Search for heavy particles with leptons at ATLAS

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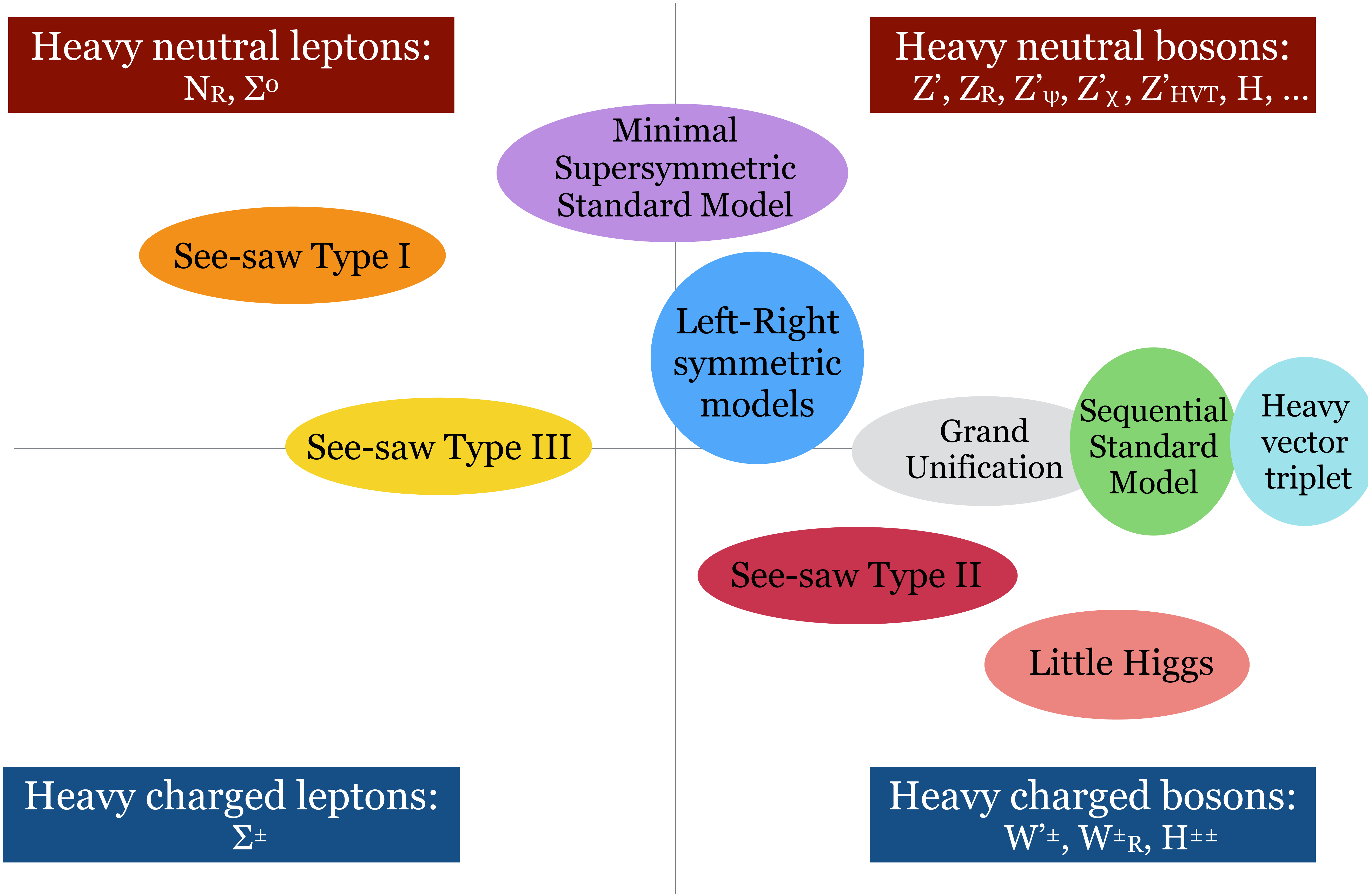
University of Melbourne
on behalf of the
ATLAS collaboration

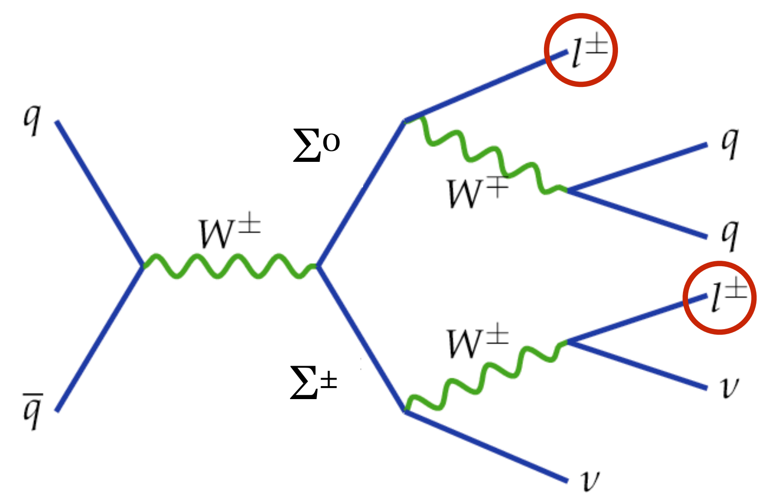
ARC Centre of Excellence for Particle Physics at the Terascale

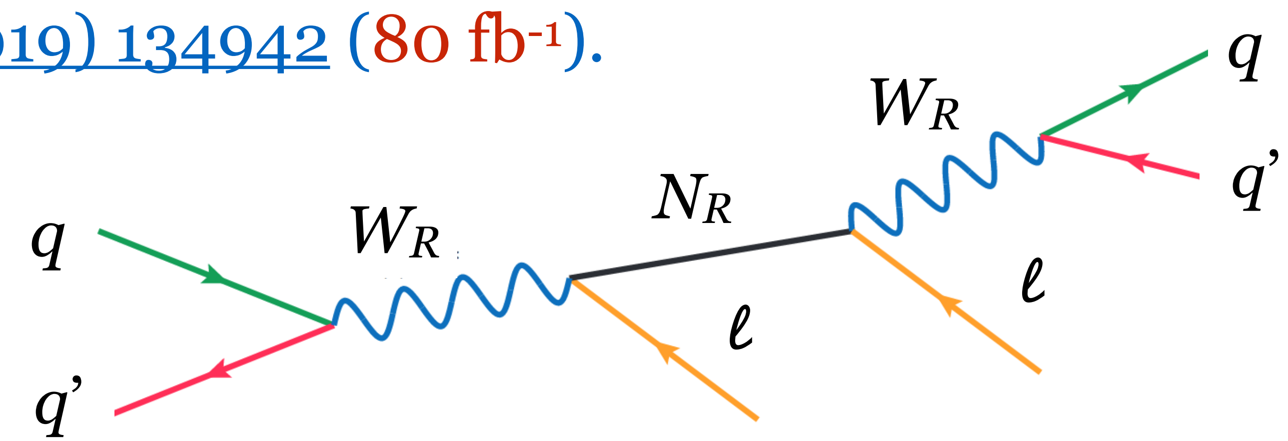
Search for new physics



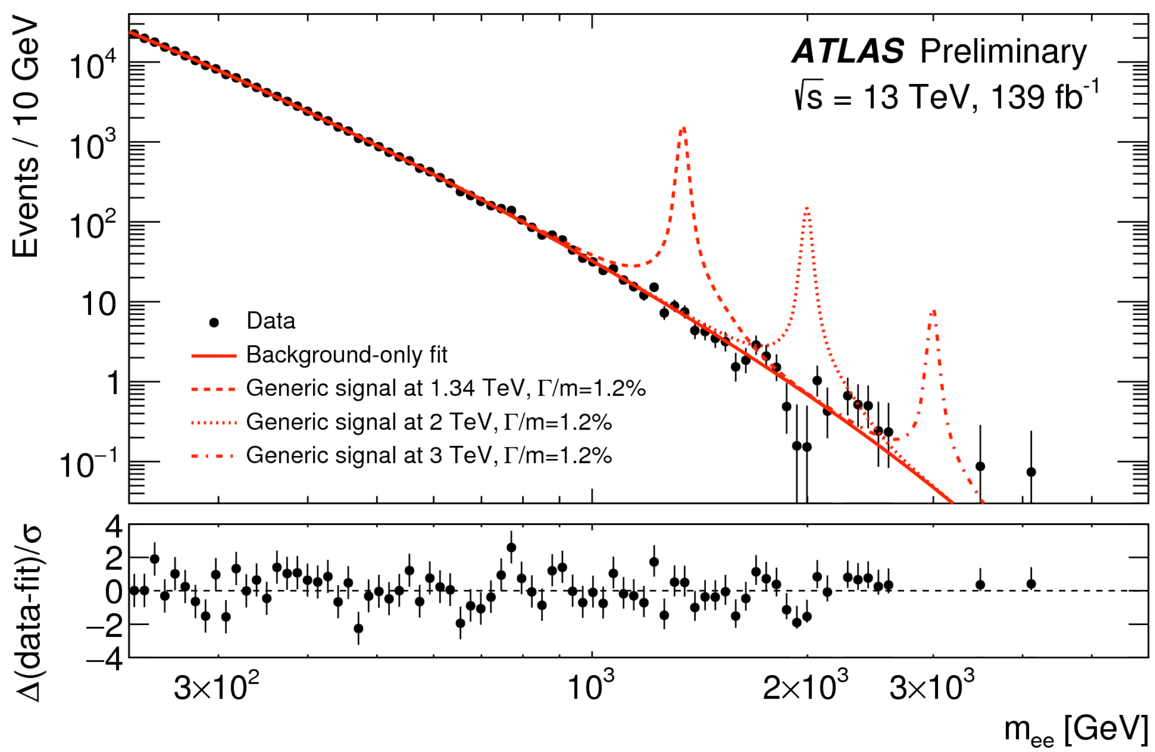
ATLAS searches @ 13 TeV

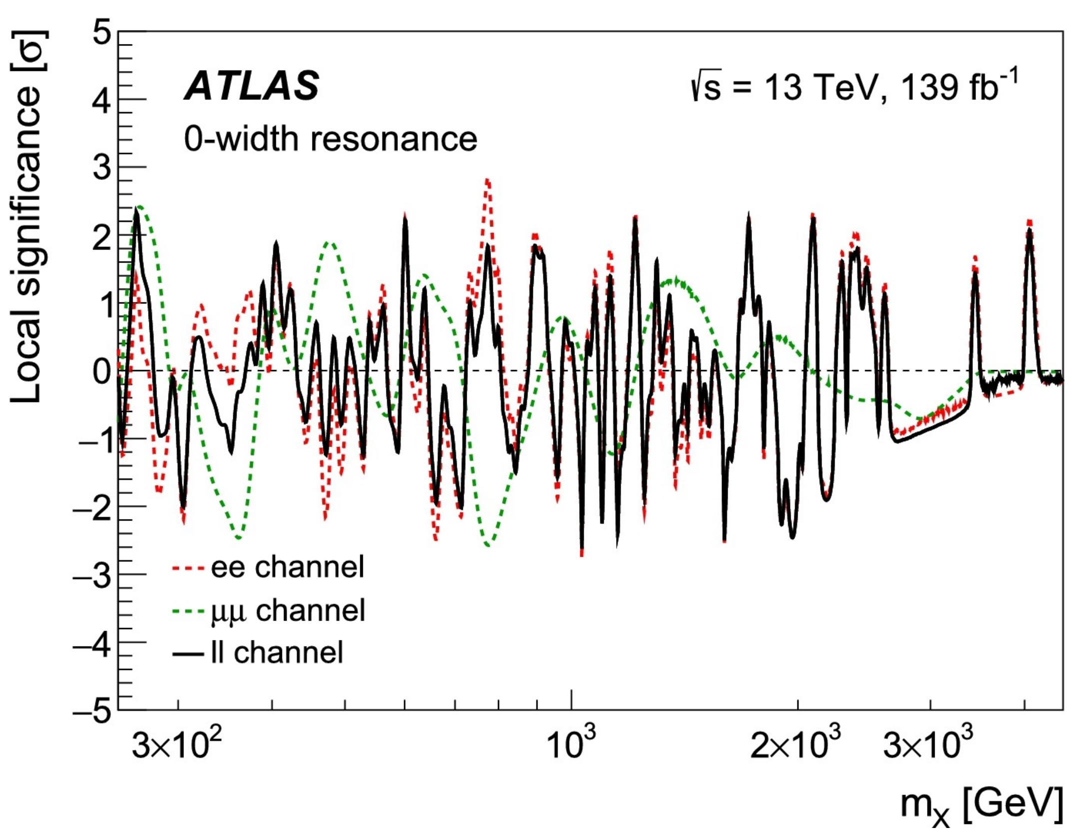
- Di-lepton:
  - **Resonant**: Phys. Lett. B 796 (2019) 68 (139 fb^{-1}).
  - **Non-resonant**: CERN-EP-2020-066 (139 fb^{-1}).
- Lepton + missing energy:
  - Phys. Rev. D 100, 052013 (2019) (139 fb^{-1}).
- Semi-leptonic:
  - **Heavy leptons**: EXOT-2018-33 (139 fb^{-1}).
  - **Heavy neutrino and W**:
    - **Resolved**: JHEP 01(2019) 016 (36.1 fb^{-1}).
    - **Boosted**: Phys. Lett. B 798 (2019) 134942 (80 fb^{-1}).





Di-lepton resonance





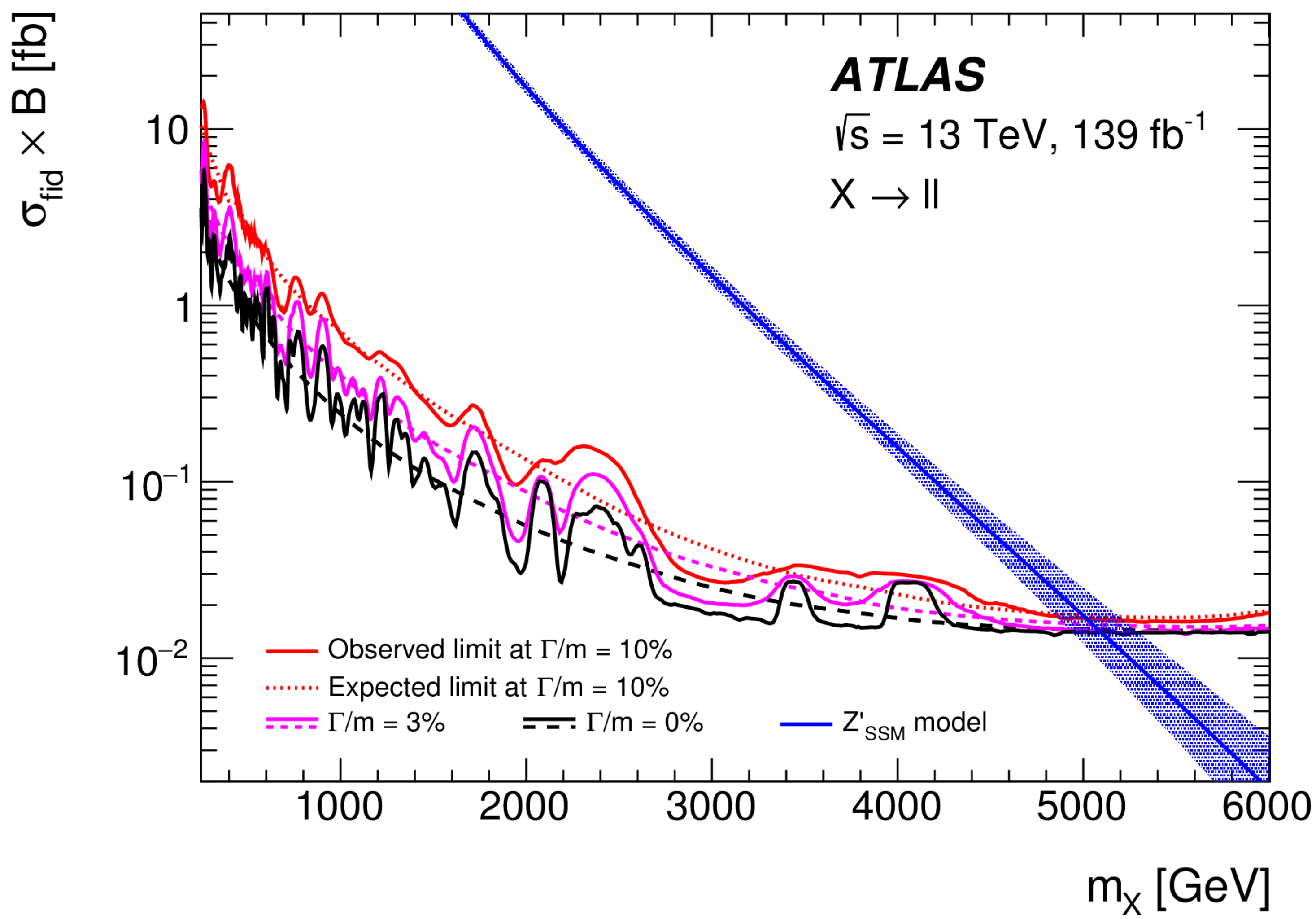
[Phys. Lett. B 796 (2019) 68]

- One *ee* or *μμ* pair.
- Bkg modelled using:

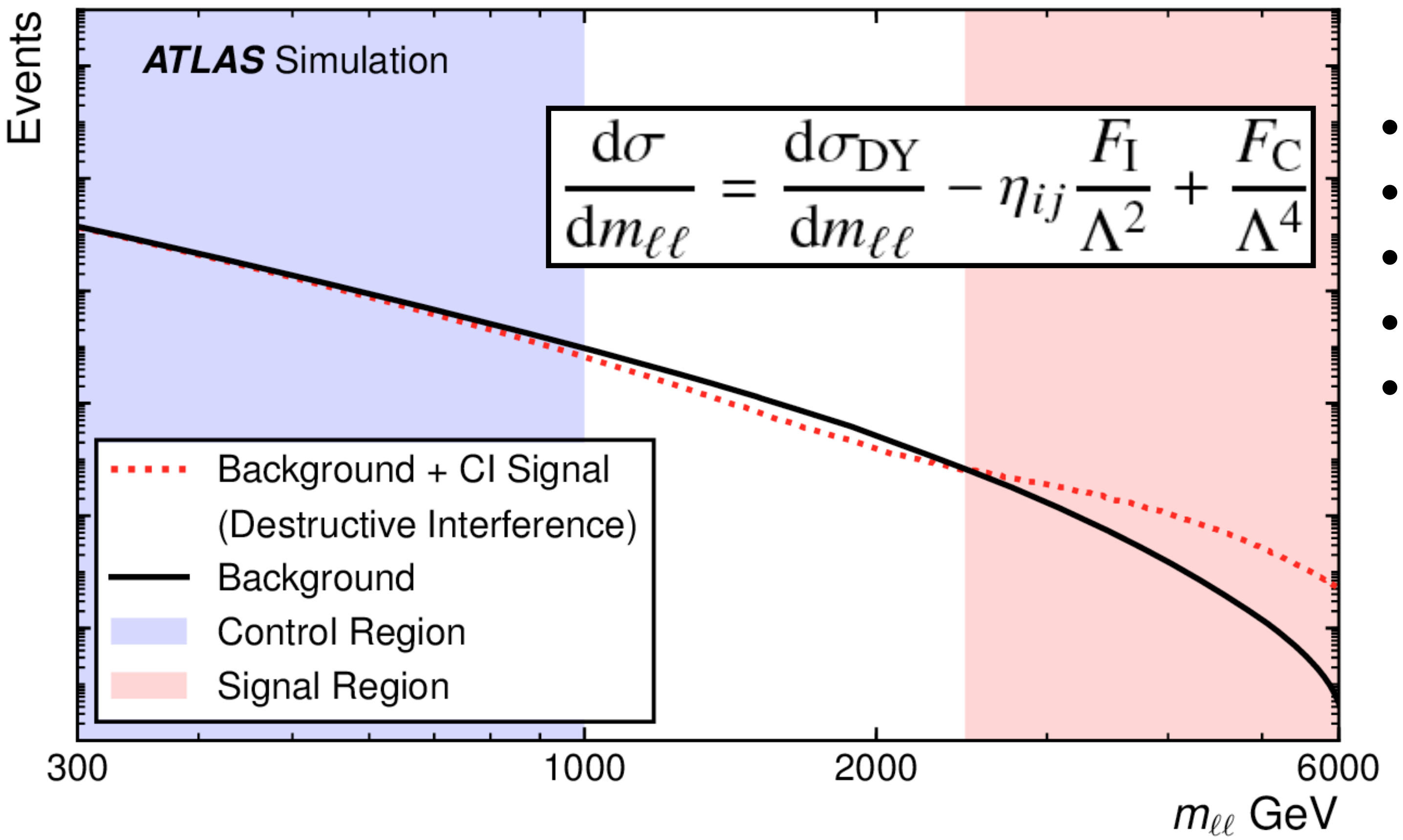
$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW},Z}(m_{\ell\ell}) \cdot (1 - x^c)^b \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i}$$

where x = $m_{\ell\ell}$ / √s, and $f_{\mathrm{BW},Z}$ is non-relativistic Breit-Wigner.

- Spin hypotheses 0, 1, 2 with consistent signal efficiency.



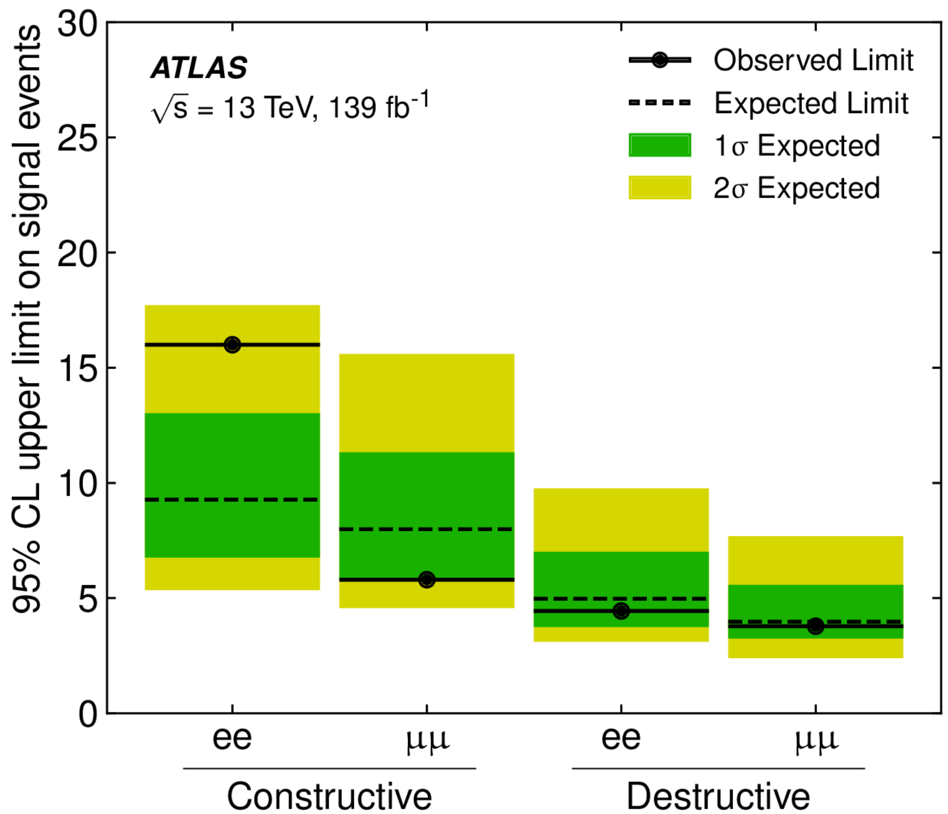
Di-lepton non-resonant

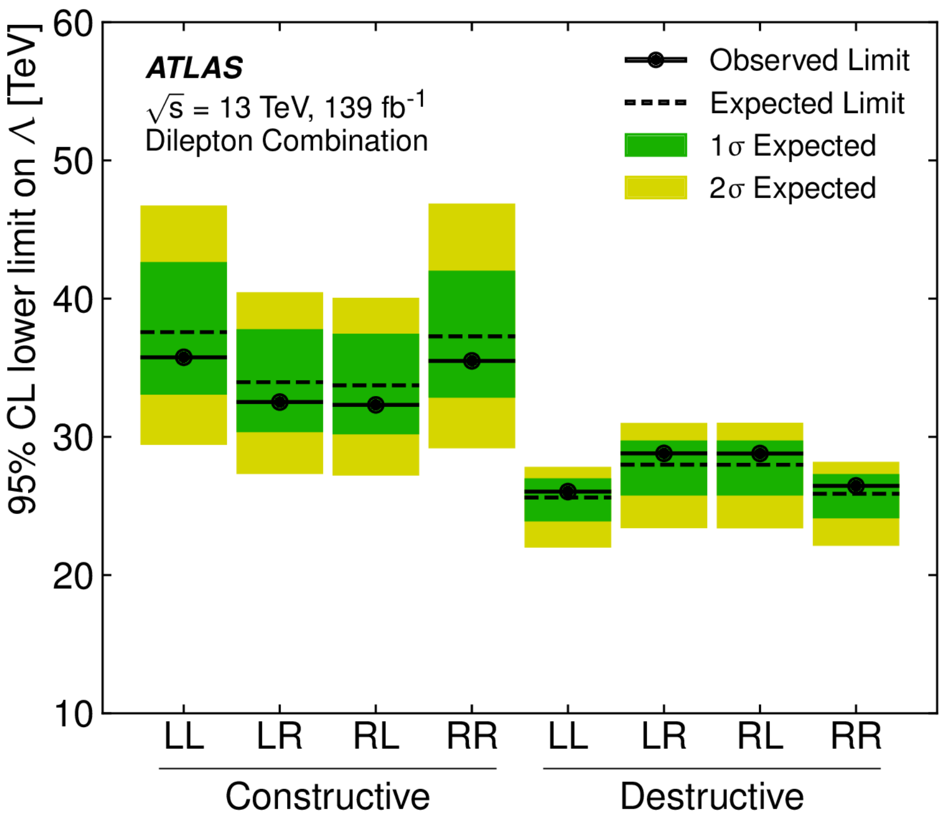


CERN-EP-2020-066

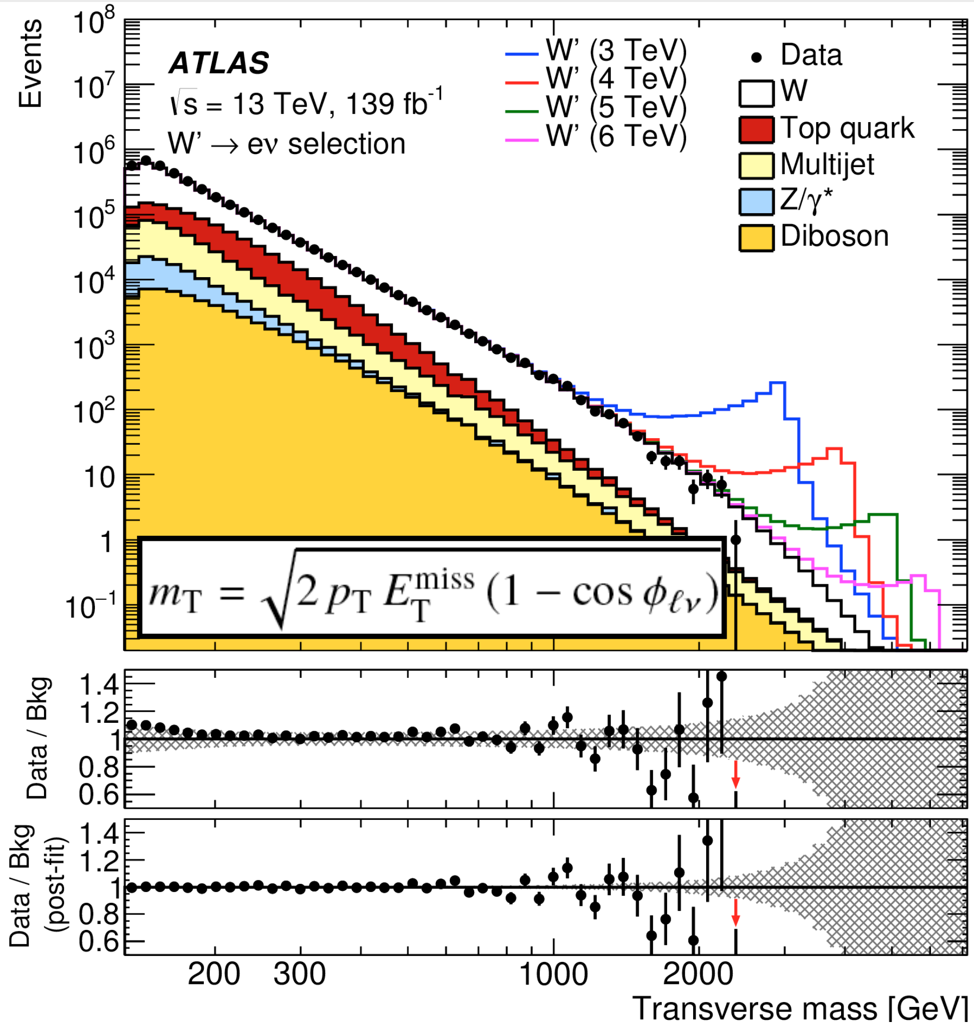
- One *ee* or $\mu\mu$ pair.
- Bkg constrained with data in low mass region.
- Contact interaction scale Λ.
- Chiral structure from η_{ij} in interference term.
- Signal + bkg model for signal contamination test in CR:

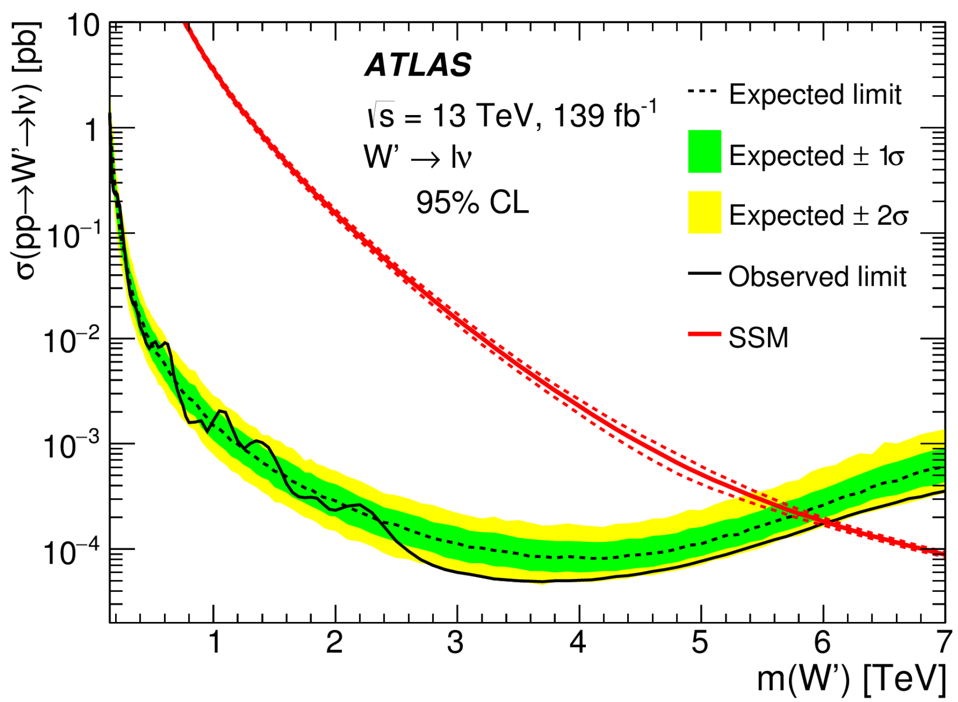
$$f_{b+s}(m_{\ell\ell}, \Lambda) = N_b \cdot f_b(m_{\ell\ell}) + N_s(\Lambda) \cdot f_s(m_{\ell\ell}, \Lambda)$$





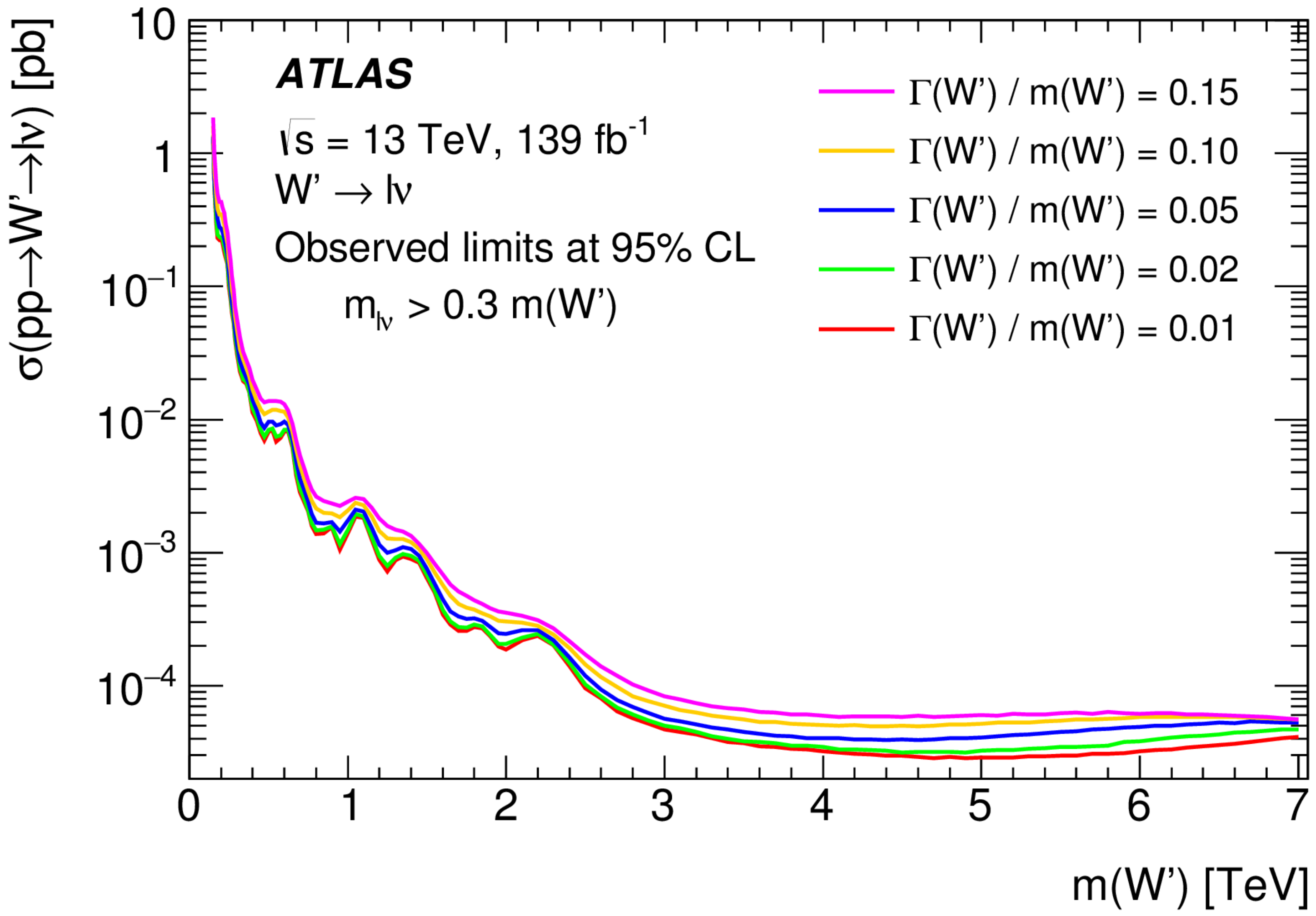
lepton + missing energy



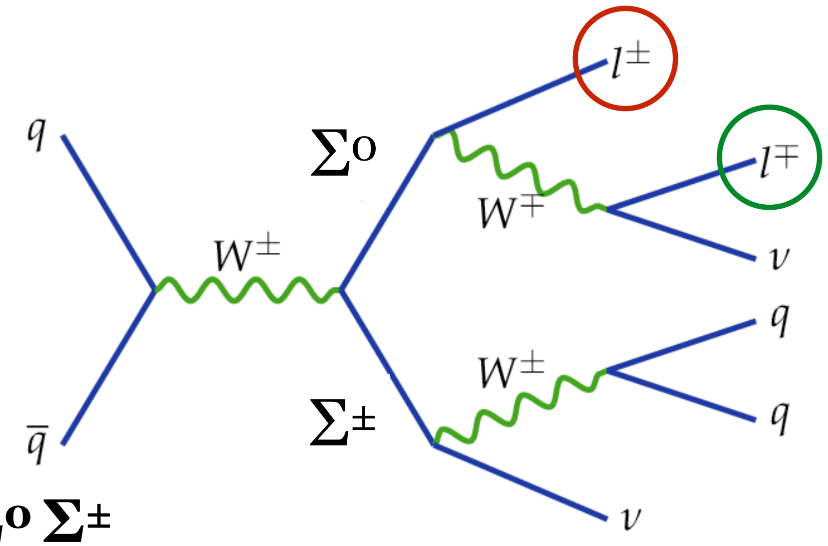


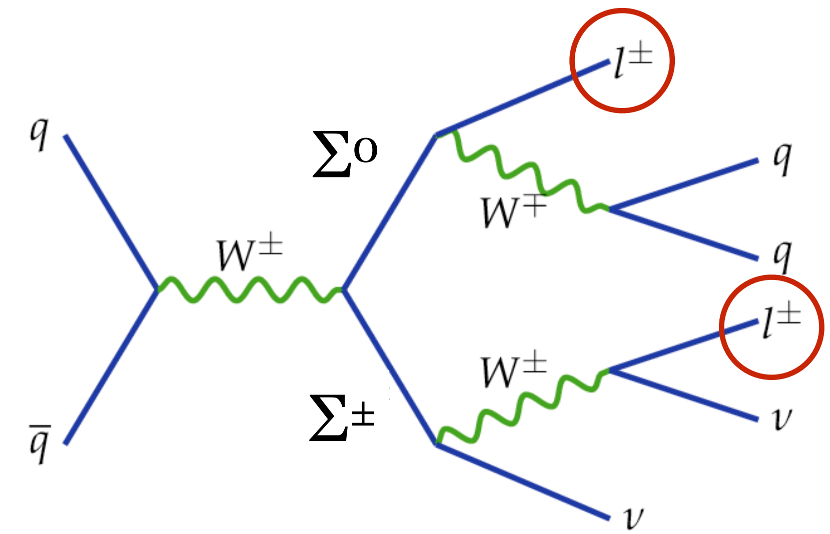
[Phys. Rev. D 100, 052013 (2019)]

- Final state with *eν* or *μν*.
- Jet -> leptons bkg modelled with data.
- Other bkg modelled with simulation.
- Different width/mass hypotheses considered.



Semi-leptonic: heavy leptons

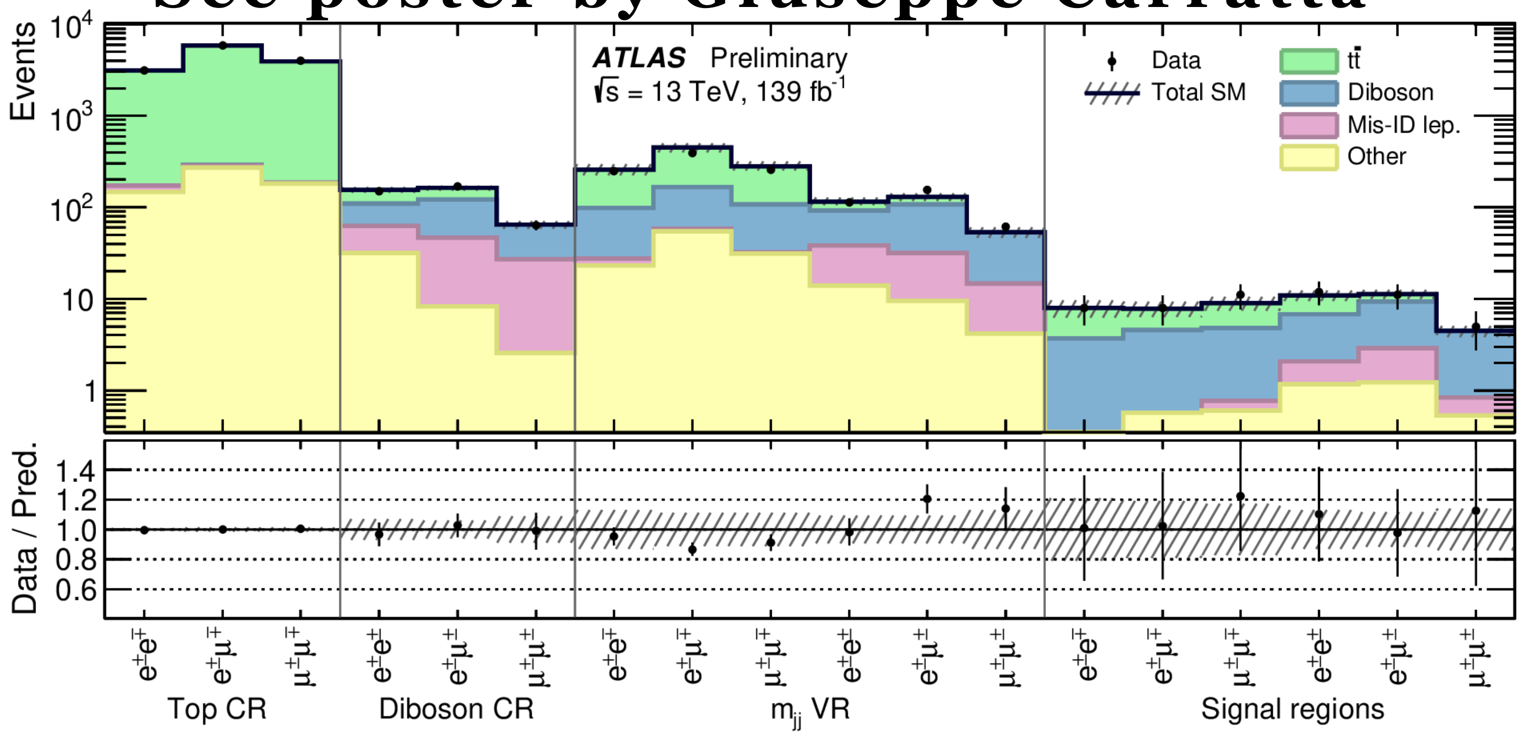


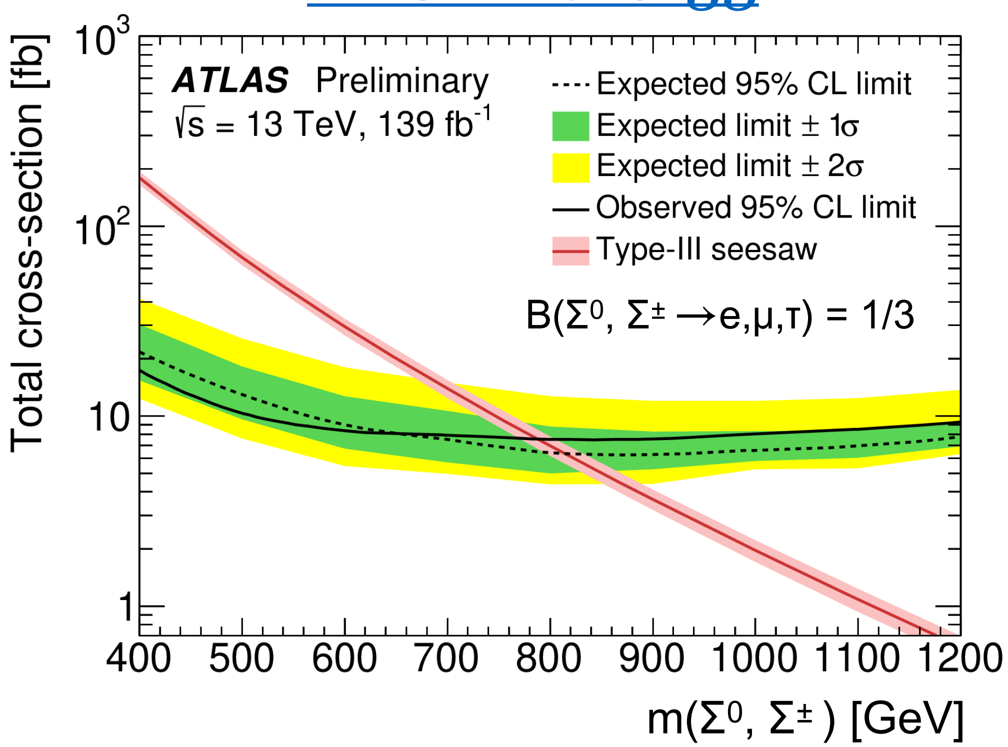


- **pp → $\Sigma^0 \Sigma^{\pm}$**
- Opposite and same-charge **di-leptons** optimised independently (*ee*, *eμ*, *μμ*).
- Two resolved jets in final state. M(j,j) consistent with W mass. E_T^{miss} required in final state.
- Scalar sum of $p_T(\ell)$, and E_T^{miss} are combined as primary discriminant.
- Assume equal branching ratio to all leptonic decays.

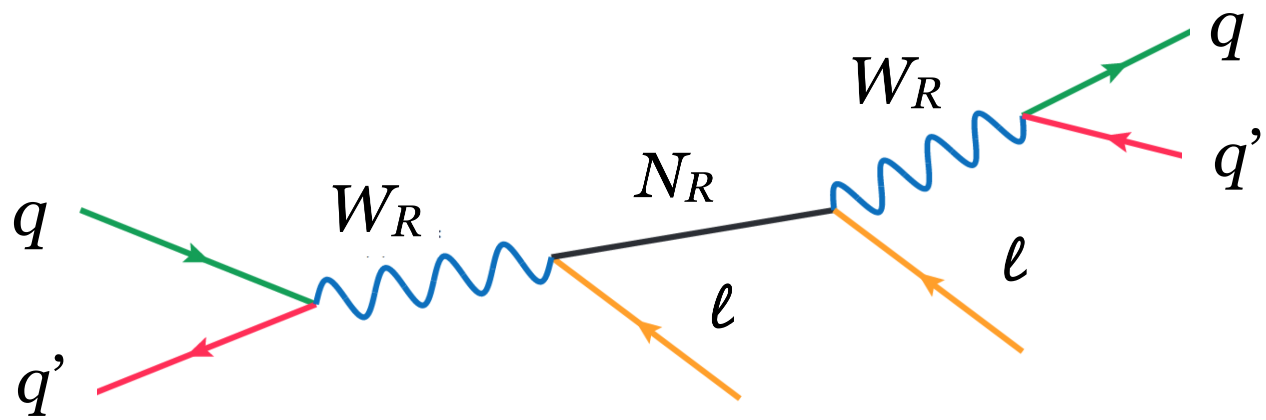
See poster by Giuseppe Carratta

EXOT-2018-33



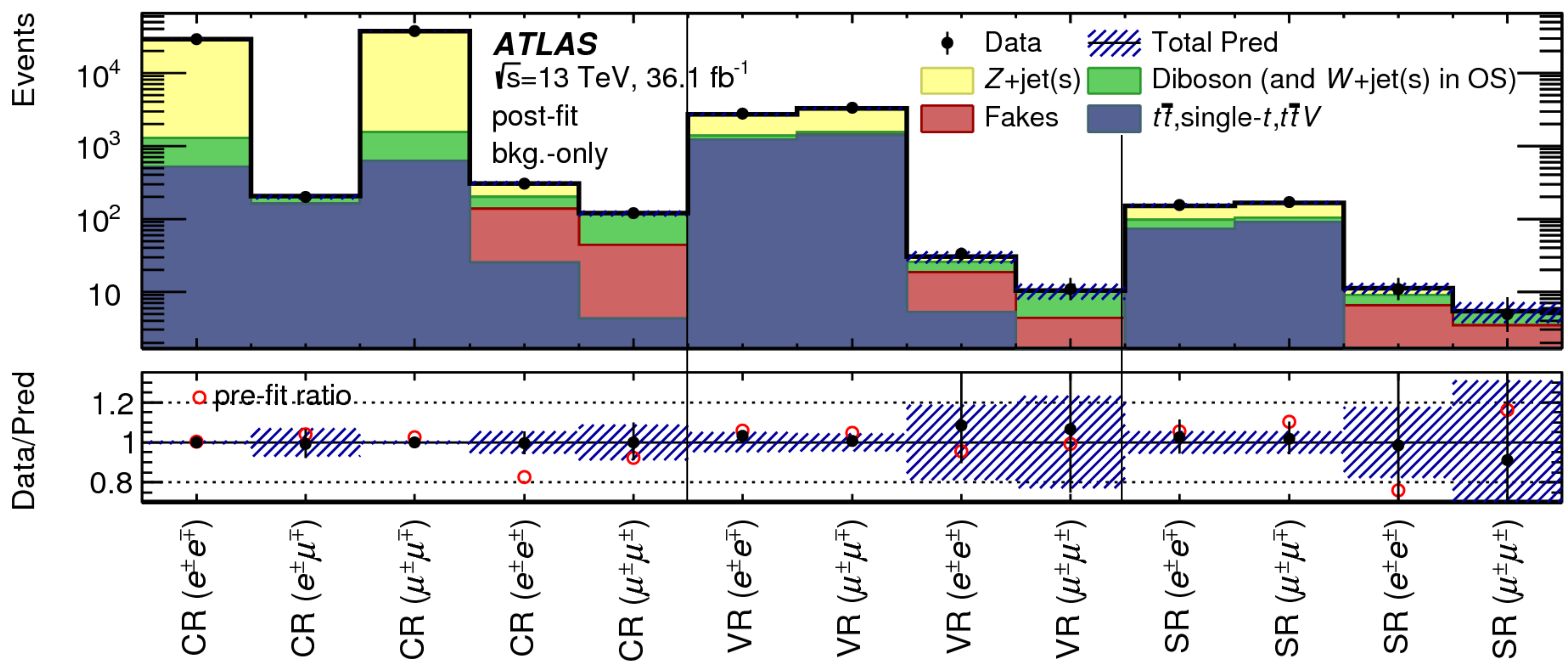


Semi-leptonic heavy neutrino and W: resolved

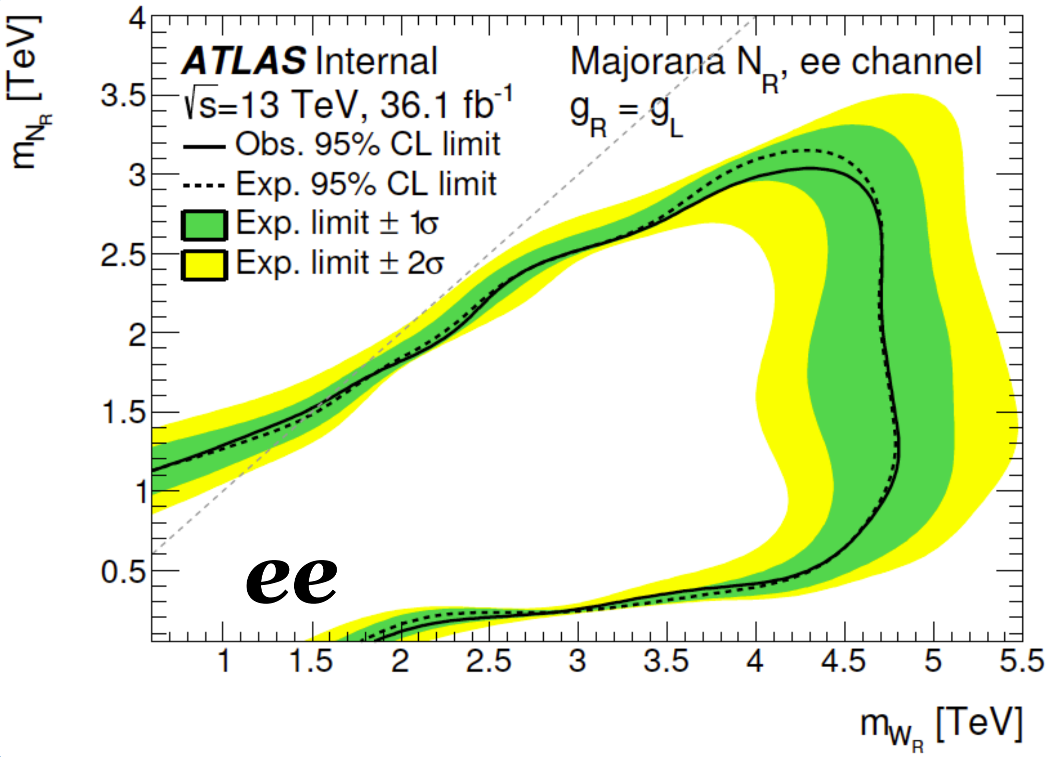


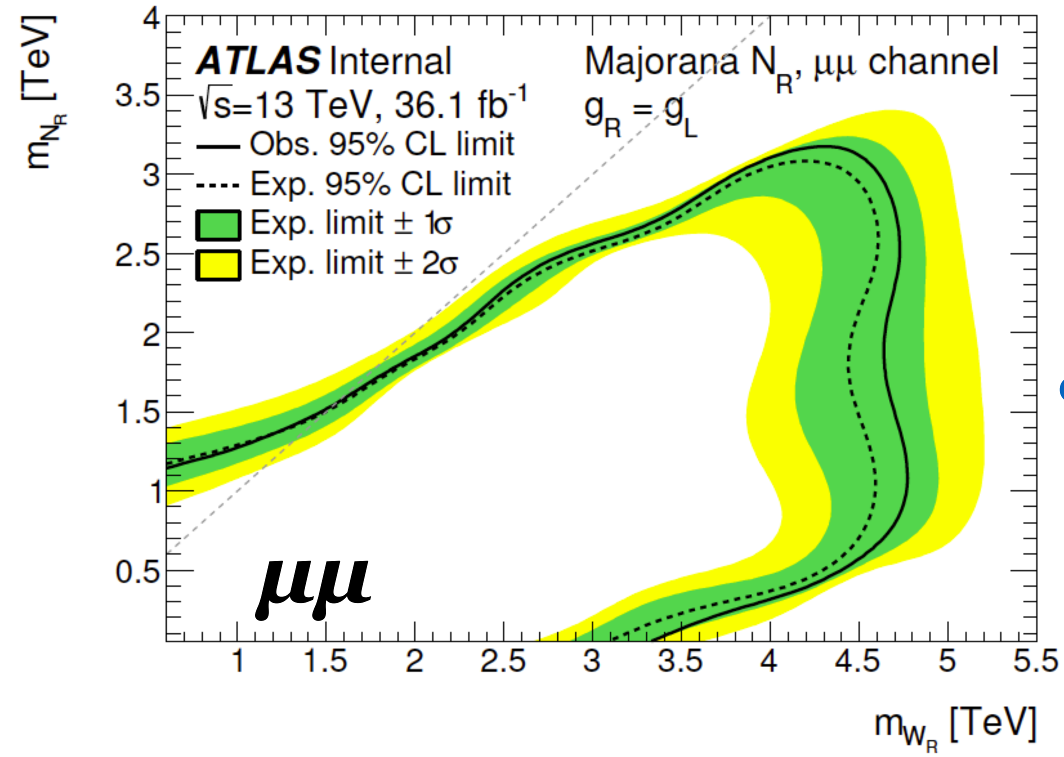
- Opposite and same -charge optimised independently. Only same-flavour leptons (*ee* or *μμ*).
- Two resolved jets in final state. No E_T^{miss} in the final state.
  - **$m_{N_R} < m_{W_R}$**: reconstruct W_R from $\boldsymbol{M(\ell, \ell, j, j)}$.
  - **$m_{N_R} > m_{W_R}$**: reconstruct W_R from $\boldsymbol{M(j, j)}$.
- H_T > 400 GeV, M(j,j) > 110 GeV, p_T(j) > 100 GeV.

JHEP 01(2019) 016

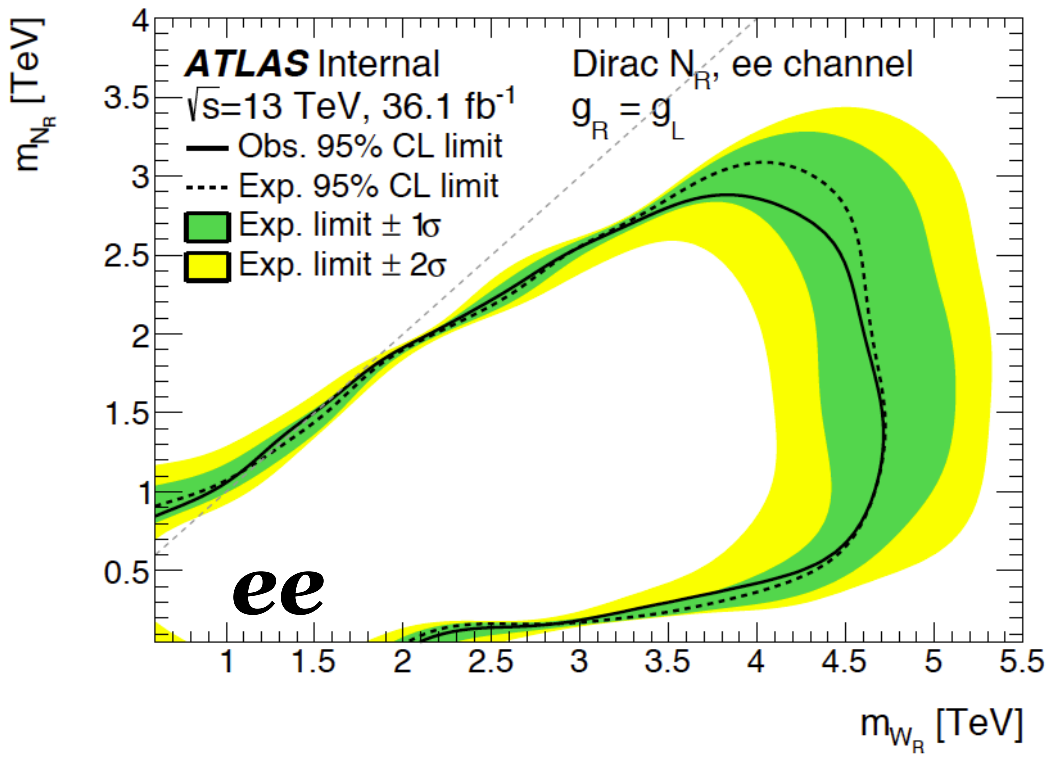


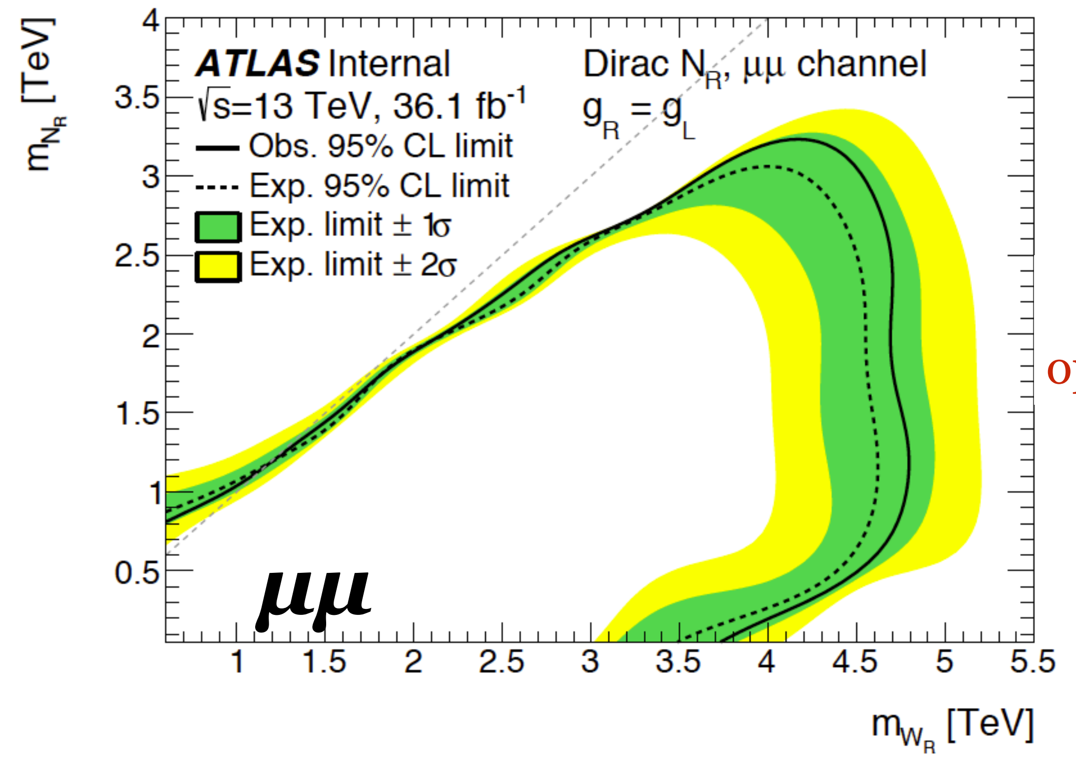
Semi-leptonic heavy neutrino and W: resolved





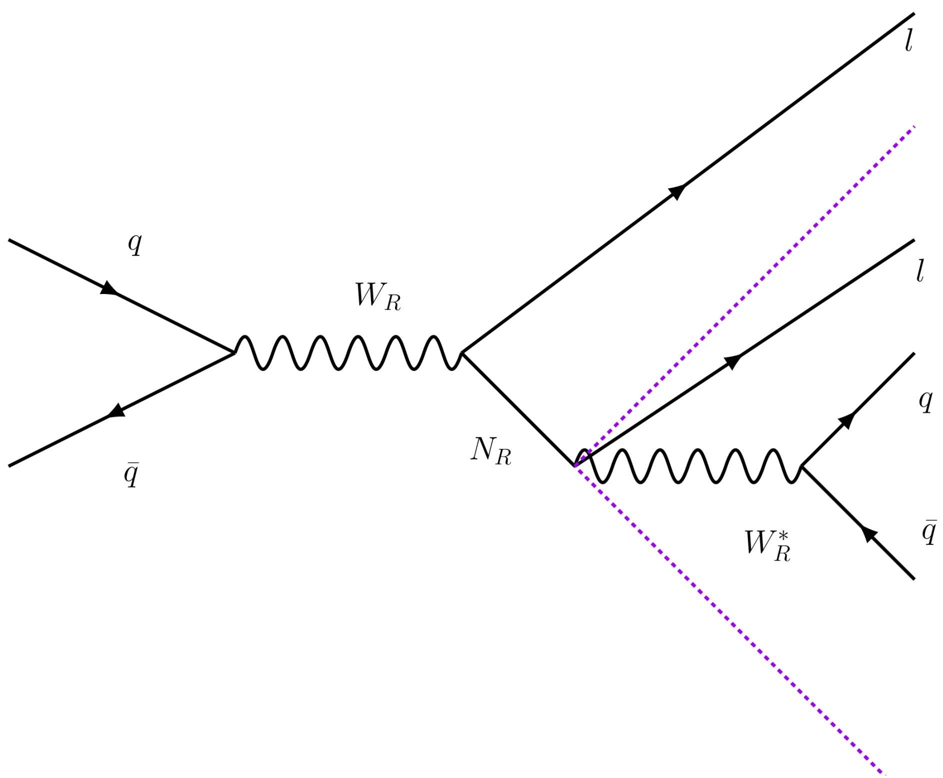
Majorana
opposite-charge (50%)
same-charge (50%)



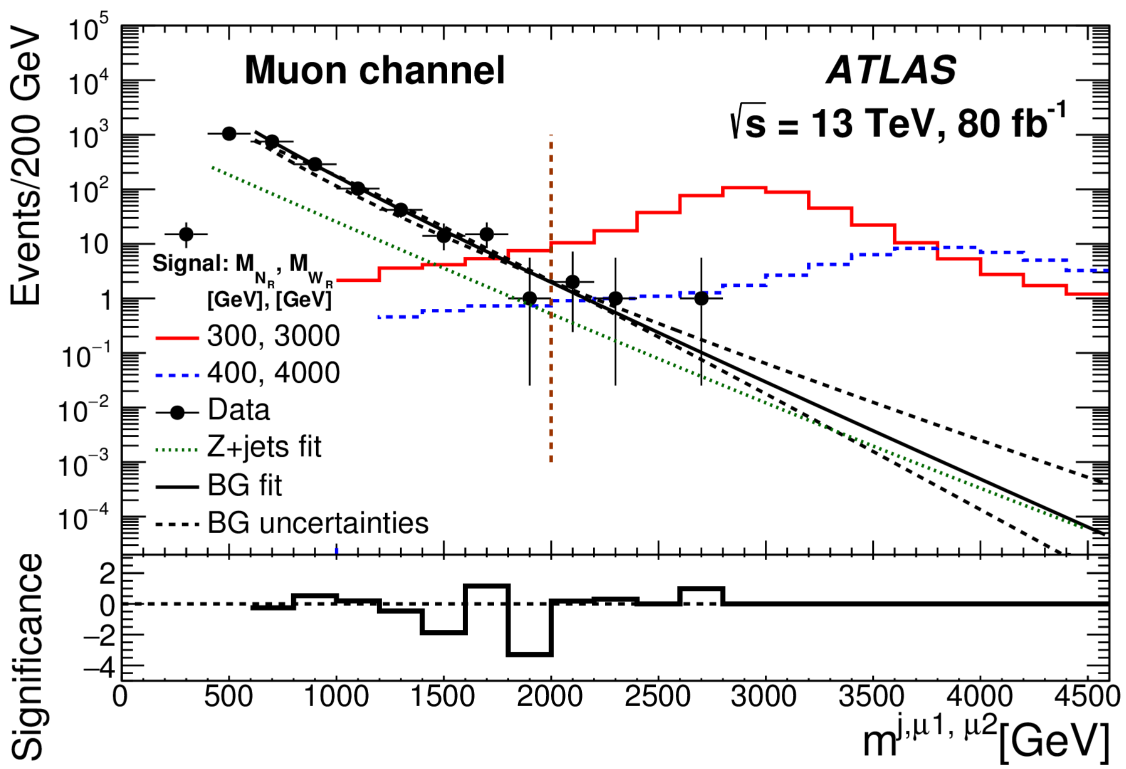


Dirac
opposite-charge (100%)

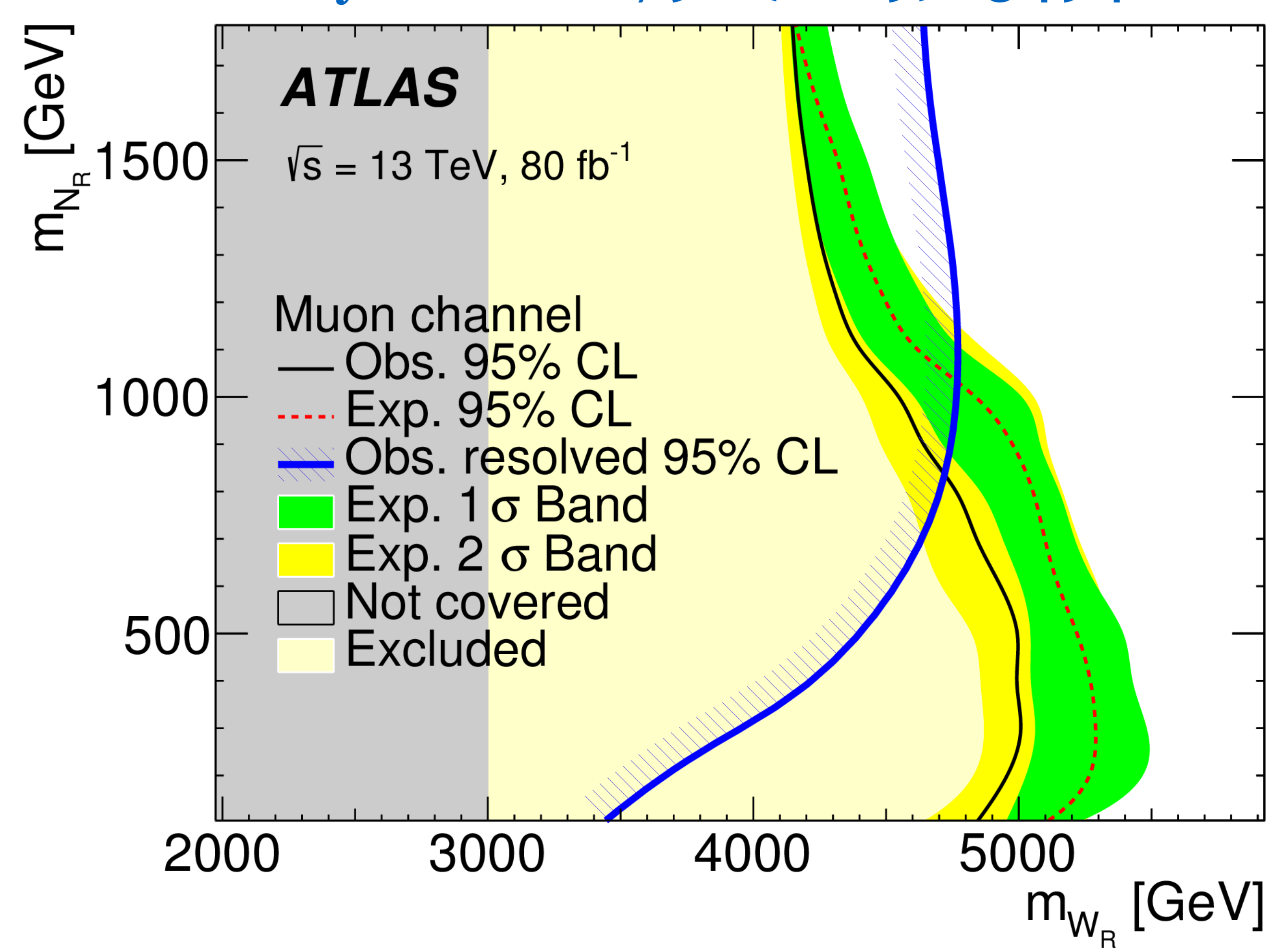
Semi-leptonic heavy neutrino and W: boosted



- *ee* or $\mu\mu$ in the final state.
- Heavy neutrinos with large transverse momenta.
- Two same-flavour leptons and one large-R jet (R=1.0) with $p_T(J)$ > 200 GeV.
- The large-R jet should contain the sub-leading lepton.
- Isolated lepton back-to-back in azimuth wrt the large-R jet.
- m(ℓ,ℓ) > 200 GeV to suppress Z+jets.



[Phys. Lett. B 798 (2019) 134942]

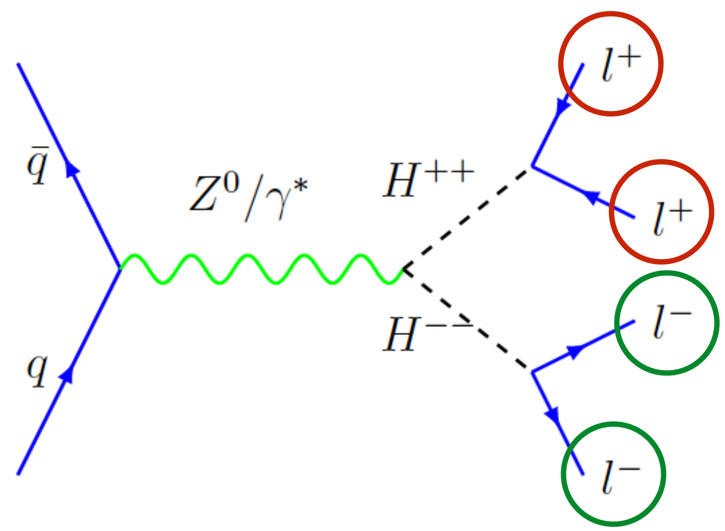


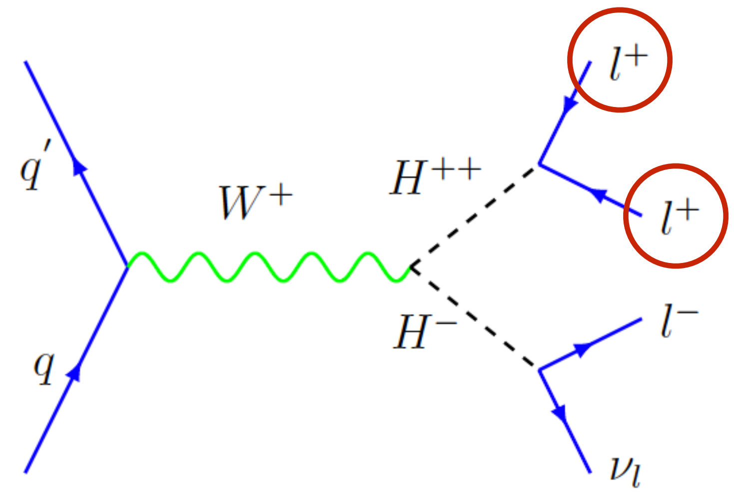
Conclusions

- Decisive updates to several analyses, ranging from data-driven methods to broader interpretation of results.
- Considerable efforts ongoing using new signatures or updating previous analyses.
- More interesting results to come in the future!

Backup

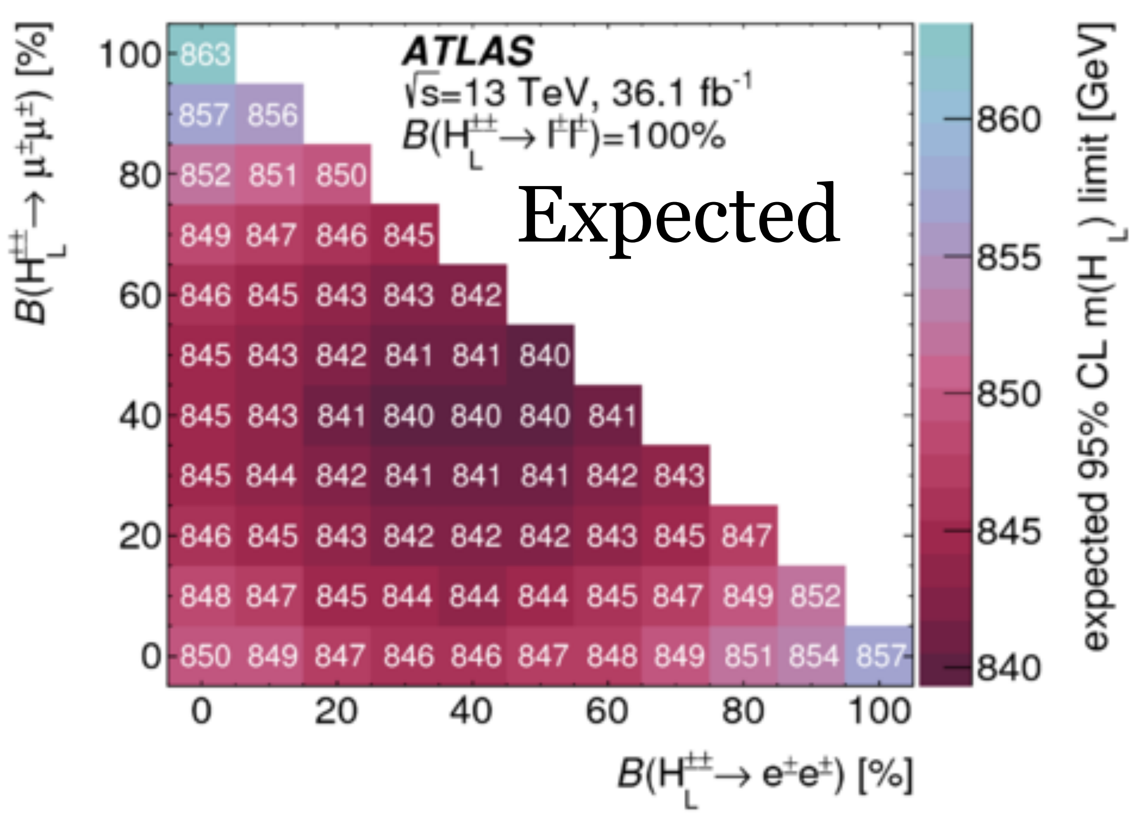
Same-sign leptons

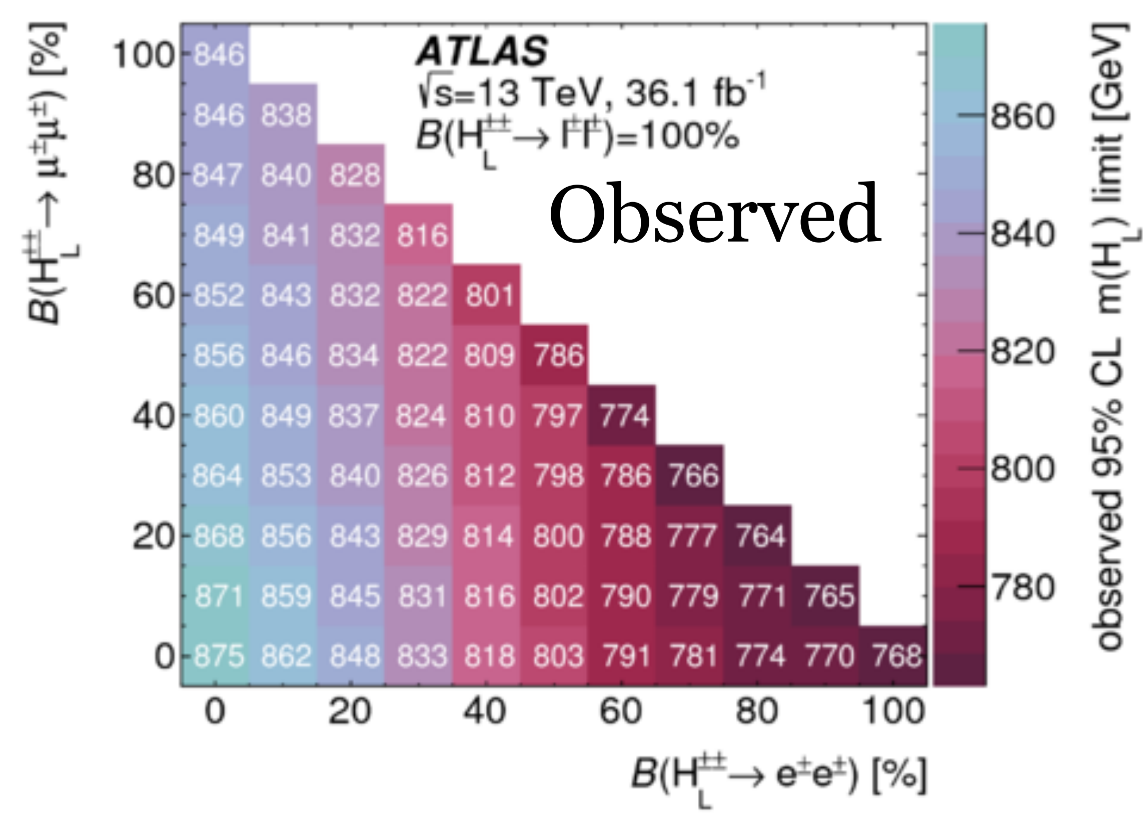




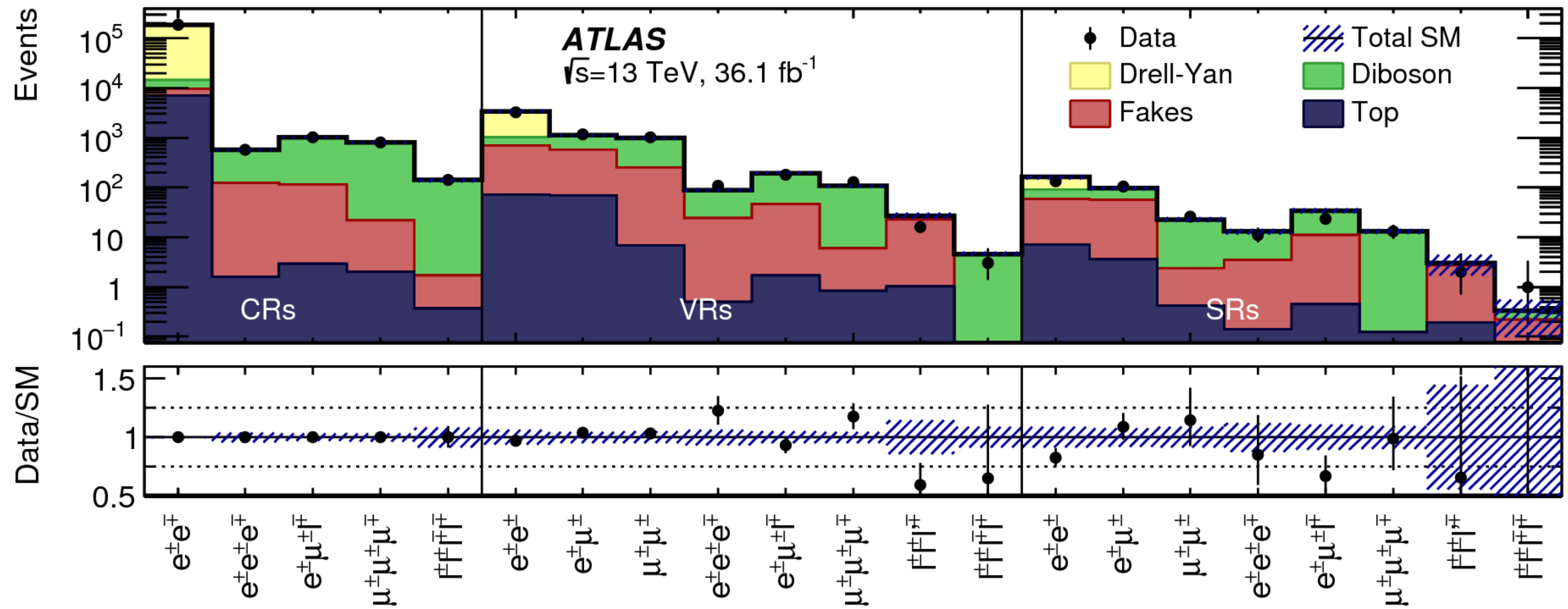
[Eur. Phys. J. C 78 (2018) 199]

- Same-charge pairs are boosted and consistent with a high mass state. Only electrons and muons.
- Categorised in same-charge pair multiplicity, lepton multiplicity and flavour combination.
- Mass exclusion limits obtained by varying branching ratios and fitting $M(\ell^\pm, \ell^\pm)$.





Same-sign leptons



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	-	-	✓	-	-	✓	✓
$\Delta R(\ell^\pm, \ell^\pm) < 3.5$	-	-	-	-	-	-	✓	✓	-
$p_T(\ell^\pm \ell^\pm) > 100$ GeV	-	-	-	-	-	-	✓	✓	-
$\sum \lvert p_T(\ell) \rvert > 300$ GeV	-	-	-	-	-	-	✓	✓	-
$\Delta M / \bar{M}$ requirement	-	-	-	-	-	-	-	-	✓

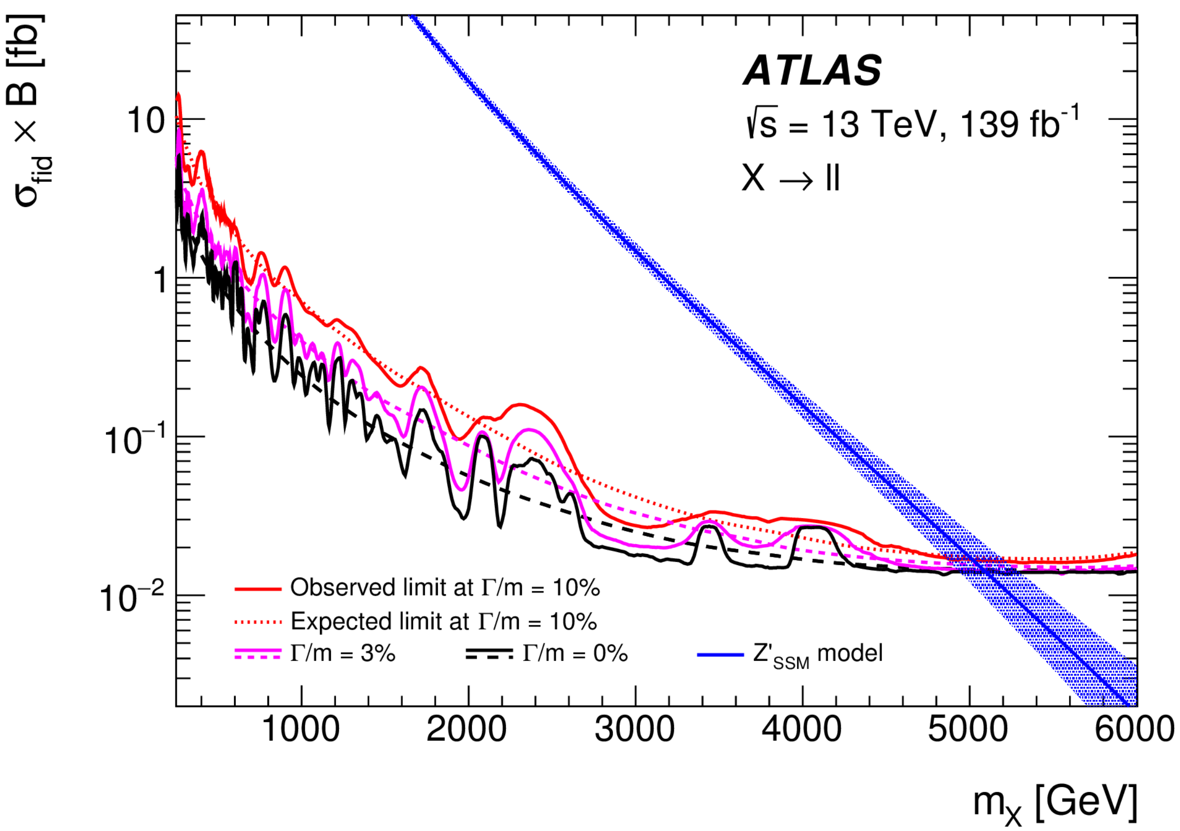
Di-lepton resonance

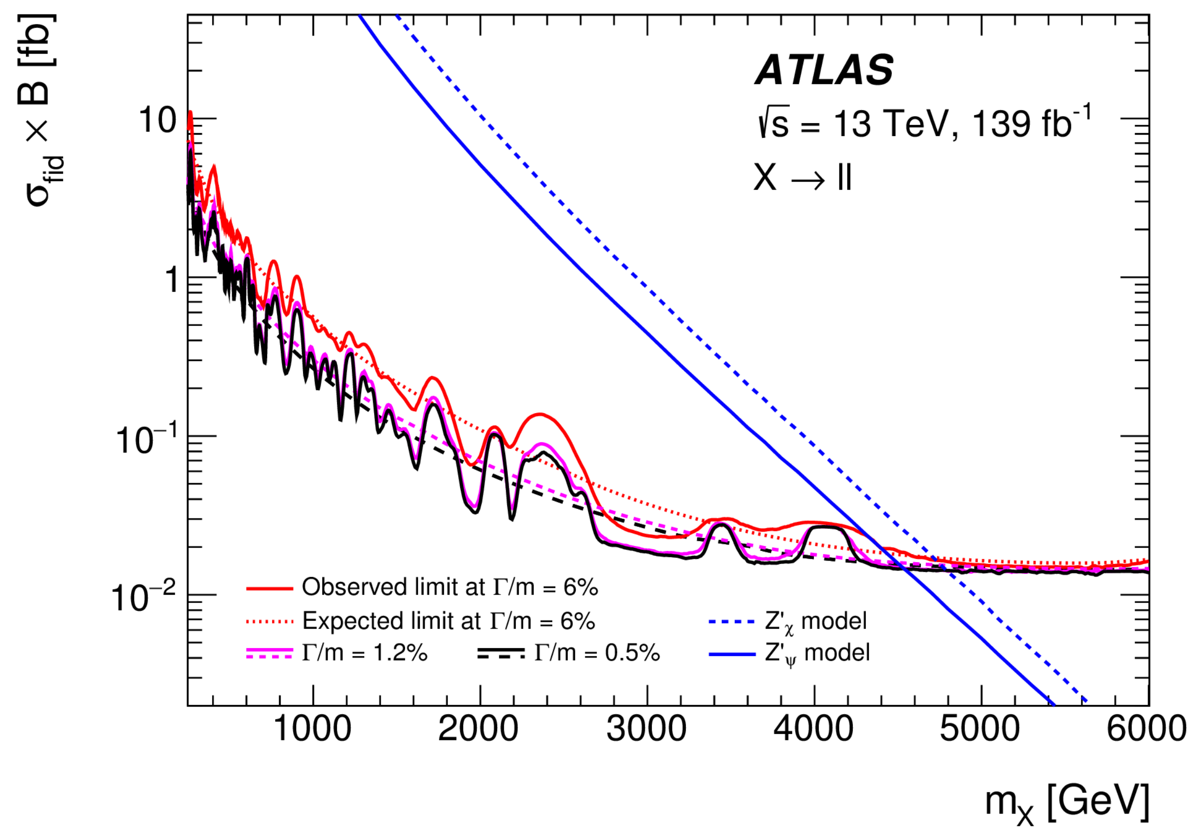
$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW},Z}(m_{\ell\ell}) \cdot (1 - x^{c})^{b} \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i}$$

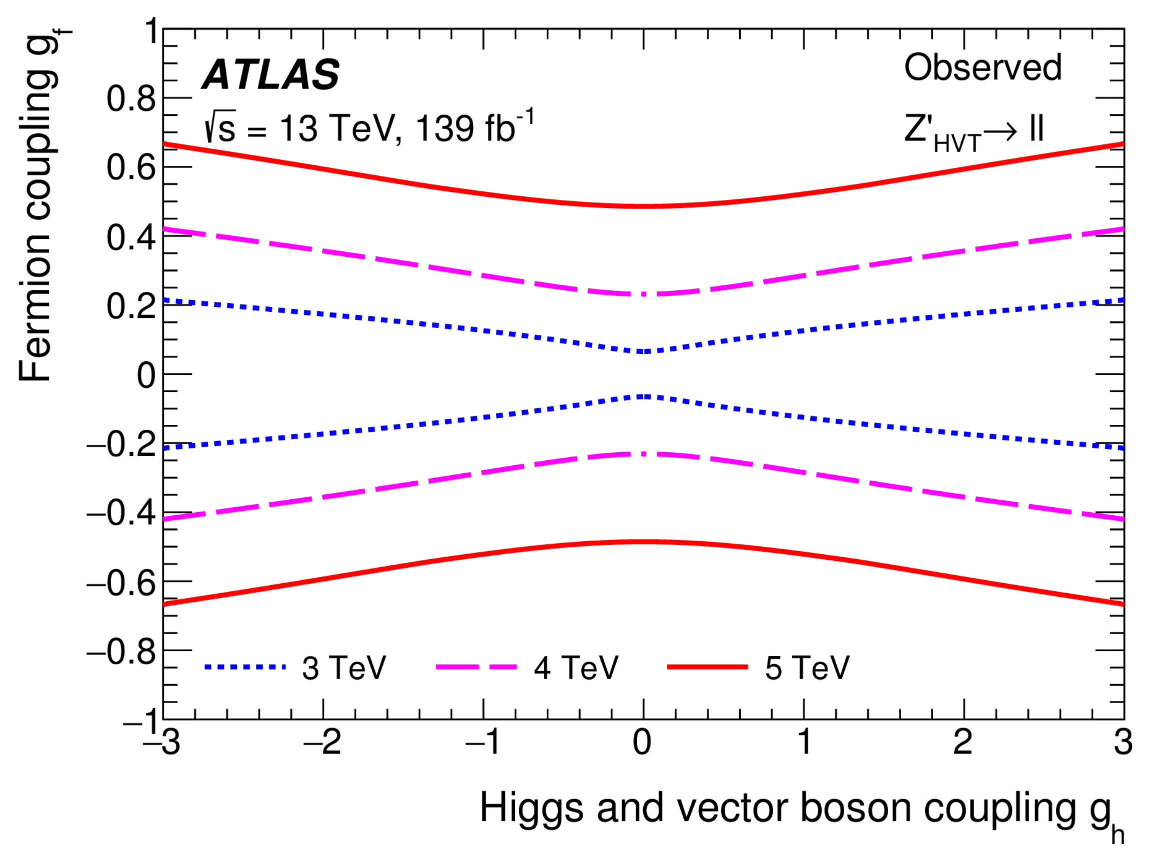
Parameter	ee channel	$\mu\mu$ channel
a	178000 ± 400	138700 ± 400
b	1.5 ± 1.0	11.8 ± 0.5
p_0	-12.38 ± 0.09	-7.38 ± 0.12
p_1	-4.295 ± 0.014	-4.132 ± 0.017
p_2	-0.9191 ± 0.0027	-1.0637 ± 0.0029
p_3	-0.0845 ± 0.0005	-0.1022 ± 0.0005

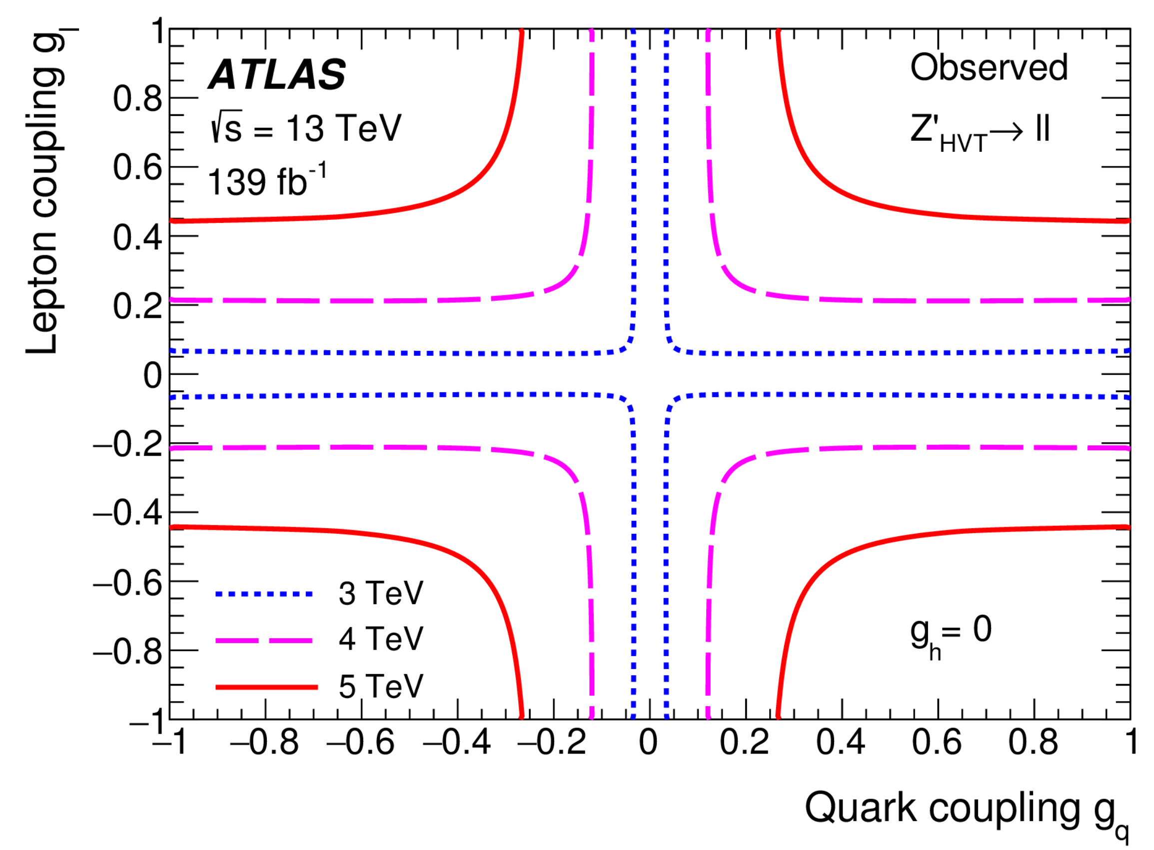
Uncertainty source	Dielectron			Dimuon		
for m_X [GeV]	300	2000	5000	300	2000	5000
Spurious signal	± 12.5 (12.0)	± 4.6 (10.8)	± 0.1 (1.0)	± 11.7 (11.0)	± 3.8 (3.5)	± 2.1 (2.2)
Lepton identification	± 1.6 (1.6)	± 5.6 (5.6)	± 5.6 (5.6)	± 1.8 (1.8)	$^{+12}_{-10}$ $\left(^{+12}_{-10}\right)$	$^{+25}_{-20}$ $\left(^{+25}_{-20}\right)$
Isolation	± 0.3 (0.3)	± 1.1 (1.2)	± 1.1 (1.1)	± 0.4 (0.4)	± 0.4 (0.4)	± 0.4 (0.5)
Luminosity	± 1.7 (1.7)	± 1.7 (1.7)	± 1.7 (1.7)	± 1.7 (1.7)	± 1.7 (1.7)	± 1.7 (1.7)
Electron energy scale	$^{-1.7}_{-4.0}$ $\left(^{+1.0}_{-1.8}\right)$	$^{-1.9}_{-6.0}$ $\left(^{+1.7}_{-2.9}\right)$	$^{+0.1}_{-0.4}$ (± 0.8)	-	-	-
Electron energy resolution	$^{+7.9}_{-8.3}$ $\left(^{+1.1}_{-0.9}\right)$	$^{+9.0}_{-11.8}$ $\left(^{+0.7}_{-0.5}\right)$	$^{+0.4}_{-0.9}$ (± 0.1)	-	-	-
Muon ID resolution	-	-	-	$^{+0.8}_{-2.3}$ $\left(^{+0.3}_{-0.8}\right)$	$^{+0.9}_{-1.3}$ $\left(^{+0.7}_{-1.1}\right)$	$^{+0.6}_{-0.4}$ $\left(^{+0.5}_{-0.3}\right)$
Muon MS resolution	-	-	-	$^{+2.8}_{-3.8}$ $\left(^{+1.0}_{-1.3}\right)$	$^{+3.2}_{-3.0}$ $\left(^{+2.6}_{-2.4}\right)$	± 2.4 (2.1)
'Good muon' requirement	-	-	-	± 0.6 (0.6)	$^{+9.0}_{-8.2}$ $\left(^{+9.0}_{-8.2}\right)$	$^{+55}_{-35}$ $\left(^{+55}_{-35}\right)$

Di-lepton resonance

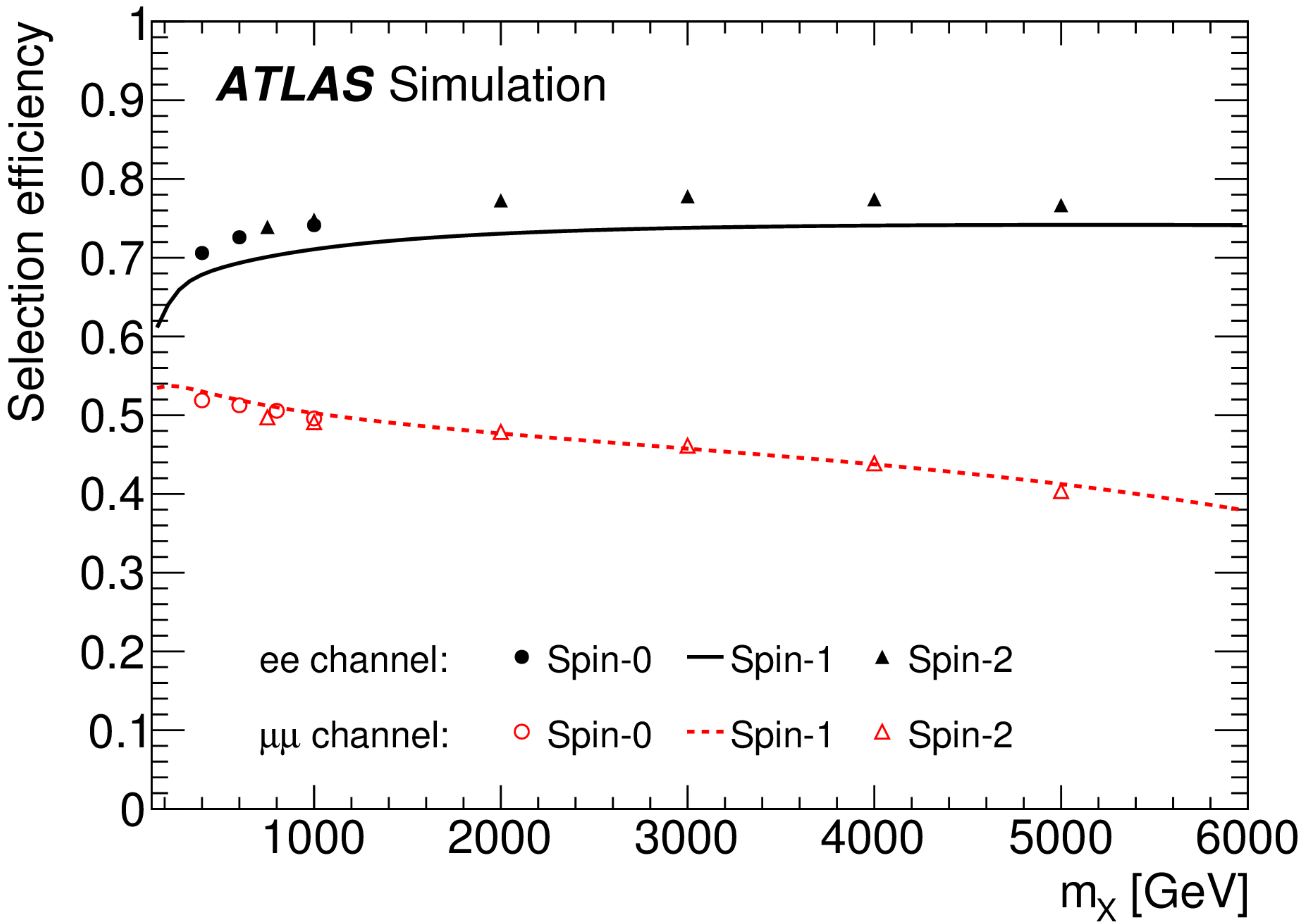






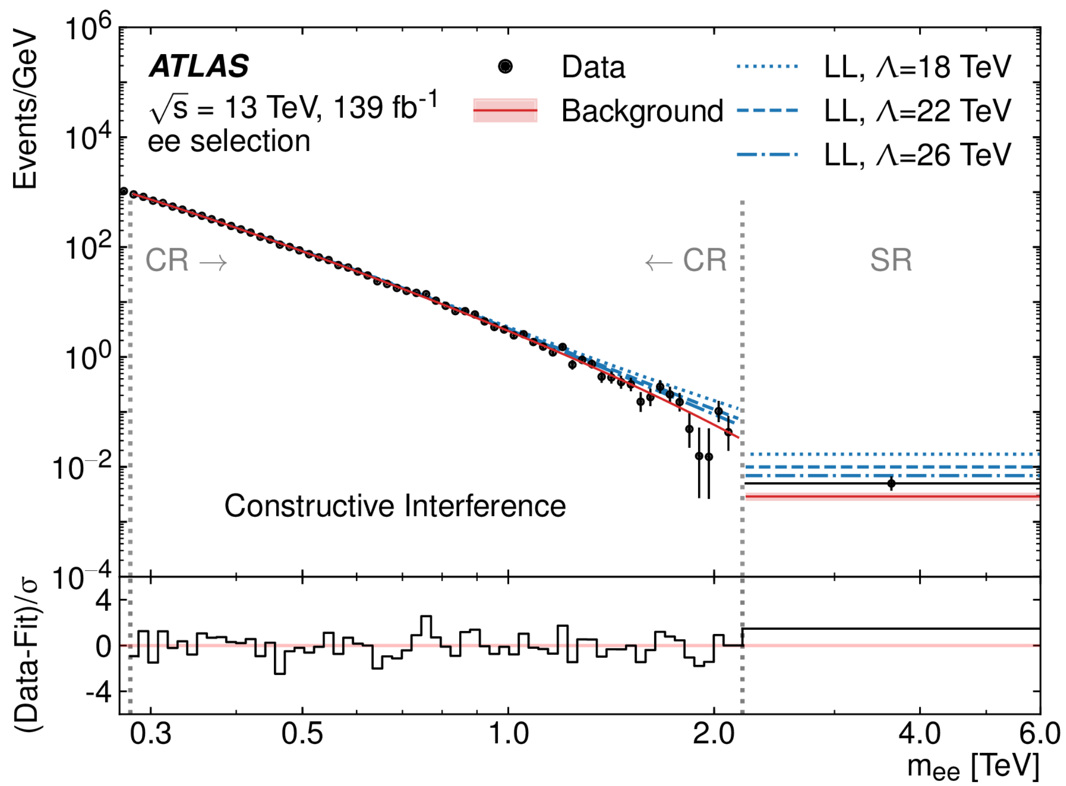


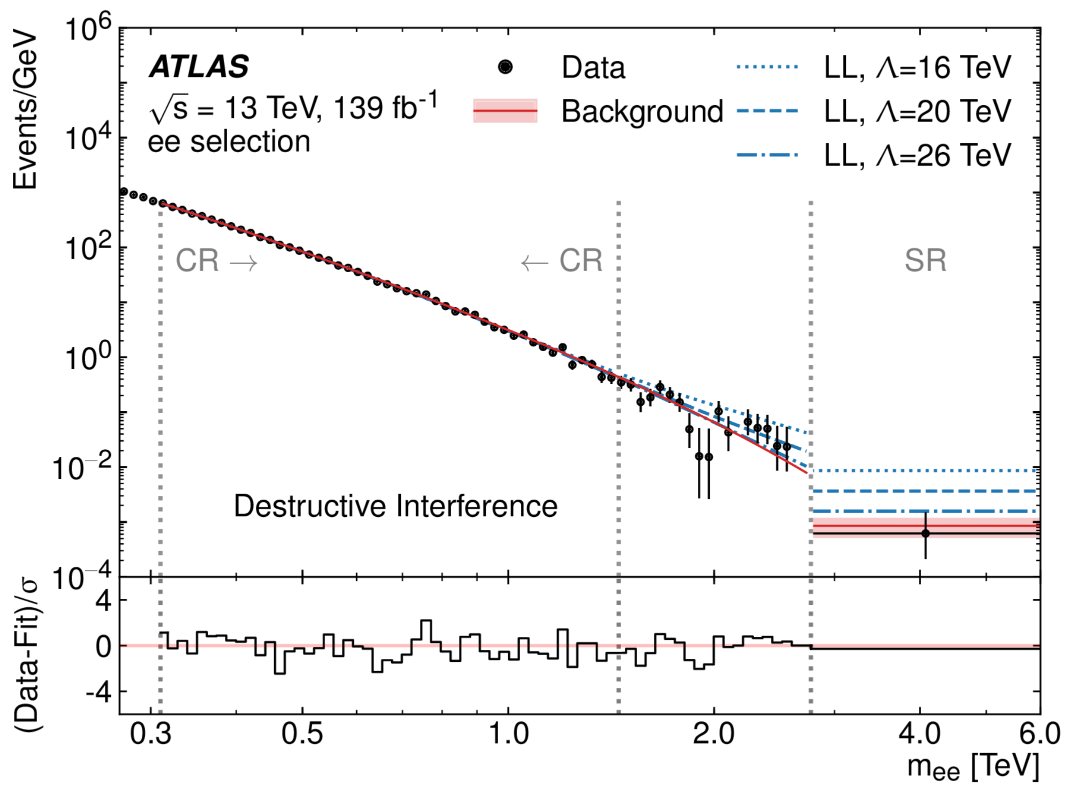
Di-lepton resonance



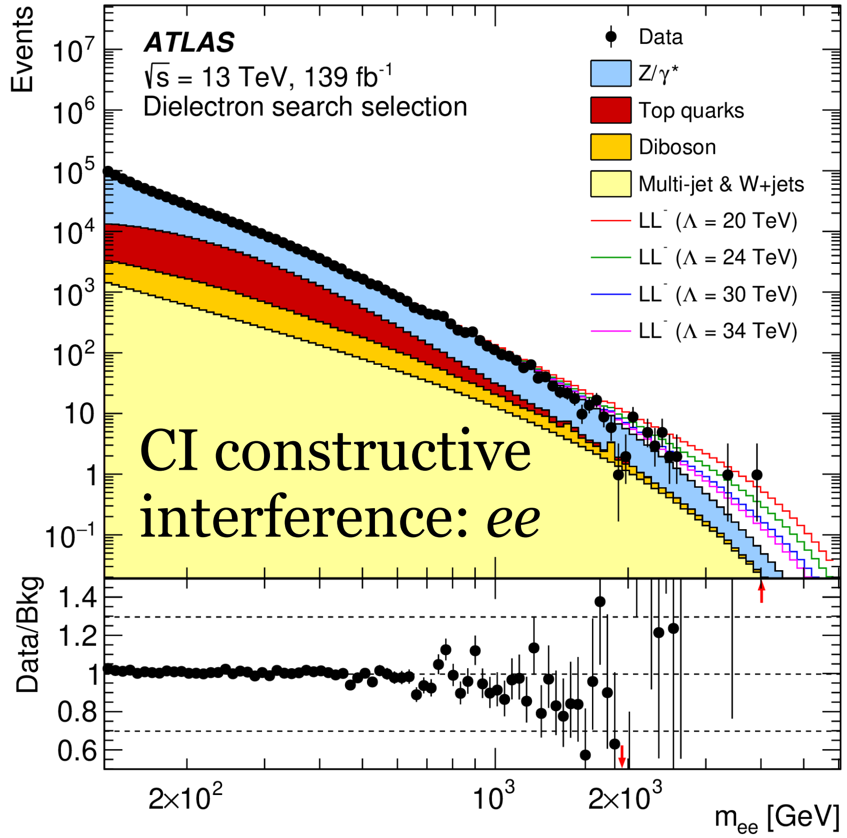
Di-lepton non-resonant

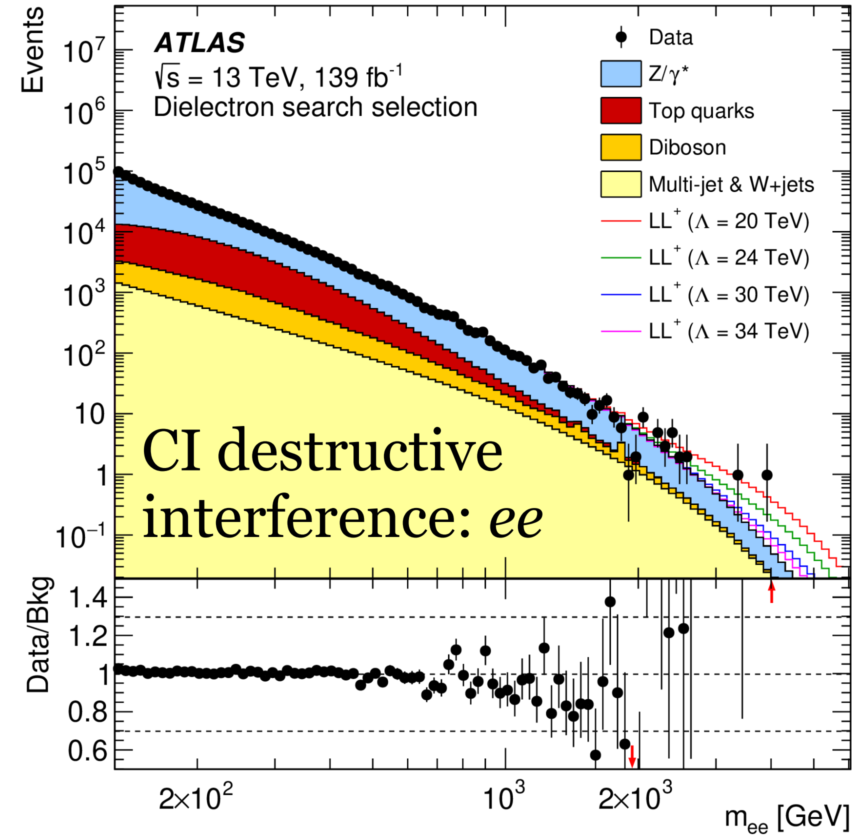
Channel	Interference	Background uncertainties σ_b^{Stat}	σ_b^{ISS}	σ_b^{CRB}	Signal uncertainties $\sigma_s^{Experiment}$	σ_s^{Theory}
e^+e^-	Constructive	14%	4%	2%	8%	$^{+11\%}_{-10\%}$
e^+e^-	Destructive	34%	7%	1%	8%	$^{+14\%}_{-13\%}$
$\mu^+\mu^-$	Constructive	21%	6%	2%	$^{+20\%}_{-17\%}$	$^{+10\%}_{-9\%}$
$\mu^+\mu^-$	Destructive	58%	24%	4%	$^{+27\%}_{-22\%}$	$^{+13\%}_{-12\%}$

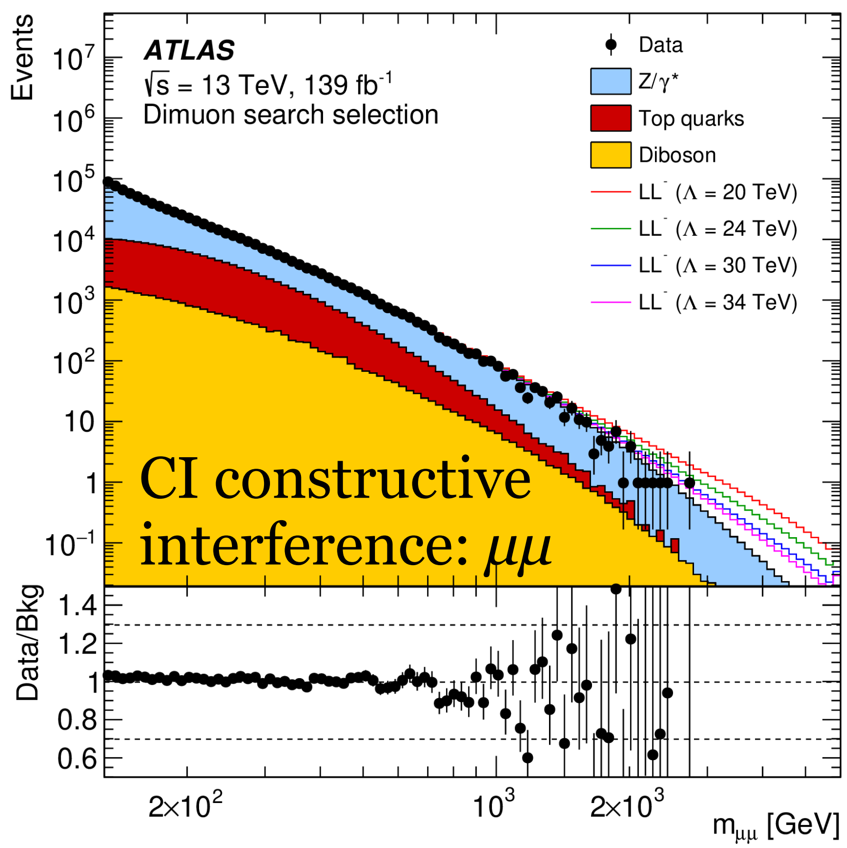


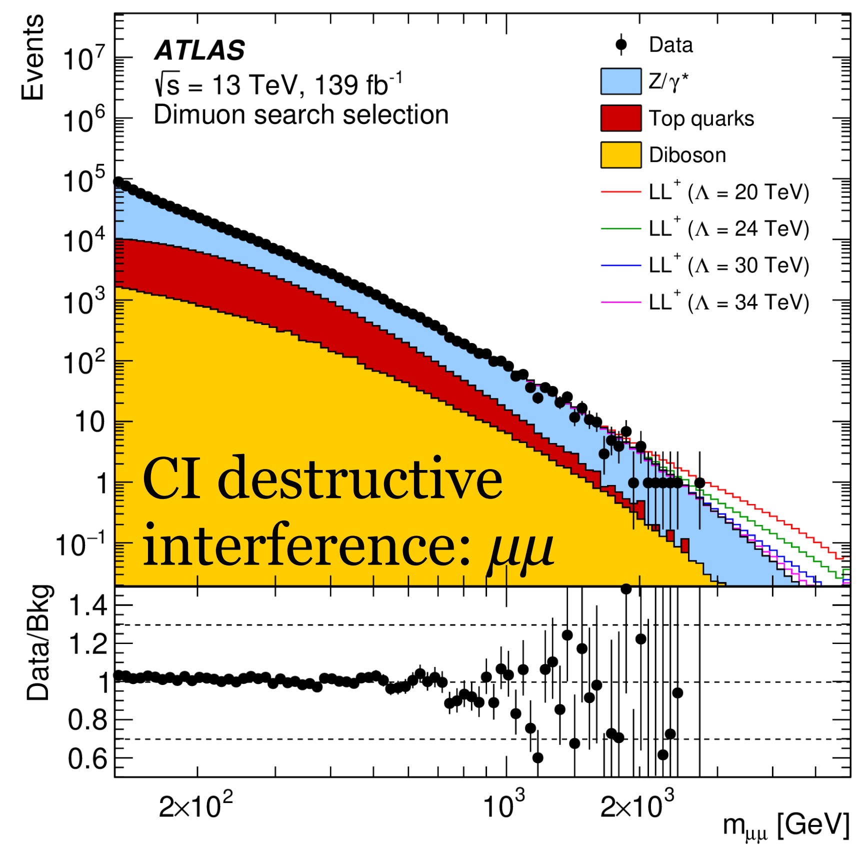


Di-lepton non-resonant









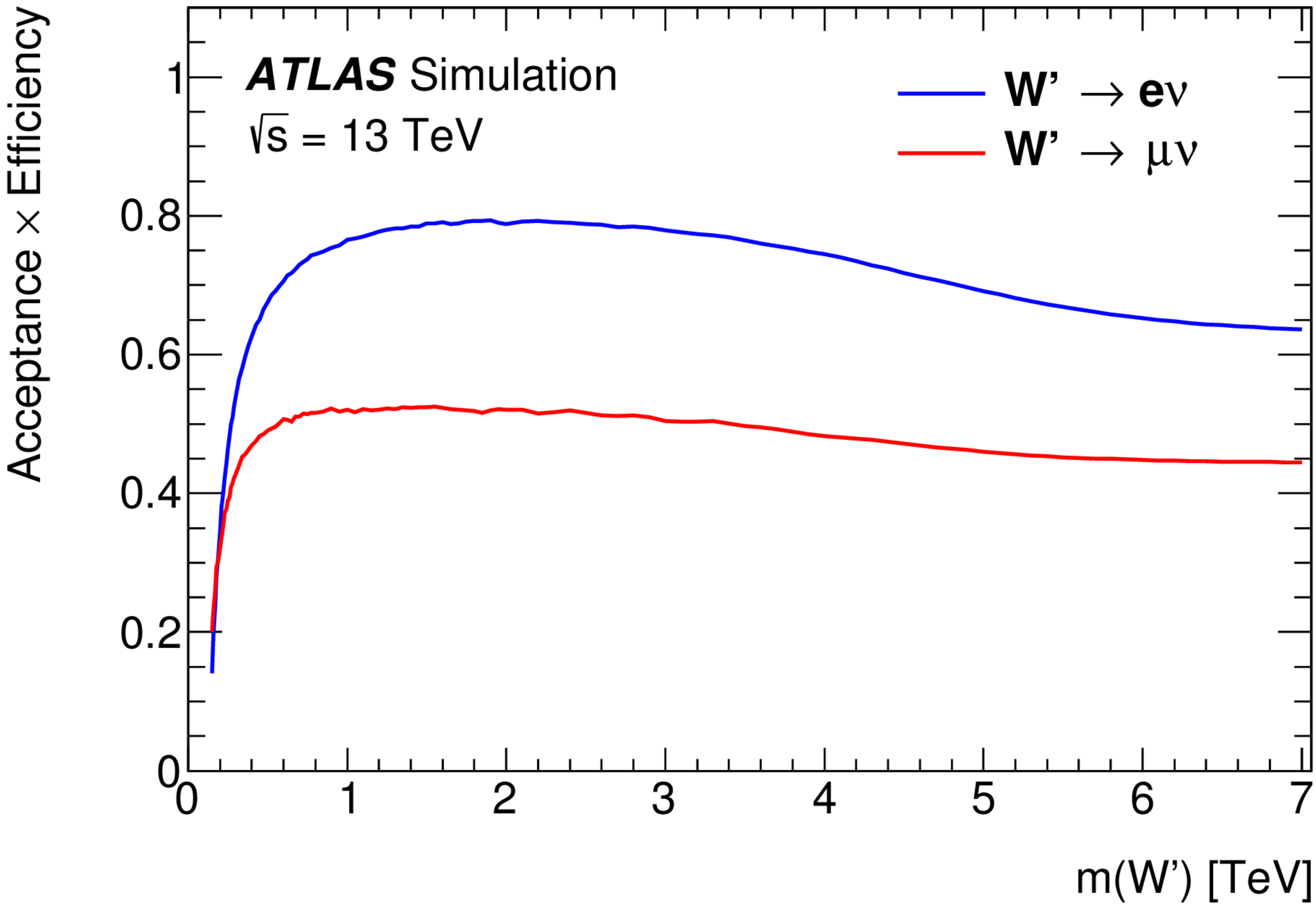
Di-lepton non-resonant

Channel	Interference	Λ = 20 TeV N_{sig}	$\mathcal{A} \times \epsilon_{sig}$ [%]	Λ = 30 TeV N_{sig}	$\mathcal{A} \times \epsilon_{sig}$ [%]	Λ = 40 TeV N_{sig}	$\mathcal{A} \times \epsilon_{sig}$ [%]
Signal(LL)							
e^+e^-	const	39.1±3.1	69	10.3±0.8	69	4.4±0.4	69
e^+e^-	dest	9.6±0.8	70	0.96±0.08	70	-0.10±0.01	69
$\mu^+\mu^-$	const	28.5±5.8	43	7.7±1.6	43	3.4±0.7	43
$\mu^+\mu^-$	dest	7.1±1.9	43	0.55±0.15	42	-0.21±0.05	44
Signal(LR)							
e^+e^-	const	34.0±2.7	69	8.0±0.6	69	3.1±0.25	69
e^+e^-	dest	11.7±1.0	70	1.9±0.2	70	0.41±0.03	70
$\mu^+\mu^-$	const	24.6±5.0	43	5.9±1.2	43	2.4±0.5	43
$\mu^+\mu^-$	dest	9.0±2.4	43	1.4±0.4	43	0.25±0.07	42
Signal(RL)							
e^+e^-	const	33.8±2.7	69	7.9±0.6	69	3.1±0.2	69
e^+e^-	dest	11.7±1.0	70	1.9±0.2	70	0.40±0.03	70
$\mu^+\mu^-$	const	24.3±4.9	43	5.8±1.2	43	2.3±0.5	43
$\mu^+\mu^-$	dest	9.0±2.4	43	1.4±0.4	43	0.26±0.07	42
Signal(RR)							
e^+e^-	const	38.6±3.1	69	10.1±0.8	69	4.3±0.3	69
e^+e^-	dest	9.9±0.8	70	1.1±0.1	70	$\|N_{sig}\| < 0.01$	67
$\mu^+\mu^-$	const	28.2±5.7	43	7.6±1.5	43	3.3±0.7	43
$\mu^+\mu^-$	dest	7.3±2.0	43	0.65±0.17	42	-0.15±0.04	44

lepton + missing energy

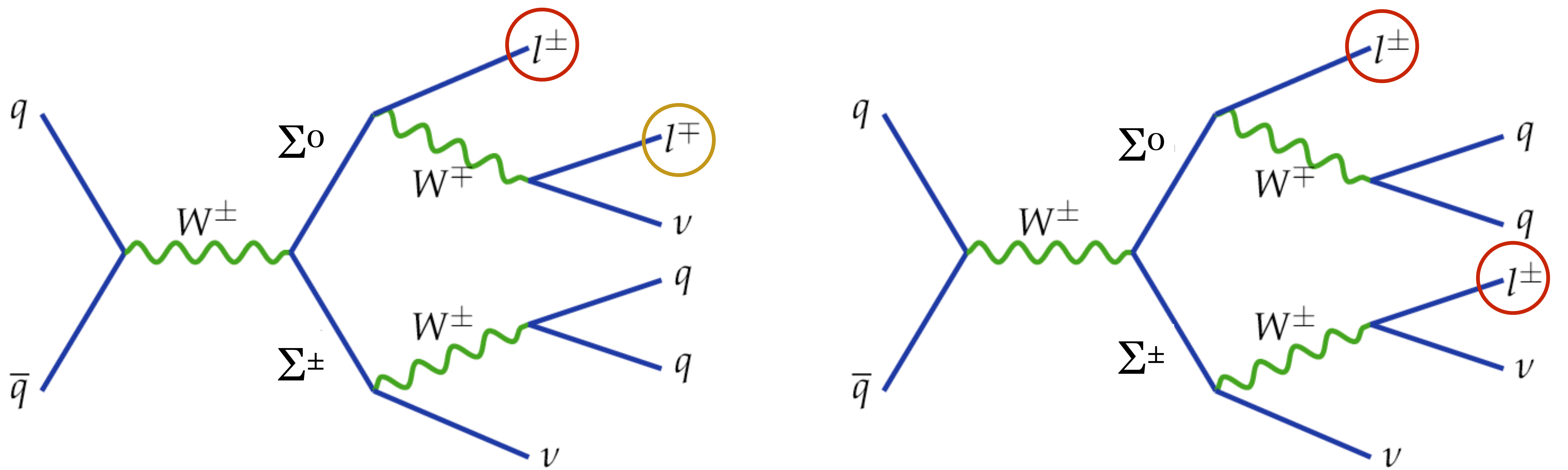
Source	Electron channel		Muon channel	
	Background	Signal	Background	Signal
	m_T = 2 (6) TeV	m_T = 2 (6) TeV	m_T = 2 (6) TeV	m_T = 2 (6) TeV
Trigger	negl. (negl.)	negl. (negl.)	1.1% (1.0%)	1.2% (1.2%)
Lepton reconstruction and identification	4.1% (1.4%)	4.3% (4.3%)	8.9% (37%)	6.6% (38%)
Lepton momentum scale and resolution	3.9% (2.7%)	2.7% (4.5%)	12% (47%)	13% (20%)
E_T^{miss} resolution and scale	<0.5% (<0.5%)	<0.5% (<0.5%)	<0.5% (<0.5%)	<0.5% (<0.5%)
Jet energy resolution	<0.5% (<0.5%)	<0.5% (<0.5%)	<0.5% (0.6%)	<0.5% (<0.5%)
Multijet background	4.4% (420%)	N/A (N/A)	0.8% (1.5%)	N/A (N/A)
Top-quark background	0.8% (1.9%)	N/A (N/A)	0.7% (<0.5%)	N/A (N/A)
Diboson extrapolation	1.5% (47%)	N/A (N/A)	1.3% (9.7%)	N/A (N/A)
PDF choice for DY	1.0% (10%)	N/A (N/A)	<0.5% (1.0%)	N/A (N/A)
PDF variation for DY	8.1% (13%)	N/A (N/A)	7.4% (14%)	N/A (N/A)
EW corrections for DY	4.2% (4.5%)	N/A (N/A)	3.7% (7.0%)	N/A (N/A)
Luminosity	1.6% (1.1%)	1.7% (1.7%)	1.7% (1.7%)	1.7% (1.7%)
Total	12% (430%)	5.4% (6.4%)	17% (62%)	15% (43%)

lepton + missing energy



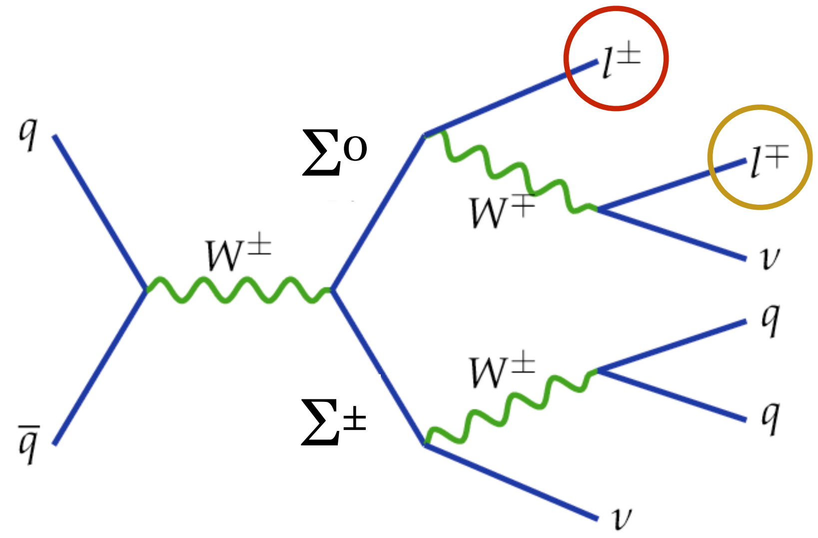
Type-III signatures

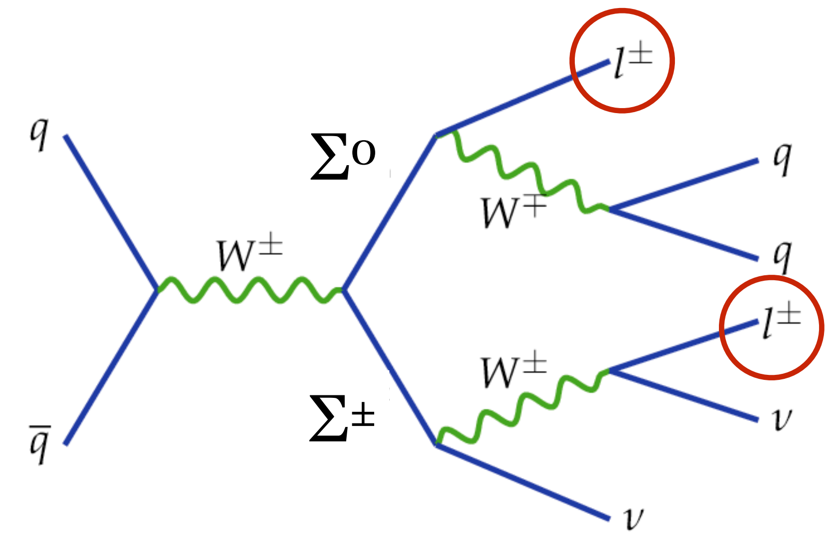
- Mass degenerate Σ^0 and $\Sigma^\pm$ due to gauge invariance: one free parameter.
- Production of Σ via gauge interaction.



- **pp → $\Sigma^0 \Sigma^\pm$ → $\ell\ell$qq**
- Two leptons in final state with same or opposite charge.
- Other decay modes found negligible in final selection.

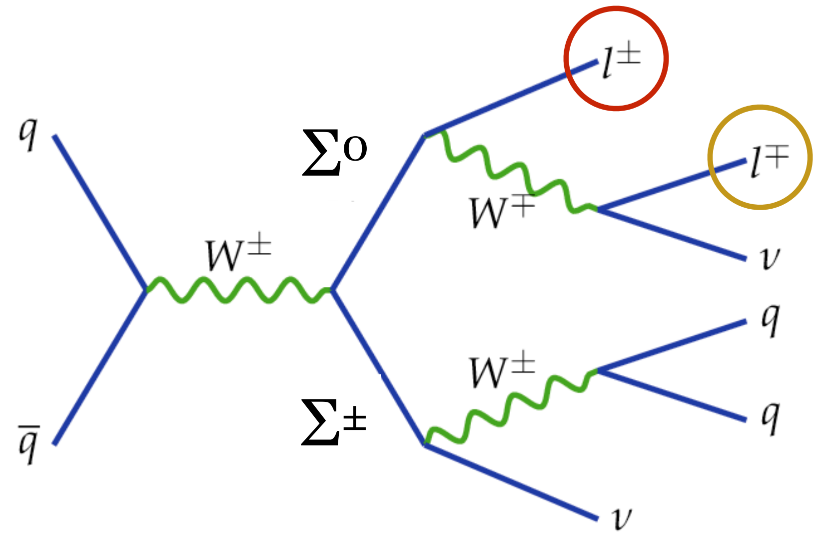
Semi-leptonic: heavy leptons

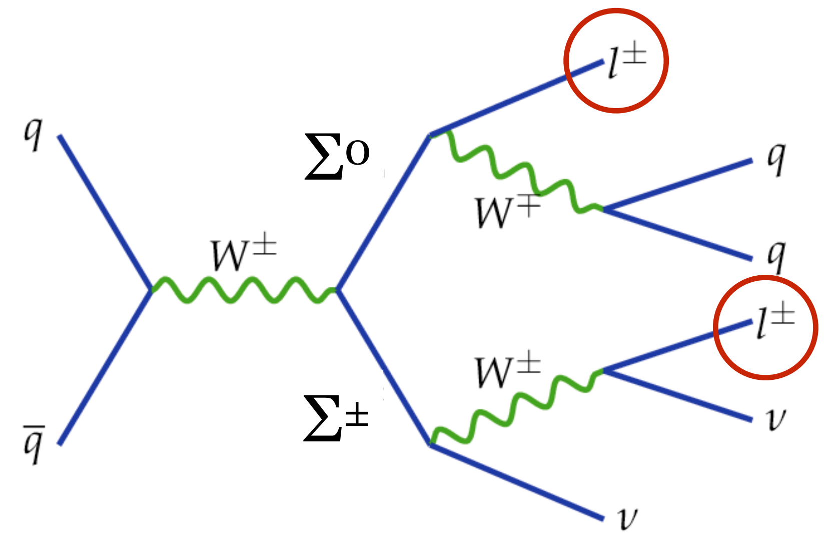


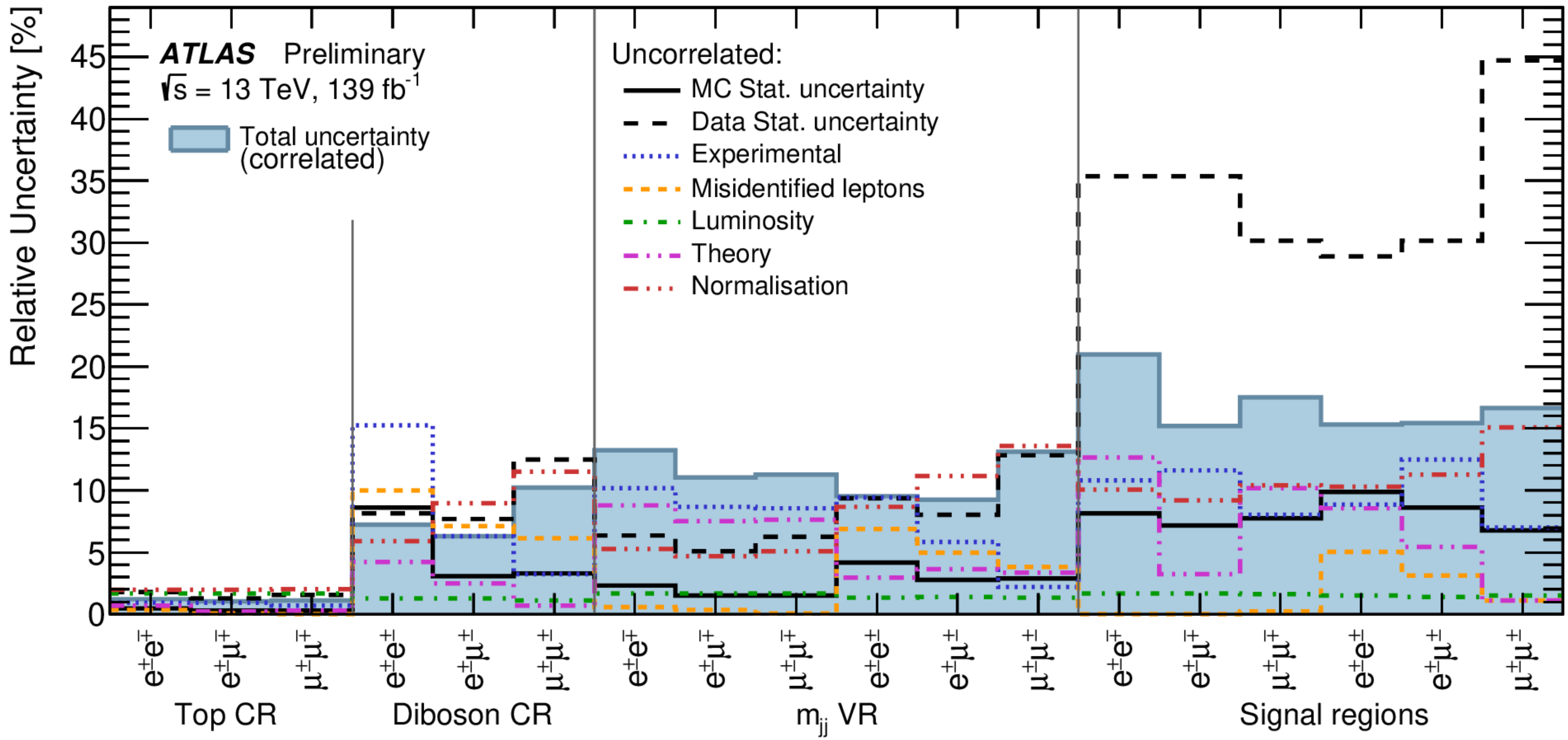


	OS ($\ell^+\ell^- = e^+e^-, e^{\pm}\mu^{\mp}, \mu^+\mu^-$)			**SS** ($\ell^{\pm}\ell^{\pm} = e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$)		
	Top CR	m_{jj} VR	SR	Diboson CR	m_{jj} VR	SR
N(jet)	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2
N(b-jet)	≥ 2	0	0	0	0	0
m_{jj} [GeV]	$(60, 100)$	$(35, 60) \cup (100, 125)$	$(60, 100)$	$(0, 60) \cup (100, 300)$	$(0, 60) \cup (100, 300)$	$(60, 100)$
$m_{\ell\ell}$ [GeV]	≥ 110	≥ 110	≥ 110	≥ 100	≥ 100	≥ 100
$\mathcal{S}(E_T^{miss})$	≥ 5	≥ 10	≥ 10	≥ 5	≥ 5	≥ 7.5
$\Delta\phi(E_T^{miss}, \ell)_{min}$	—	—	≥ 1	—	—	—
$p_T(jj)$ [GeV]	—	—	≥ 100	—	—	≥ 60
$p_T(\ell\ell)$ [GeV]	—	—	≥ 100	—	—	≥ 100
$H_T + E_T^{miss}$ [GeV]	≥ 300	≥ 300	≥ 300	$(300, 500)$	≥ 500	≥ 300

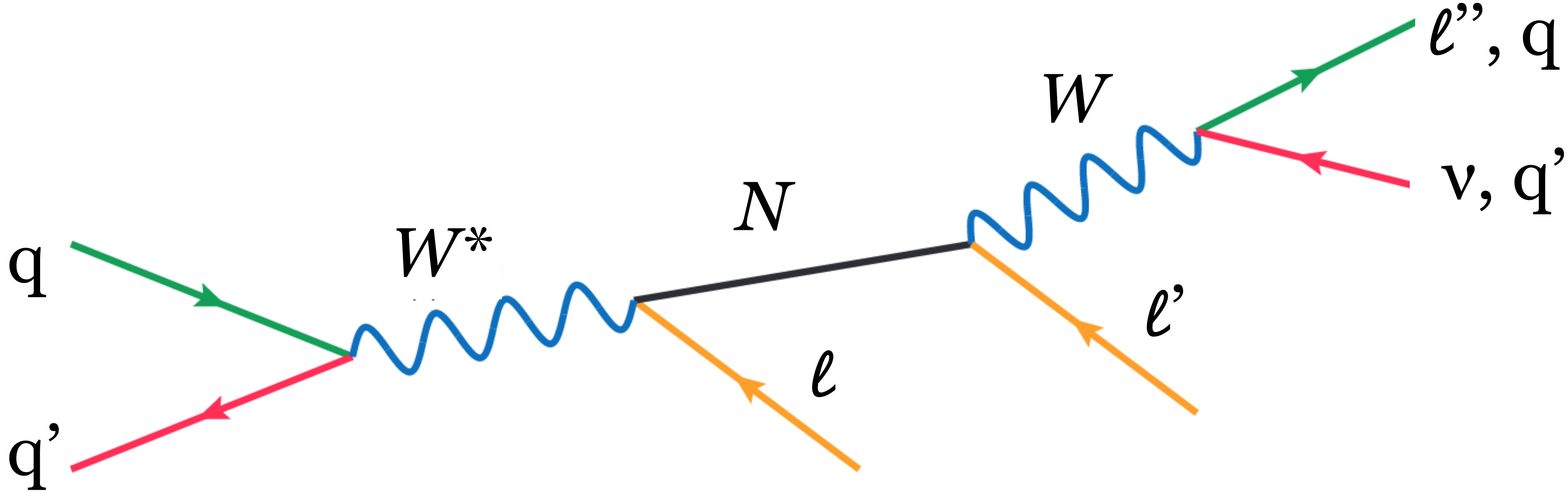
Semi-leptonic: heavy leptons







Type-I signatures

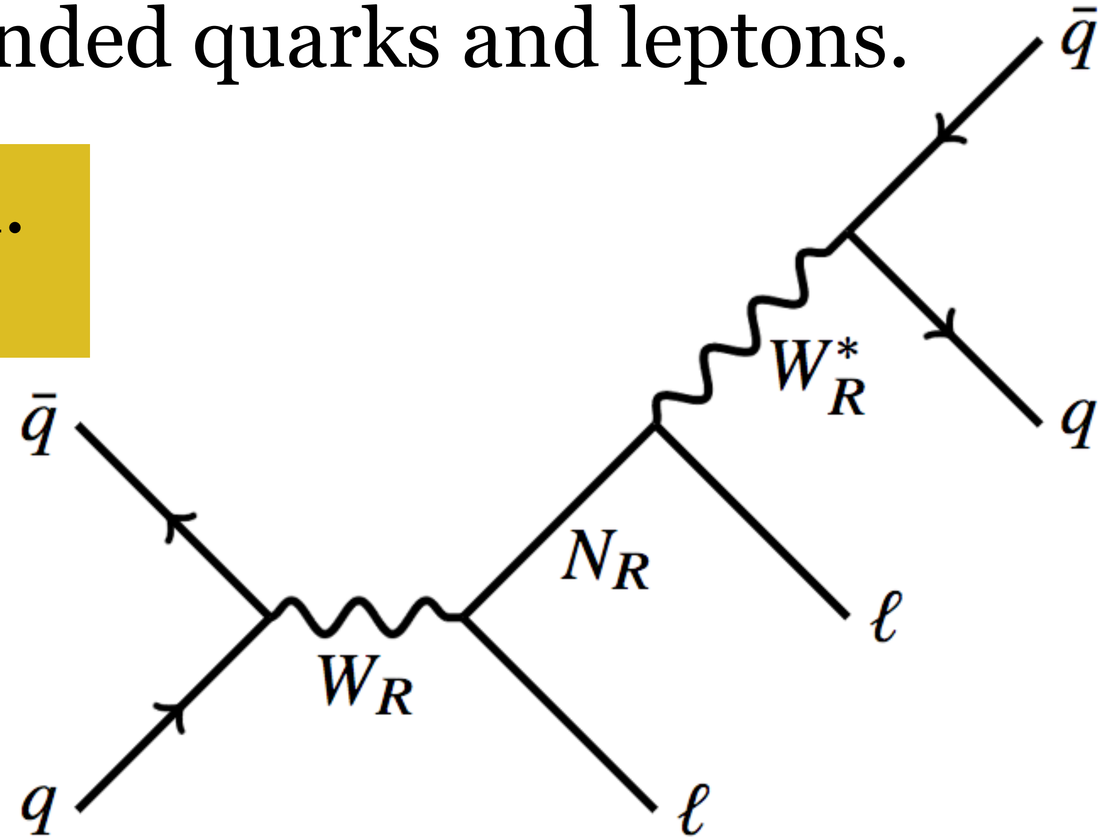


- In minimal and MI Type-I see-saw, the heavy neutrino parameters, $\mathbf{m}_N$ and mixing matrix elements $|\mathbf{U}_{\nu N}|^2$ are free.
- Heavy neutrino produced via mixings with SM neutrinos.
- Search strategies based on m_N vs m_W hypothesis.
- **W*** is **on-shell** at very low m_N. **Off-shell** otherwise. Also:
  - $\mathbf{m}_N \ll \mathbf{m}_W$: soft and displaced *N* decay products.
  - $\mathbf{m}_N < / \lesssim / > \mathbf{m}_W$: hierarchies of $p_T(\ell)$ vs $p_T(\ell')$. E.g. ℓ' dominates at high $\mathbf{m}_N$.
  - $\mathbf{m}_N \gg \mathbf{m}_W$: boosted decay products (jets).

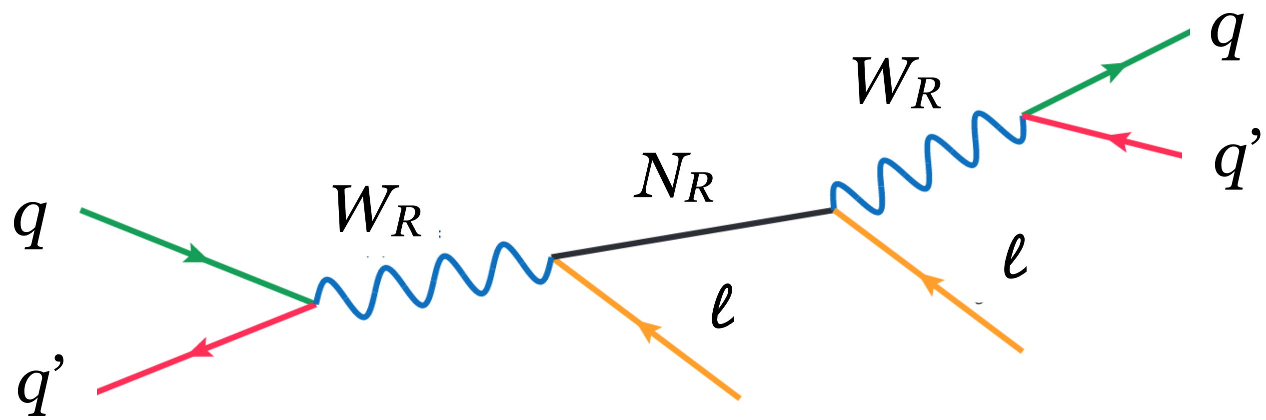
Left-Right symmetric models

- Naturally embed the **Type-I** see-saw mechanism after EWSB.
- Motivated by explaining parity violation in weak decays by introducing a **new high-scale SU(2)$_R$** group.
- Extend gauge sector with **W_R, Z'** with right-handed counterparts of SM leptons, including three flavours of N_R with identical masses.
- Perfect symmetry at high-scales: new gauge bosons interact with SM particles with **g_R=g_L**. Also **(CKM)$_R$ = (CKM)$_L$**.
- Assumes **universality** of all right-handed quarks and leptons.

- LRSM addressed in the $\ell\ell$qq channel.
- m_N and m_W as free parameters.

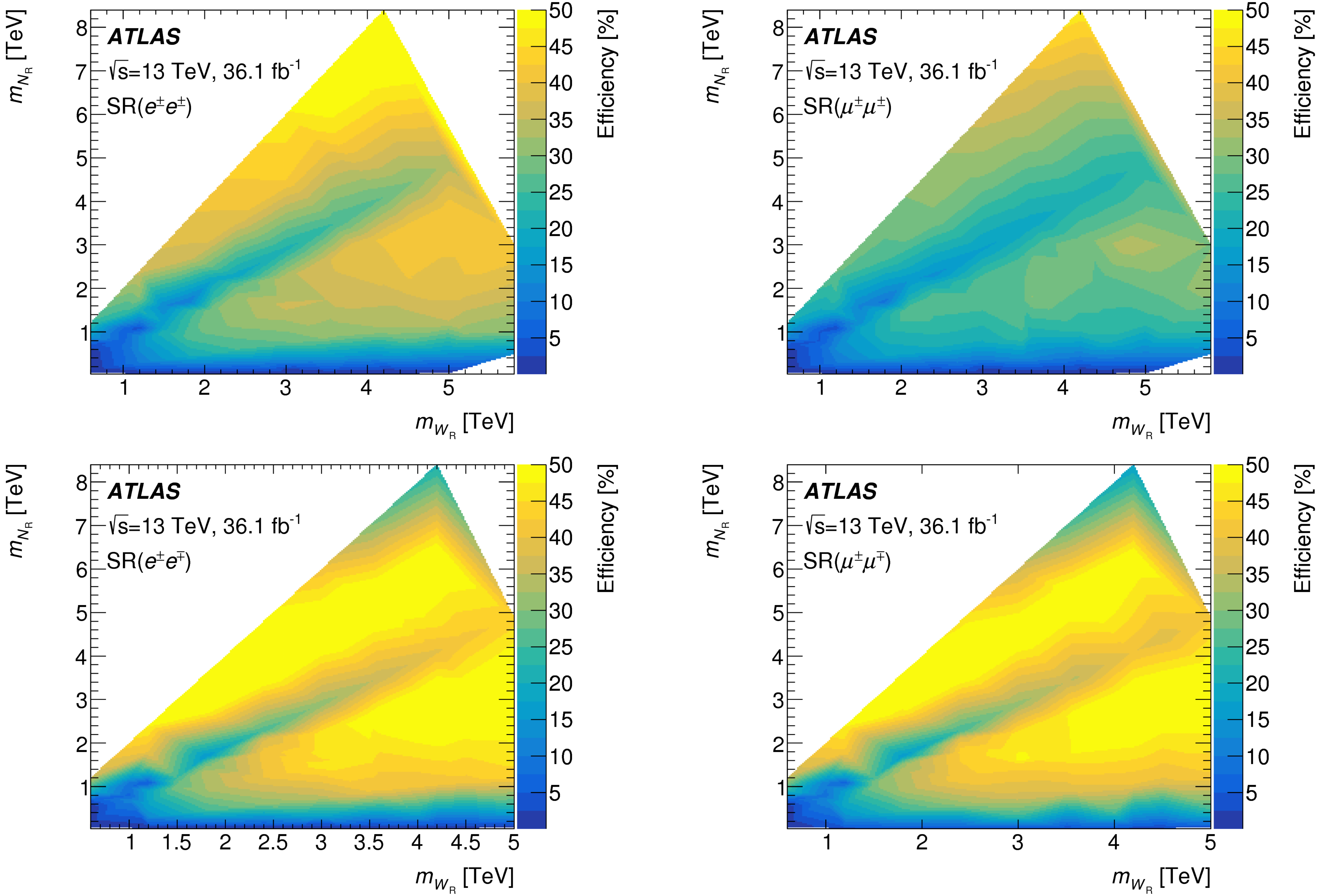


Semi-leptonic heavy neutrino and W: resolved

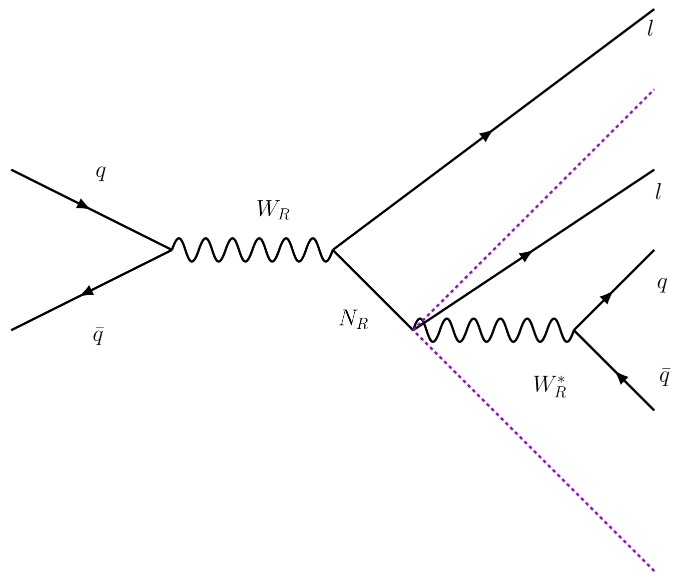


Region	Control region			Validation region		Signal region	
Channel	CR($\ell^\pm\ell^\mp$)	CR($\ell^\pm\ell'^\mp$)	CR($\ell^\pm\ell^\pm$)	VR($\ell^\pm\ell^\mp$)	VR($\ell^\pm\ell^\pm$)	SR($\ell^\pm\ell^\mp$)	SR($\ell^\pm\ell^\pm$)
m_{ee} [GeV]	$[60, 110]$	—	$[110, 300]$	$[110, 400]$	$[300, 400]$	> 400	> 400
$m_{\mu\mu}$ [GeV]	$[60, 110]$	—	$[60, 300]$	$[110, 400]$	$[300, 400]$	> 400	> 400
$m_{e\mu}$ [GeV]	—	> 400	—	—	—	—	—
H_T [GeV]	> 400	> 400	—	> 400	—	> 400	> 400
m_{jj} [GeV]	> 110	> 110	—	> 110	—	> 110	> 110
Jet p_T [GeV]	> 100	> 100	> 50	> 100	> 50	> 100	> 100

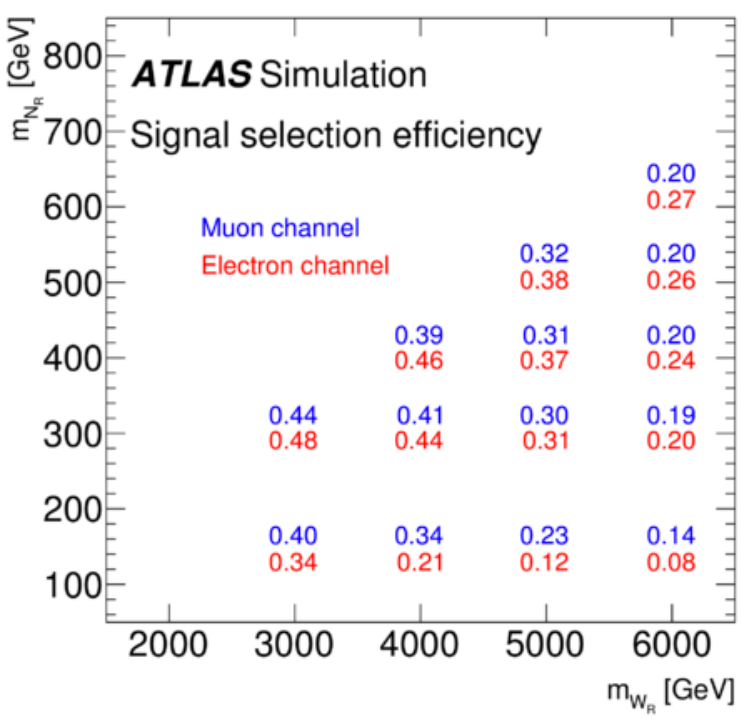
Semi-leptonic heavy neutrino and W: resolved



Semi-leptonic heavy neutrino and W: boosted

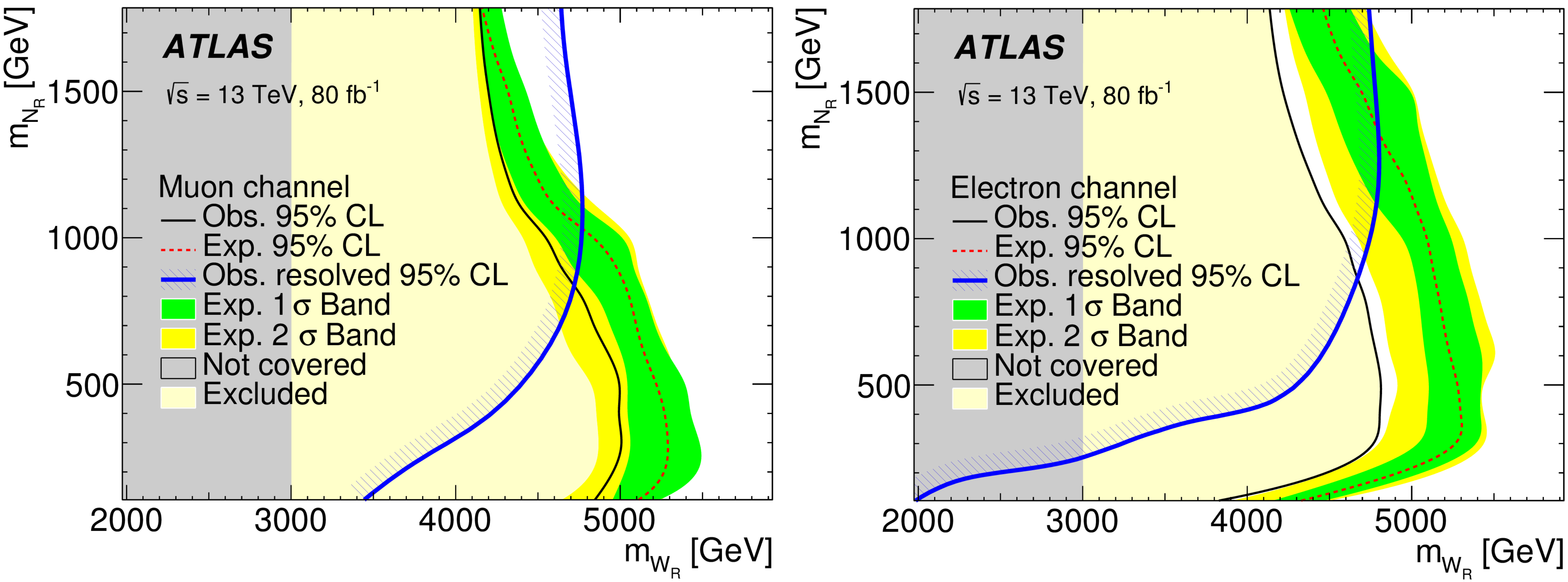


	Electron channel	Muon channel
Lepton:		
p_T	> 26 GeV	> 28 GeV
$\|\eta\|$	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	< 2.5
Leading lepton quality	Medium [61], isolated [61]	Medium [62], isolated [62]
Subleading lepton quality	Medium, no isolation	Medium, no isolation
Transverse impact parameter significance	$\|d_0\|/\sigma_{d_0} < 5.0$	$\|d_0\|/\sigma_{d_0} < 3.0$
Longitudinal impact parameter	$\|z_0\| \sin\theta < 0.5$ mm	
Trimmed large-*R* jet:		
p_T	> 200 GeV	
$\|\eta\|$	< 2.0	
Mass	> 50 GeV	None



Region	Range of $m_{W_R}^{reco}$	Lepton flavour
Signal region (SR)	> 2 TeV	Same flavour
Control region (CR)	< 2 TeV	Same flavour
Validation region (VR)	All	Mixed flavour (leading: muon; subleading: electron)

Semi-leptonic heavy neutrino and W: resolved

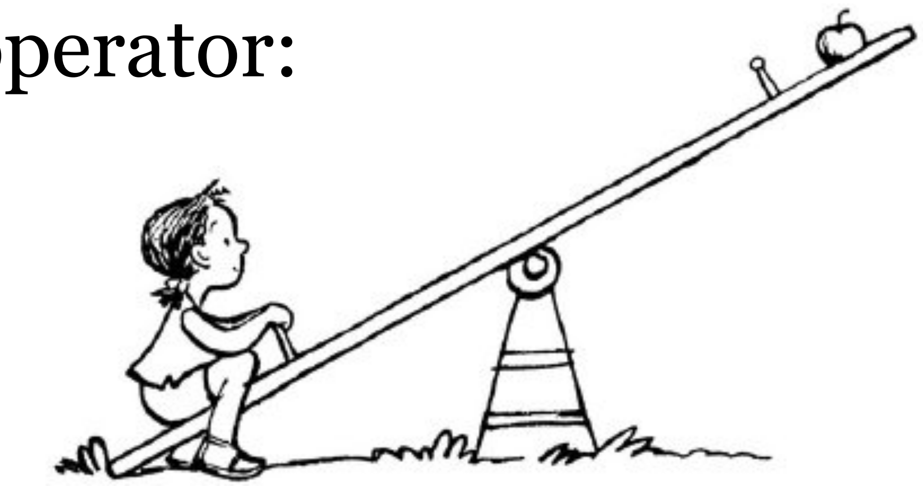


- Limits obtained from single-bin poissonian experiments show little dependence on the particle masses and are only sensitive to the signal efficiencies.

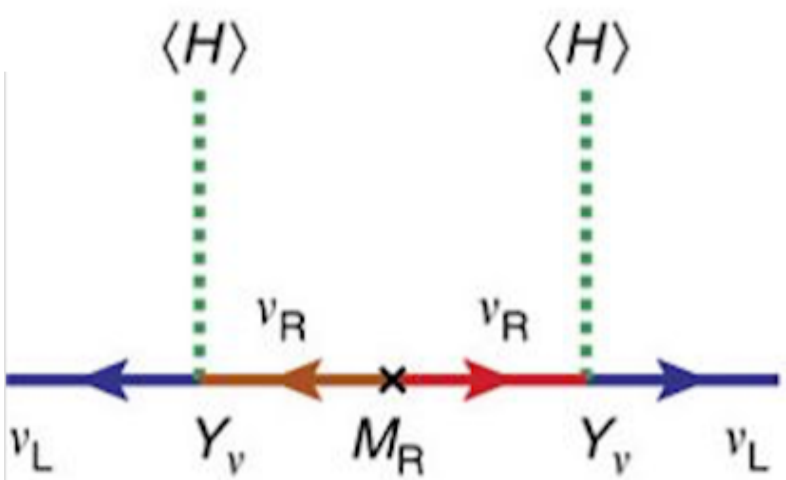
The See-Saw mechanism

- **See-saw mechanisms:** neutrinos can be their own antiparticles. New heavy states generate a suppressed neutrino mass M_ν.
- Within the Standard Model expand dim-5 operator:

$$\mathcal{L}_Y(d=5) \approx \frac{Y_\nu^{ij}(\nu_L)_i H(\nu_L)_j H}{M}$$



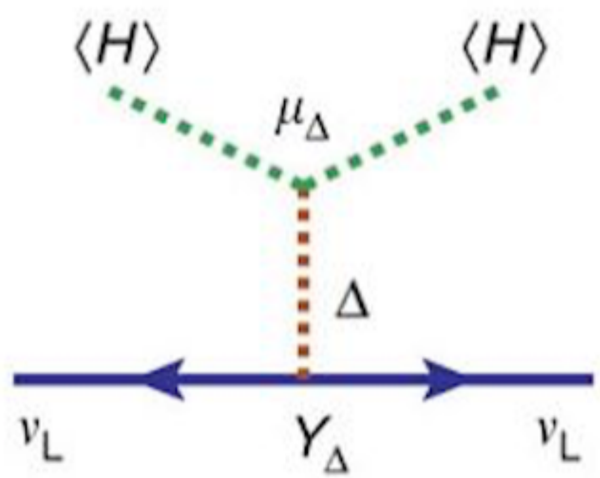
Type-I



$$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$$

Right-handed fermion singlet N_R

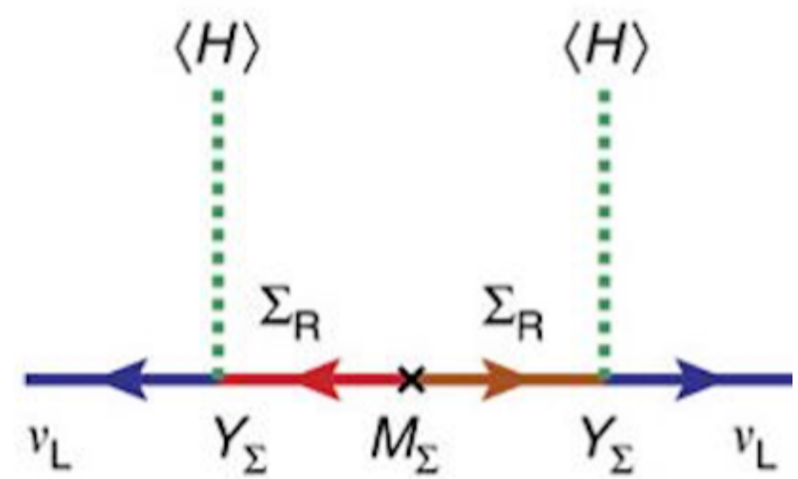
Type-II



$$M_\nu = \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$$

Scalar triplet $\Delta^{0,\pm,\pm\pm}$

Type-III



$$M_\nu = -\langle H\rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$$

Fermion triplet $\Sigma^{0,\pm}$

Multi-leptonic prompt/displaced

- Signatures including muons and electrons probed using different strategies.
- Just a single right-handed Majorana neutrino postulated.
- Lepton number violated (LNV) or conserved (LNC).
- Prompt: tree leptons from the interaction point $e^{\pm}e^{\pm}\mu^{\mp}$, $\mu^{\pm}\mu^{\pm}e^{\mp}$.
- Displaced: prompt **muon** and displaced vertex with $\mu\mu$ or μe.

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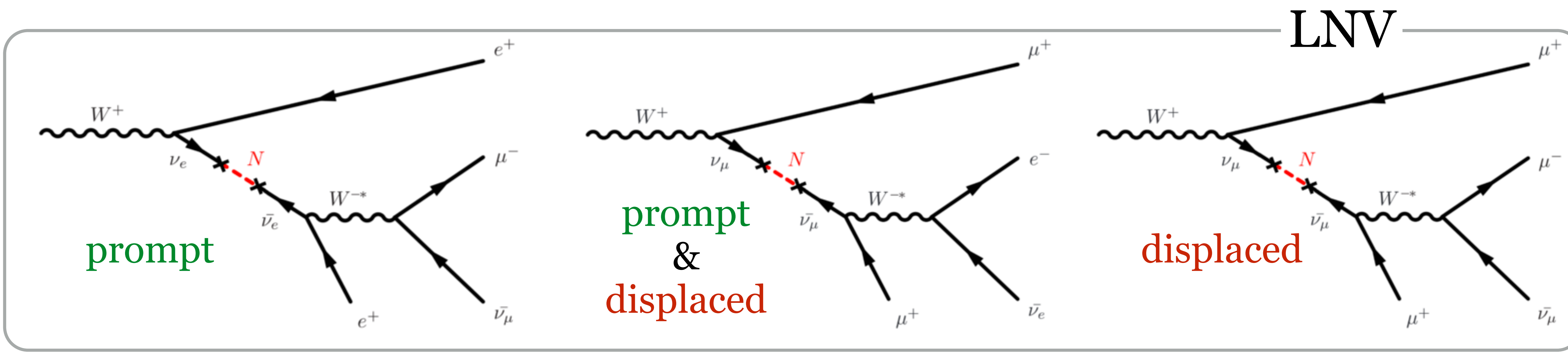
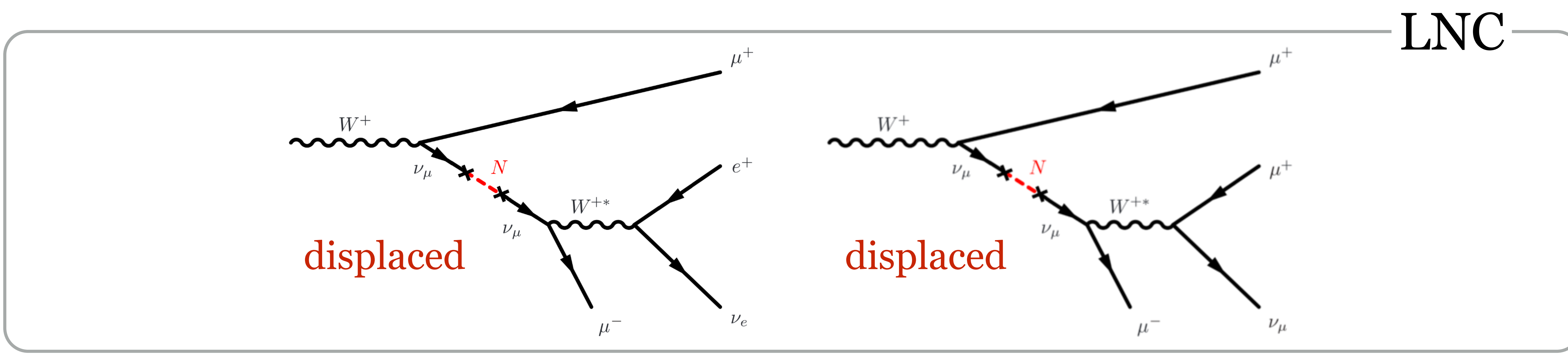
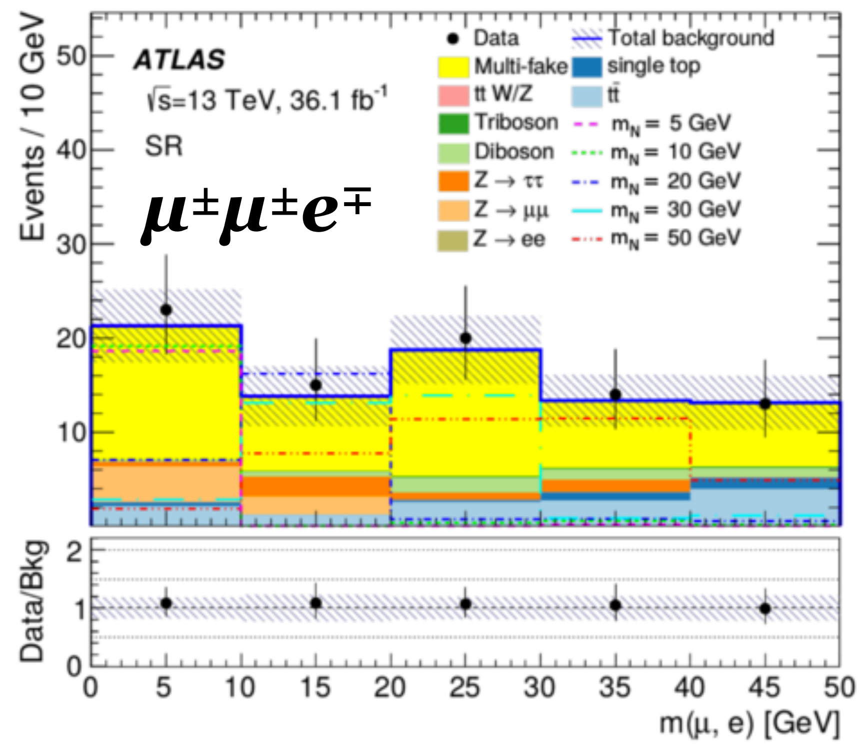


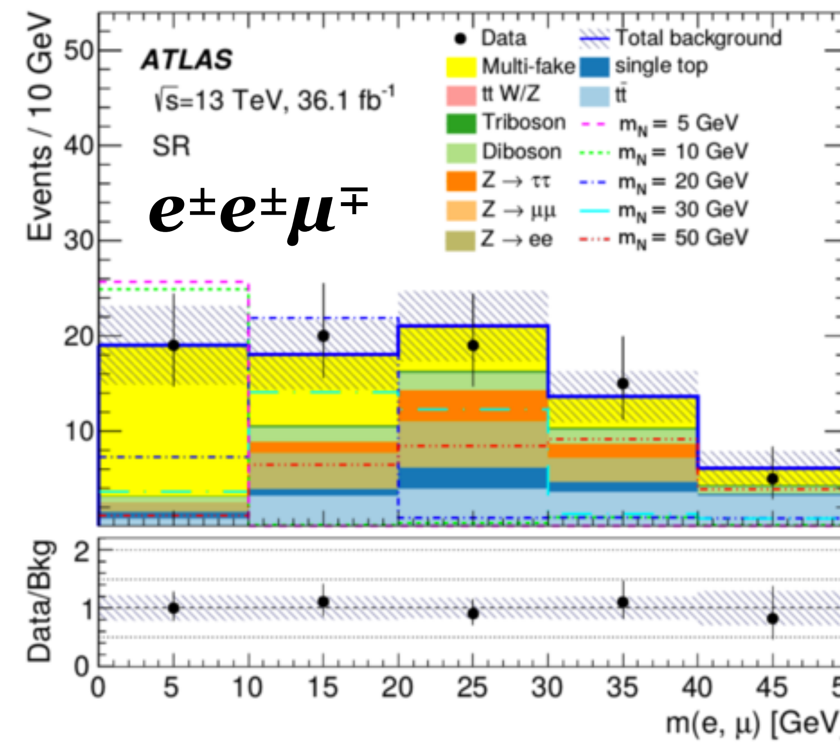


Multi-leptonic prompt/displaced

Prompt

- $40 < m(\ell,\ell,\ell') < 90$ GeV
- b-jet veto
- $E_T^{miss} < 60$ GeV
- Mass reconstructed using e and μ and excluding the leading lepton in the event.





Displaced

- SM backgrounds mostly negligible.
- At least one displaced vertex (DV) within fiducial volume $4 < r_{DV} < 300$ mm with two opposite charge particles.
- Cosmic ray veto eliminates fake "back-to-back" muons.
- $m_{DV} > 4$ GeV using tracks from the DV.

control regions for background estimation

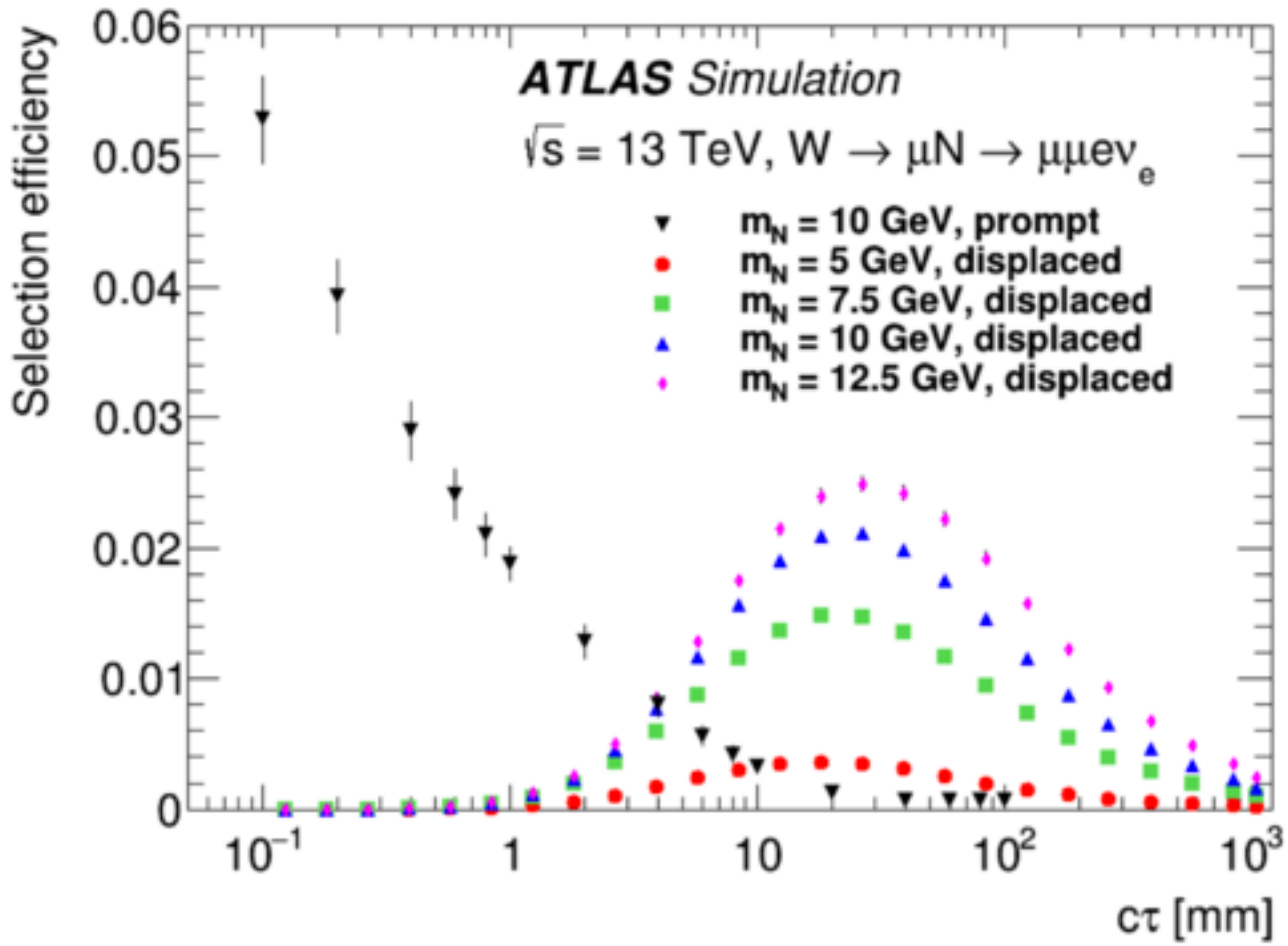
Leptons in DV	Same-charge DV	Opposite-charge DV	Opposite-charge DV estimated
2	0	0 (signal region)	< 2.3 at 90% CL
1 (μ)	83	89	82.4±9.0
1 (e)	28	35	27.8±5.3
0	169254	168037	

Multi-leptonic prompt/displaced

$$\tau_{N_e} = (4.15 \cdot 10^{-12}\ \mathrm{s})|U|^{-2}(m_N/1\ \mathrm{GeV})^{-5.17}$$

$$\tau_{N_\mu} = (4.49 \cdot 10^{-12}\ \mathrm{s})|U|^{-2}(m_N/1\ \mathrm{GeV})^{-5.19}$$

- These assume no LNV decays. If LNV is allowed twice as many decay channels are allowed and lifetime is reduced by a factor of two.



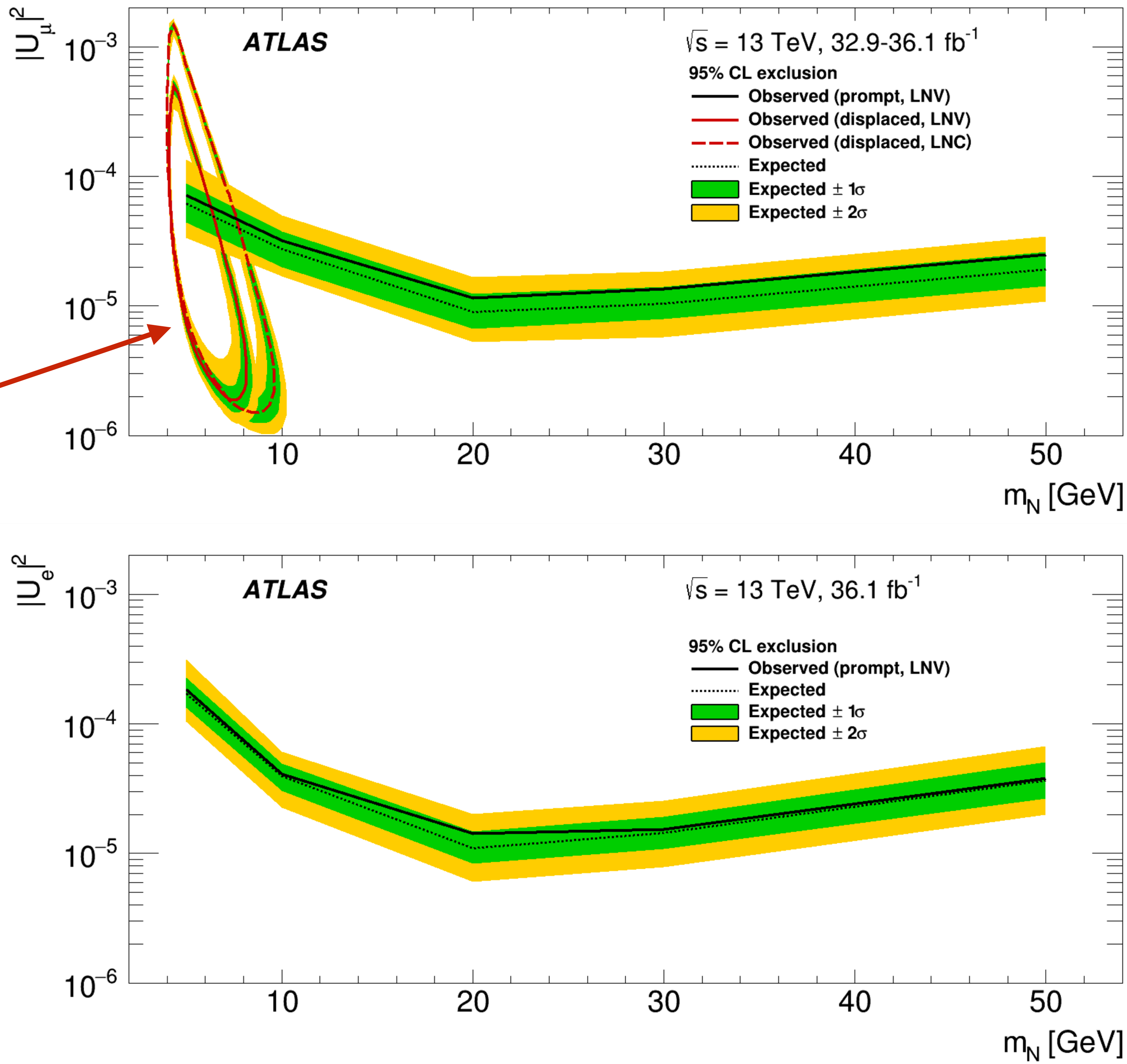
Multi-leptonic prompt/displaced

Muon channel	Electron channel
exactly $\mu^{\pm}\mu^{\pm}e^{\mp}$ signature	exactly $e^{\pm}e^{\pm}\mu^{\mp}$ signature
$p_{\mathrm{T}}(\mu) > 4\,\mathrm{GeV}$ $p_{\mathrm{T}}(e) > 7\,\mathrm{GeV}$ (2015), 4.5 GeV (2016)	
leading muon $p_{\mathrm{T}} > 23\,\mathrm{GeV}$ subleading muon $p_{\mathrm{T}} > 14\,\mathrm{GeV}$	leading electron $p_{\mathrm{T}} > 27\,\mathrm{GeV}$ subleading electron $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ $m(e, e) < 78\,\mathrm{GeV}$
$40 < m(\ell, \ell, \ell') < 90\,\mathrm{GeV}$ b-jet veto $E_{\mathrm{T}}^{\mathrm{miss}} < 60\,\mathrm{GeV}$	

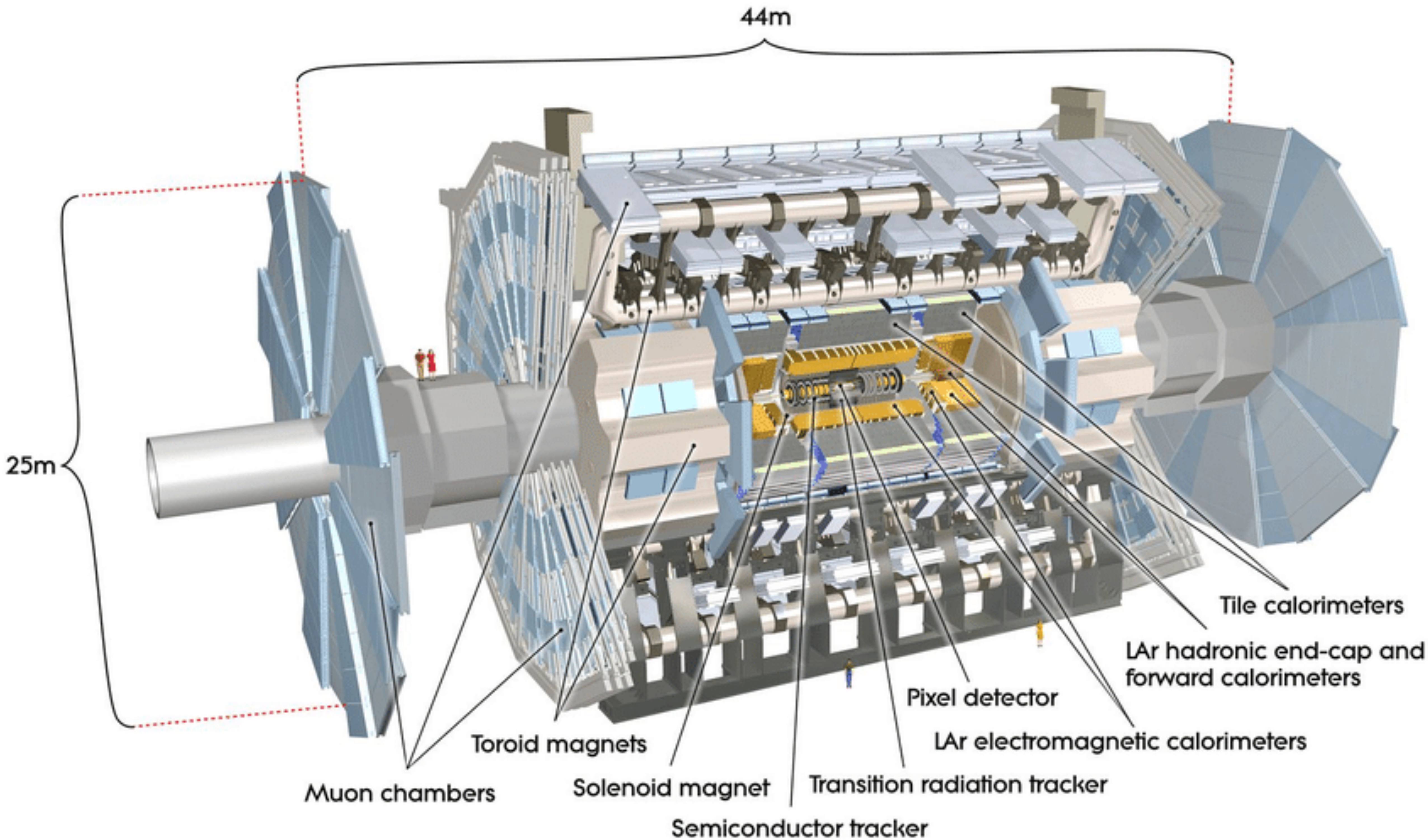
Criterion	Signal region	Control region	Fit distribution
0	exactly one SCSF lepton pair		$m(\ell, \ell')$
1	$40 < m(\ell, \ell, \ell') < 90\,\mathrm{GeV}$	$m(\ell, \ell, \ell') \leq 40\,\mathrm{GeV} \mid\mid m(\ell, \ell, \ell') \geq 90\,\mathrm{GeV}$	$p_{\mathrm{T}}(\ell')$
2	b-jet veto	at least one b-jet	$p_{\mathrm{T}}(\ell')$
3	$E_{\mathrm{T}}^{\mathrm{miss}} < 60\,\mathrm{GeV}$	$E_{\mathrm{T}}^{\mathrm{miss}} \geq 60\,\mathrm{GeV}$	$p_{\mathrm{T}}(\ell')$

Multi-leptonic prompt/displaced

Assuming lepton number violation (LNV) for displaced signatures yields weaker limits as lifetime reduced by a factor of two for LNV for a given coupling strength

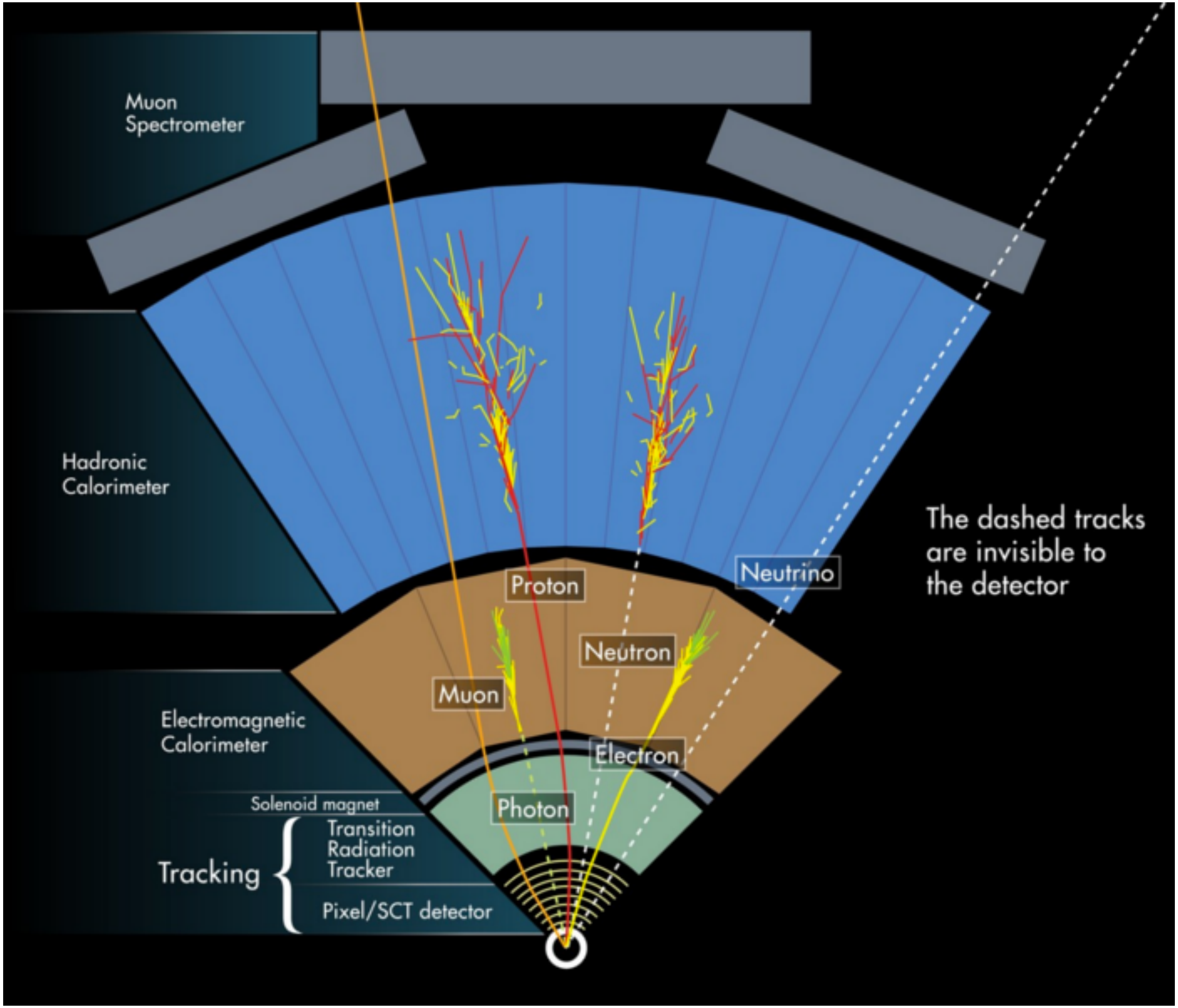


The ATLAS detector



- In Run-II *pp* collisions were delivered at $\sqrt{s}$ = 13 TeV.

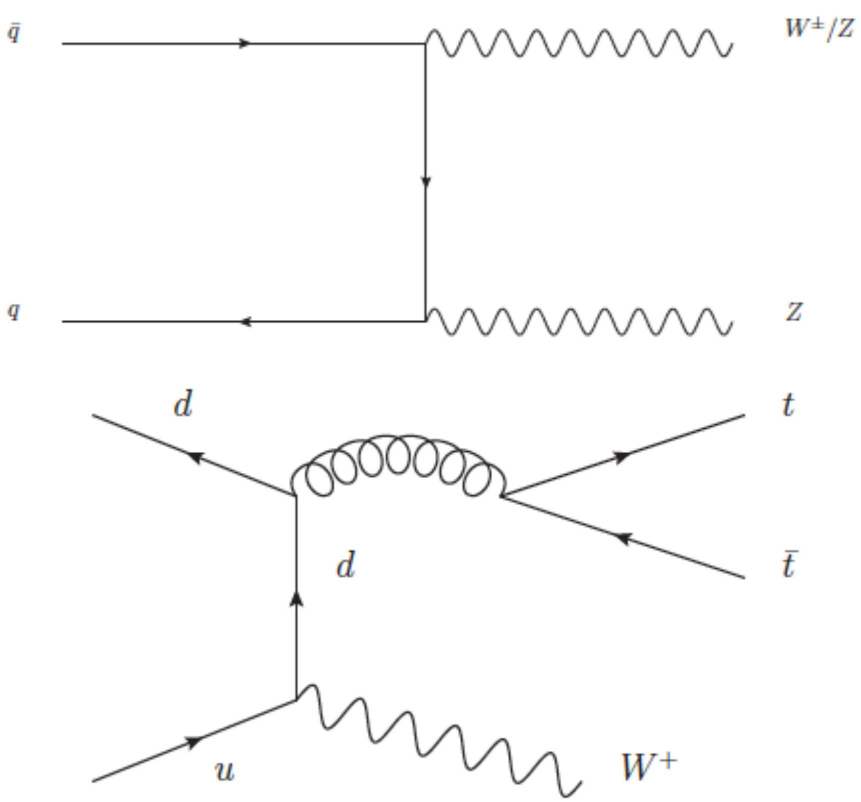
ATLAS


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks are invisible to the detector

Backgrounds

Prompt

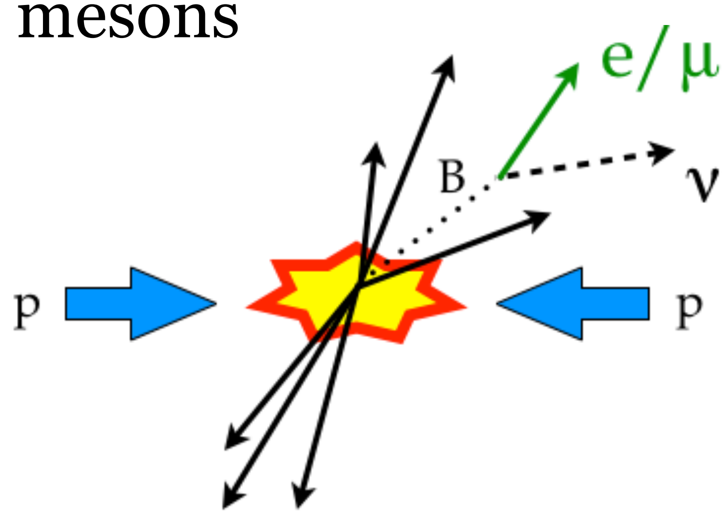
Real prompt leptons:
ZW, ZZ, ttW, ttZ, ttH, $W^{\pm}W^{\pm}$



Estimated with simulation. ttbar yield estimated using fit in control regions.

Mis-ID leptons

- Real electrons or muons from non-prompt decays, e.g. from heavy flavoured mesons



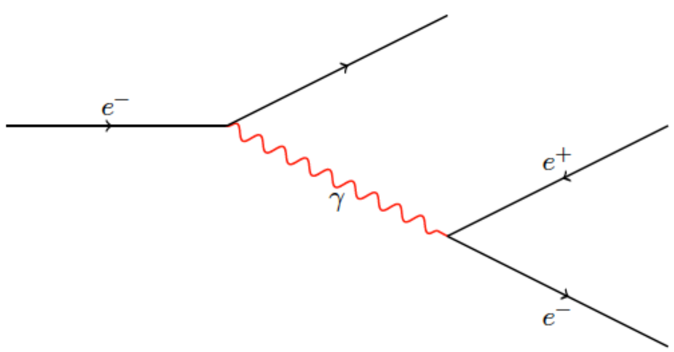
- Jets mis-reconstructed as electrons

Data-driven estimation

Mis-ID charge

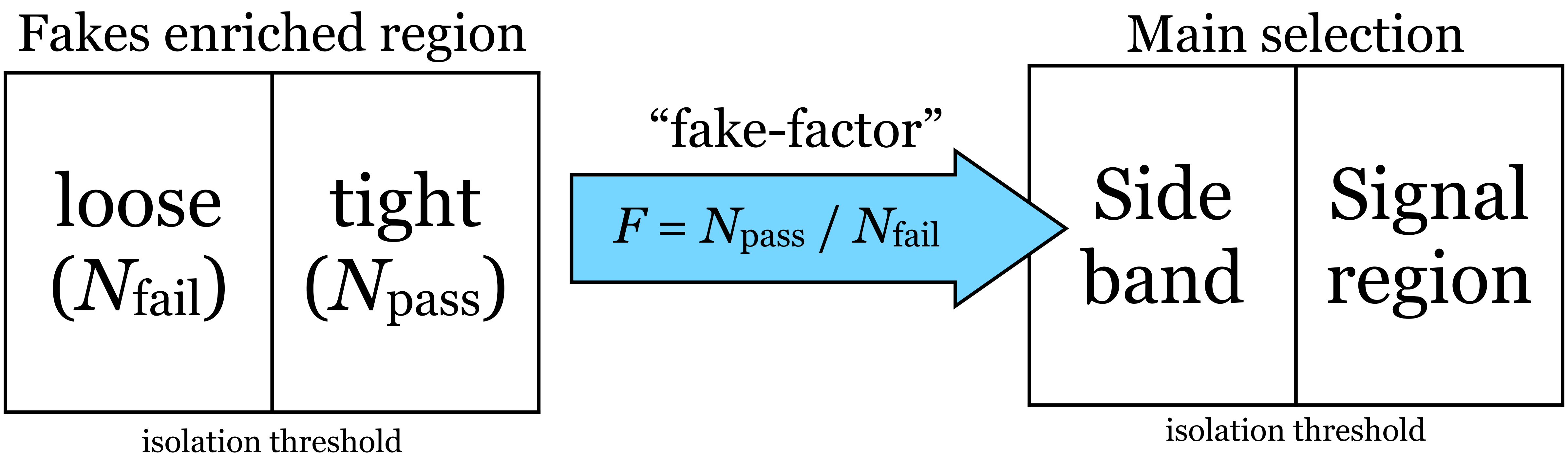
If same-charge signatures required!

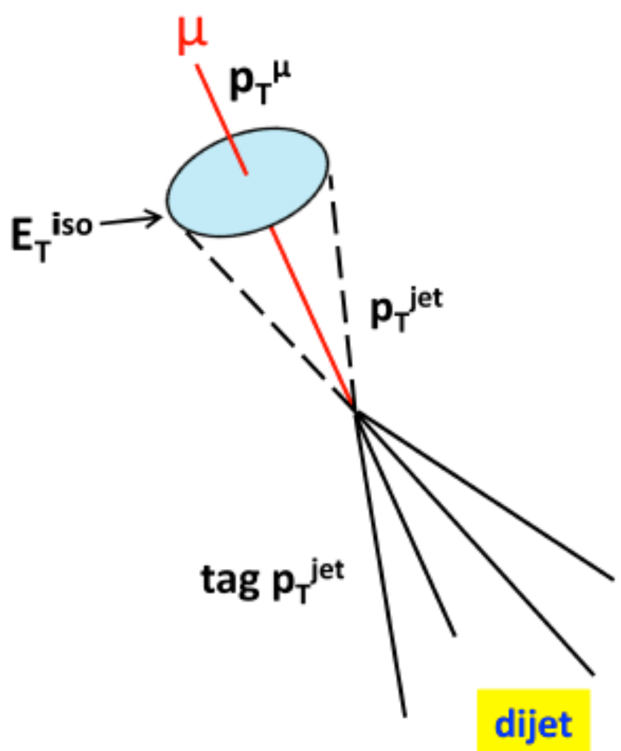
Oppositely charged leptons with charge mis-identification: Z/γ^*, ZZ, $W^{\pm}W^{\mp}$, tt



Mis-ID probability measured with a likelihood method

Mis-identified leptons





Tag-and-probe selections on di-jet events

- Signal region extrapolation: e.g. two lepton case:

$$N_{TT}^{\rm fakes} = \left[\sum_{TL} F_2 + \sum_{LT} F_1 - \sum_{LL} F_1 F_2\right]_{\rm data} - \left[\sum_{TL} F_2 + \sum_{LT} F_1 - \sum_{LL} F_1 F_2\right]_{\rm prompt\ simulation}$$

- Can be extended for more than two leptons
- Parameterisation of F based on lepton kinematic

Mis-identified charge

- ***Z* → *ee*** events used from data and simulation.
- Fit simultaneously **opposite** and **same -charge events** and separately for data and simulation.
- Derive parameterised probabilities and measure a correction based on data/simulation trends.
- Correction is applied to any simulated electron with mis-identified charge.