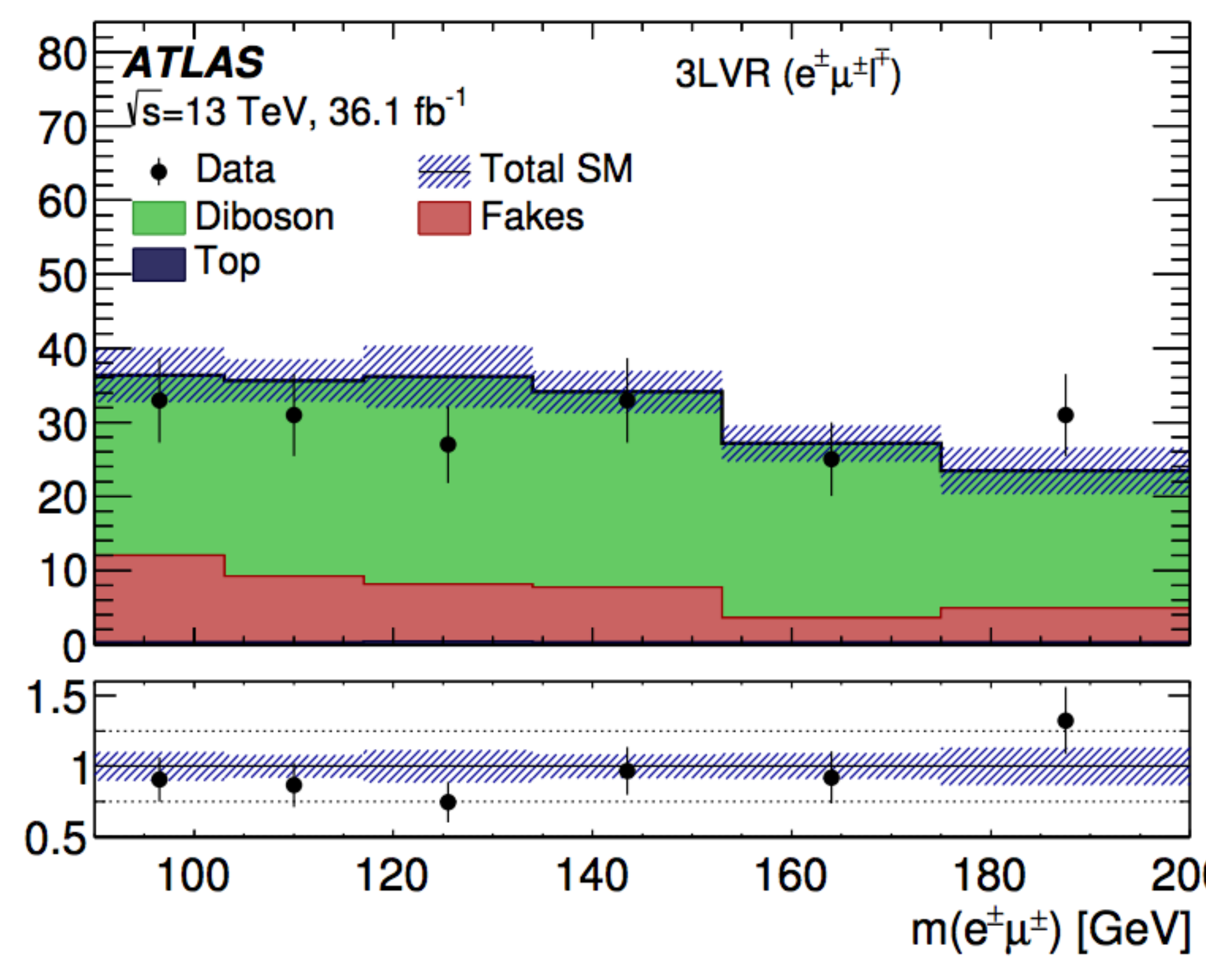
test charge-misidentication, fakes, diboson predictions

Channel \ Region	Control Regions			Validation Regions		
	OSCR	DBCR	4LCR	SCVR	3LVR	4LVR
Electron channel	$e^{\pm}e^{\mp}$	$e^{\pm}e^{\pm}e^{\mp}$		$e^{\pm}e^{\pm}$	$e^{\pm}e^{\pm}e^{\mp}$	
Mixed channel	-	$e^{\pm}\mu^{\pm}\ell^{\mp}$	$\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$	$e^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell'^{\mp}$	$\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$
Muon channel	-	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$		$\mu^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$	
$m(e^{\pm}e^{\pm})$ [GeV]	$[130, 2000]$	$[90, 200)$		$[130, 200)$	$[90, 200)$	
$m(\ell^{\pm}\ell^{\pm})$ [GeV]	-	$[90, 200)$	$[60, 150)$	$[130, 200)$	$[90, 200)$	$[150, 200)$
$m(\mu^{\pm}\mu^{\pm})$ [GeV]	-	$[60, 200)$		$[60, 200)$	$[60, 200)$	
b-jet veto	✓	✓	✓	✓	✓	✓
Z veto	-	inverted	-	-	✓	-







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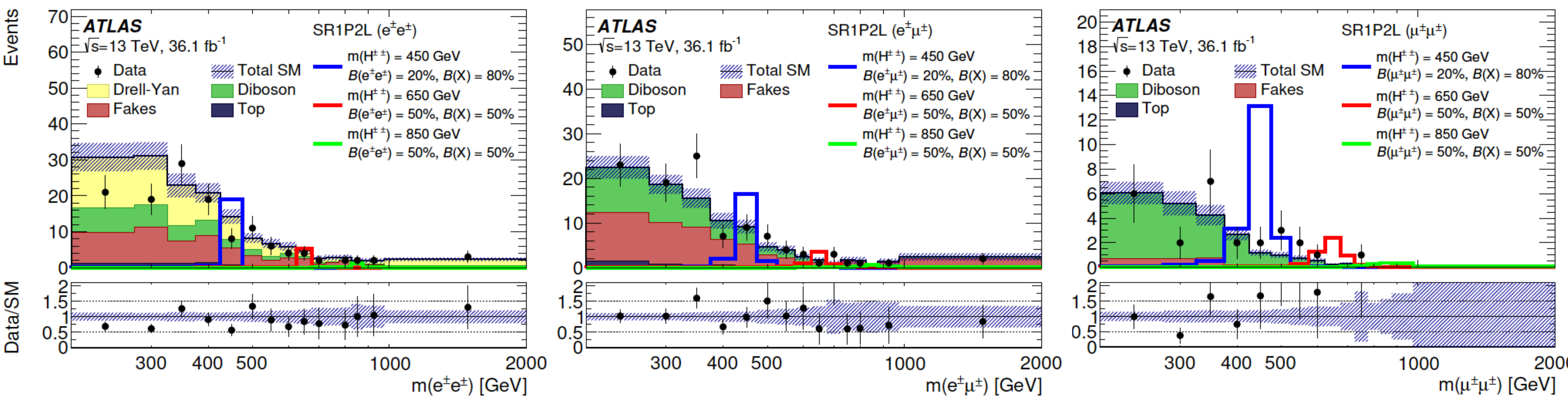
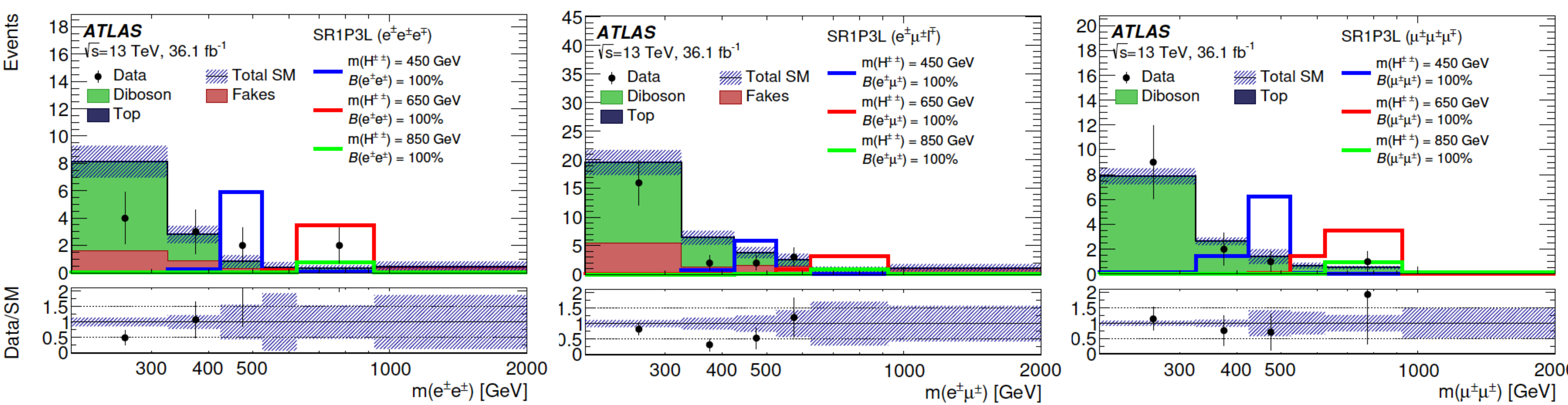
✤ $H^{\pm\pm}$ branching ratio not fixed across models

2 leptons signal region



3 leptons signal region



No excess over Standard Model observed

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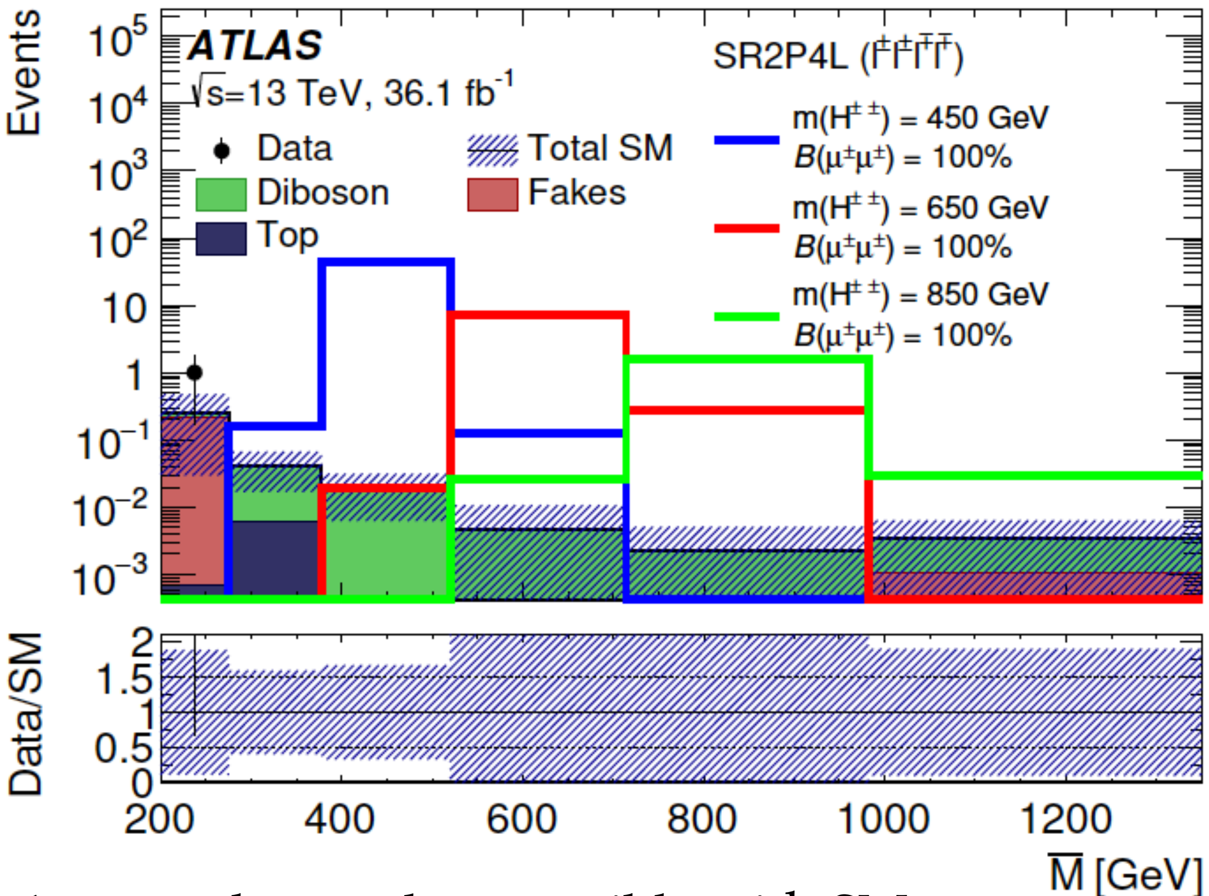
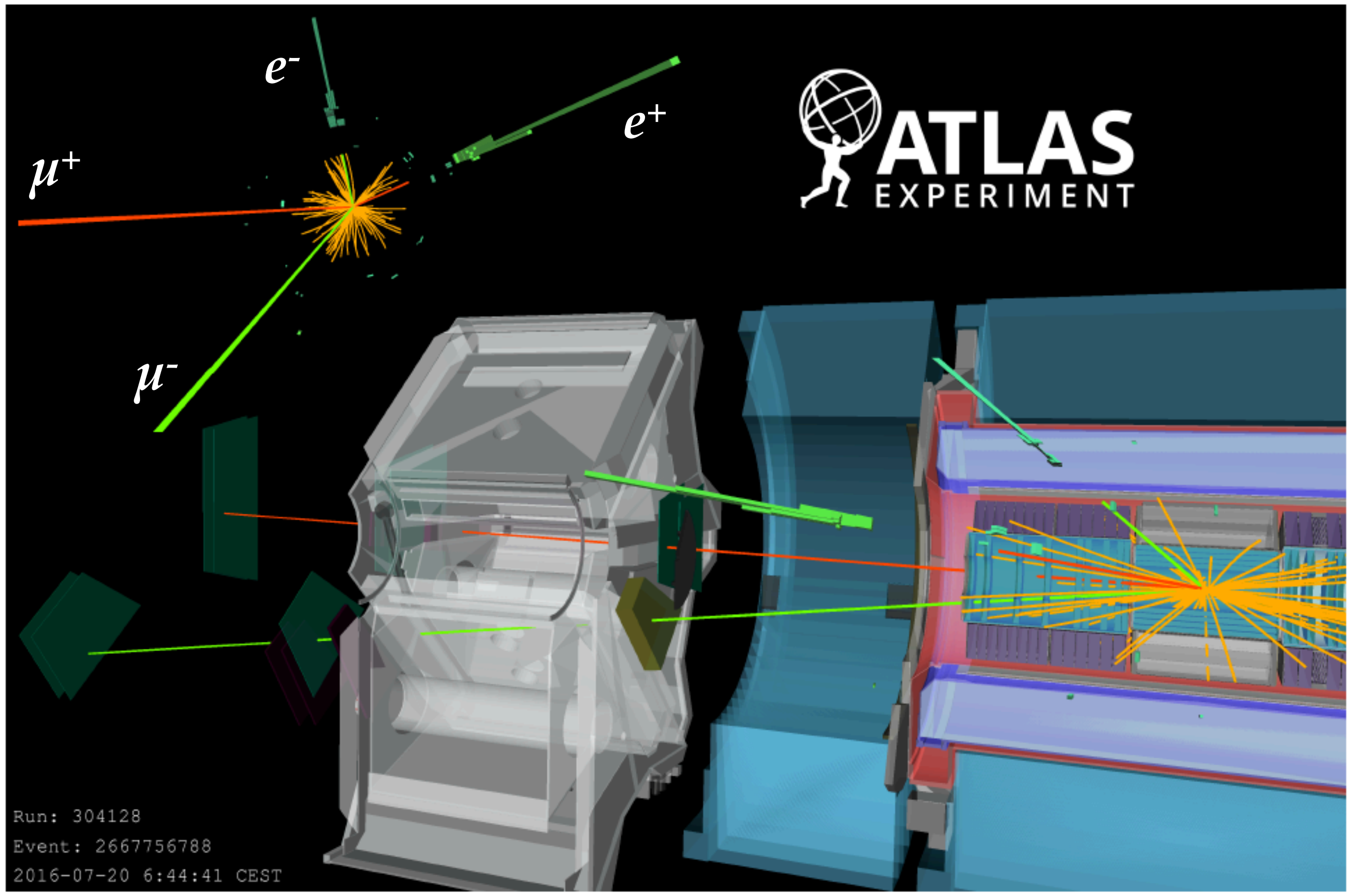
4 leptons signal region



Observed eeμμ event compatible with ZZ production



1 event observed compatible with SM

Limits on mass and cross-section:

$$BR(e^{\pm}e^{\pm}) + BR(e^{\pm}\mu^{\pm}) + BR(\mu^{\pm}\mu^{\pm}) = 100\%, \quad BR(X) = 0$$

- sensitivity dominated by 4L signal region

$$BR(e^{\pm}e^{\pm}) + BR(e^{\pm}\mu^{\pm}) + BR(\mu^{\pm}\mu^{\pm}) \leq 100\%, \quad BR(X) \neq 0$$

where X does not enter the signal regions, i.e. hadronic τ or W decays

- $2L/3L$ signal regions gain sensitivity

signal samples rescaled to reach the desired BR combination

$H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ - results:

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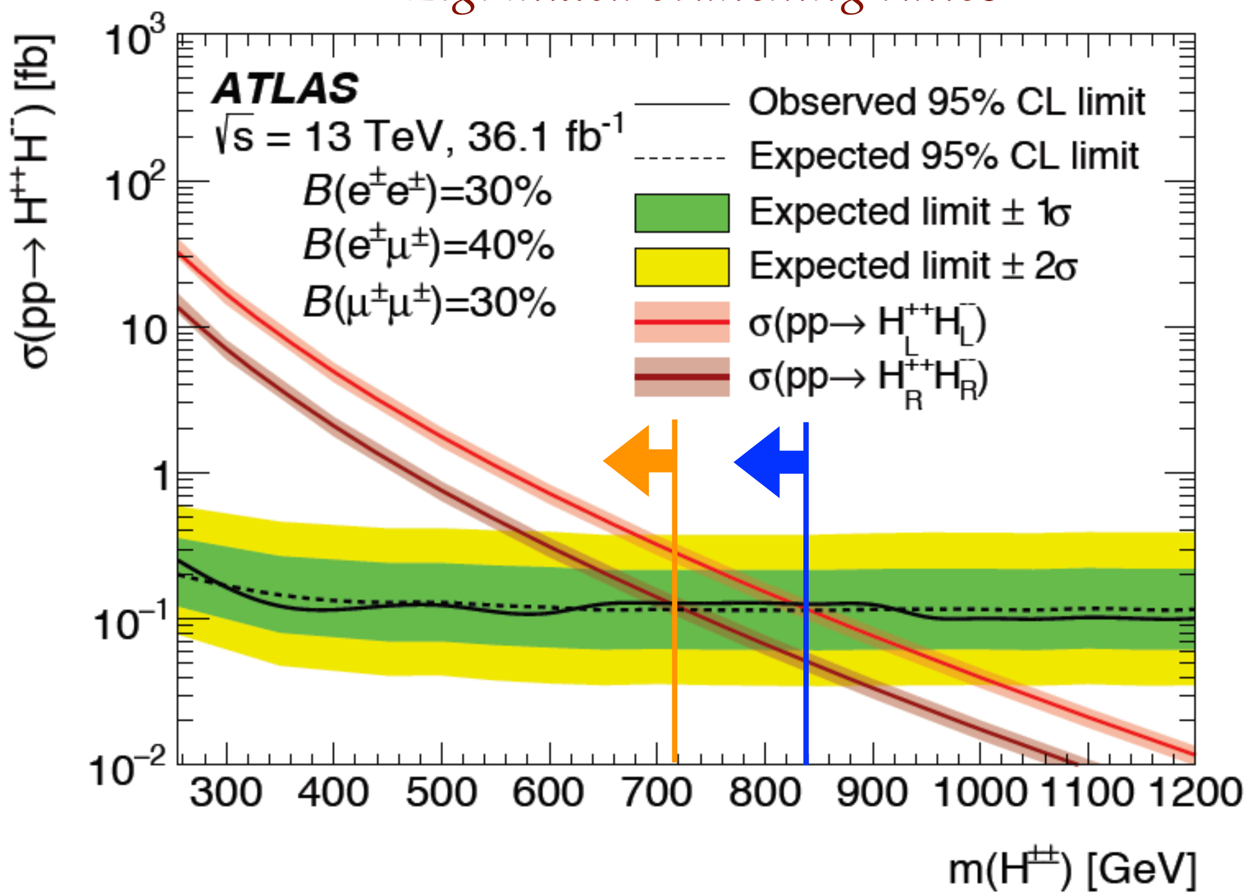
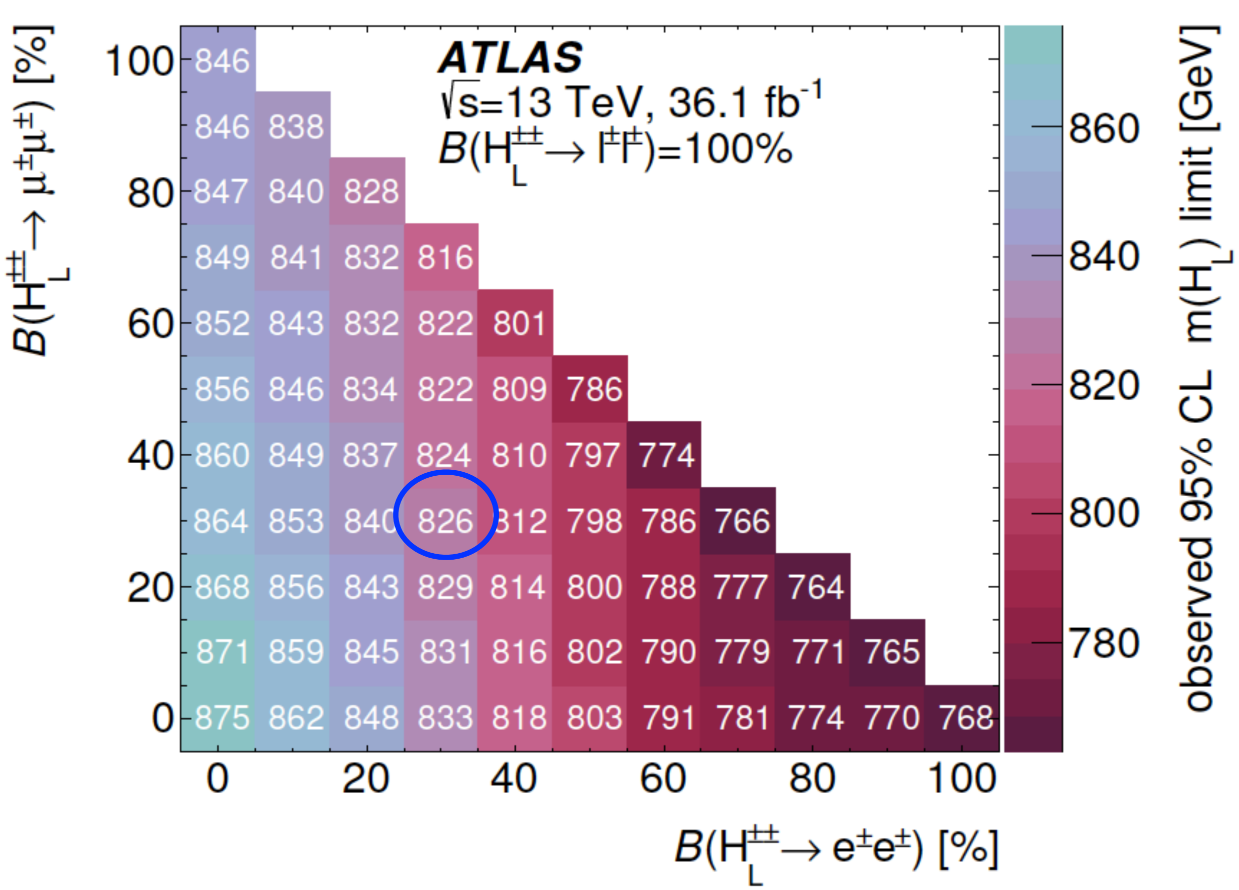
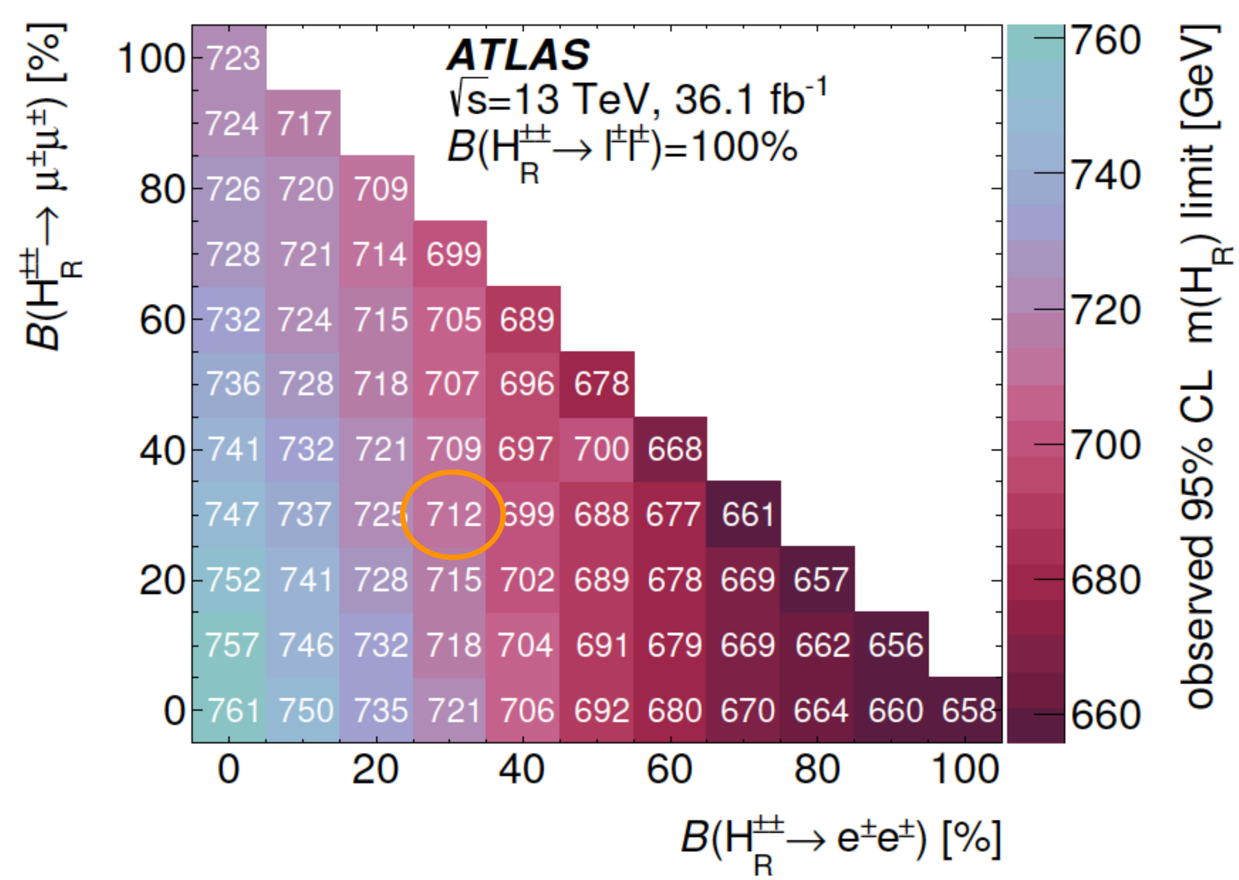
E.g: mixed branching ratios

$BR(\ell^{\pm}\ell^{\pm}) = 100\%$







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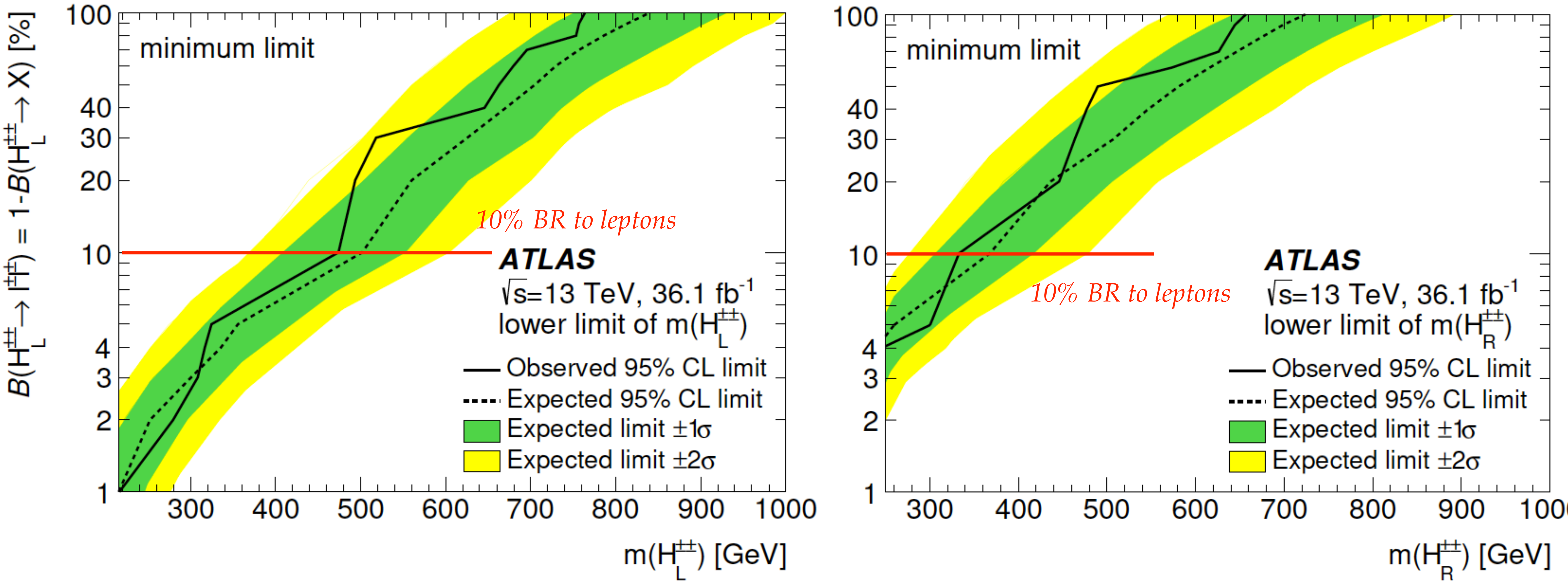
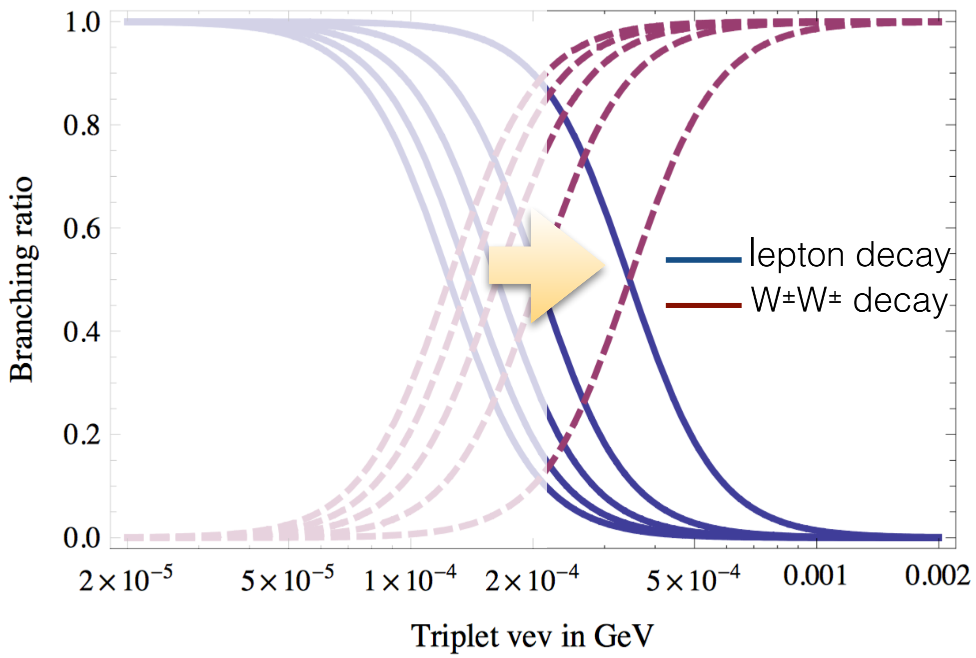
$BR(l^{\pm}l^{\pm}) + BR(X) = 100\%$



Dominating uncertainties:

statistics, data-driven fakes and charge mis-identification

$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ - analysis regions:



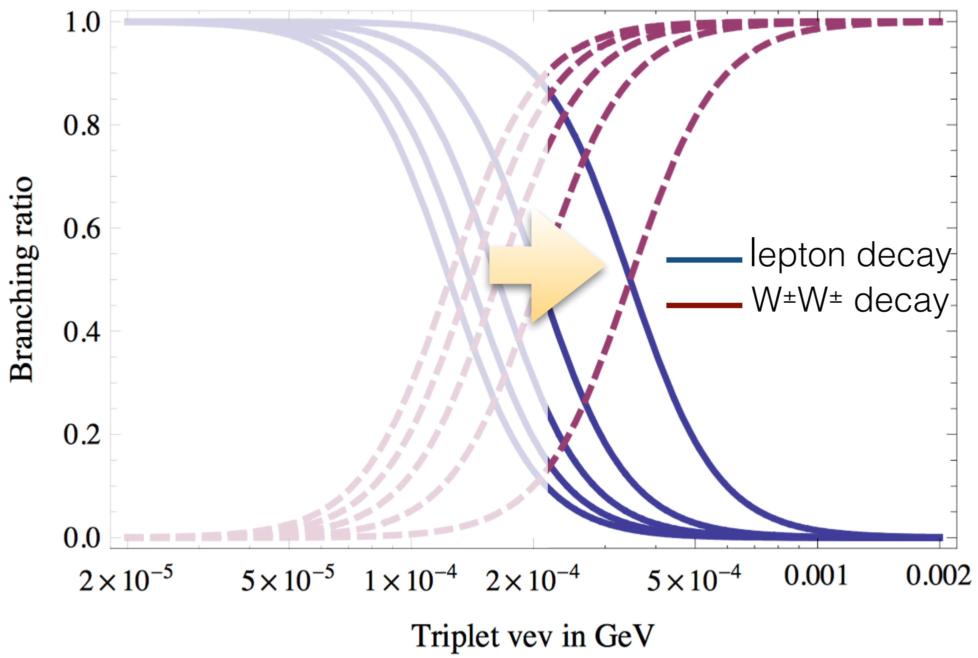
- *signature:* 2,3,4 **light** leptons + missing E_T
- masses *200-700 GeV*

- Major backgrounds:
  WZ production, electron charge mis-ID, fakes
  - *estimated with a technique similar to what discussed before*

Preselection:

Selection criteria	$2\ell^{ss}$	3ℓ	4ℓ
Trigger	At least one lepton with $p_T^{\ell} > 30$ GeV that fulfils the requirements of single-lepton triggers		
N_ℓ(L-type, $p_T > 10$ GeV, $\lvert\eta_\ell\rvert < 2.47$)	2	3	4
N_ℓ(T-type, $p_T > 10$ GeV, $\lvert\eta_\ell\rvert < 2.47$)	2	2 ($\ell_{1,2}$)	–
$\lvert\sum Q_\ell\rvert$	2	1	0
Lepton p_T threshold	$p_T^{\ell_1,\ell_2} > 30, 20$ 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 SFOS $m_{\ell\ell}$ veto	–	$m_{\ell^\pm\ell^\mp} > 15$ GeV	$m_{\ell^\pm\ell^\mp} > 12$ GeV
Z boson decays veto	$\lvert m_{e^\pm e^\pm} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell^\pm\ell^\mp} - m_Z\rvert > 10$ GeV	

$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - analysis regions:



- *signature:* 2,3,4 light leptons + missing E_T
- masses *200-700 GeV*

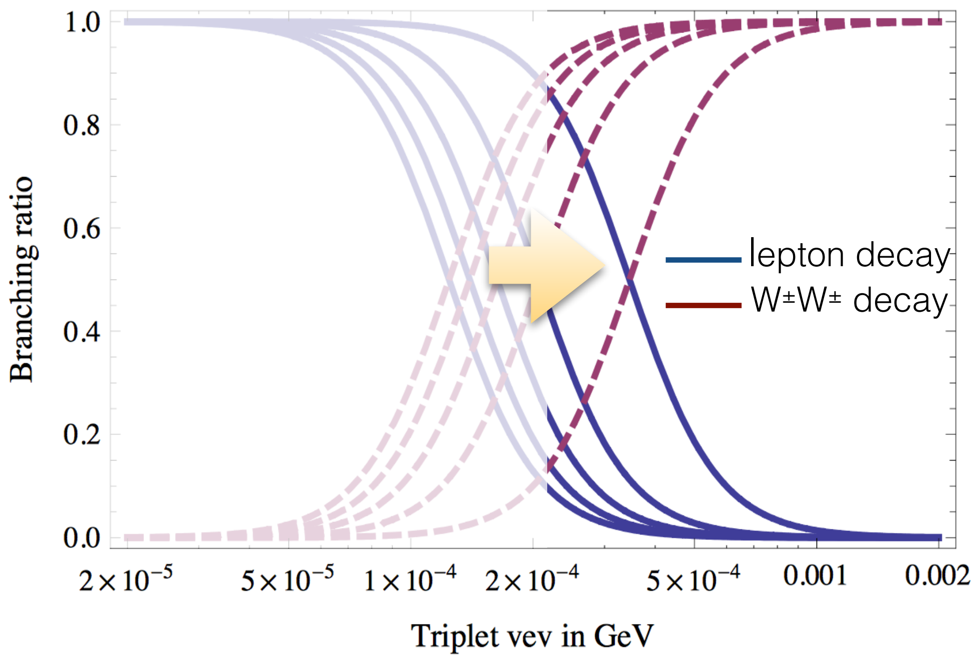
- Major backgrounds: *WZ* production, fakes

Preselection:

Selection criteria	$2\ell^{ss}$	3ℓ	4ℓ
Trigger	At least one lepton with $p_T^{\ell} > 30$ GeV that fulfils the requirements of single-lepton triggers		
$N_\ell(L\text{-type}, p_T > 10\text{ GeV}, \|\eta_\ell\| < 2.47)$	2	3	4
$N_\ell(T\text{-type}, p_T > 10\text{ GeV}, \|\eta_\ell\| < 2.47)$	2	2 ($\ell_{1,2}$)	–
$\|\sum Q_\ell\|$	2	1	0
Lepton p_T threshold	$p_T^{\ell_1,\ell_2} > 30, 20$ 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 SFOS $m_{\ell\ell}$ veto	–	$m_{\ell^\pm\ell^\mp} > 15$ GeV	$m_{\ell^\pm\ell^\mp} > 12$ GeV
Z boson decays veto	$\|m_{e^\pm e^\pm} - m_Z\| > 10$ GeV	$\|m_{\ell^\pm\ell^\mp} - m_Z\| > 10$ GeV	

$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - analysis regions:

arXiv:1808.01899v1



- *signature:* 2,3,4 light leptons + missing E_T
- masses *200-700 GeV*

- Major backgrounds: ZZ, ttV production

Preselection:

Selection criteria	$2\ell^{ss}$	3ℓ	4ℓ
Trigger	At least one lepton with $p_T^{\ell} > 30$ GeV that fulfils the requirements of single-lepton triggers		
$N_{\ell}(L\text{-type}, p_T > 10 \text{ GeV}, \lvert\eta_{\ell}\rvert < 2.47)$	2	3	4
$N_{\ell}(T\text{-type}, p_T > 10 \text{ GeV}, \lvert\eta_{\ell}\rvert < 2.47)$	2	2 ($\ell_{1,2}$)	–
$\lvert\sum Q_{\ell}\rvert$	2	1	0
Lepton p_T threshold	$p_T^{\ell_1,\ell_2} > 30, 20$ 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 SFOS $m_{\ell\ell}$ veto	–	$m_{\ell^{\pm}\ell^{\mp}} > 15$ GeV	$m_{\ell^{\pm}\ell^{\mp}} > 12$ GeV
Z boson decays veto	$\lvert m_{e^{\pm}e^{\pm}} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell^{\pm}\ell^{\mp}} - m_Z\rvert > 10$ GeV	

$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - fake lepton background:

arXiv:1808.01899v1

using fake-factor (2ℓ^ss, 3ℓ) — *using data-driven SFs* (4ℓ-Z, 4ℓ-T)

Sample	$2\ell^{ss}$	3ℓ	4ℓ-Z	4ℓ-T
N_ℓ (type L)	2	3	3	3
$\lvert\sum Q_\ell\rvert$	2	1	1	1
p_T^ℓ	> 30, 20 GeV	> 10, 20, 20 GeV	> 10, 10, 10 GeV	> 10, 10, 10 GeV
N_{jets}	≥ 3	1	1 or 2	1 or 2
$N_{b\text{-jet}}$	0	–	–	–
p_T^{jet}	> 25 GeV	> 25 GeV	> 25 GeV	> 30(25) GeV
Z-window	$\lvert m_{ee}^{ss} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell\ell}^{os} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell\ell}^{os} - m_Z\rvert < 10$ GeV	No same-flavour opposite-sign lepton pair
$m_{\ell\ell}^{os}$	–	> 15 GeV	–	–
E_T^{miss}	< 70 GeV	–	< 50 GeV	–
m_T	–	–	< 50 GeV	–

$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ - fake lepton background:

arXiv:1808.01899v1

Sample	$2\ell^{ss}$	3ℓ	4ℓ-Z	4ℓ-T
N_ℓ (type L)	2	3	3	3
$\lvert\sum Q_\ell\rvert$	2	1	1	1
p_T^ℓ	$> 30, 20$ GeV	$> 10, 20, 20$ GeV	$> 10, 10, 10$ GeV	$> 10, 10, 10$ GeV
N_{jets}	≥ 3	1	1 or 2	1 or 2
$N_{b\text{-jet}}$	0	–	–	–
p_T^{jet}	> 25 GeV	> 25 GeV	> 25 GeV	$> 30(25)$ GeV
Z-window	$\lvert m_{ee}^{ss} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell\ell}^{os} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell\ell}^{os} - m_Z\rvert < 10$ GeV	No same-flavour opposite-sign lepton pair
$m_{\ell\ell}^{os}$	–	> 15 GeV	–	–
E_T^{miss}	< 70 GeV	–	< 50 GeV	–
m_T	–	–	< 50 GeV	–

$$F = \frac{N_{TT}}{N_{TL}}$$

$F_\mu = 0.14 \pm 0.03$ → systematic uncertainty of 35%

$F_e = 0.48 \pm 0.07$ → systematic uncertainty of 56%

from changing the kinematic selection of the $2l^{SS}$ region

$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - fake lepton background:

arXiv:1808.01899v1

Sample	$2\ell^{ss}$	3ℓ	4ℓ-Z	4ℓ-T
N_ℓ (type L)	2	3	3	3
$\|\sum Q_\ell\|$	2	1	1	1
p_T^ℓ	> 30, 20 GeV	> 10, 20, 20 GeV	> 10, 10, 10 GeV	> 10, 10, 10 GeV
N_{jets}	≥ 3	1	1 or 2	1 or 2
$N_{b\text{-jet}}$	0	–	–	–
p_T^{jet}	> 25 GeV	> 25 GeV	> 25 GeV	> 30(25) GeV
Z-window	$\|m_{ee}^{ss} - m_Z\| > 10$ GeV	$\|m_{\ell\ell}^{os} - m_Z\| > 10$ GeV	$\|m_{\ell\ell}^{os} - m_Z\| < 10$ GeV	No same-flavour opposite-sign lepton pair
$m_{\ell\ell}^{os}$	–	> 15 GeV	–	–
E_T^{miss}	< 70 GeV	–	< 50 GeV	–
m_T	–	–	< 50 GeV	–

$$F = \frac{N_{TT}}{N_{TL}}$$

$F_\mu = 0.17 \pm 0.06$ → systematic uncertainty of 55%

$F_e = 0.39 \pm 0.07$ → systematic uncertainty of 81%

from changing the kinematic selection of the $3l^{SS}$ region

Here the opposite-charge lepton is always assumed to be prompt: the *3L* formula reduces to the *2L* case

$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - fake lepton background:

arXiv:1808.01899v1

Sample	$2\ell^{ss}$	3ℓ	4ℓ-Z (Z+jets dominated)	4ℓ-T (tt dominated)
N_ℓ (type L)	2	3	3	3
$\lvert\sum Q_\ell\rvert$	2	1	1	1
p_T^ℓ	> 30, 20 GeV	> 10, 20, 20 GeV	> 10, 10, 10 GeV	> 10, 10, 10 GeV
N_{jets}	≥ 3	1	1 or 2	1 or 2
$N_{b\text{-jet}}$	0	–	–	–
p_T^{jet}	> 25 GeV	> 25 GeV	> 25 GeV	> 30(25) GeV
Z-window	$\lvert m_{ee}^{ss} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell\ell}^{os} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell\ell}^{os} - m_Z\rvert < 10$ GeV	No same-flavour opposite-sign lepton pair
$m_{\ell\ell}^{os}$	–	> 15 GeV	–	–
E_T^{miss}	< 70 GeV	–	< 50 GeV	–
m_T	–	–	< 50 GeV	–

- mainly non-prompt from b-jets from ttV production, small component from light-quarks
  - heavy-flavour: the lower p_T lepton in the SS pair
  - light-flavour: the fake is assumed not to be from Z

$$N^\ell_{\text{Data}|X} - N^\ell_{\text{Prompt}|X} = \lambda^\ell_T N^\ell_{t\bar{t}|X} + \lambda^\ell_Z N^\ell_{Z+\text{jets}|X} \qquad X = Z,T$$

$$\lambda^e_T = 1.12 \pm 0.05,\ \lambda^e_Z = 1.02 \pm 0.07,\ \lambda^\mu_T = 1.11 \pm 0.05\ \lambda^\mu_Z = 0.94 \pm 0.07$$

with a systematic uncertainty of 50%. Applied as “event weight” to simulation.

$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ - signal region optimization:

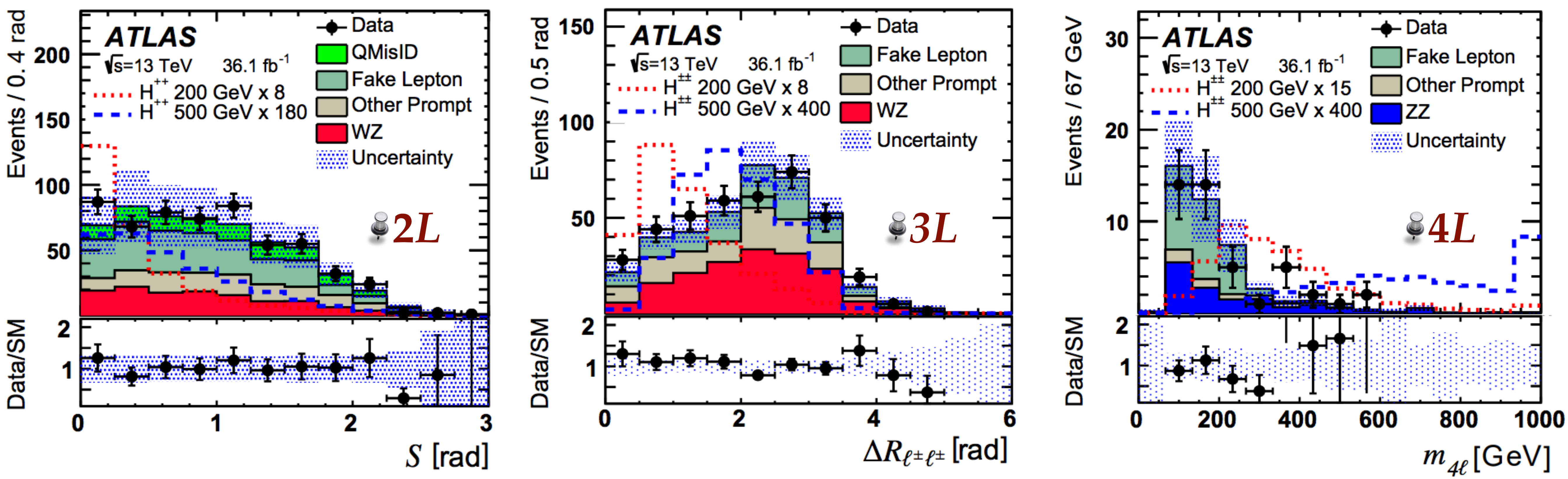
arXiv:1808.01899v1

Mass-dependent and channel-dependent optimizations, exploiting:

- m_{Xl} of all leptons in the event;
- $\Delta R(l^{\pm}l^{\pm})$ and $\Delta R(l^{\pm}l^{\pm})^{max} / \Delta R(l^{\pm}l^{\pm})^{min}$ in the $4L$ channel
- m_{jets} only in the $2L$ channel
- p_T leading jet
- $\Delta\Phi(l^{\pm}l^{\pm}, E_T^{miss})$ in the $2L$ channel
- $\Delta R(l, jet)$ any lepton and its closest jet in the $3L$ channel

used in rectangular cut optimization

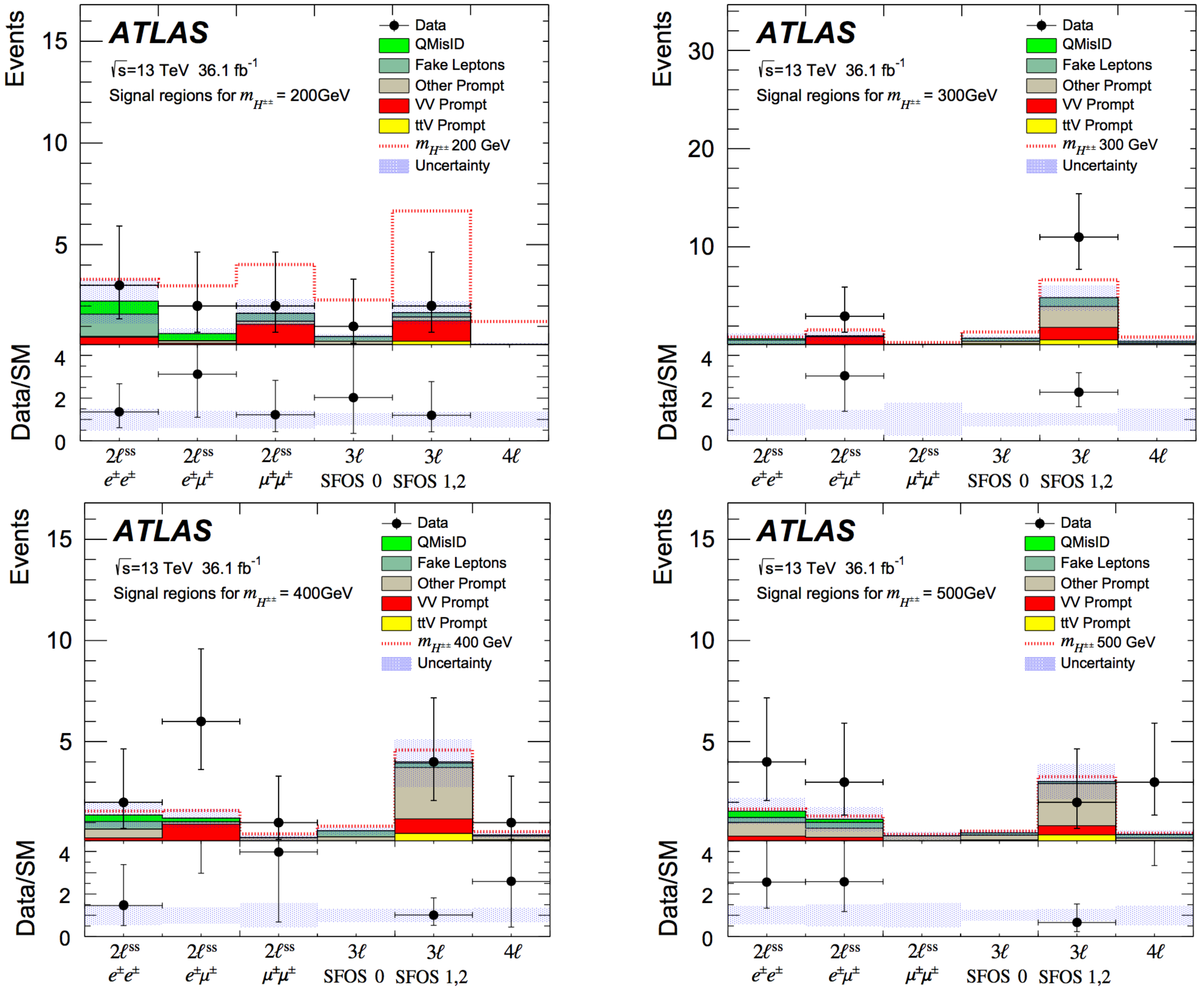
$$S = \frac{\mathcal{R}(\phi_{\ell_1}, \phi_{\ell_2}, \phi_{E_T^{\text{miss}}}) \cdot \mathcal{R}(\phi_{j1}, \phi_{j2}, \cdots)}{\mathcal{R}(\phi_{\ell_1}, \phi_{\ell_2}, \phi_{E_T^{\text{miss}}}, \phi_{j1}, \phi_{j2}, \cdots)}$$ in the $2L$ channel $$\mathcal{R}(\phi_1, \cdots, \phi_n) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\phi_i - \overline{\phi})^2}.$$



signal acceptance ~0.2%

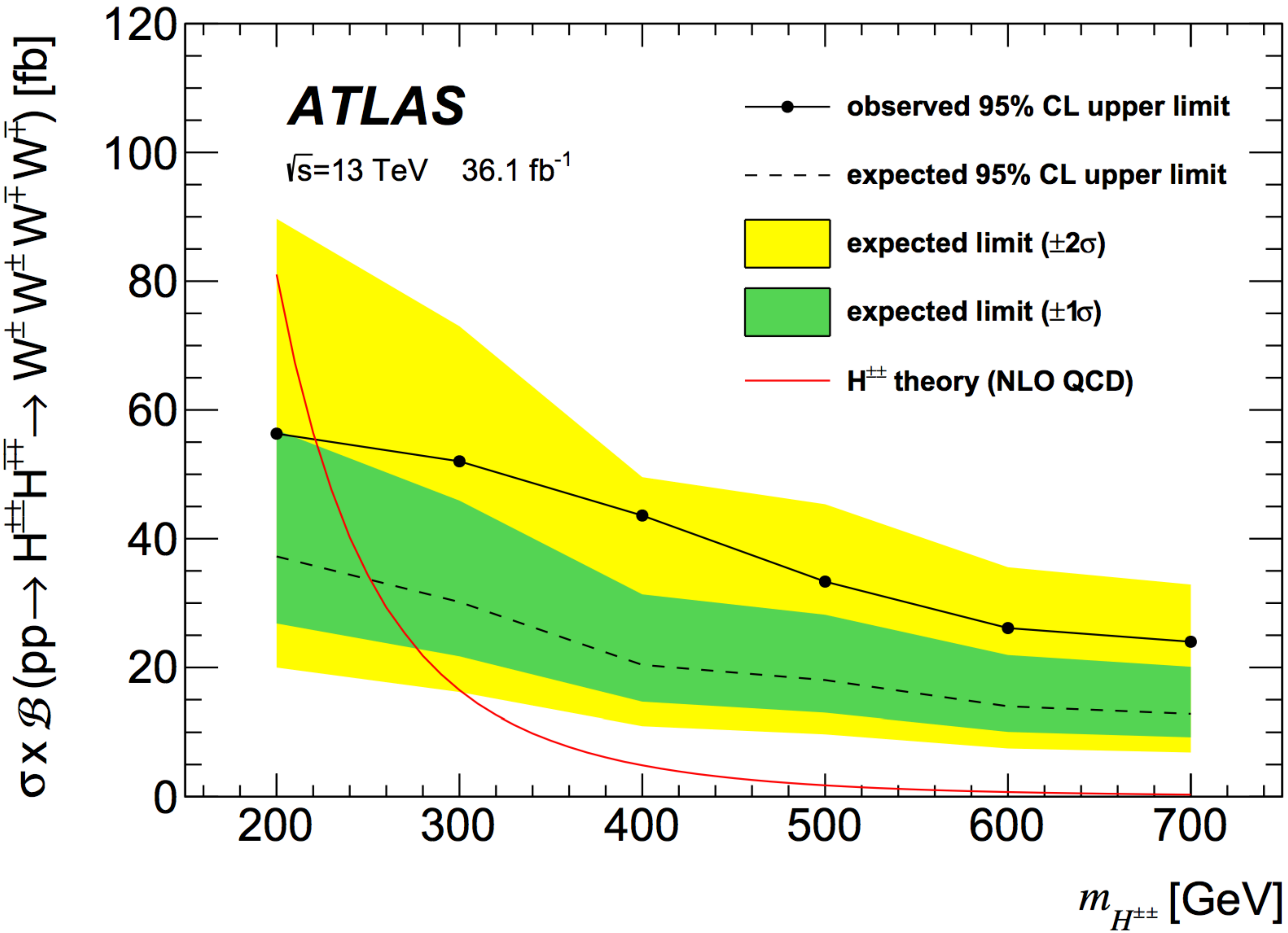
$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - results: likelihood function built using *six bin* counting experiment

arXiv:1808.01899v1



$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - results:

arXiv:1808.01899v1



Dominating uncertainties:

statistics, data-driven fakes and charge mis-identification

Conclusions and outlook:

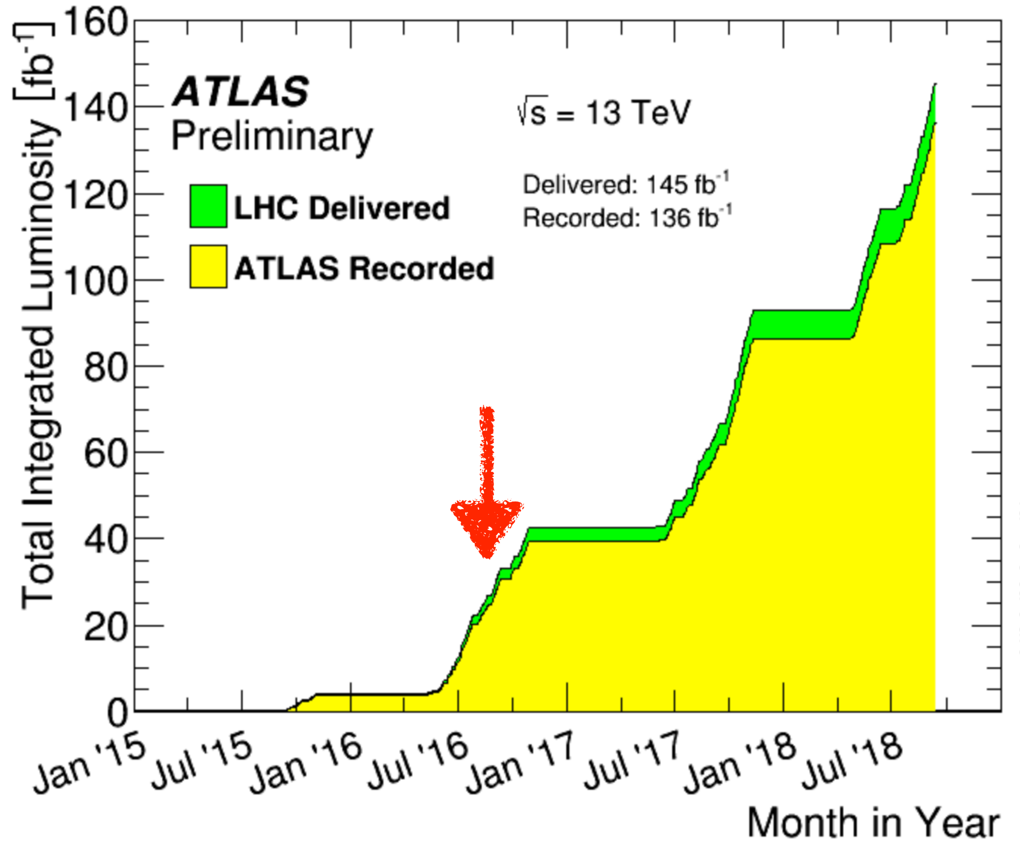
- No evidence for doubly charged Higgs boson production

Conclusions and outlook:

- No evidence for doubly charged Higgs boson production..yet!

Conclusions and outlook:

- *more and more data* in Run2 to analyse!
- presented *two complementary searches:*
  - $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ **in LRSM**:higher sensitivity, possible to reconstruct $H^{\pm\pm}$ mass (current best limit)
  - $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ **in HTM**: lower sensitiviy due to presence of E_T^{miss}, searched for the first time in ATLAS
- incoming LHC/ATLAS upgrades foreseen for Run 3 (300 fb^{-1})/HL-LHC (3000 fb^{-1}): *potential for HBSM discoveries!*



Conclusions and outlook:

- ***more and more data*** in Run2 to analyse!
- presented *two complementary searches:*
  - **$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ in LRSM**:higher sensitivity, possible to reconstruct $H^{\pm\pm}$ mass (current best limit)
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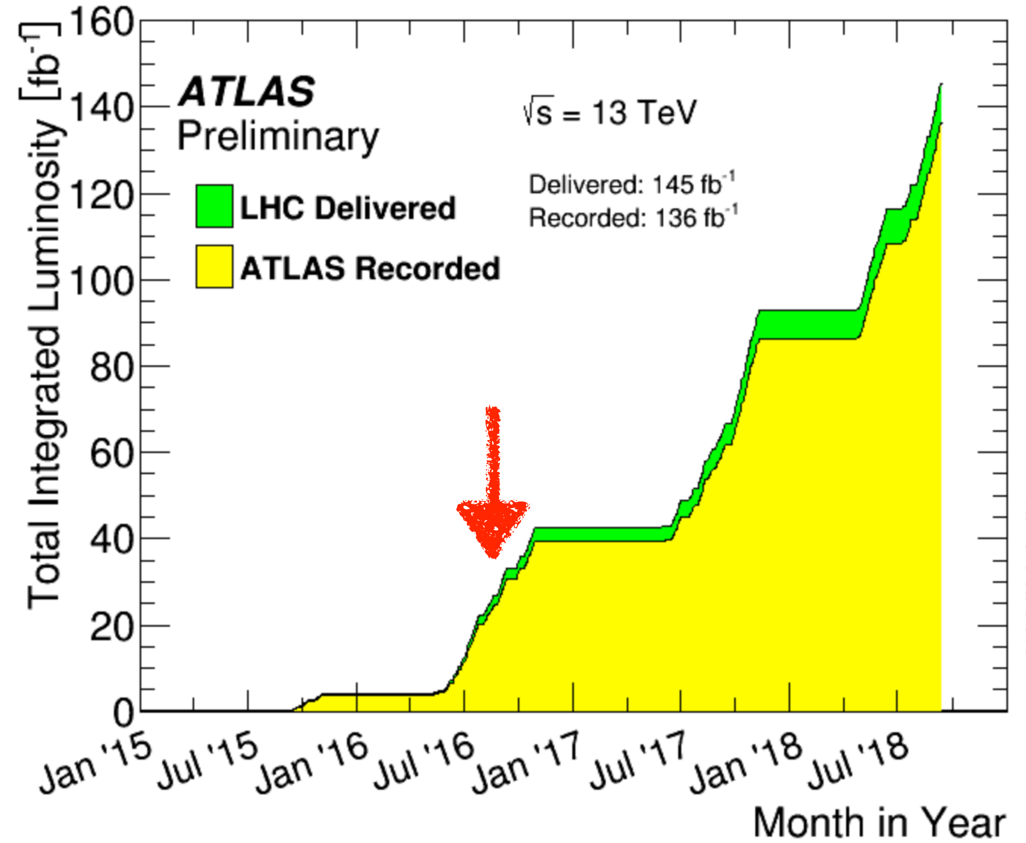

Thank you for your attention!!

Additional Material

$H^{\pm\pm}$ -Previous ATLAS searches:

Model: LRMS, pair production, BR(leptons)=100%

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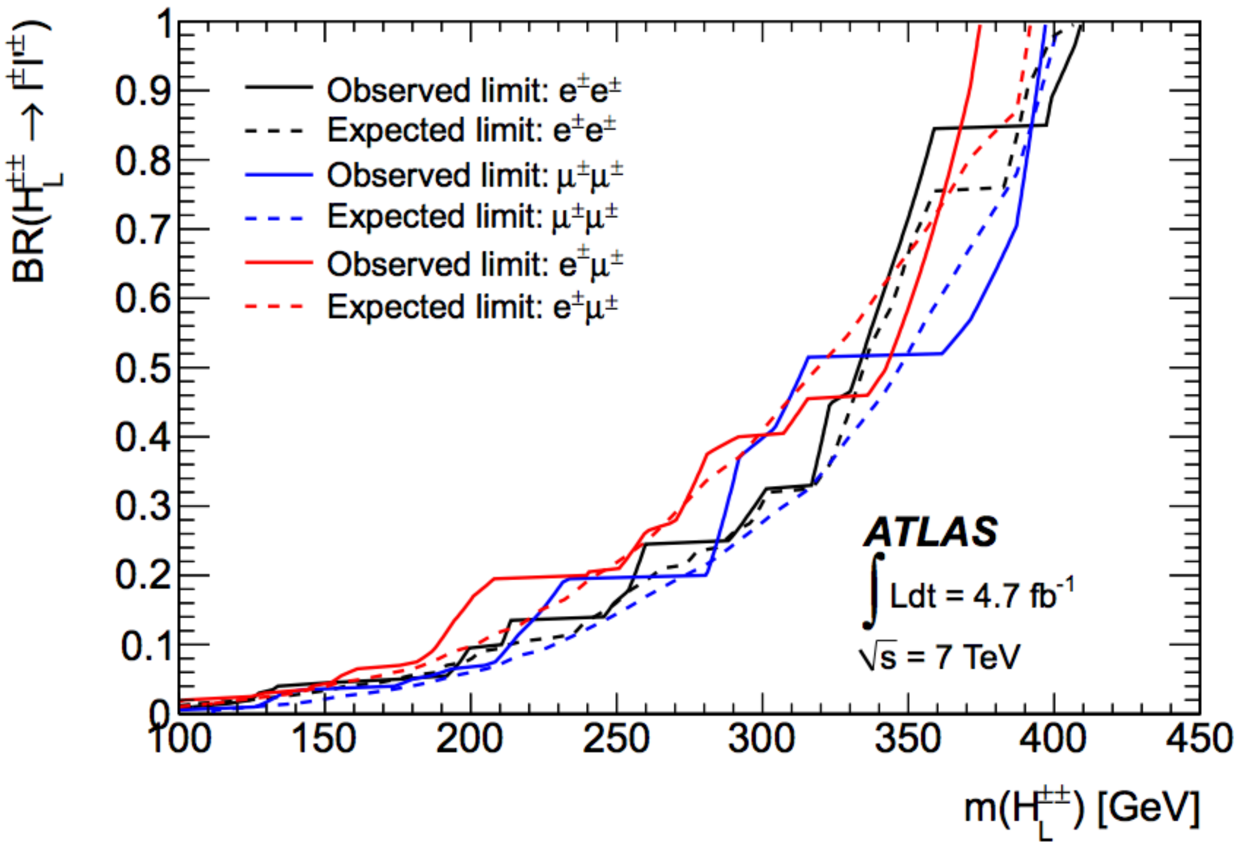

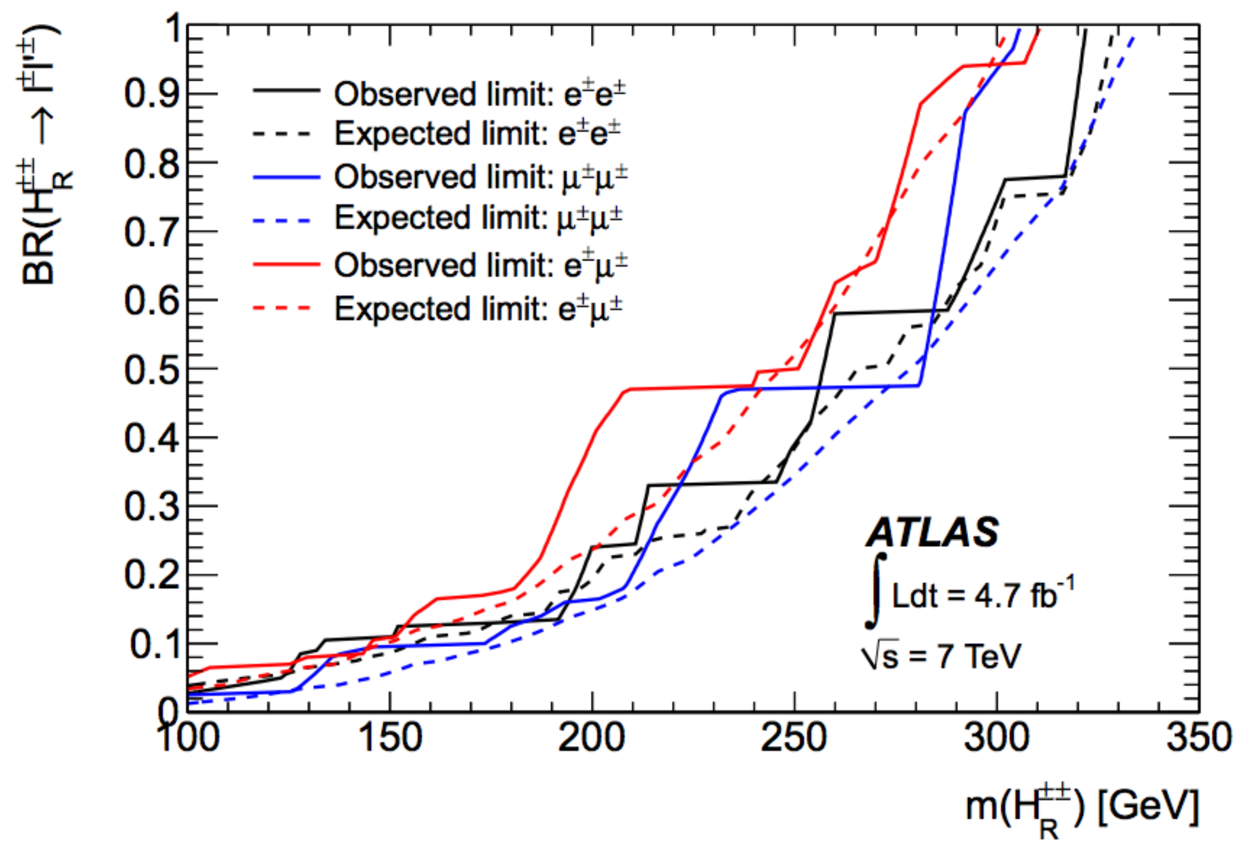

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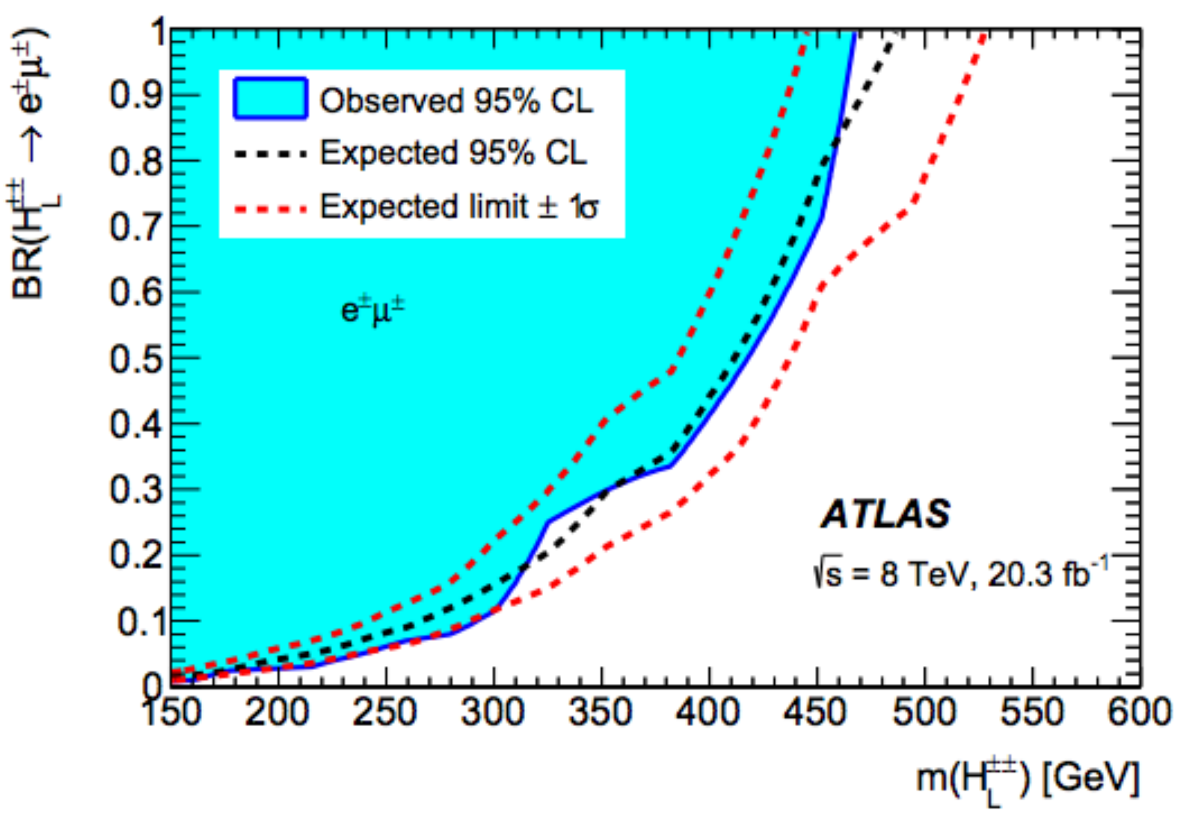
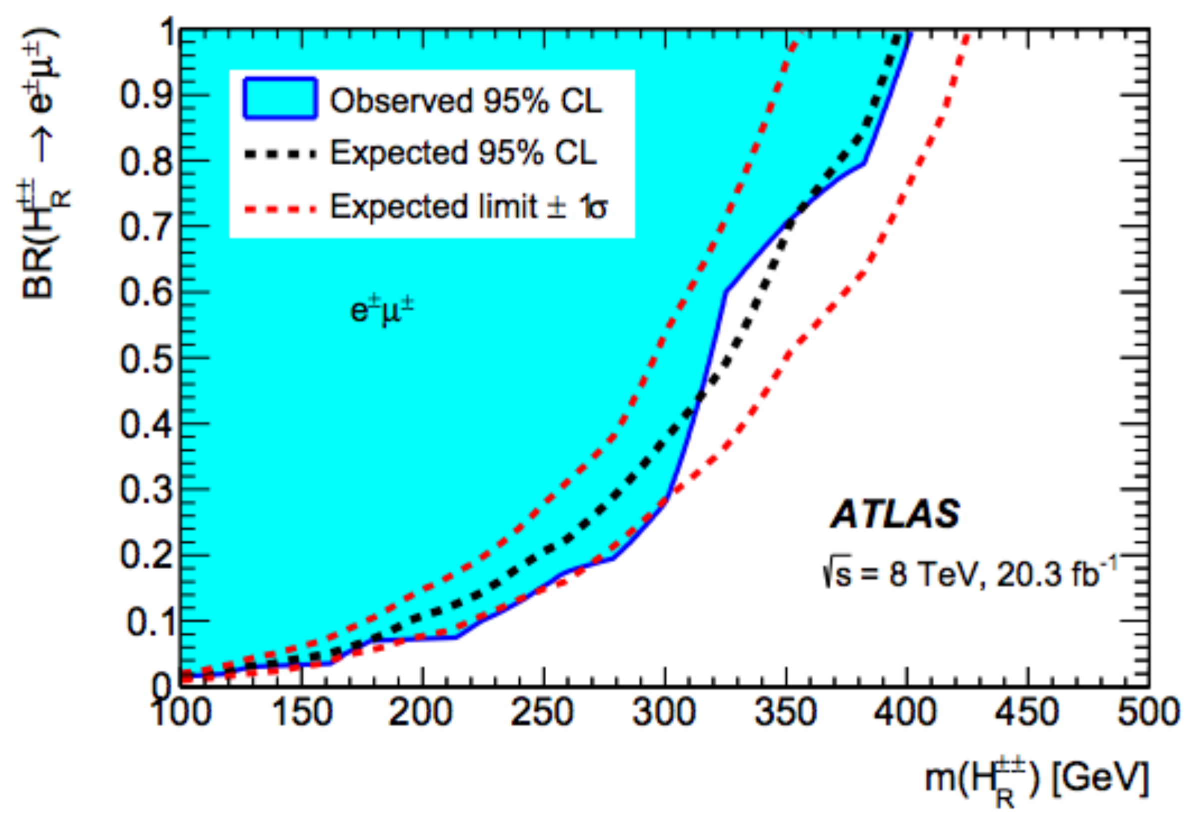




$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ - simulated samples:

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 [37–39]	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

$m(H^{\pm\pm})$ [GeV]	$\sigma(H_L^{\pm\pm})$ [fb]	K-factor ($H_L^{\pm\pm}$)	$\sigma(H_R^{\pm\pm})$ [fb]	K-factor ($H_R^{\pm\pm}$)
300	13	1.25	5.6	1.25
350	7.0	1.25	3.0	1.25
400	3.9	1.24	1.7	1.24
450	2.3	1.24	0.99	1.24
500	1.4	1.24	0.61	1.24
600	0.58	1.23	0.25	1.24
700	0.26	1.23	0.11	1.23
800	0.12	1.22	0.054	1.23
900	0.062	1.22	0.027	1.23
1000	0.032	1.22	0.014	1.24
1100	0.017	1.23	0.0076	1.24
1200	0.0094	1.23	0.0042	1.25
1300	0.0052	1.24	0.0023	1.26

$H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ - systematic uncertainties:

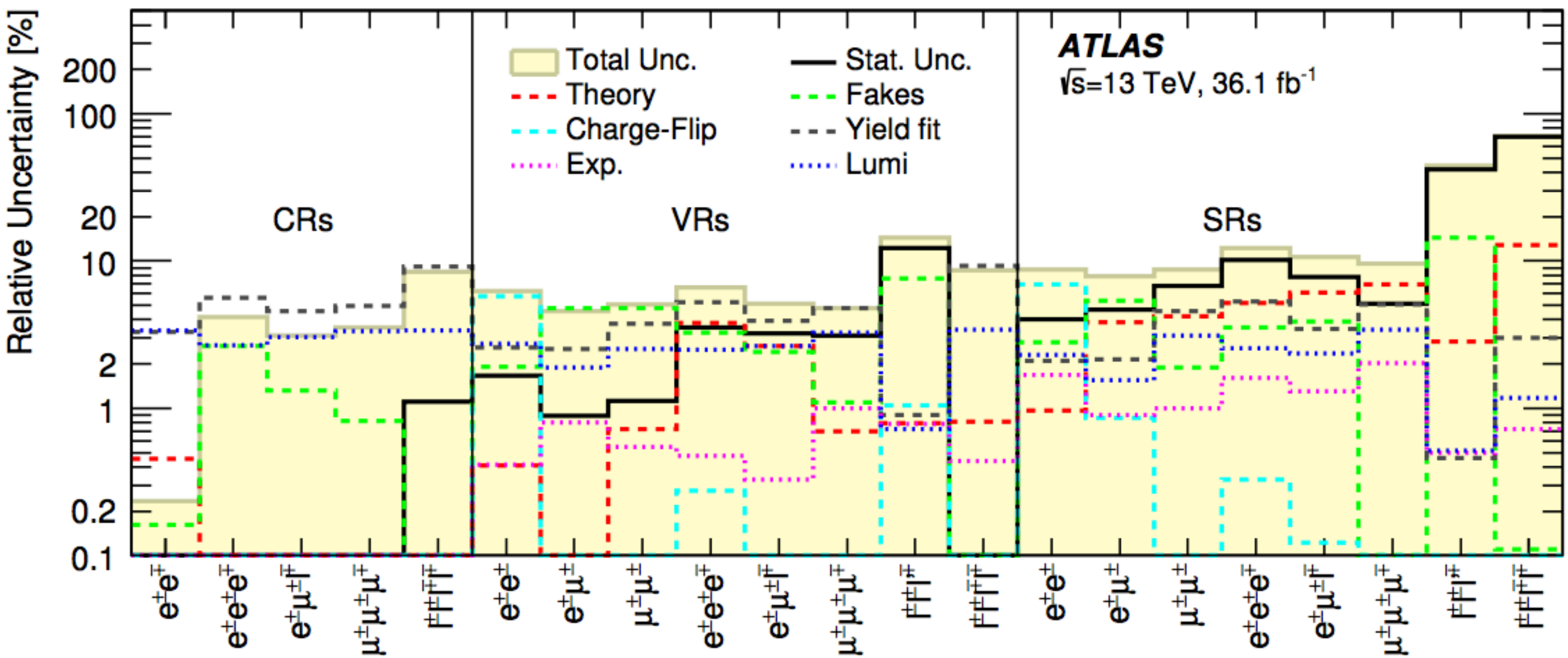
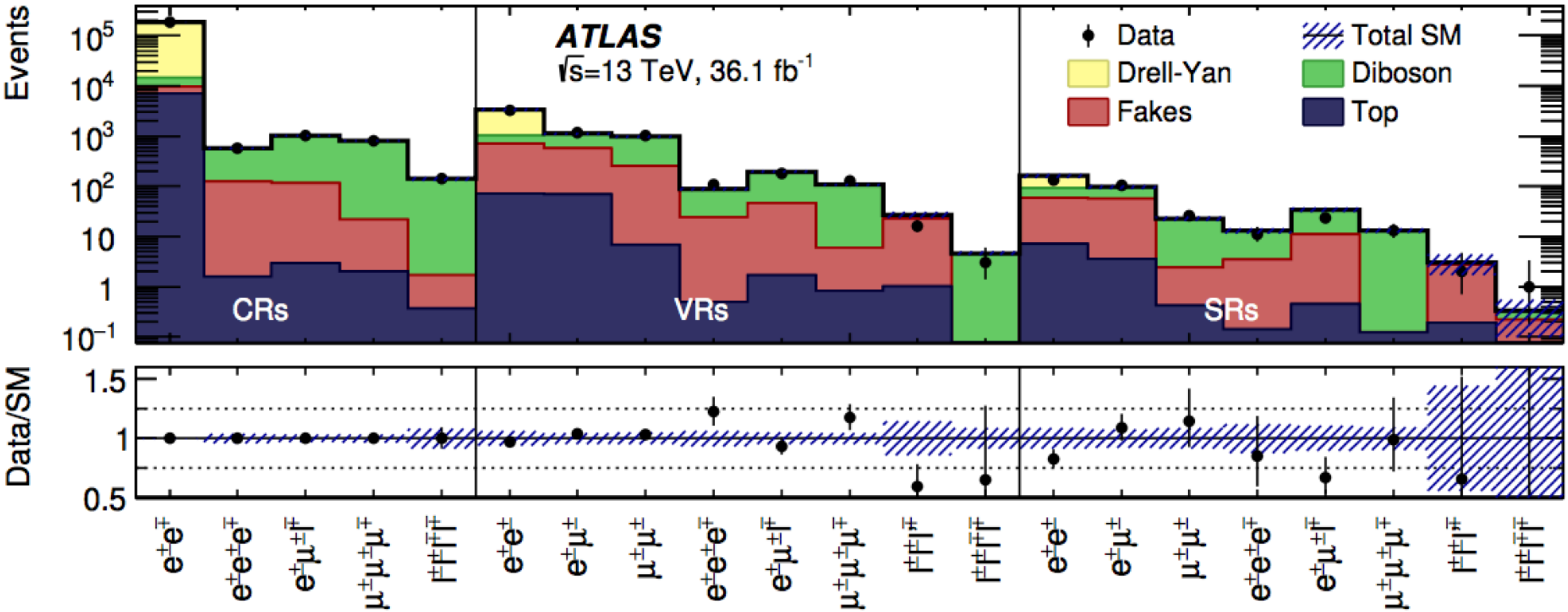


Figure 6: Relative uncertainties in the total background yield estimation after the fit. 'Stat. Unc.' corresponds to reducible and irreducible background statistical uncertainties. 'Yield fit' corresponds to the uncertainty arising from fitting the yield of diboson and Drell–Yan backgrounds. 'Lumi' corresponds to the uncertainty in the luminosity. 'Theory' indicates the theoretical uncertainty in the physics model used for simulation (e.g. cross-sections). 'Exp.' indicates the uncertainty in the simulation of electron and muon efficiencies (e.g. trigger, identification). 'Fakes' is the uncertainty associated with the model of the fake background. Individual uncertainties can be correlated, and do not necessarily add in quadrature to the total background uncertainty, which is indicated by 'Total Unc.'.

$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ - Fit results:



$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ - Fit results:

	OCCR $e^{\pm}e^{\mp}$	DBCR $e^{\pm}e^{\pm}e^{\mp}$	DBCR $e^{\pm}\mu^{\pm}\ell^{\mp}$	DBCR $\mu^{\pm}\mu^{\pm}\mu^{\mp}$	4LCR $\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$
Observed events	184 569	576	1025	797	140
Total background	184 570 ± 430	574 ± 24	1025 ± 32	797 ± 28	140 ± 12
Drell–Yan	169 980 ± 990	–	–	–	–
Diboson	5060 ± 900	449 ± 28	909 ± 35	775 ± 29	138 ± 12
Fakes	2340 ± 300	123 ± 15	113 ± 14	19.9 ± 6.5	1.31 ± 0.16
Top	7200 ± 250	1.58 ± 0.06	2.90 ± 0.11	2.04 ± 0.08	0.37 ± 0.01

	SCVR $e^{\pm}e^{\pm}$	SCVR $e^{\pm}\mu^{\pm}$	SCVR $\mu^{\pm}\mu^{\pm}$	4LVR $\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$
Observed events	3237	1162	1006	3
Total background	3330 ± 210	1119 ± 51	975 ± 50	4.62 ± 0.40
Drell–Yan	2300 ± 190	–	–	–
Diboson	319 ± 25	547 ± 23	719 ± 30	4.59 ± 0.4
Fakes	640 ± 65	502 ± 54	249 ± 47	–
Top	71.5 ± 6.8	70.5 ± 2.6	6.93 ± 0.27	0.033 ± 0.001

$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ - Fit results:

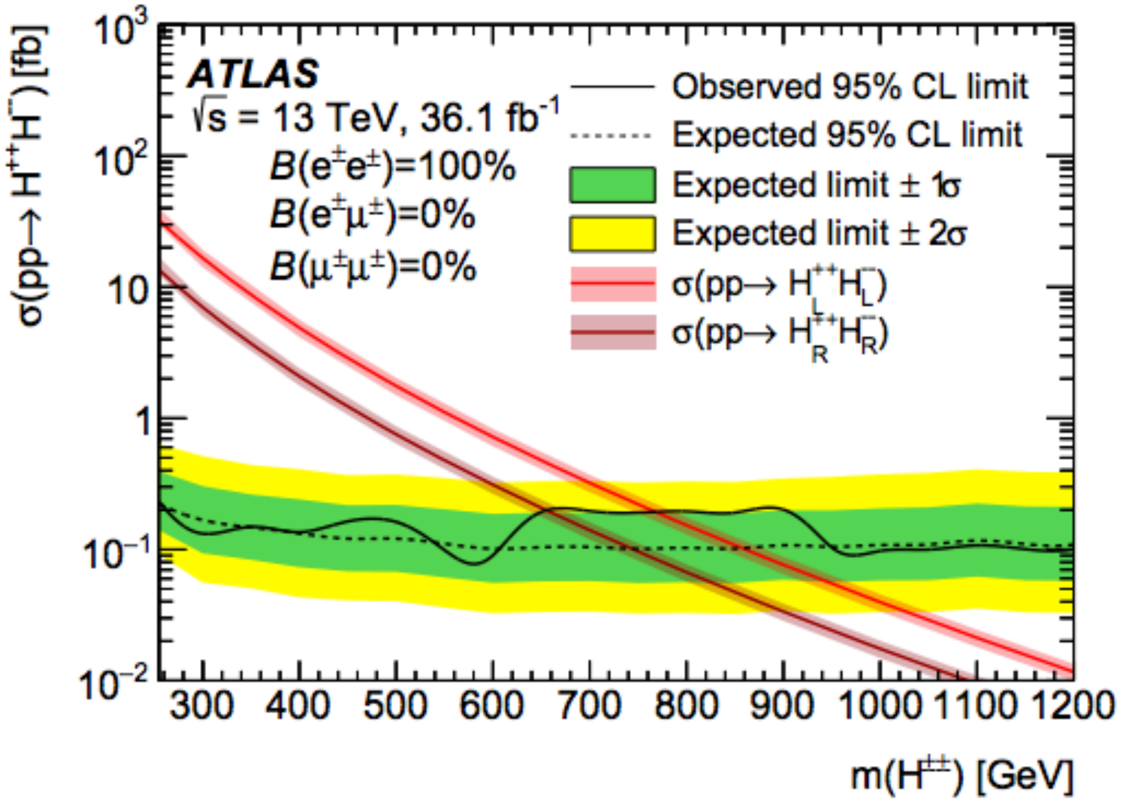
	3LVR $e^{\pm}e^{\pm}e^{\mp}$	3LVR $e^{\pm}\mu^{\pm}\ell^{\mp}$	3LVR $\mu^{\pm}\mu^{\pm}\mu^{\mp}$	3LVR $\mu^{\pm}\mu^{\pm}e^{\mp}, e^{\pm}e^{\pm}\mu^{\mp}$
Observed events	108	180	126	16
Total background	88.1 ± 5.8	192.9 ± 9.9	107.0 ± 5.1	27.0 ± 3.9
Diboson	64.4 ± 5.8	147.3 ± 9.0	100.9 ± 5.0	4.72 ± 0.79
Fakes	23.3 ± 3.0	43.9 ± 4.9	5.3 ± 1.2	21.3 ± 3.4
Top	0.50 ± 0.03	1.73 ± 0.09	0.82 ± 0.05	1.01 ± 0.15

	SR1P2L $e^{\pm}e^{\pm}$	SR1P2L $e^{\pm}\mu^{\pm}$	SR1P2L $\mu^{\pm}\mu^{\pm}$	SR2P4L $\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$
Observed events	132	106	26	1
Total background	160 ± 14	97.1 ± 7.7	22.6 ± 2.0	0.33 ± 0.23
Drell–Yan	70 ± 10	–	–	–
Diboson	30.5 ± 3.0	40.4 ± 4.5	20.3 ± 1.8	0.11 ± 0.06
Fakes	52.2 ± 5.0	53.1 ± 5.8	1.94 ± 0.47	0.22 ± 0.19
Top	7.20 ± 0.97	3.62 ± 0.53	0.42 ± 0.03	0.007 ± 0.002

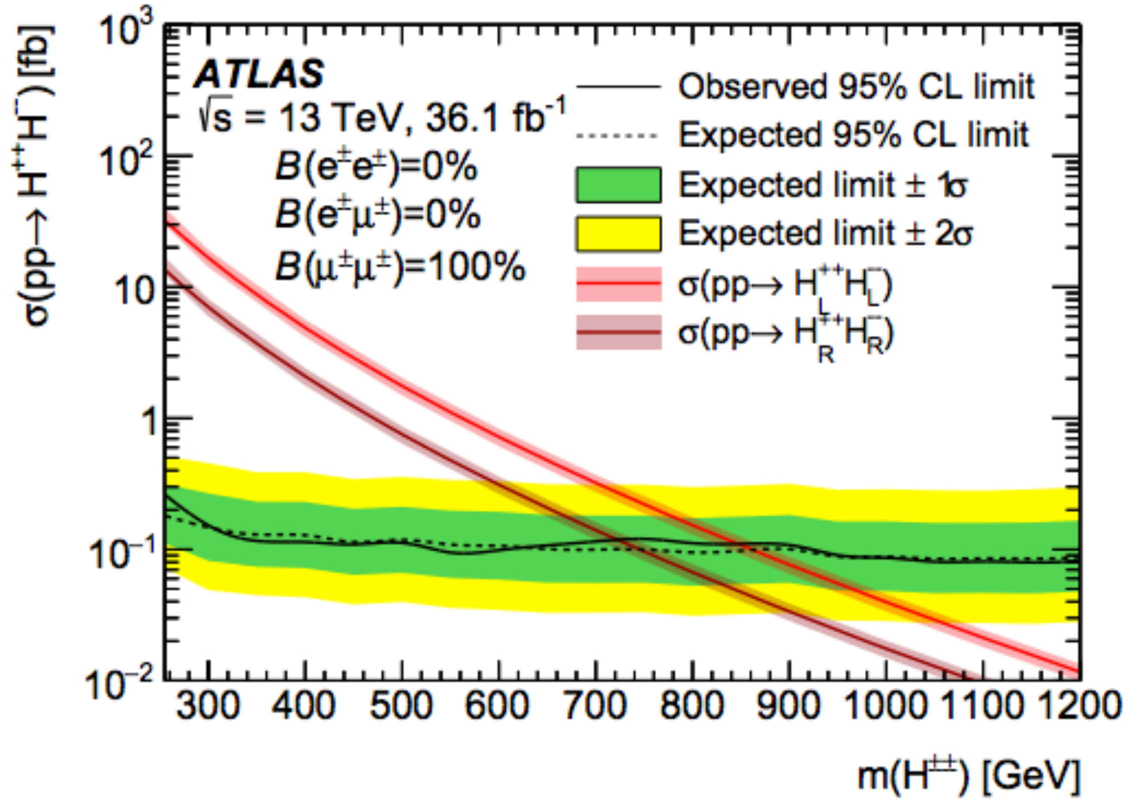
$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ - Fit results:

	SR1P3L $e^{\pm}e^{\pm}e^{\mp}$	SR1P3L $e^{\pm}\mu^{\pm}\ell^{\mp}$	SR1P3L $\mu^{\pm}\mu^{\pm}\mu^{\mp}$	SR1P3L $\mu^{\pm}\mu^{\pm}e^{\mp}, e^{\pm}e^{\pm}\mu^{\mp}$
Observed events	11	23	13	2
Total background	13.0 ± 1.6	34.2 ± 3.6	13.2 ± 1.3	3.1 ± 1.4
Diboson	9.5 ± 1.3	23.1 ± 2.9	13.1 ± 1.3	0.27 ± 0.14
Fakes	3.3 ± 0.67	10.7 ± 1.7	–	2.6 ± 1.2
Top	0.14 ± 0.02	0.45 ± 0.04	0.12 ± 0.01	0.19 ± 0.08

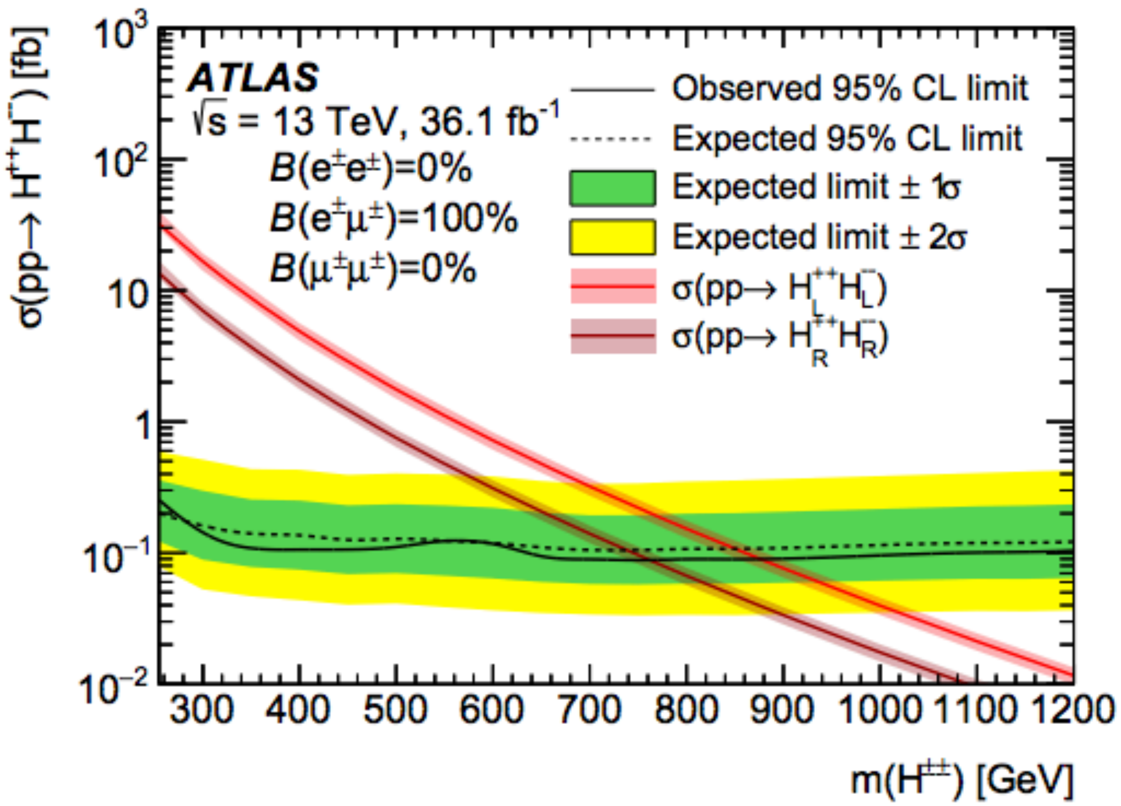
$H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ - Fit results:

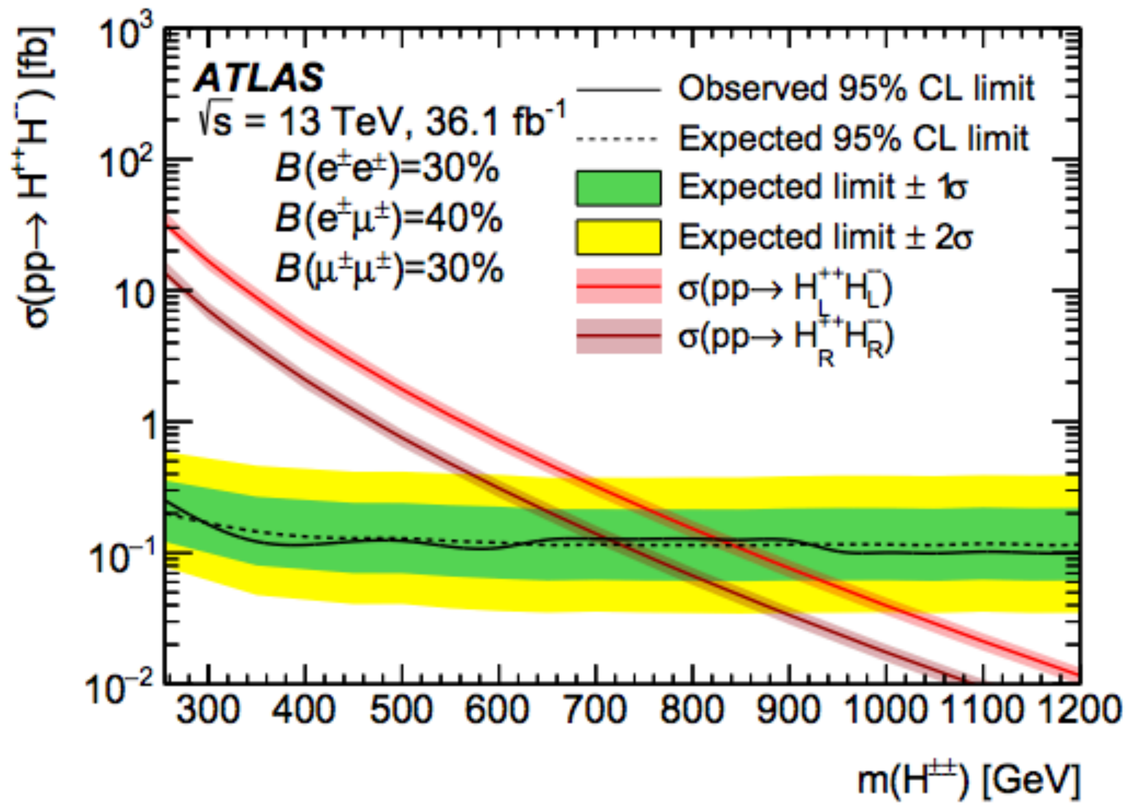


(a)

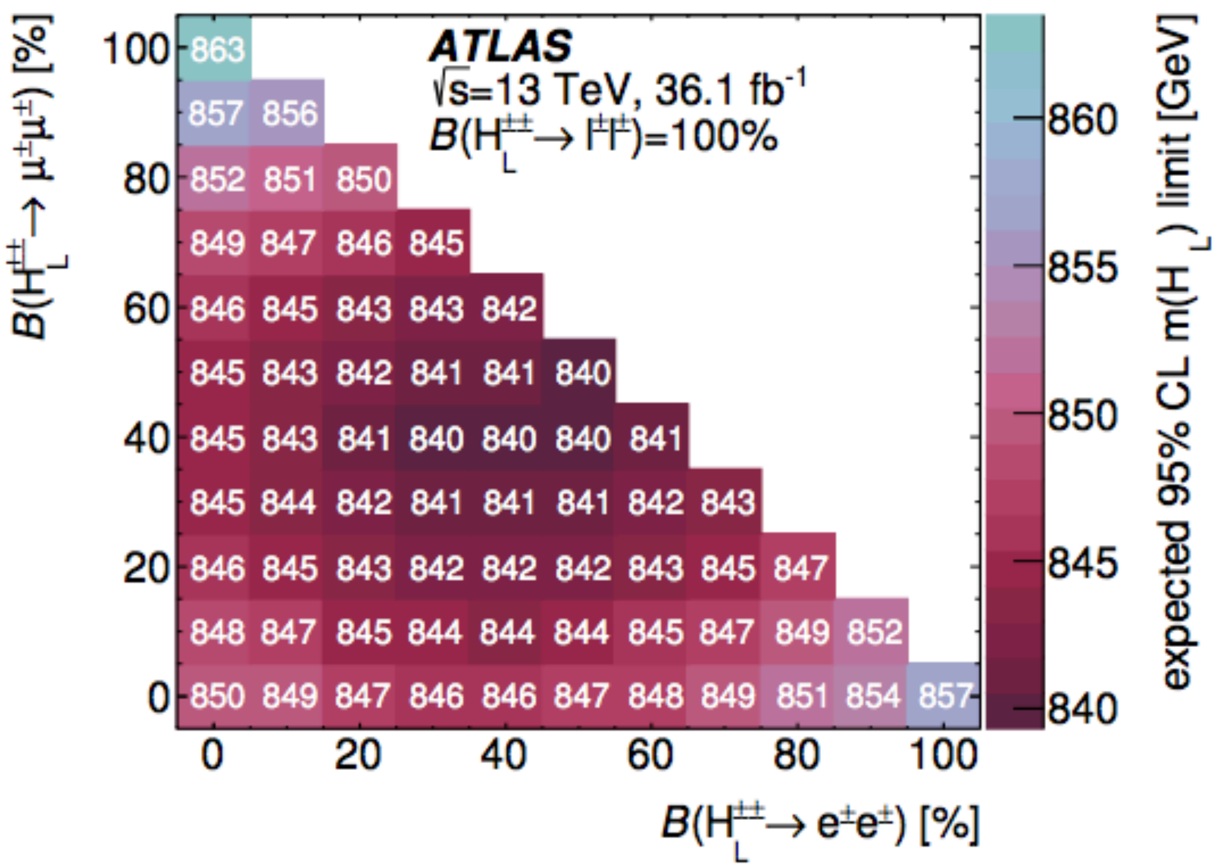


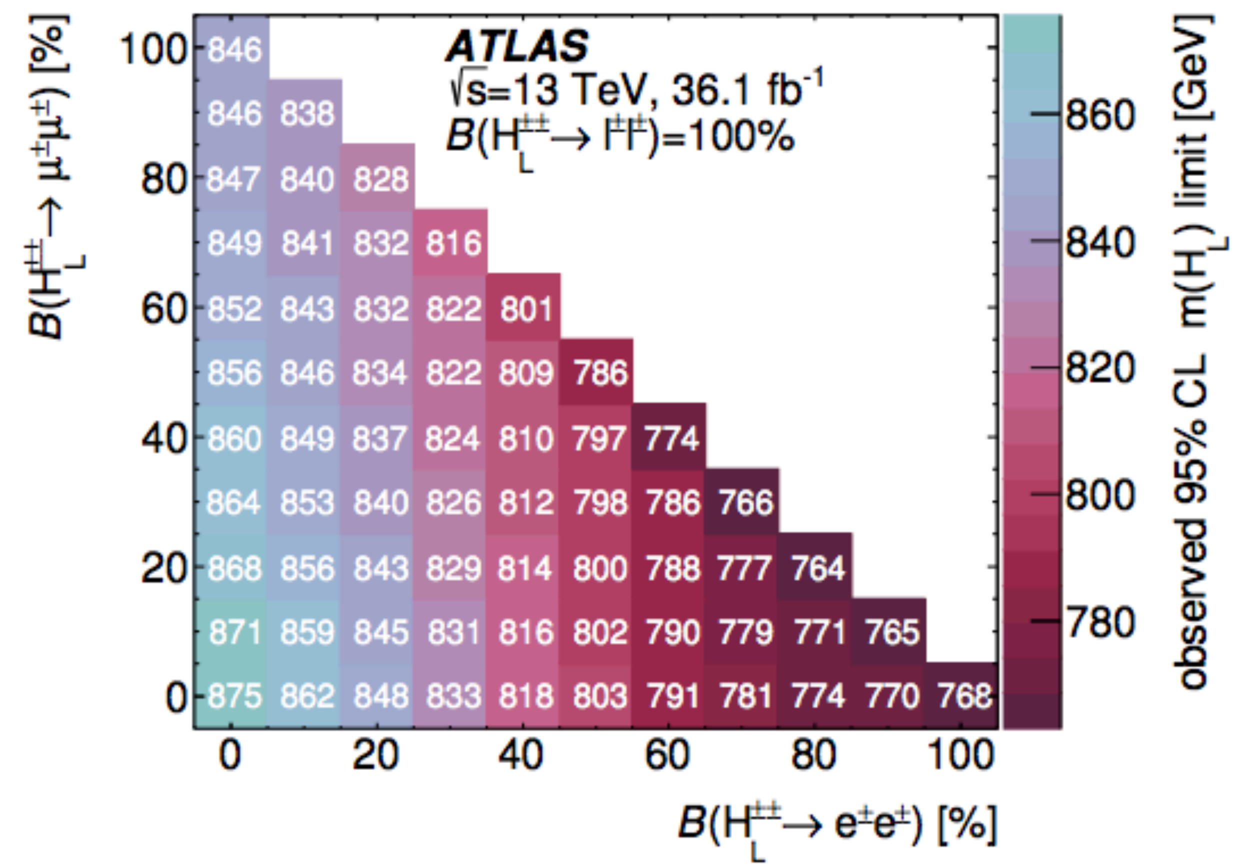
(b)

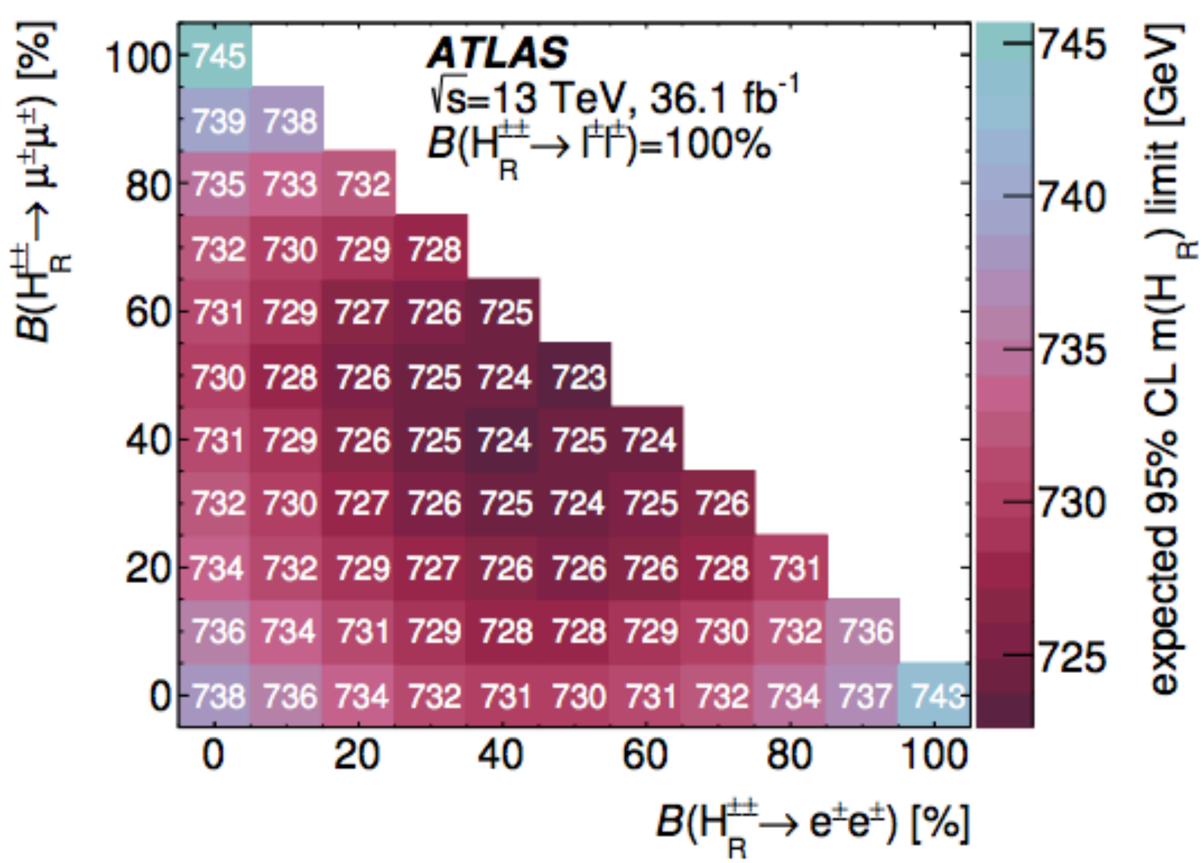


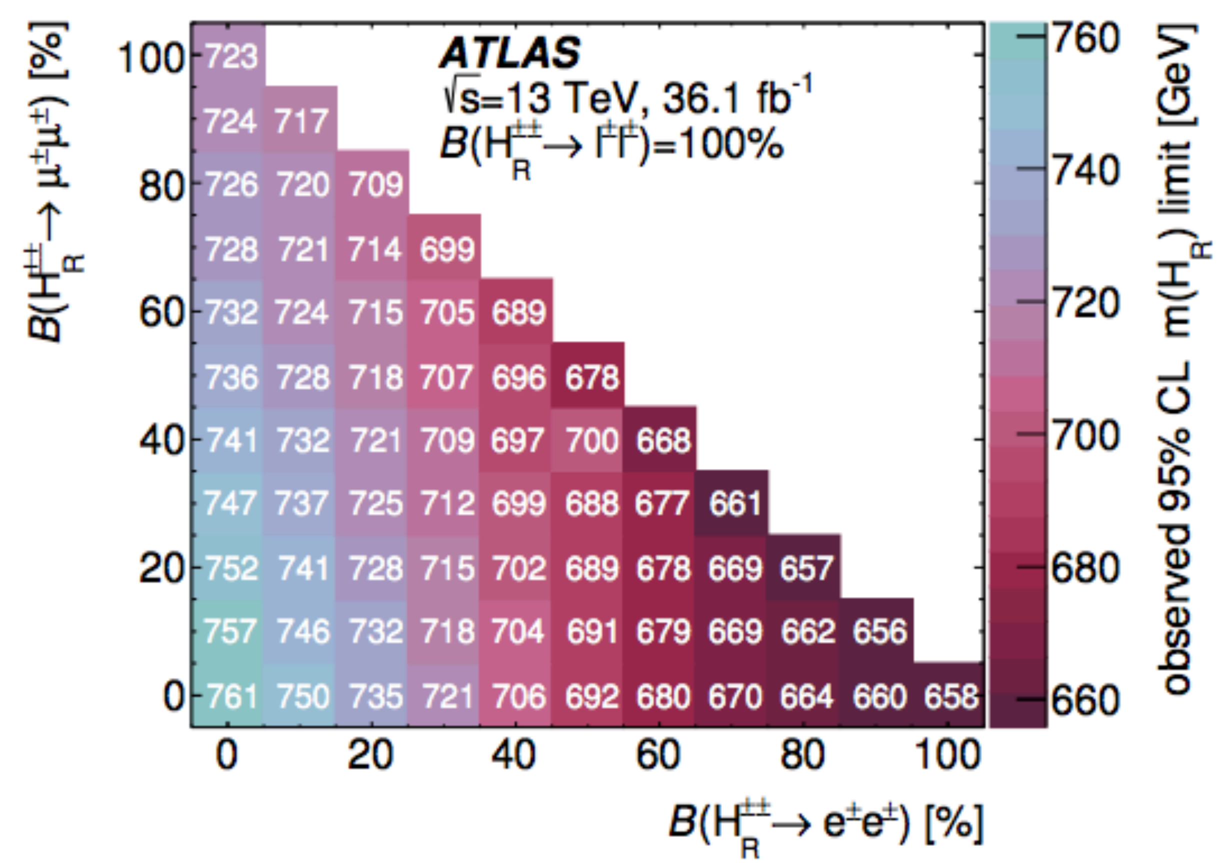


$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ - Fit results:

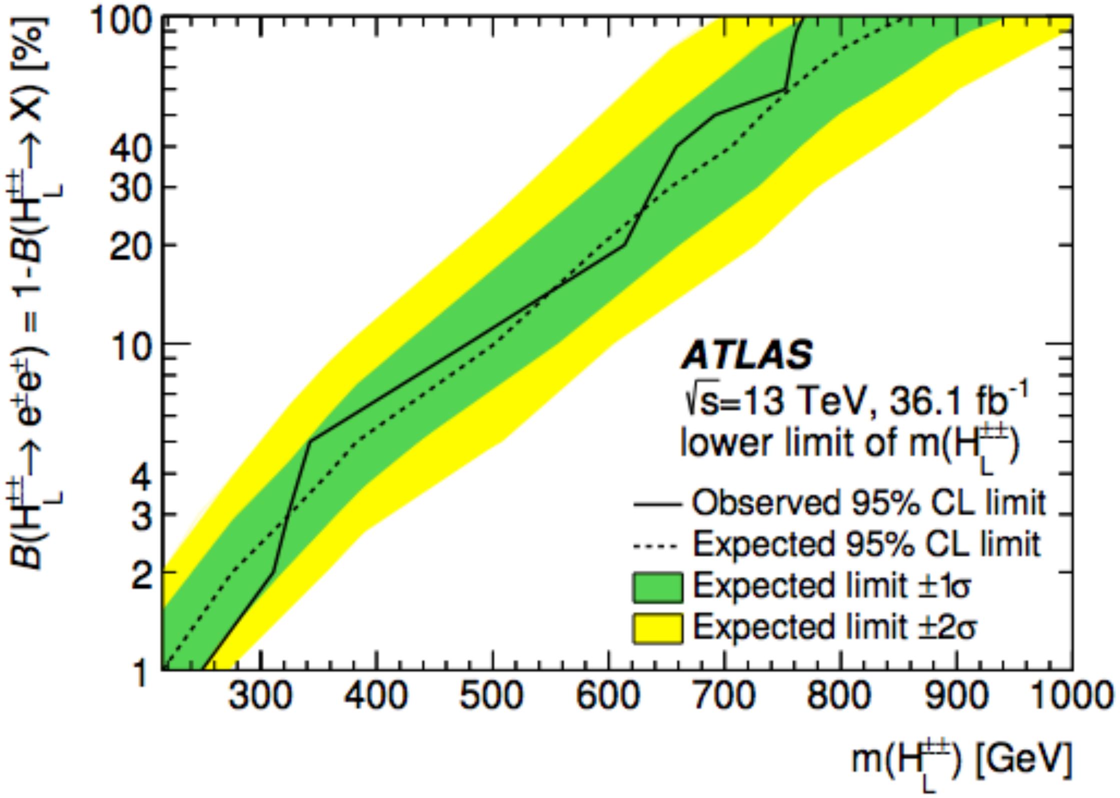




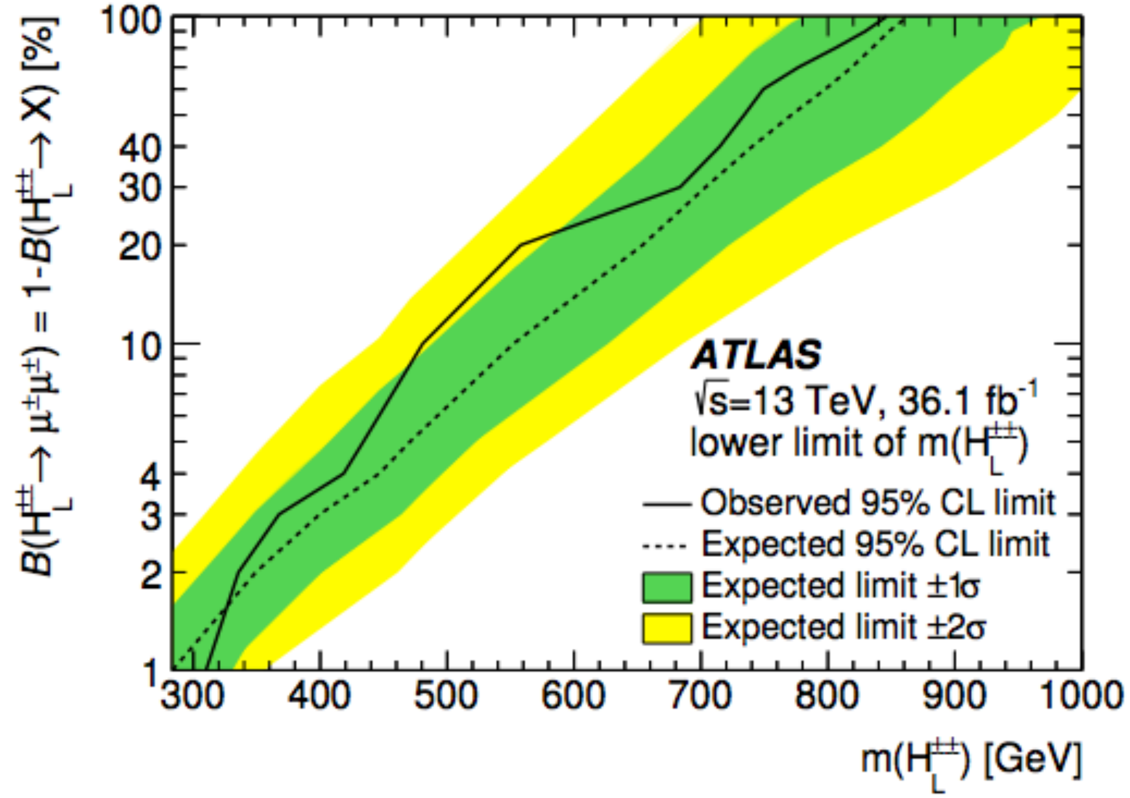




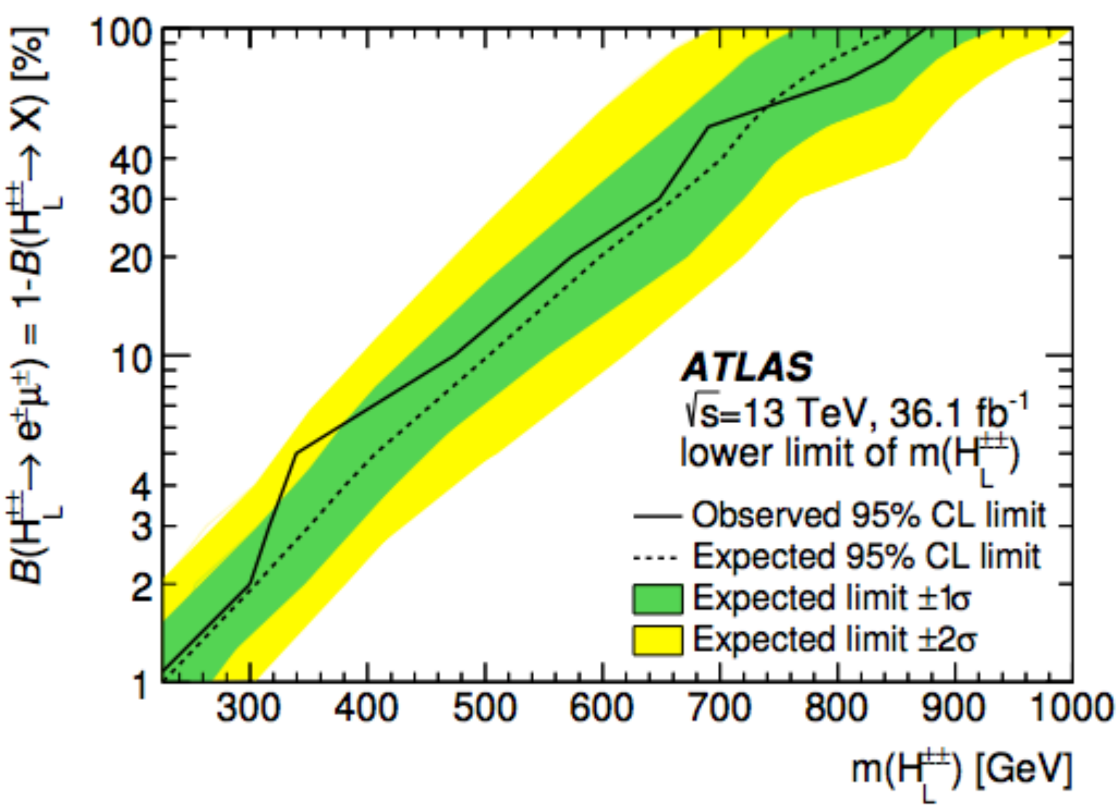
$H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ - Fit results:

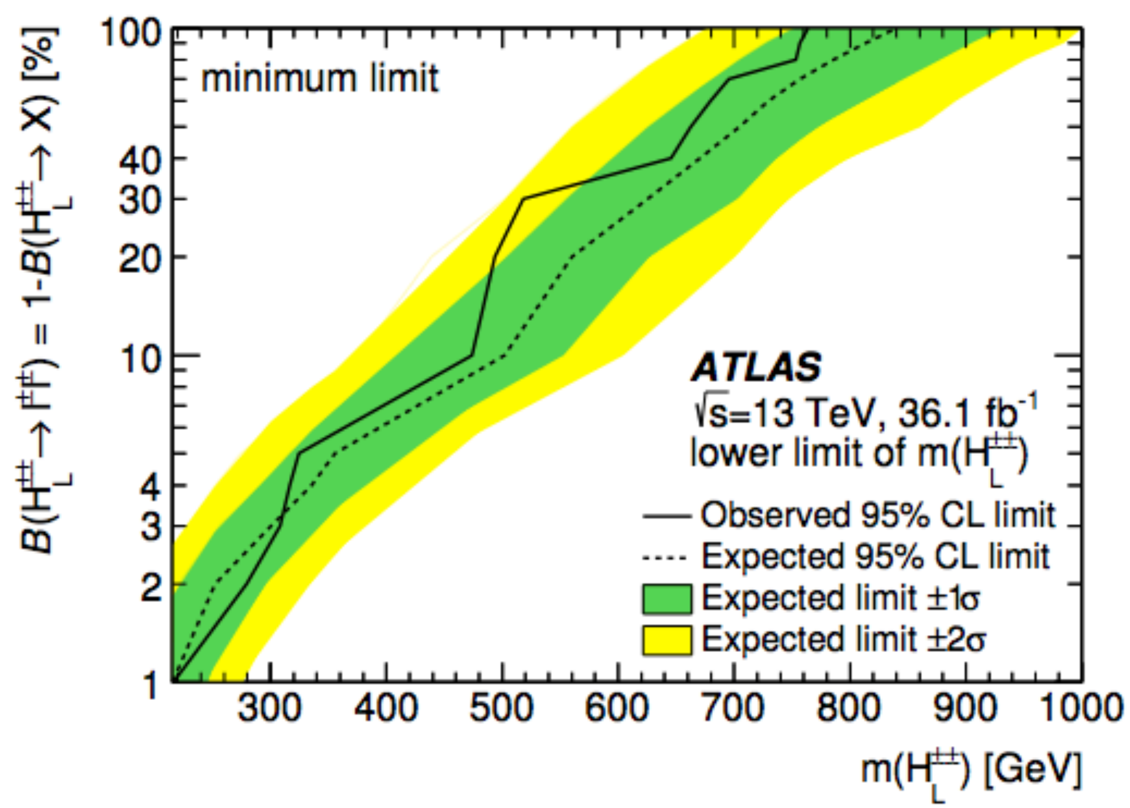


(a)

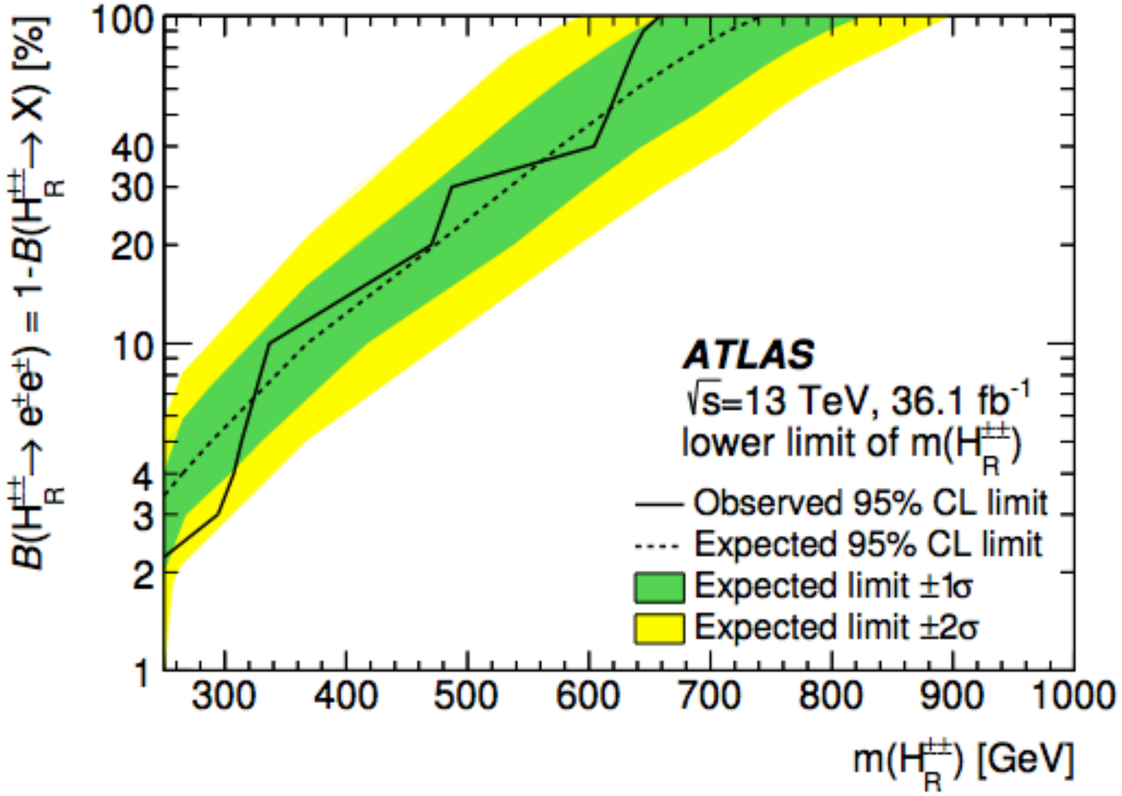


(b)

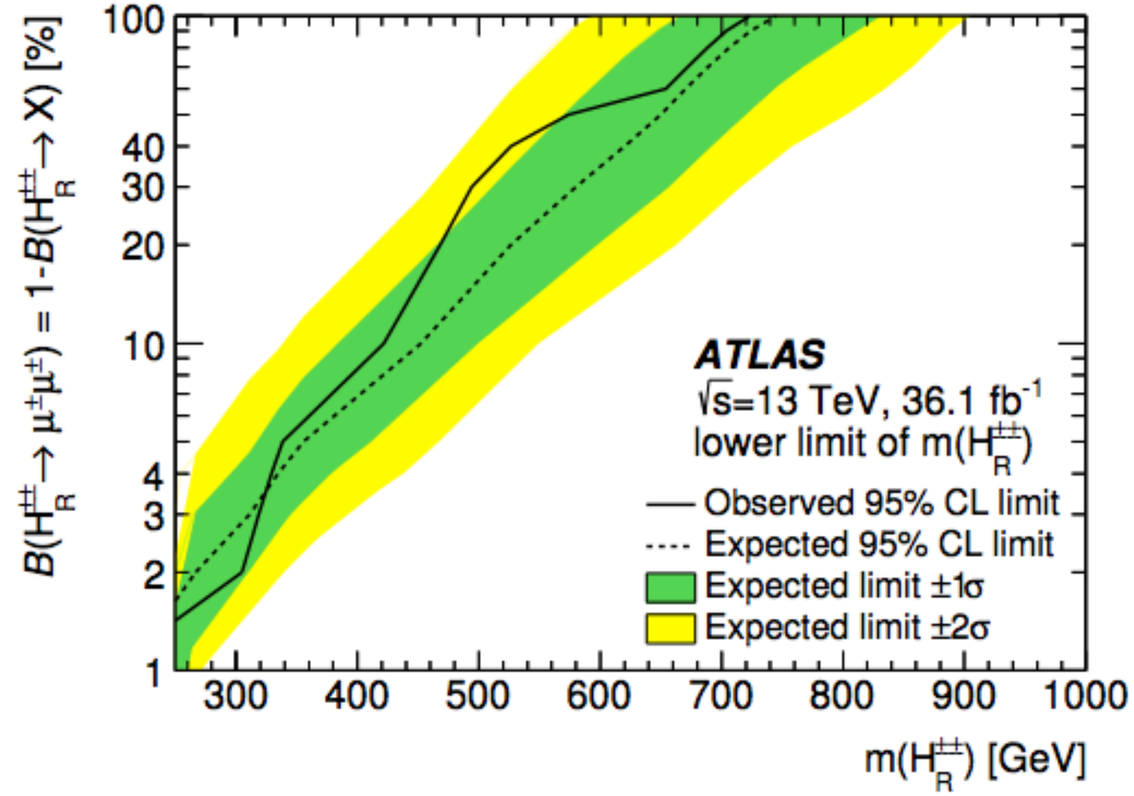




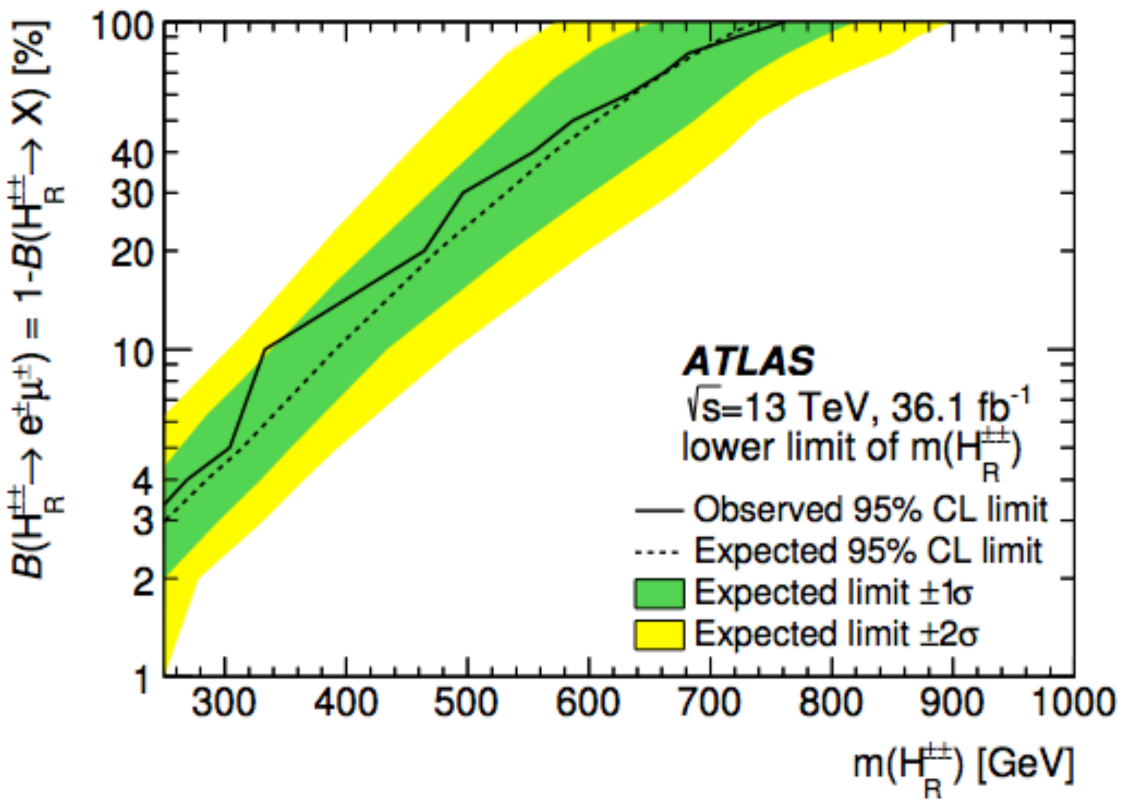
$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ - Fit results:

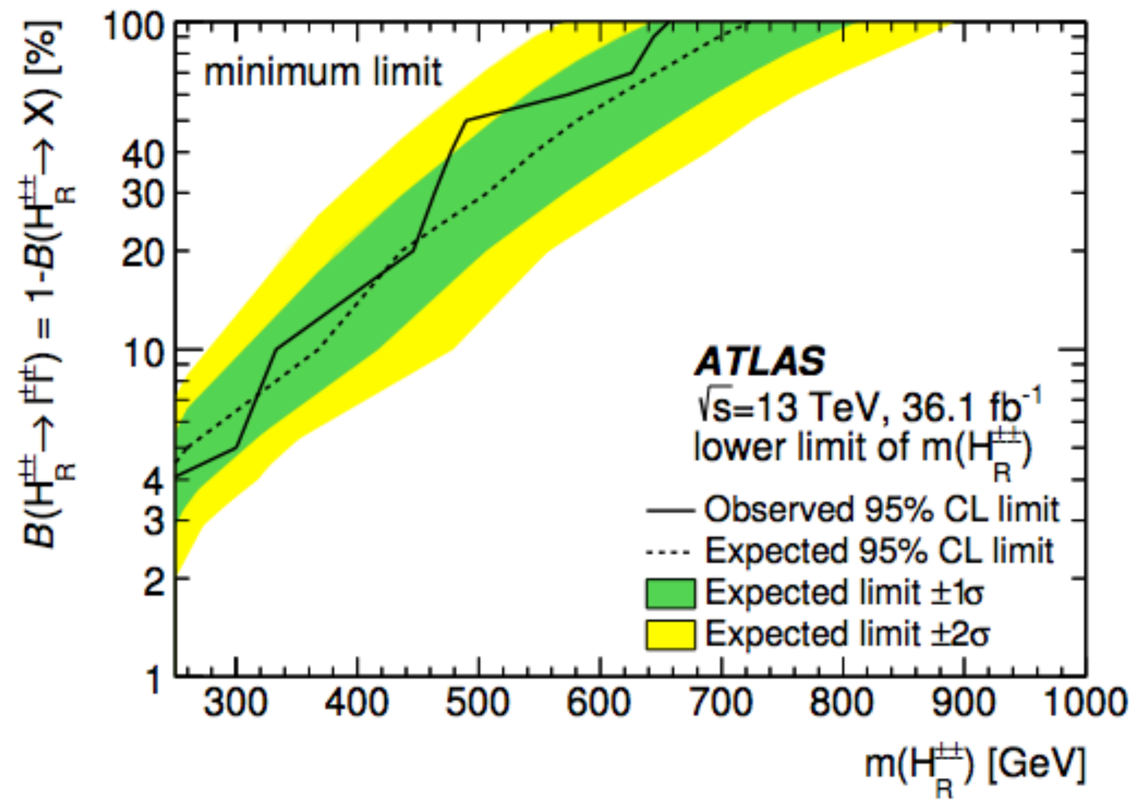


(a)



(b)



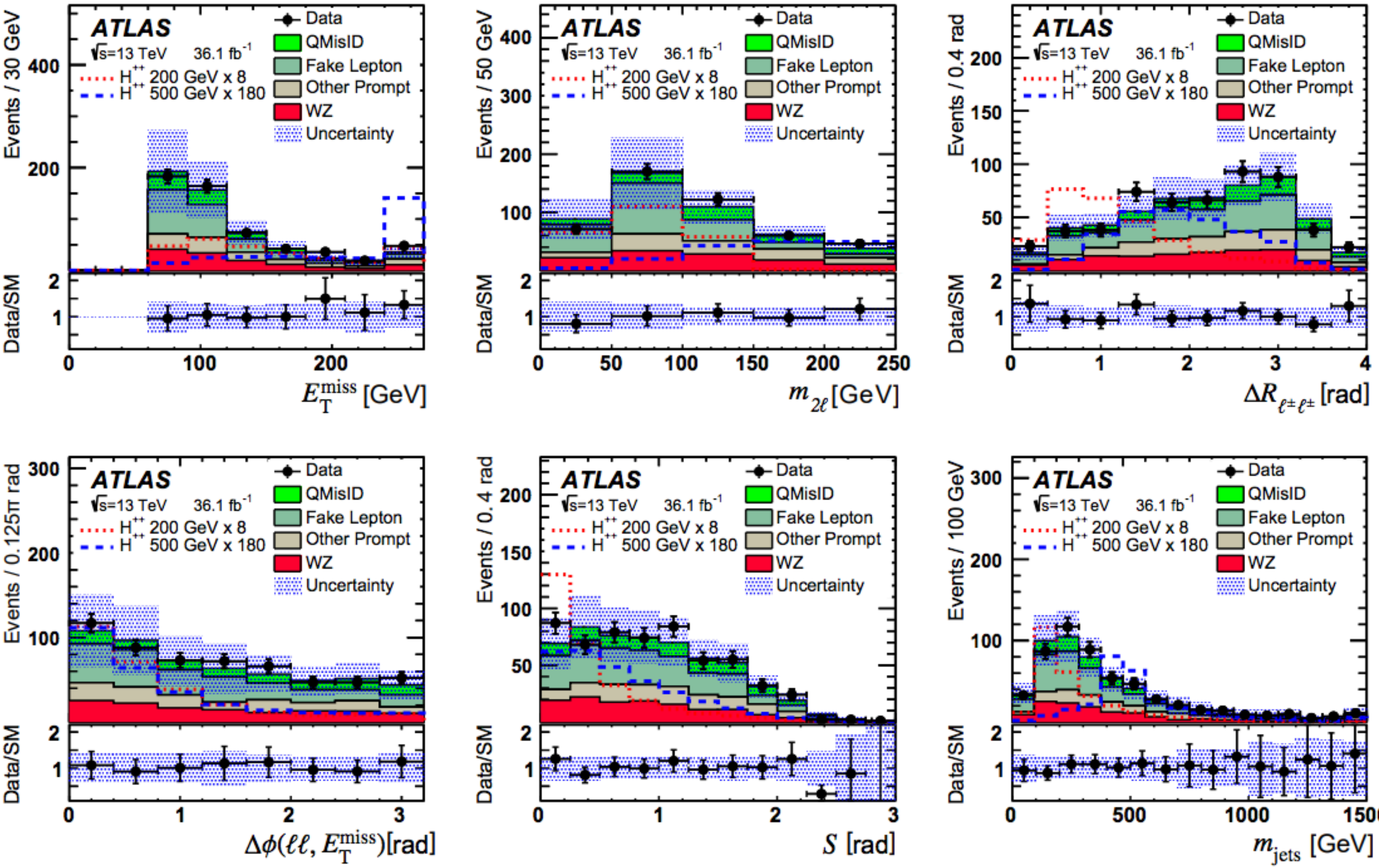


$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - simulated samples:

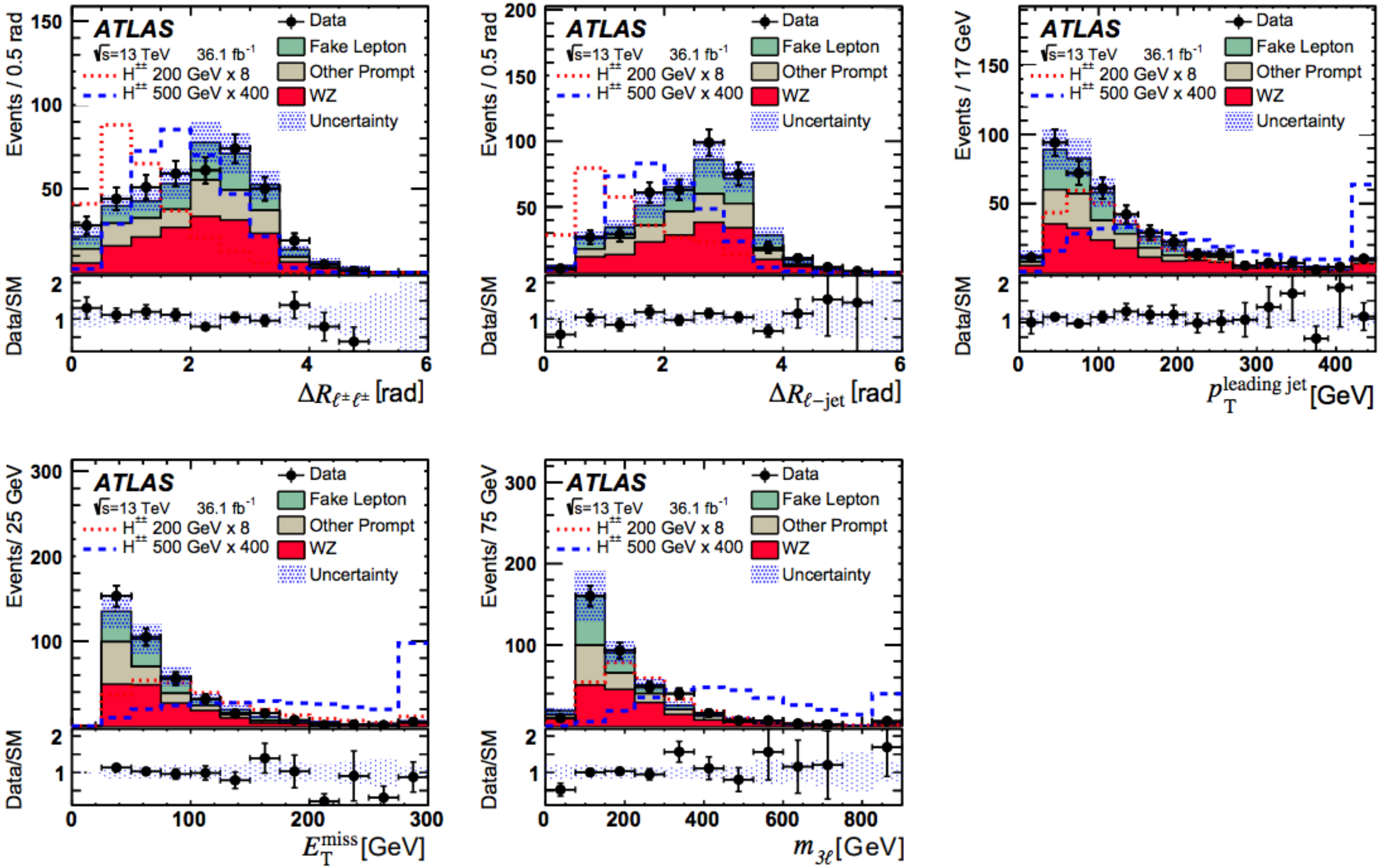
v.e.v = 0.1 GeV

Process	Event Generator	ME order	Parton Shower	PDF	Tune
VV, $qqVV$, VVV	Sherpa 2.1.1 [31]	MEPS NLO	Sherpa 2.1.1	CT10 [32]	Sherpa 2.1.1 default
$t\bar{t}H$	MG5_aMC [33]	NLO	Pythia 8 [22]	NNPDF 3.0 NLO [34]	A14 [28]
VH	Pythia 8	LO	Pythia 8	NNPDF 2.3 LO	A14
$tHqb$	MG5_aMC	LO	Pythia 8	CT10	A14
tHW	MG5_aMC	NLO	Herwig++ [35]	CT10	UE-EE-5 [36]
$t\bar{t}W$, $t\bar{t}(Z/\gamma^*)$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
$t(Z/\gamma^*)$	MG5_aMC	LO	Pythia 6 [21]	CTEQ6L1 [26, 27]	Perugia2012 [37]
$tW(Z/\gamma^*)$	MG5_aMC	NLO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}t$, $t\bar{t}t\bar{t}$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}W^+W^-$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
$V\gamma$	Sherpa 2.2	MEPS NLO	Sherpa 2.2	NNPDF 3.0 NLO	Sherpa 2.2 default
s-, t-channel, Wt single top	Powheg-Box v 2 [38, 39]	NLO	Pythia 6	CT10/CTEQ6L1	Perugia2012

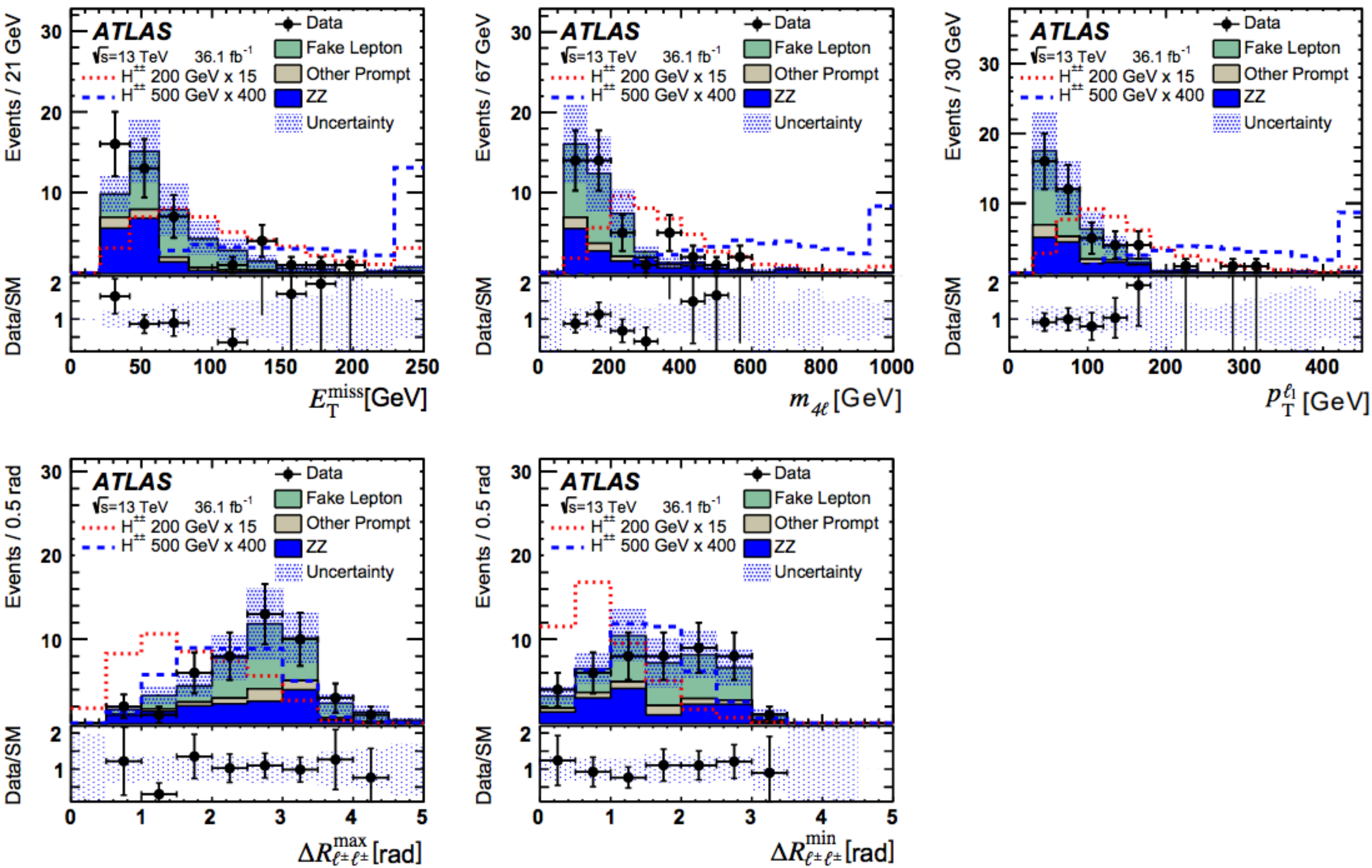
$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ - signal region optimization: 2L



$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ - signal region optimization: 3L



$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ - signal region optimization: 4L



$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - signal region optimization:

	$2\ell^{ss}$			3ℓ		4ℓ
Selection criteria	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	SFOS 0	SFOS 1,2	
	$m_{H^{\pm\pm}}$ = 200 GeV					
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV]	> 100	> 100	> 100	> 45	> 45	> 60
$m_{x\ell}$[GeV]	[25, 130]	[15, 150]	[35, 150]	> 160	> 170	> 230
$\Delta R_{\ell^{\pm}\ell^{\pm}}$[rad.]	< 0.8	< 1.8	< 0.9	[0.15, 1.57]	[0.00, 1.52]	
$\Delta\phi(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$[rad.]	< 1.1	< 1.3	< 1.3			
S[rad.]	< 0.3	< 0.3	< 0.2			
m_{jets}[GeV]	[140, 770]	[95, 330]	[95, 640]			
$\Delta R_{\ell-\mathrm{jet}}$[rad.]				[0.08, 1.88]	[0.07, 1.31]	
$p_{\mathrm{T}}^{\mathrm{leading\ jet}}$[GeV]				> 80	> 55	
$p_{\mathrm{T}}^{\ell_1}$[GeV]						> 65
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{min}}$[rad.]						[0.16, 1.21]
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{max}}$[rad.]						[0.27, 2.03]
	$m_{H^{\pm\pm}}$ = 300 GeV					
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV]	> 200	> 200	> 200	> 65	> 55	> 60
$m_{x\ell}$[GeV]	[105, 340]	[80, 320]	[80, 320]	> 170	> 210	> 270
$\Delta R_{\ell^{\pm}\ell^{\pm}}$[rad.]	< 1.4	< 1.8	< 1.8	[0.18, 2.23]	[0.08, 2.23]	
$\Delta\phi(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$[rad.]	< 2.1	< 2.4	< 2.4			
S[rad.]	< 0.4	< 0.4	< 0.4			
m_{jets}[GeV]	[180, 770]	[130, 640]	[130, 640]			
$\Delta R_{\ell j}$[rad.]				[0.27, 2.37]	[0.21, 2.08]	
$p_{\mathrm{T}}^{\mathrm{leading\ jet}}$[GeV]				> 95	> 80	
$p_{\mathrm{T}}^{\ell_1}$[GeV]						> 45
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{min}}$[rad.]						[0.09, 1.97]
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{max}}$[rad.]						[0.44, 2.68]

$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ - signal region optimization:

	$m_{H^{\pm\pm}} = 400$ GeV					
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV]	> 200	> 200	> 200	> 65	> 85	> 60
$m_{x\ell}$[GeV]	[105, 340]	[80, 350]	[80, 350]	> 230	> 250	> 270
$\Delta R_{\ell^{\pm}\ell^{\pm}}$[rad.]	< 2.2	< 1.8	< 1.8	[0.22, 2.39]	[0.29, 2.69]	
$\Delta\phi(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$[rad.]	< 2.4	< 2.4	< 2.4			
S[rad.]	< 0.6	< 0.6	< 0.5			
m_{jets}[GeV]	[280, 1200]	[220, 1200]	[220, 1200]			
$\Delta R_{\ell j}$[rad.]				[0.30, 2.59]	[0.31, 2.30]	
$p_{\mathrm{T}}^{\mathrm{leading\ jet}}$[GeV]				> 120	> 100	
$p_{\mathrm{T}}^{\ell_1}$[GeV]						> 110
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{min}}$ [rad.]						[0.39, 2.22]
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{max}}$[rad.]						[0.55, 2.90]
	$m_{H^{\pm\pm}} = 500$–700 GeV					
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV]	> 250	> 250	> 250	> 120	> 100	> 60
$m_{x\ell}$[GeV]	[105, 730]	[110, 440]	[110, 440]	> 230	> 300	> 370
$\Delta R_{\ell^{\pm}\ell^{\pm}}$[rad.]	< 2.6	< 2.2	< 2.2	[0.39, 3.11]	[0.29, 2.85]	
$\Delta\phi(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$[rad.]	< 2.6	< 2.4	< 2.4			
S[rad.]	< 1.1	< 1.1	< 1.1			
m_{jets}[GeV]	> 440	> 470	> 470			
$\Delta R_{\ell j}$[rad.]				[0.60, 2.68]	[0.31, 2.53]	
$p_{\mathrm{T}}^{\mathrm{leading\ jet}}$[GeV]				> 130	> 130	
$p_{\mathrm{T}}^{\ell_1}$[GeV]						> 160
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{min}}$ [rad.]						[0.53, 3.24]
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{max}}$[rad.]						[0.59, 2.94]

$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - signal region optimization:

	$2\ell^{ss}$			3ℓ		4ℓ
Subchannel	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	SFOS 0	SFOS 1,2	
			$m_{H^{\pm\pm}}$ = 200 GeV			
Prompt lepton	0.5 ± 0.2	0.3 ± 0.2	1.3 ± 0.6	0.3 ± 0.1	1.4 ± 0.5	0.07 ± 0.03
QMisID	0.6 ± 0.2	0.4 ± 0.1	–	–	–	–
Fake lepton	1 ± 1	< 0.4	0.4 ± 0.3	0.2 ± 0.1	0.2 ± 0.1	0.03 ± 0.02
Total background	2 ± 1	0.6 ± 0.3	1.7 ± 0.7	0.5 ± 0.1	1.7 ± 0.6	0.11 ± 0.05
Signal	1.1 ± 0.2	2.3 ± 0.4	2.4 ± 0.4	1.8 ± 0.3	5.0 ± 0.9	1.1 ± 0.2
A [%]	0.037	0.080	0.082	0.061	0.17	0.038
n_{95}	12.3	7.1	7.5	4.1	7.7	3.8
Data	3	2	2	1	2	0
			$m_{H^{\pm\pm}}$ = 300 GeV			
Prompt lepton	0.1 ± 0.1	0.9 ± 0.4	0.02 ± 0.02	0.4 ± 0.1	4 ± 1	0.3 ± 0.1
QMisID	0.1 ± 0.1	0.07 ± 0.04	–	–	–	–
Fake lepton	0.4 ± 0.5	< 0.2	< 0.4	0.3 ± 0.2	0.8 ± 0.4	0.2 ± 0.2
Total background	0.7 ± 0.5	1.0 ± 0.5	0.02 ± 0.02	0.8 ± 0.2	5 ± 2	0.5 ± 0.2
Signal	0.16 ± 0.03	0.6 ± 0.1	0.29 ± 0.05	0.6 ± 0.1	1.8 ± 0.3	0.43 ± 0.08
A [%]	0.027	0.10	0.049	0.11	0.30	0.071
n_{95}	4.0	9.6	3.0	3.1	22.7	3.8
Data	0	3	0	0	11	0

$H^{\pm\pm} \to W^{\pm}W^{\pm}$ - signal region optimization:

	$2\ell^{ss}$			3ℓ		4ℓ
Subchannel	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	SFOS 0	SFOS 1,2	
$m_{H^{\pm\pm}} = 400$ GeV						
Prompt lepton	0.7 ± 0.3	1.0 ± 0.4	0.2 ± 0.1	0.3 ± 0.1	4 ± 1	0.3 ± 0.1
QMisID	0.3 ± 0.1	0.2 ± 0.1	–	–	–	–
Fake lepton	0.4 ± 0.5	< 0.3	< 0.4	0.3 ± 0.2	0.2 ± 0.1	0.05 ± 0.04
Total background	1.4 ± 0.6	1.2 ± 0.5	0.3 ± 0.1	0.6 ± 0.2	4 ± 1	0.4 ± 0.1
Signal	0.20 ± 0.04	0.38 ± 0.07	0.19 ± 0.03	0.23 ± 0.04	0.6 ± 0.1	0.17 ± 0.03
A [%]	0.11	0.21	0.11	0.13	0.36	0.092
n_{95}	10.4	18.3	6.4	3.1	10.4	4.3
Data	2	6	1	0	4	1
$m_{H^{\pm\pm}} = 500$ GeV						
Prompt lepton	1.0 ± 0.4	0.7 ± 0.3	0.3 ± 0.2	0.4 ± 0.1	3 ± 1	0.2 ± 0.1
QMisID	0.3 ± 0.1	0.2 ± 0.1	–	–	–	–
Fake lepton	0.2 ± 0.5	0.3 ± 0.5	< 0.4	0.11 ± 0.06	0.10 ± 0.05	0.2 ± 0.2
Total background	1.6 ± 0.6	1.2 ± 0.6	0.3 ± 0.2	0.5 ± 0.1	3.0 ± 0.8	0.4 ± 0.2
Signal	0.10 ± 0.02	0.16 ± 0.03	0.07 ± 0.01	0.09 ± 0.02	0.24 ± 0.04	0.06 ± 0.01
A [%]	0.16	0.25	0.11	0.14	0.37	0.098
A [%] $m_{H^{\pm\pm}} = 600$ GeV	0.22	0.36	0.16	0.17	0.44	0.11
A [%] $m_{H^{\pm\pm}} = 700$ GeV	0.26	0.38	0.17	0.19	0.48	0.12
n_{95}	8.6	12.7	3.8	3.0	7.9	4.9
Data	4	3	0	0	2	3