Search for heavy neutrinos with the ATLAS detector

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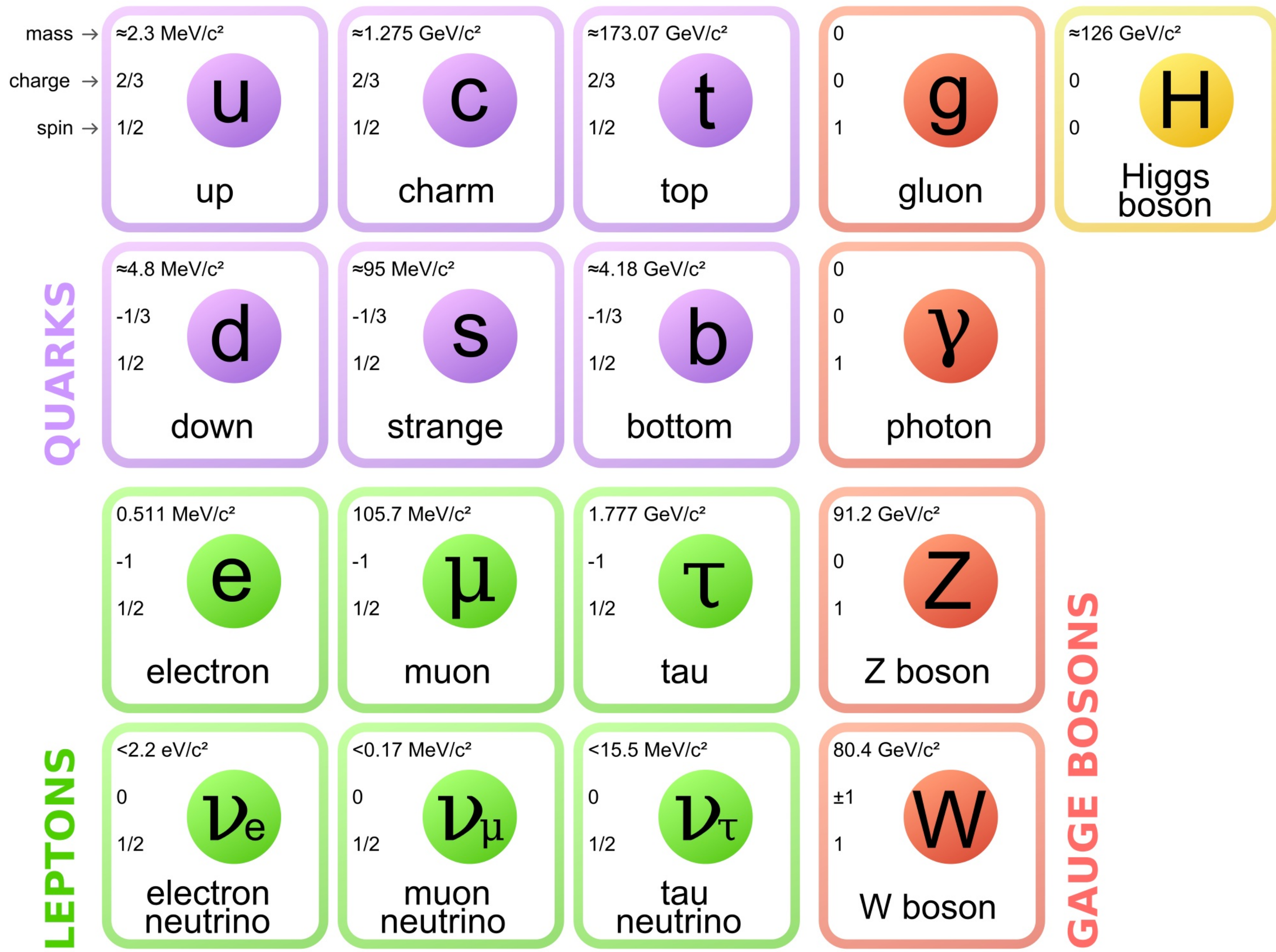
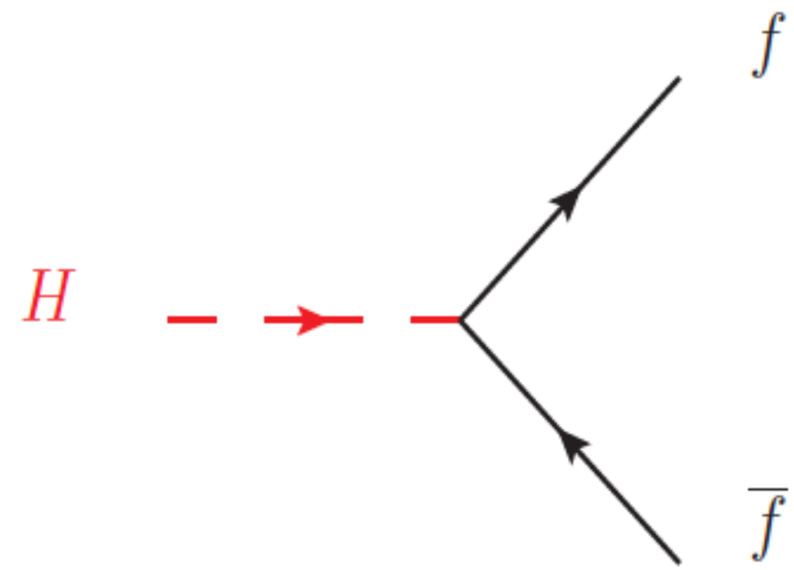
on behalf of the
ATLAS collaboration

Neutrino masses in the Standard Model





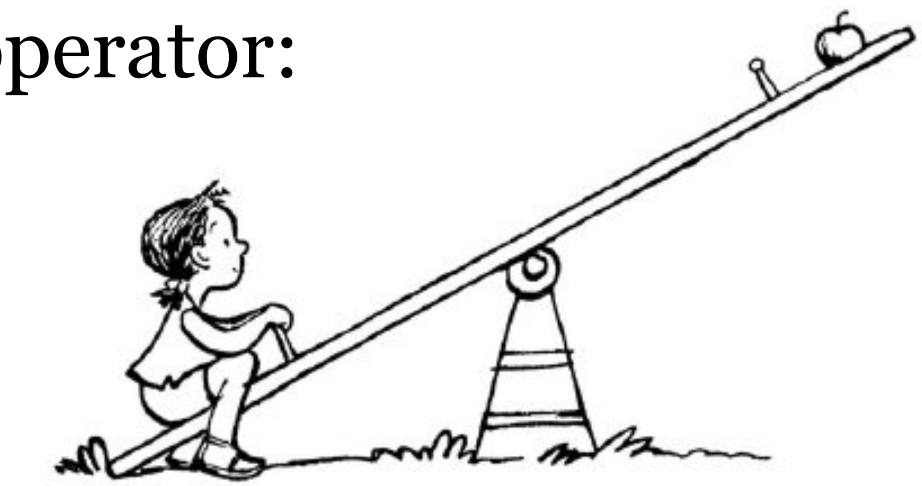
$$Y_f = M_f \,/\, 246 \text{ GeV}$$

- The Higgs mechanism explains how particles acquire mass in the Standard Model.
- But neutrinos would require unnaturally small Yukawa couplings with the Higgs boson of $Y_f \approx 10^{-12}$.
- Also, need to accommodate right-handed neutrinos ν_R which are not observed.

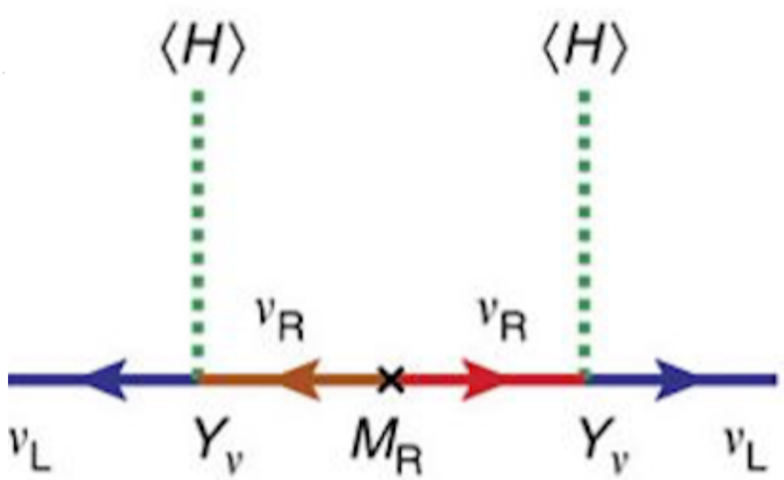
The See-Saw mechanism

- **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:

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



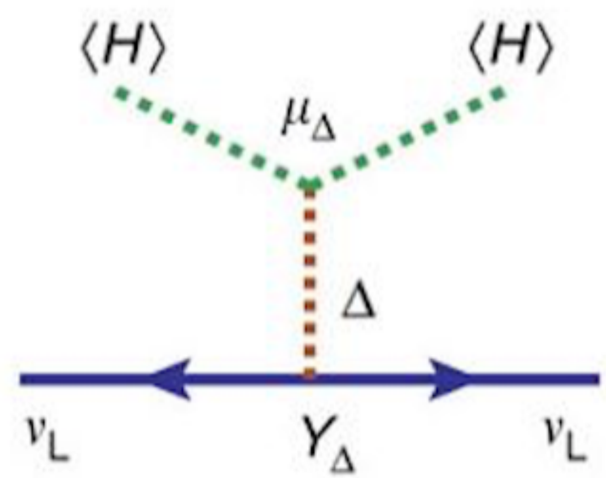
Type-I



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

Right-handed fermion singlet N_R

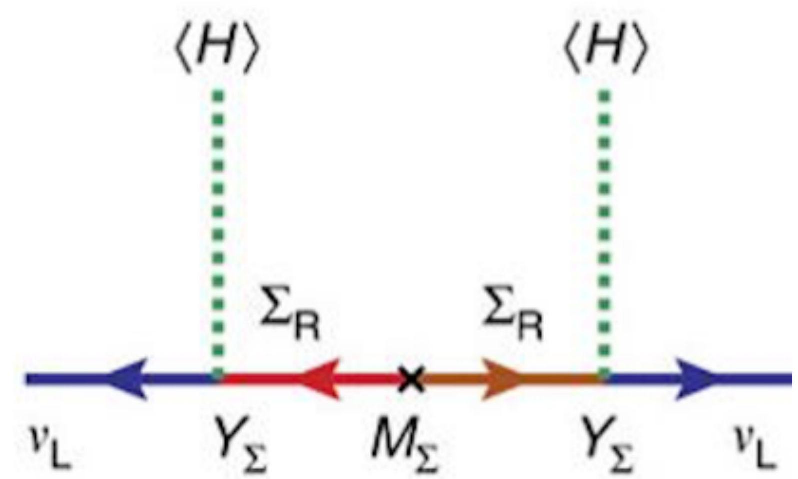
Type-II



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

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

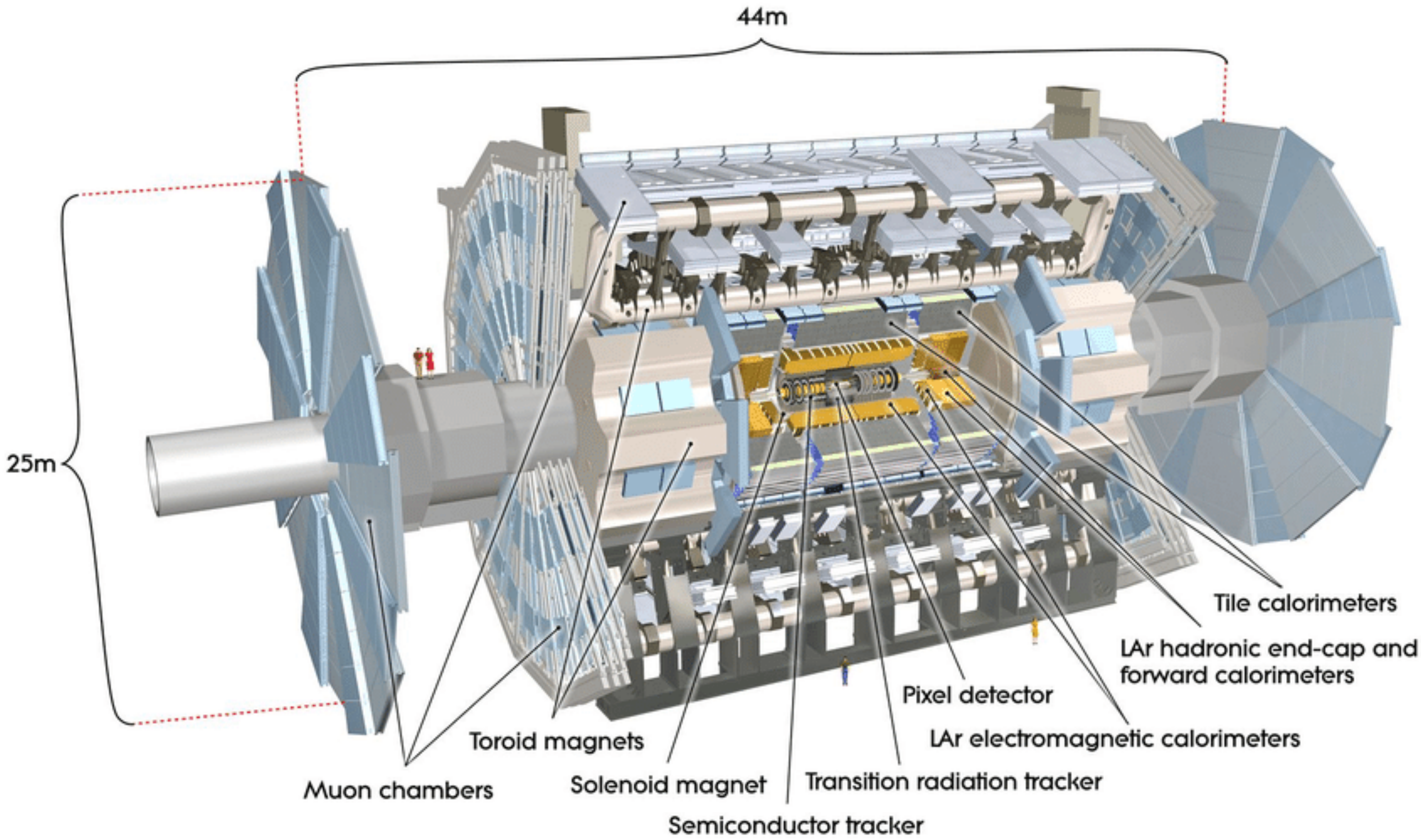
Type-III



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

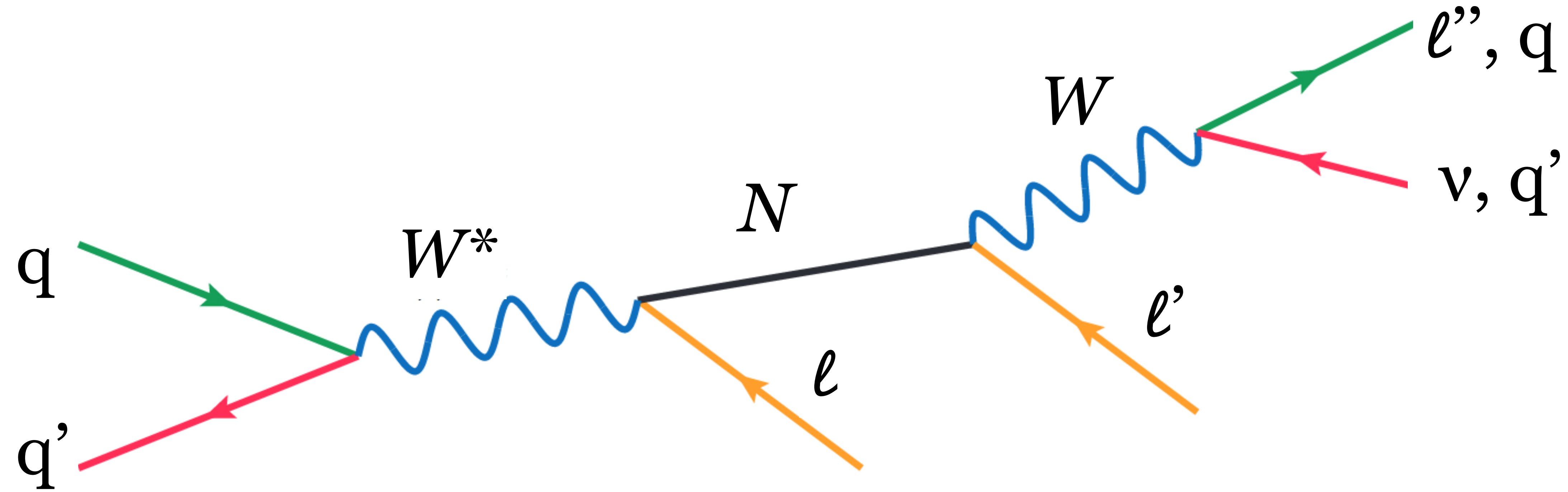
Fermion triplet $\Sigma^{0,\pm}$

The ATLAS detector



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

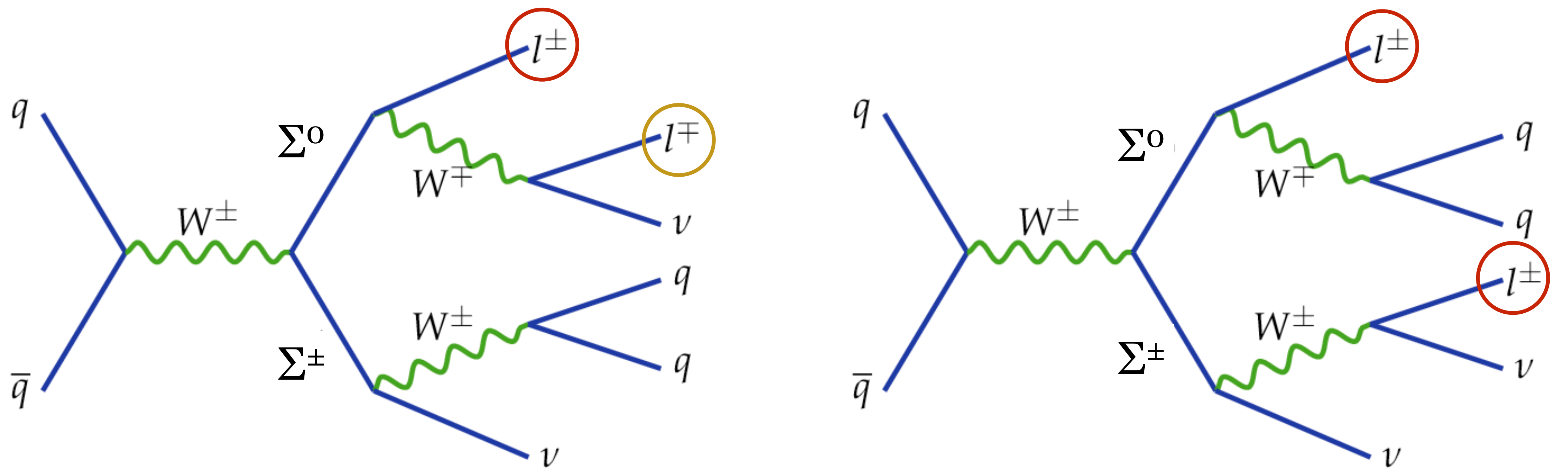
Type-I signatures



- In minimal Type-I, 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).

Type-III signatures

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



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

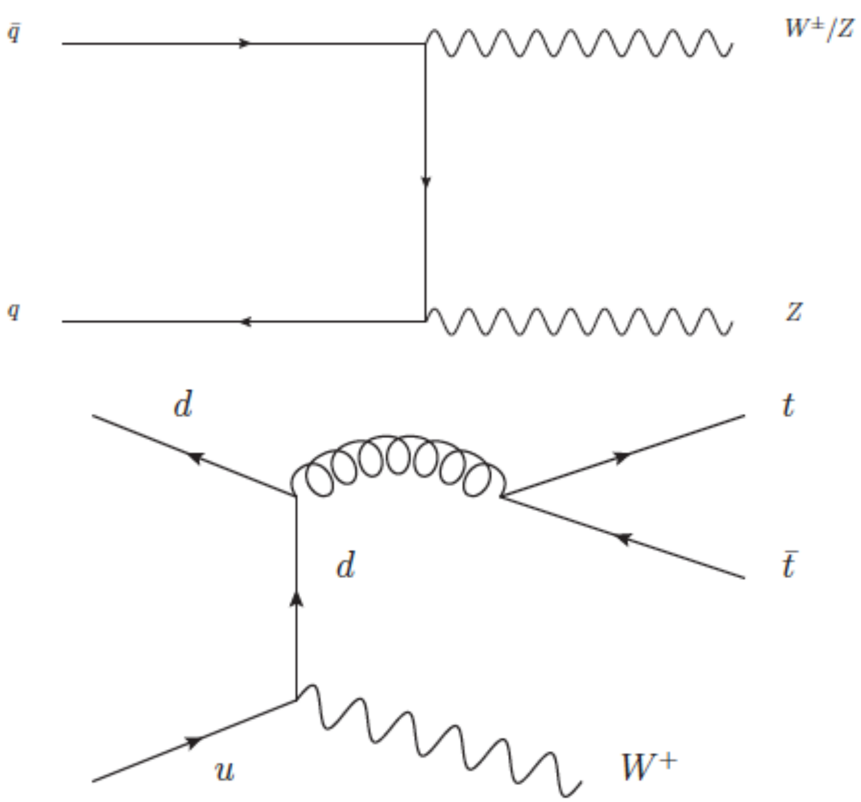
This talk

- Minimal Type-I multi-leptonic:
  - (L_{int} = 36.1 / 32.9 fb^{-1}): 1905.09787.
- Minimal Type-III semi-leptonic:
  - (L_{int} = 79.8 fb^{-1}): ATLAS-CONF-2018-020.
- Left-Right symmetric Type-I semi-leptonic with *resolved* topology:
  - (L_{int} = 36.1 fb^{-1}): JHEP 01 (2019) 016.
- Left-Right symmetric Type-I semi-leptonic with *boosted* topology:
  - (L_{int} = 80 fb^{-1}): 1904.12679.

Backgrounds

Prompt

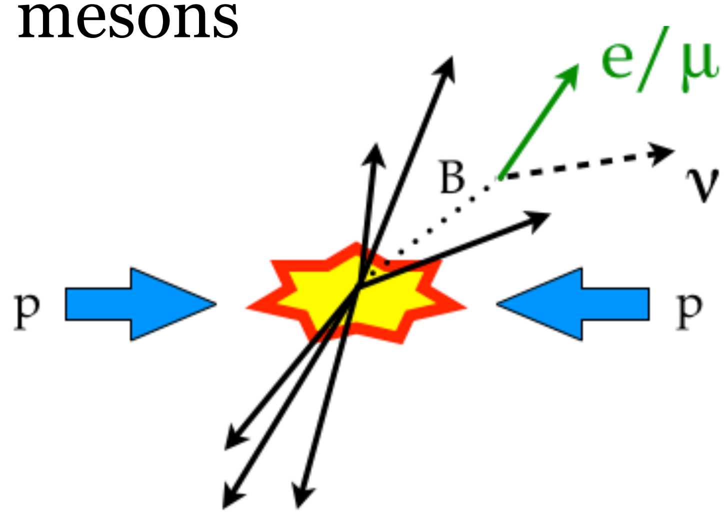
Real prompt leptons:
ZW, ZZ, ttW, ttZ, ttH, $W^{\pm}W^{\pm}$



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



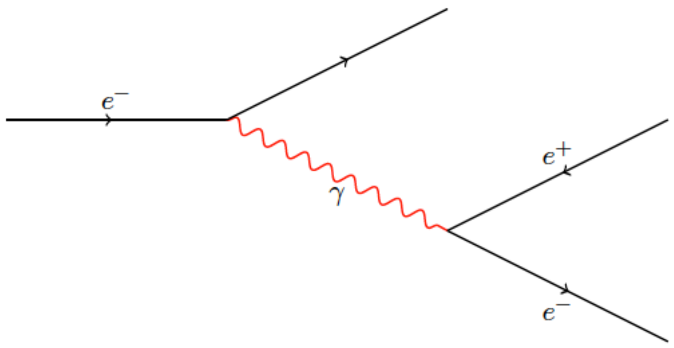
- Jets mis-reconstructed as electrons

Data-driven estimation

Mis-ID charge

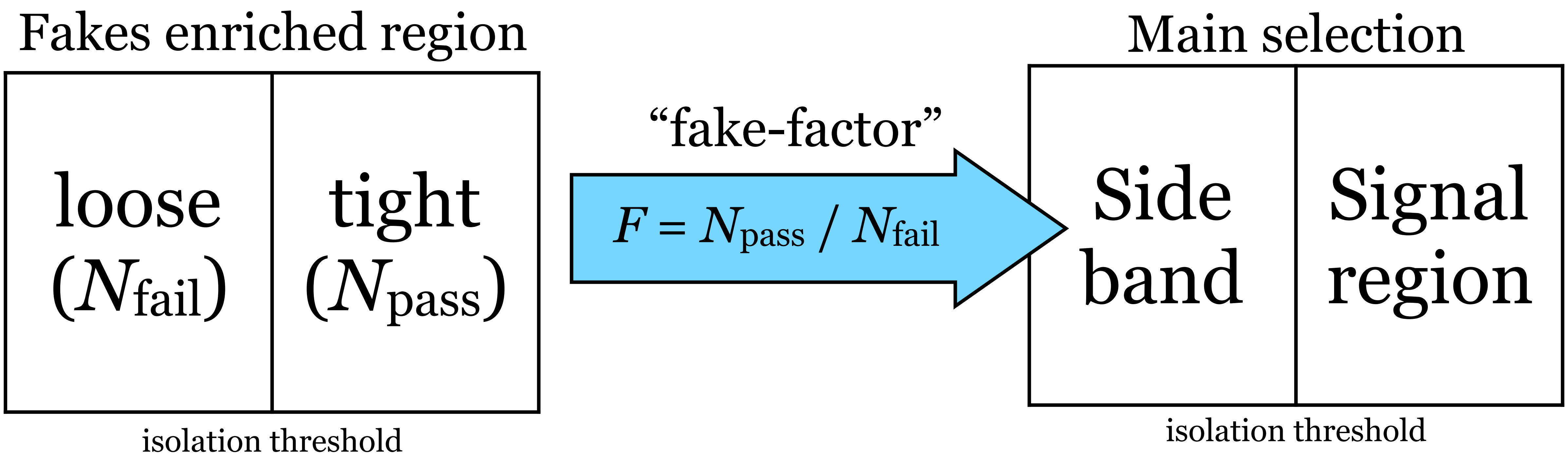
If same-charge signatures required!

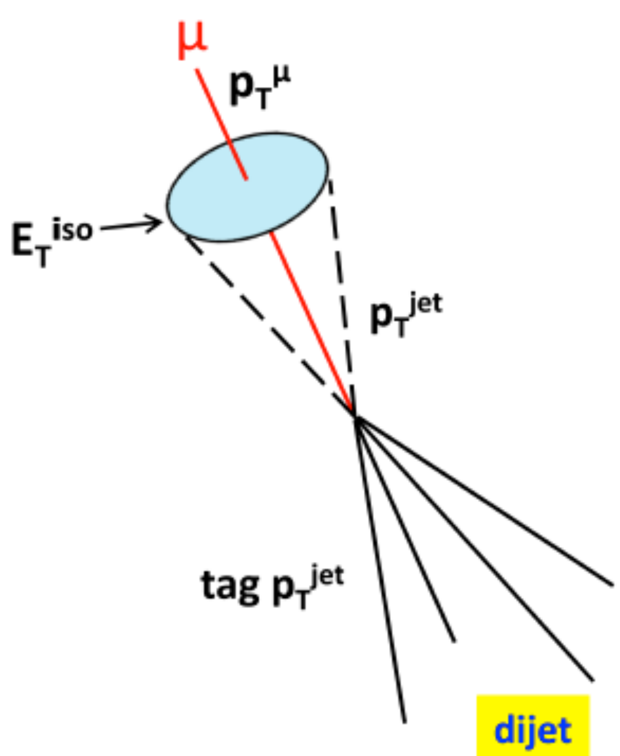
Oppositely charged leptons with charge mis-identification: Z/γ^*, ZZ, $W^{\pm}W^{\mp}$, tt



Mis-ID probability measured with a likelihood method

Mis-identified leptons





Tag-and-probe selections on di-jet events

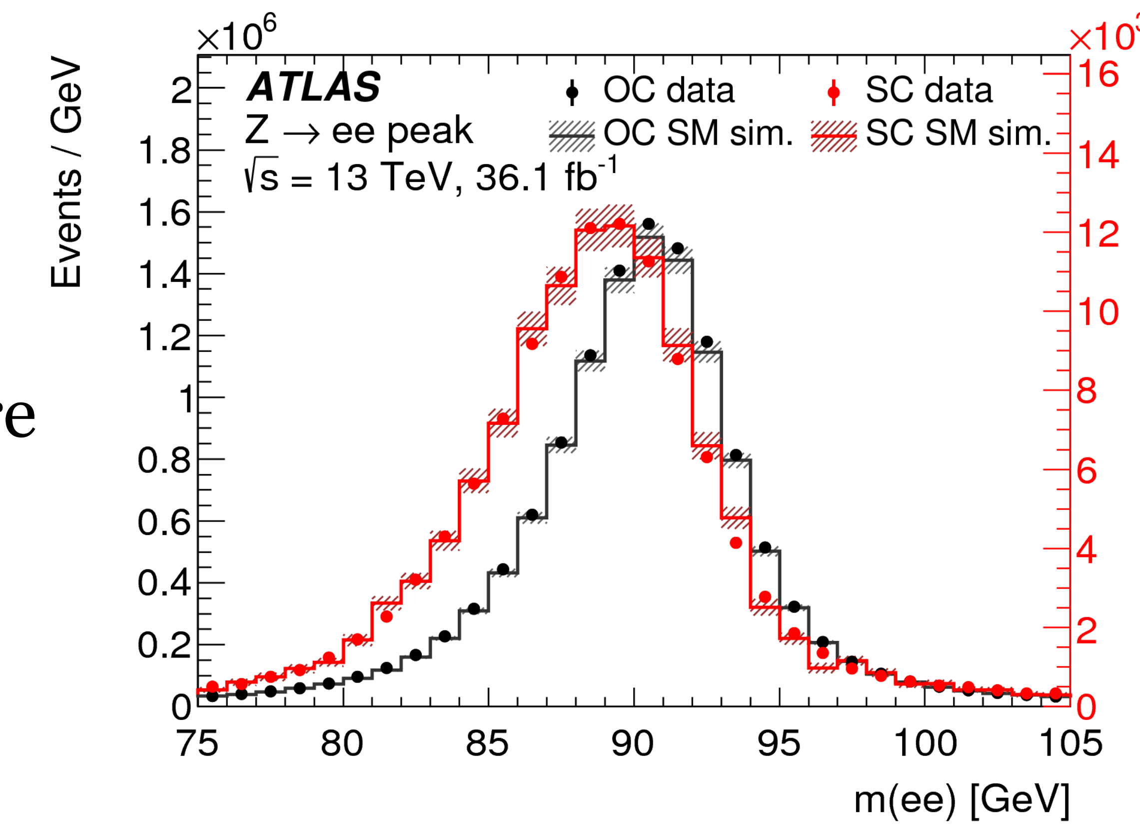
- Signal region extrapolation: e.g. two lepton case:

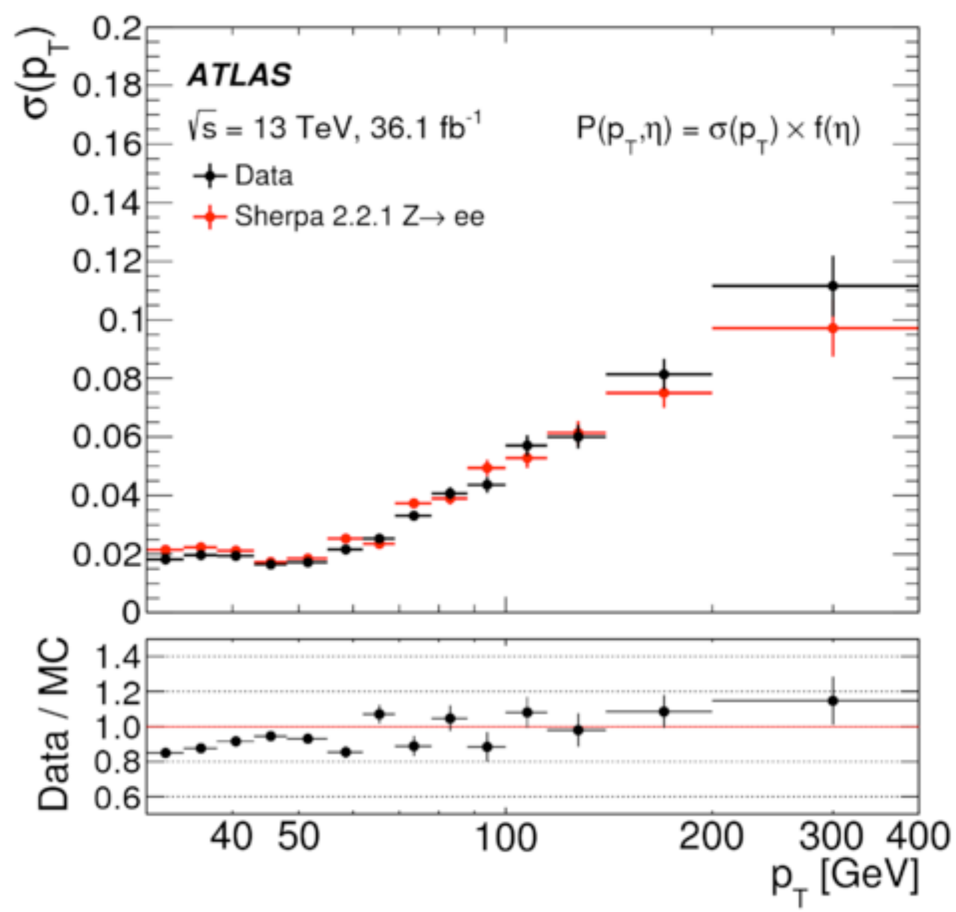
$$N_{TT}^{\text{fakes}} = \left[\sum_{TL} F_2 + \sum_{LT} F_1 - \sum_{LL} F_1 F_2\right]_{\text{data}} - \left[\sum_{TL} F_2 + \sum_{LT} F_1 - \sum_{LL} F_1 F_2\right]_{\text{prompt simulation}}$$

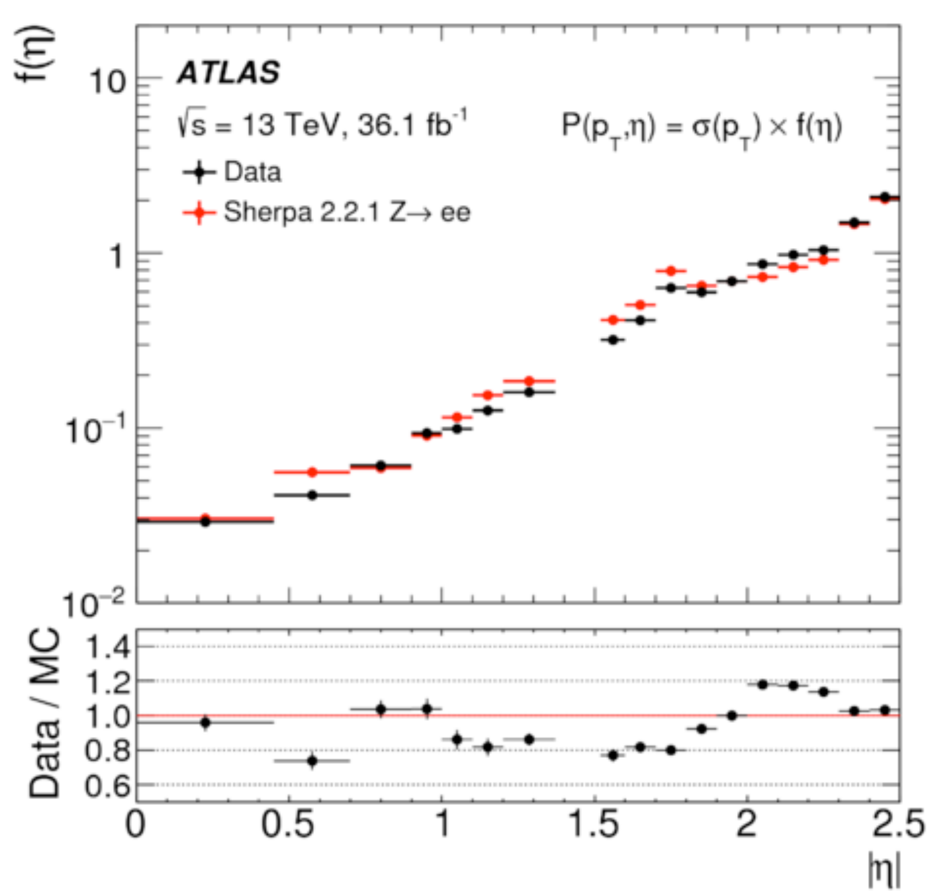
- Can be extended for more than two leptons
- Parameterisation of F based on lepton kinematic

Mis-identified charge

- $Z \rightarrow ee$ 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.



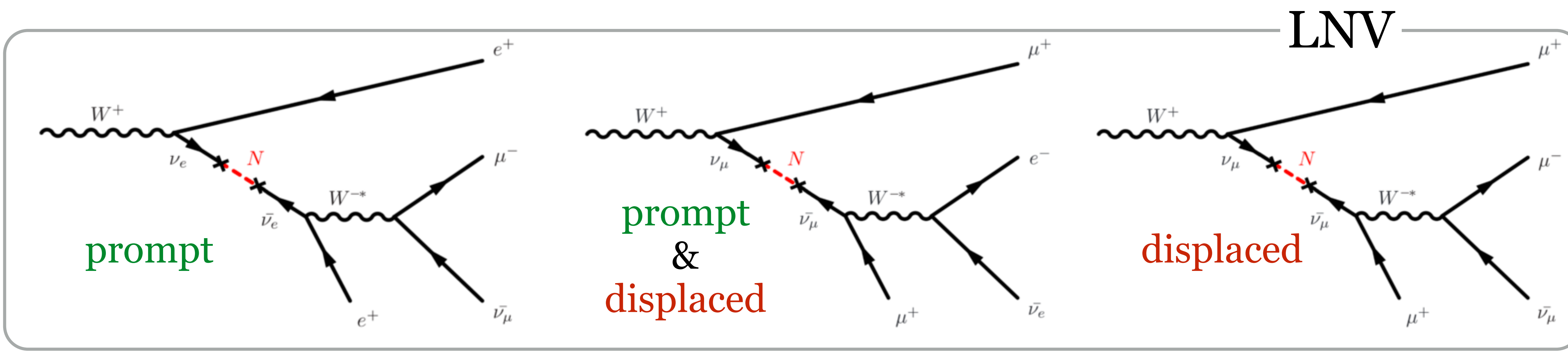


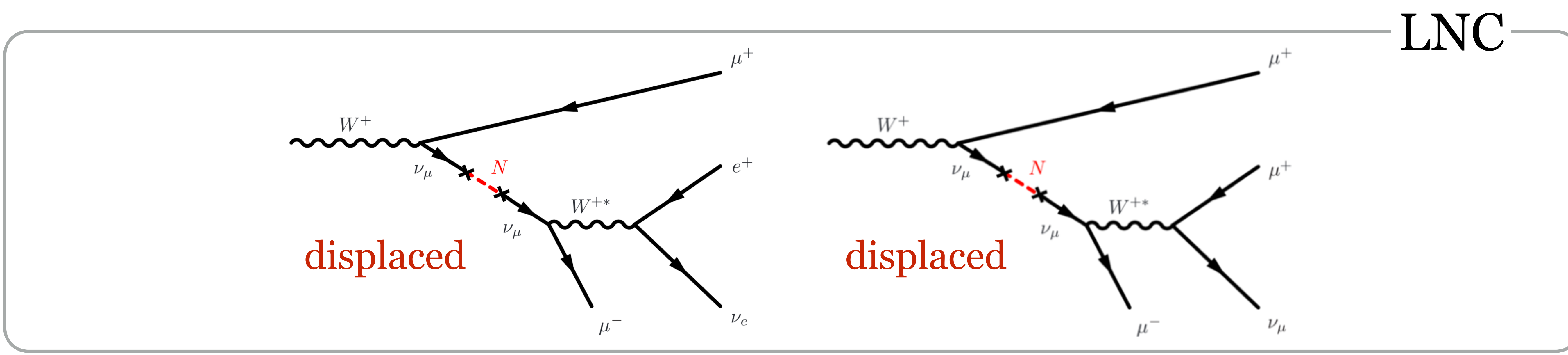


Minimal Type-I, III

Multi-leptonic Type-I search [1905.09787]

- 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.

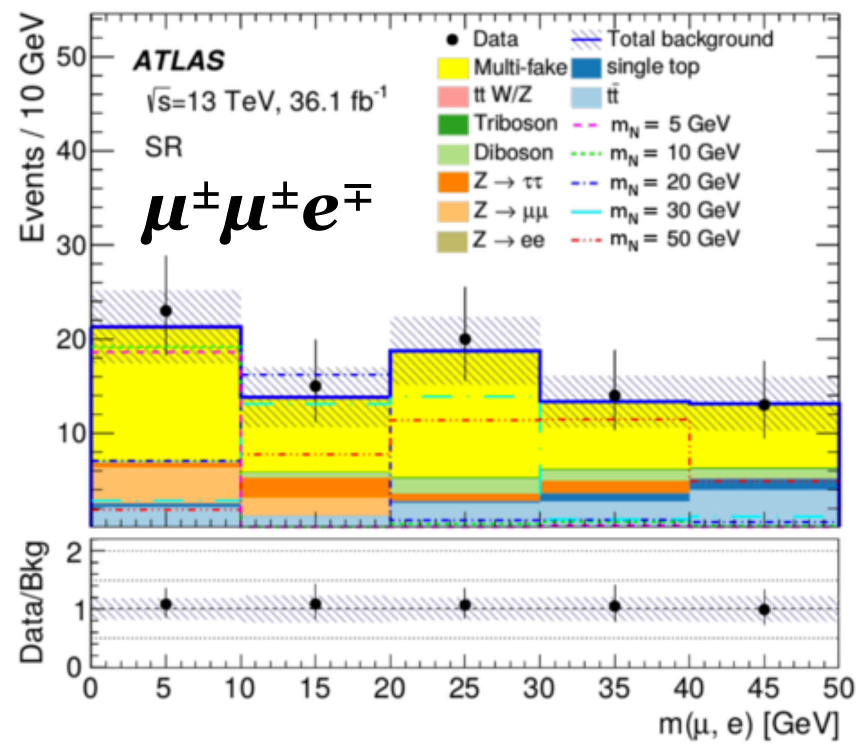


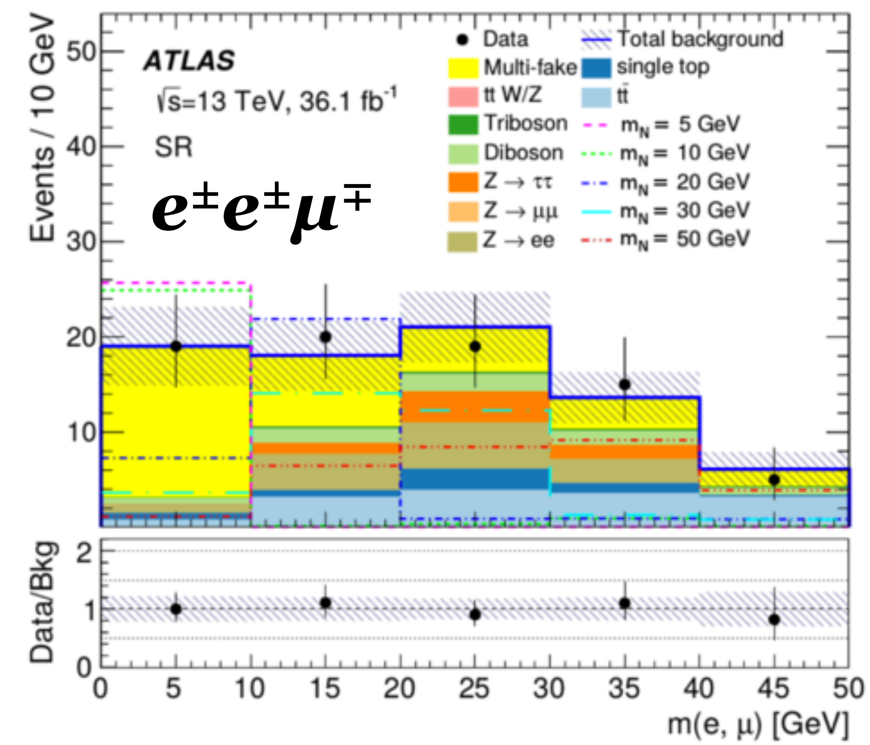


Multi-leptonic Type-I search

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

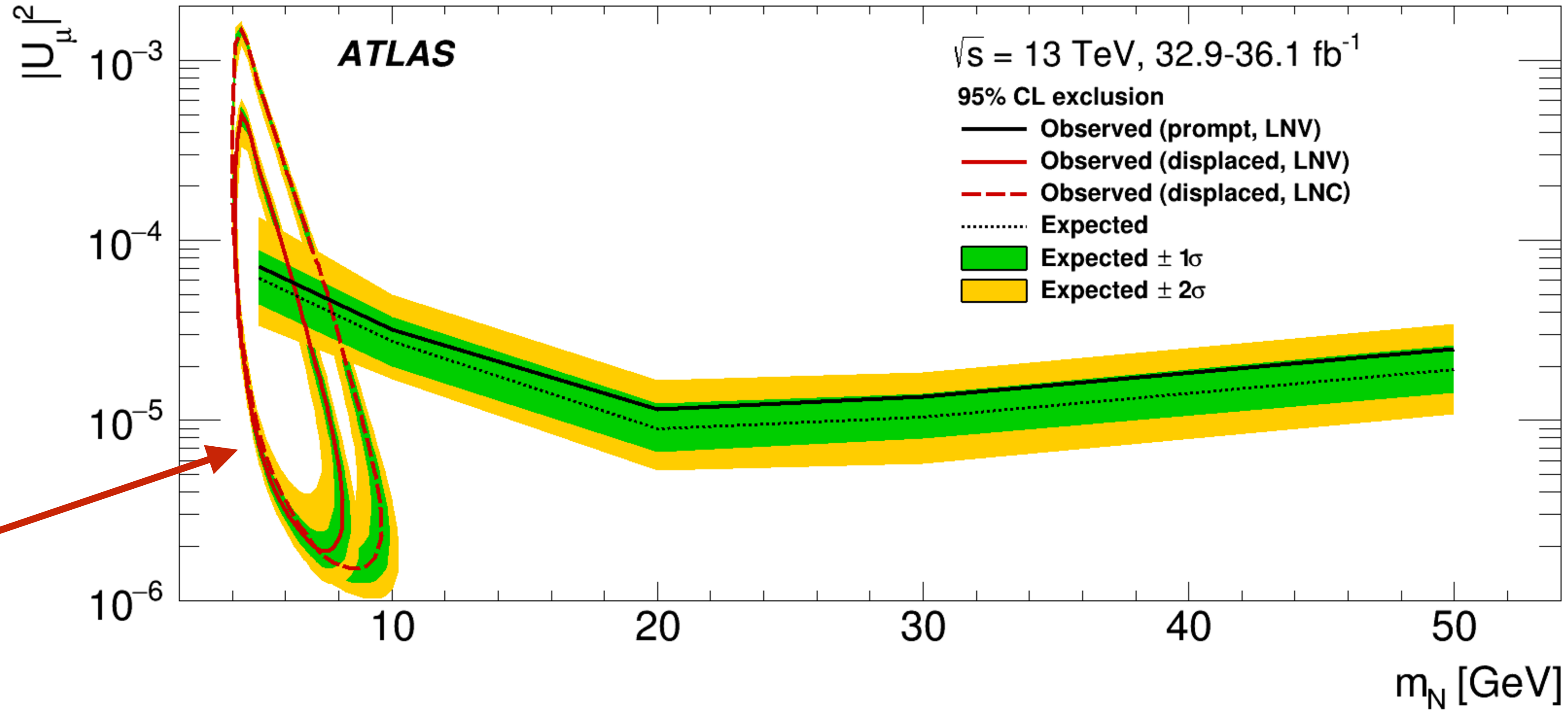
- SM backgrounds mostly negligible.
- At least one displaced vertex (DV) within fiducial volume $4 < r_{DV} < 300$ mm with two opposite charge particles.
- Cosmic ray veto eliminates fake "back-to-back" muons.
- $m_{DV} > 4$ GeV using tracks from the DV.

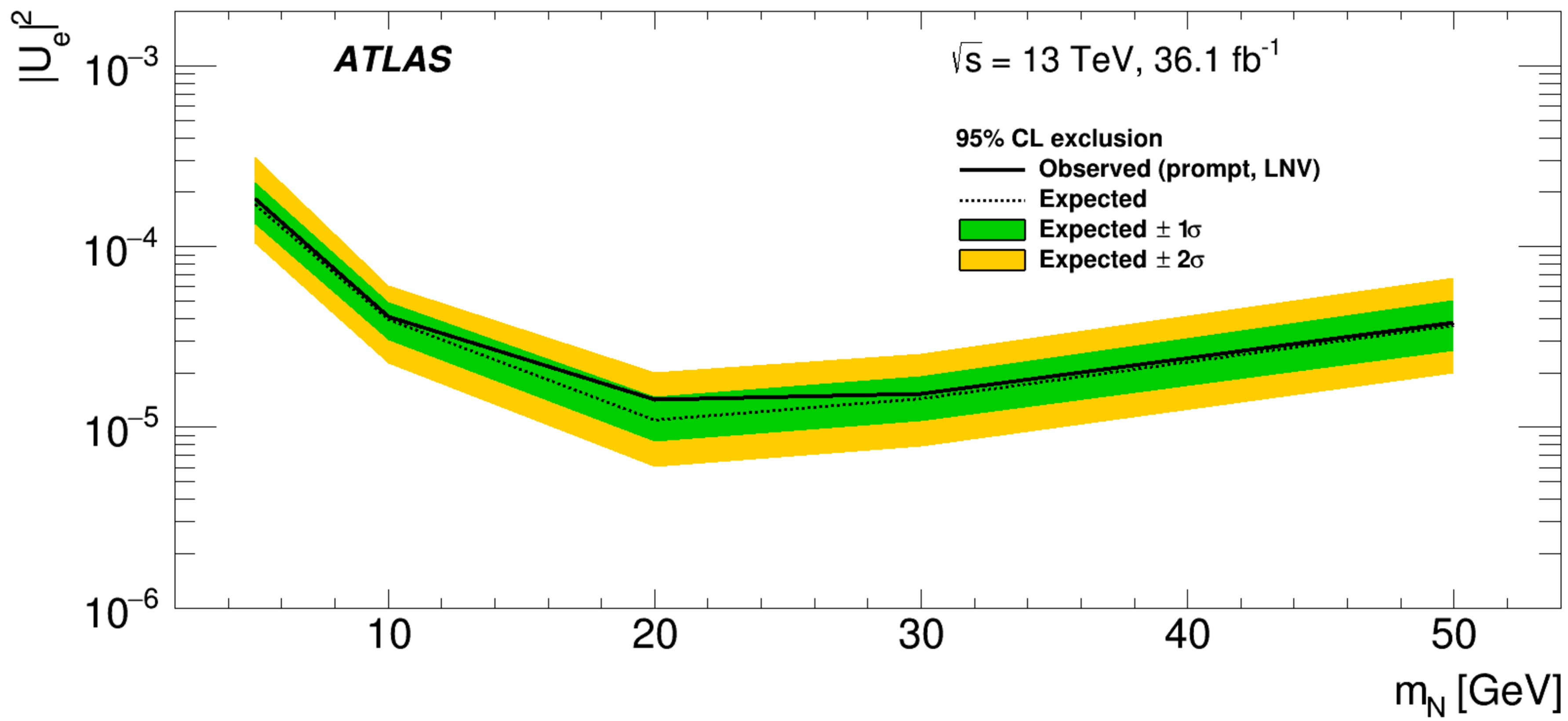
control regions for background estimation

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	

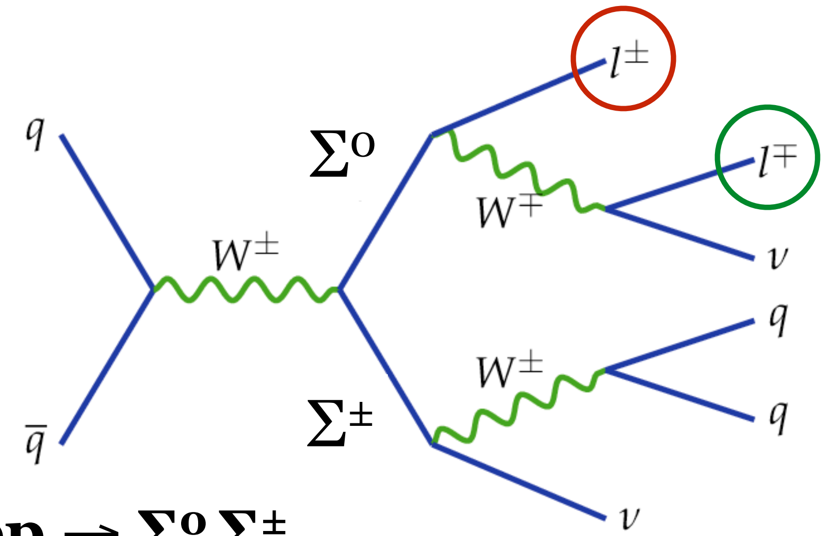
Multi-leptonic Type-I search

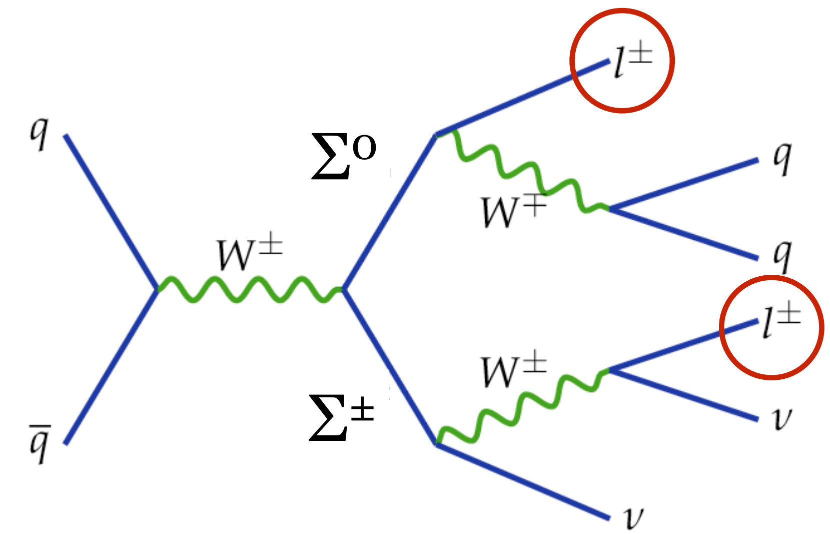
Assuming lepton number violation (LNV) for displaced signatures yields weaker limits as lifetime reduced by a factor of two for LNV for a given coupling strength





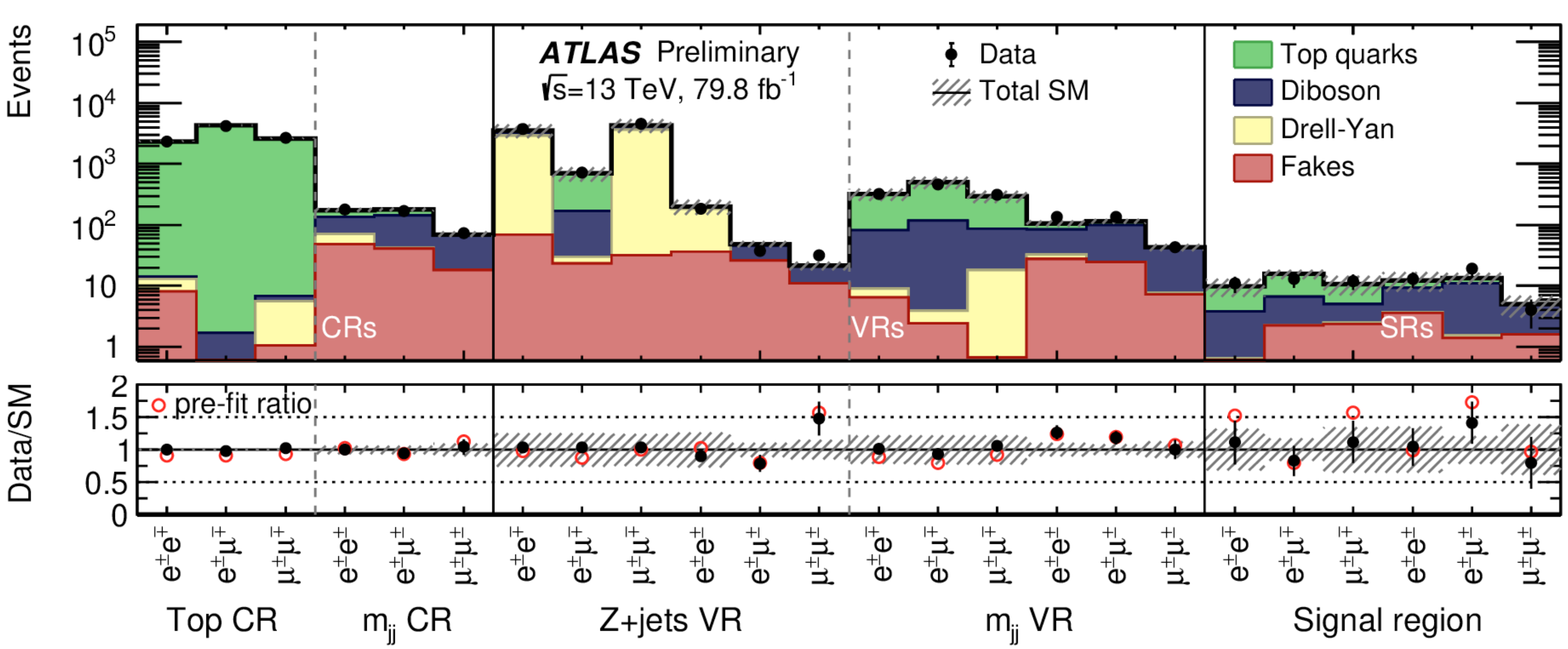
Semi-leptonic Type-III search

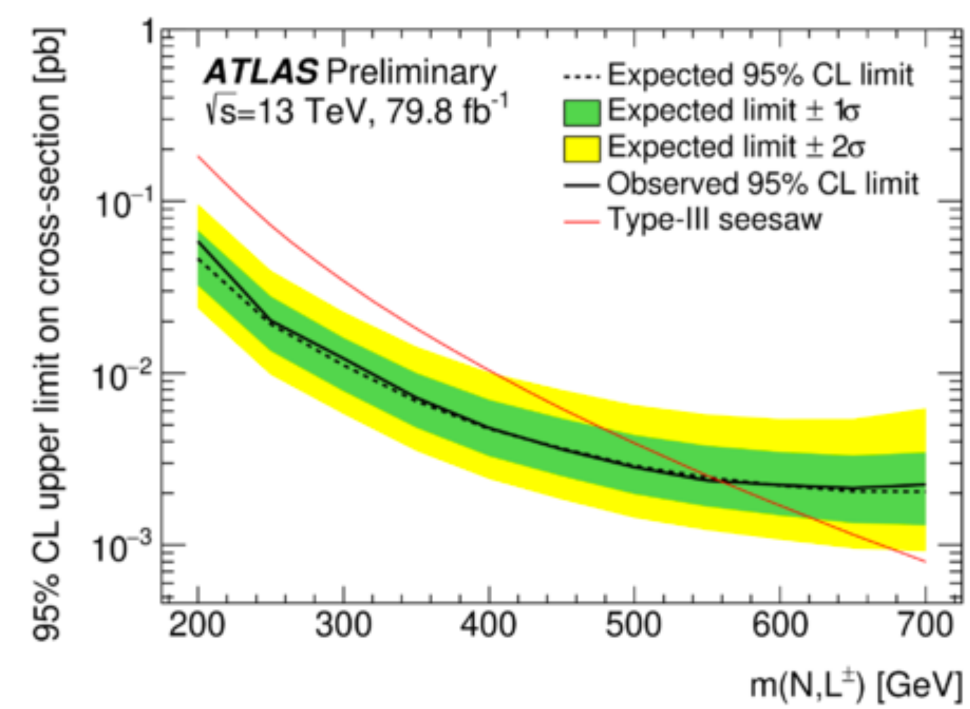




- **pp → $\Sigma^{0}\Sigma^{\pm}$**
- Opposite and same -charge optimised independently.
- Two resolved jets in final state. M(j,j) consistent with W mass and E_T^{miss}.
- Scalar sum of $p_T(\ell)$, and E_T^{miss} are combined as primary discriminant.
- Assume equal branching ratio to all leptonic decays.

ATLAS-CONF-2018-020



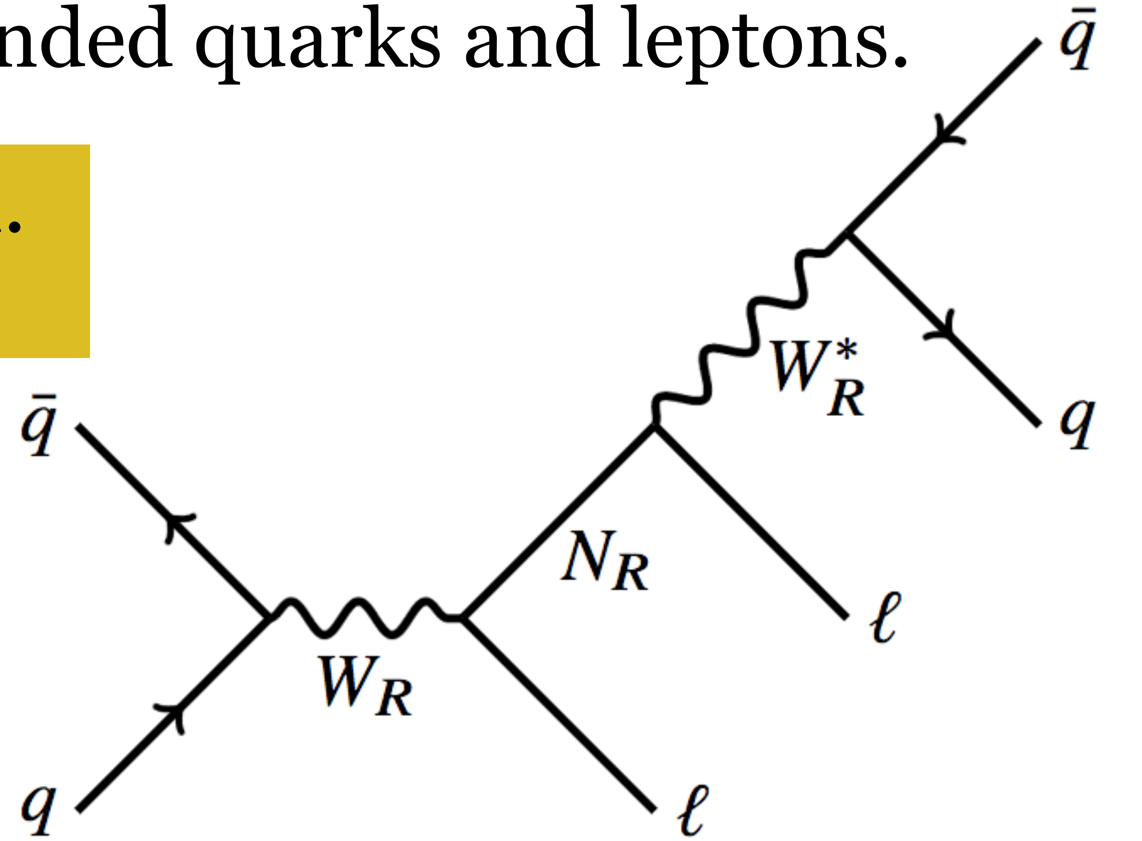


Left-Right symmetric Type-I

Left-Right symmetric models

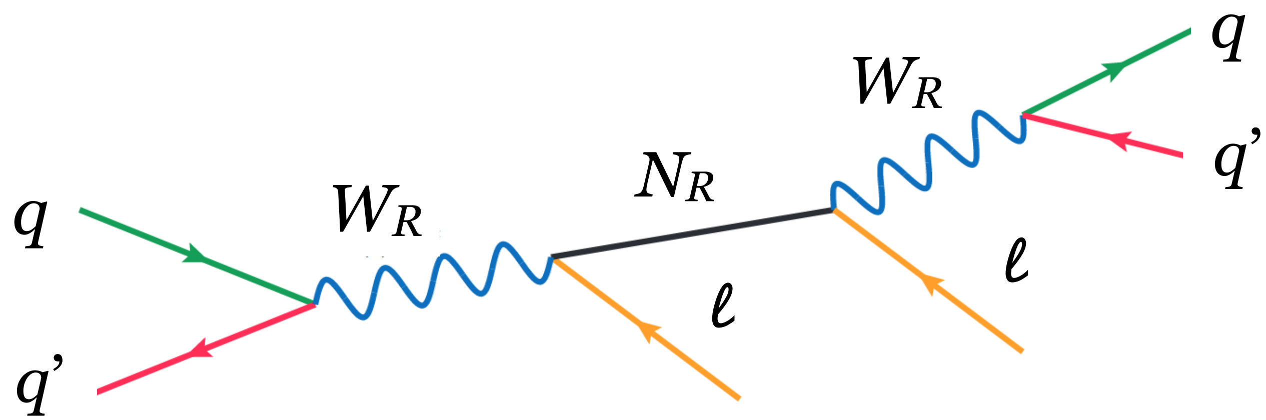
- Naturally embed the **Type-I** see-saw mechanism after EWSB.
- Motivated by explaining parity violation in weak decays by introducing a **new high-scale $\mathbf{SU(2)_R}$** group.
- Extend gauge sector with $\mathbf{W_R}$, **Z'** with right-handed counterparts of SM leptons, including three flavours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

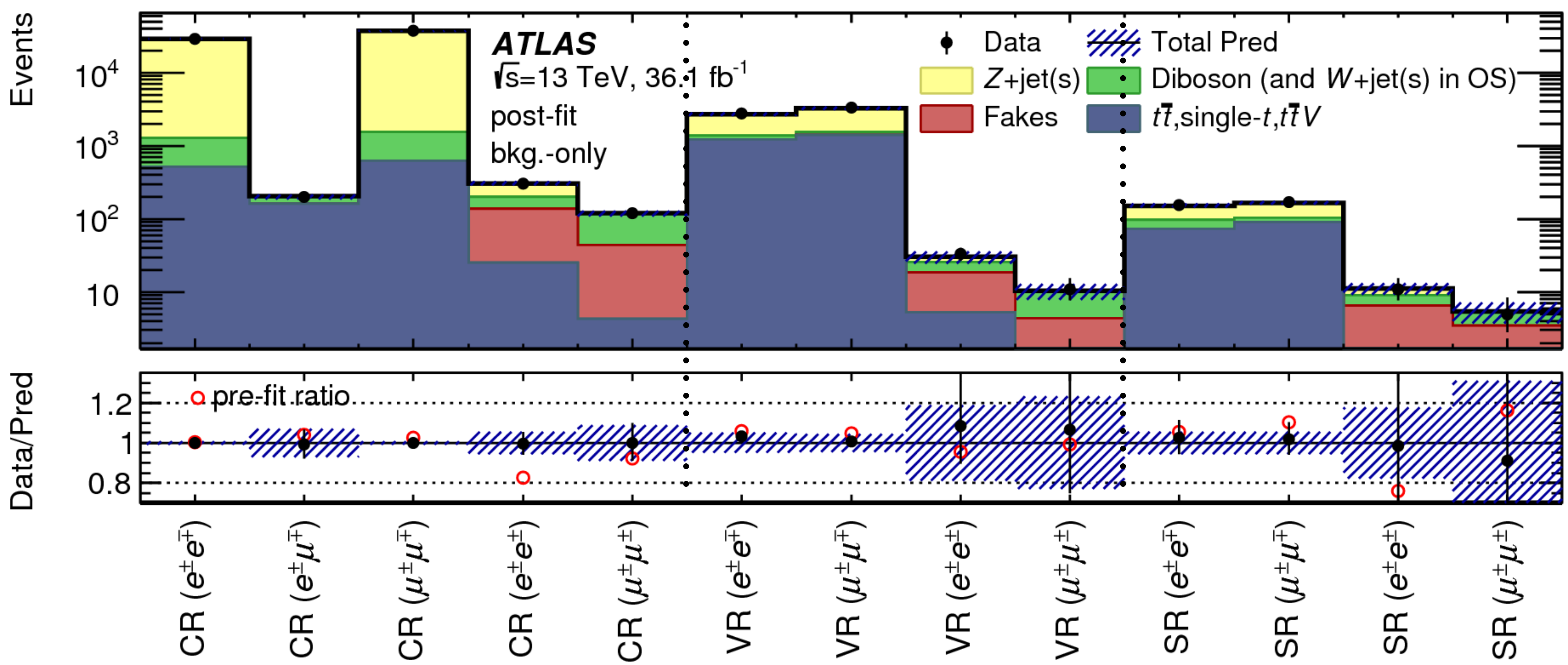


Resolved topology

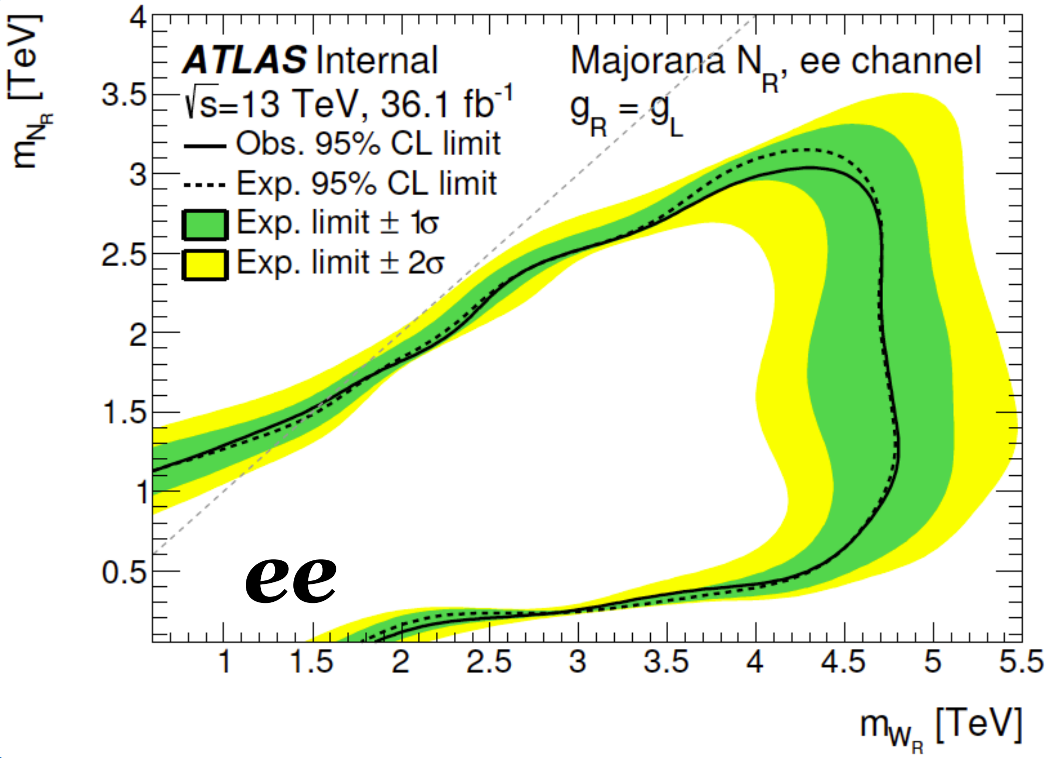
JHEP01 (2019) 016

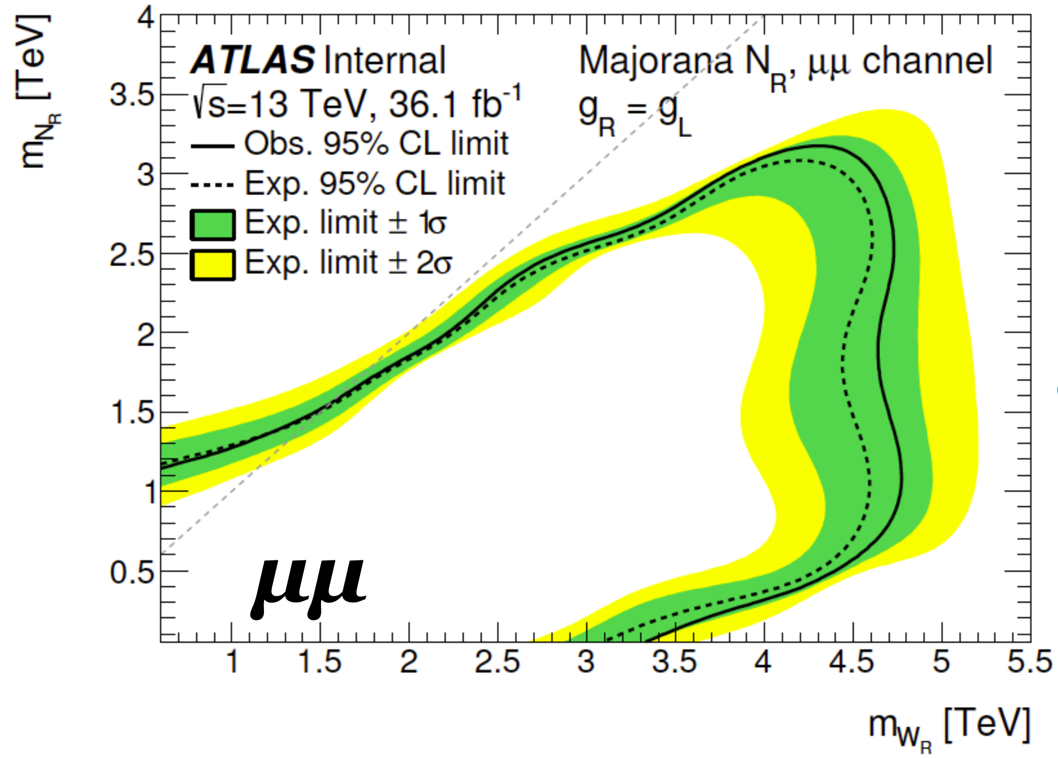


- Opposite and same -charge optimised independently. Only same-flavour leptons (*ee* or *μμ*).
- Two resolved jets in final state. No E_T^{miss} in the final state.
  - **$m_{NR} < m_{WR}$**: reconstruct W_R from $\boldsymbol{M(\ell, \ell, j, j)}$.
  - **$m_{NR} > m_{WR}$**: reconstruct W_R from $\boldsymbol{M(j,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

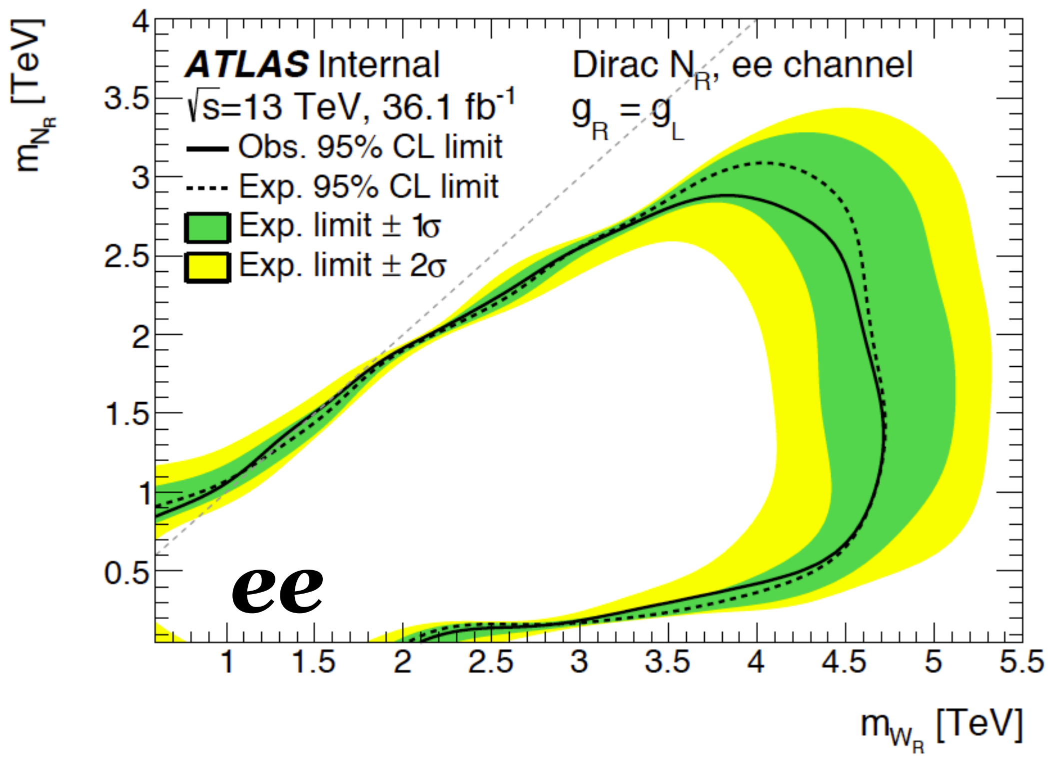


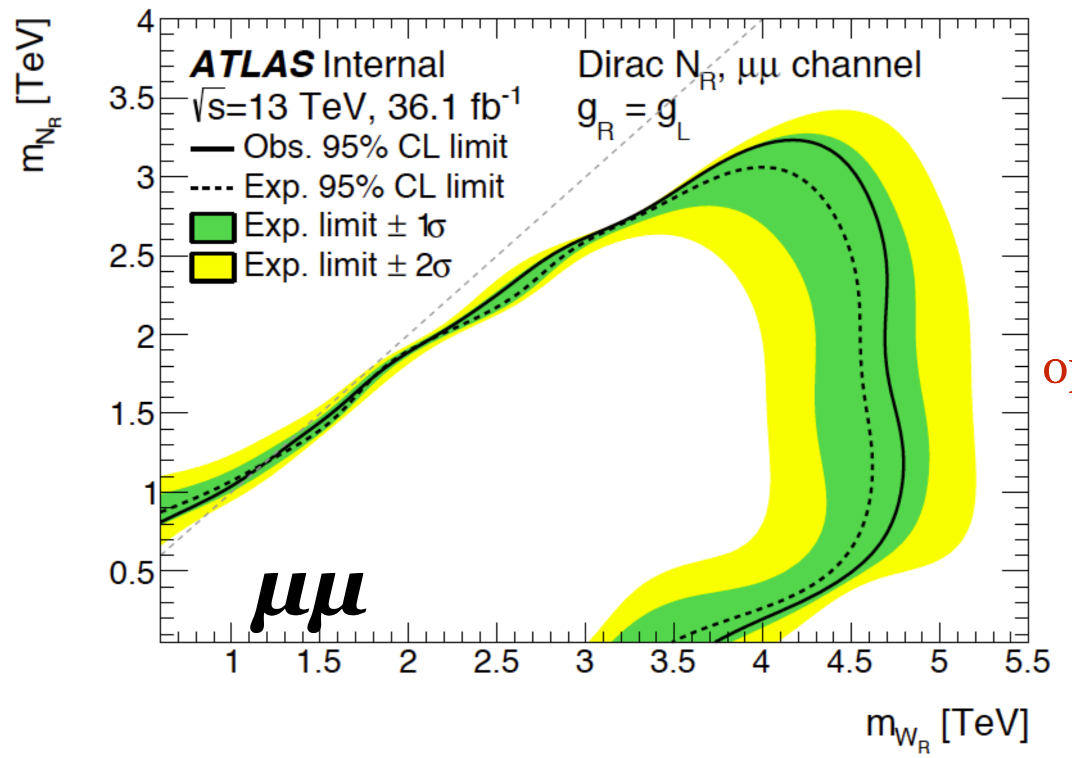
Resolved topology





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

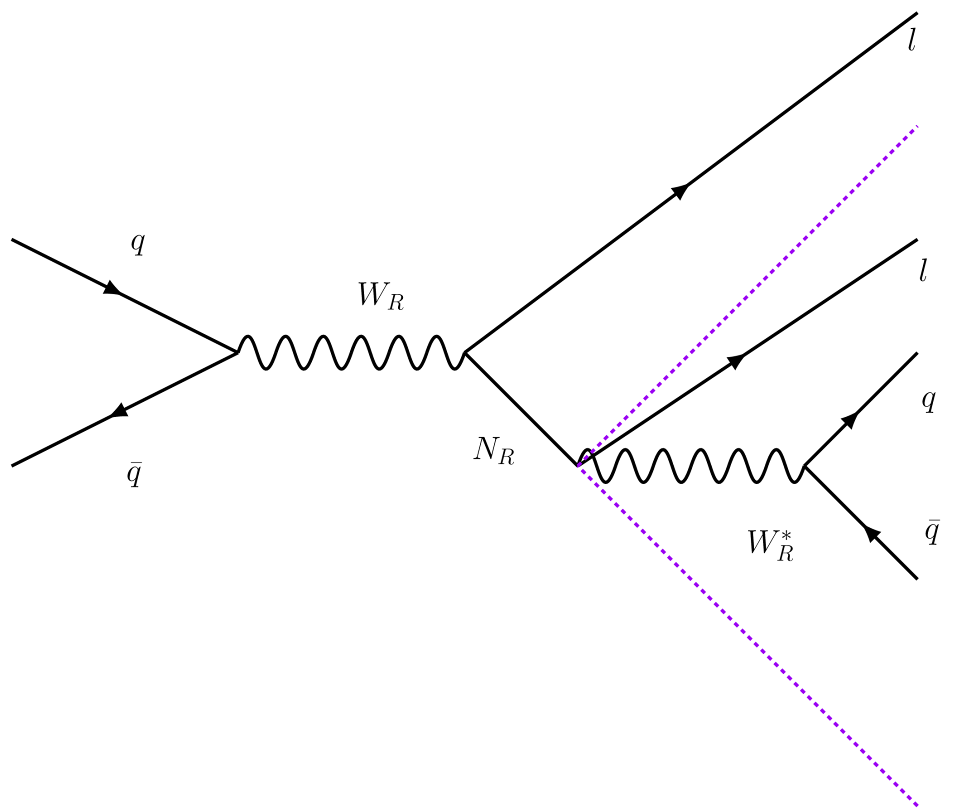




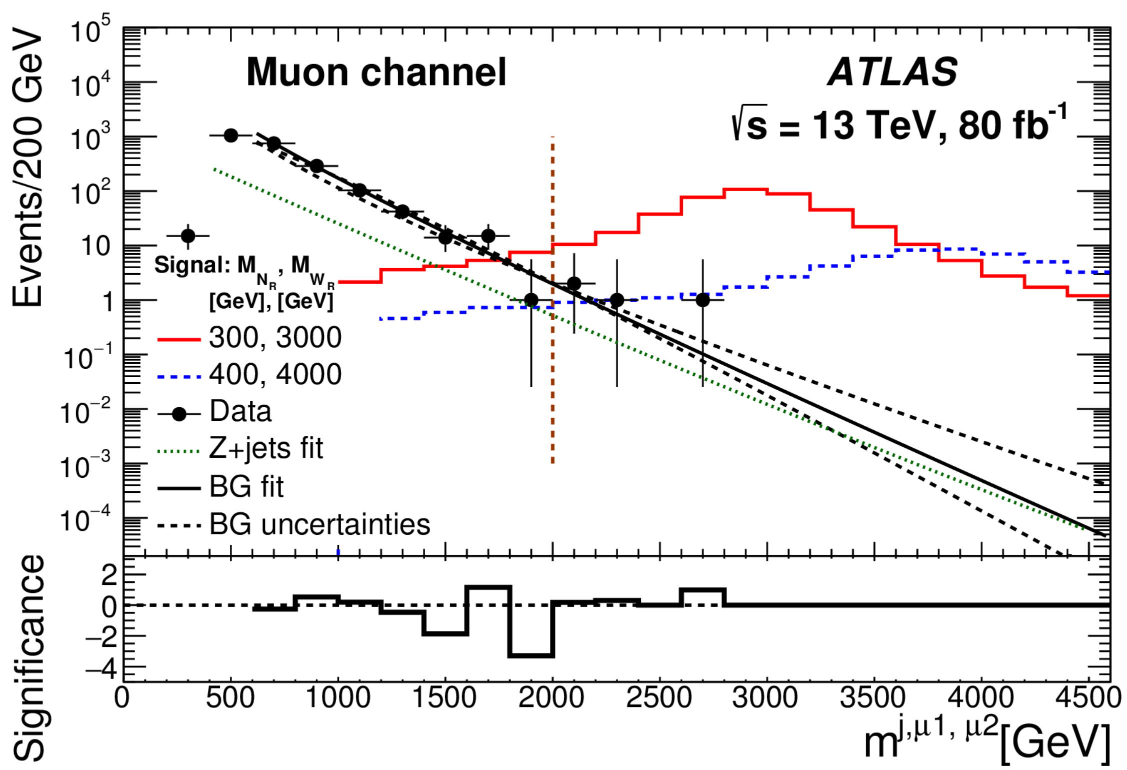
Dirac
opposite-charge (100%)

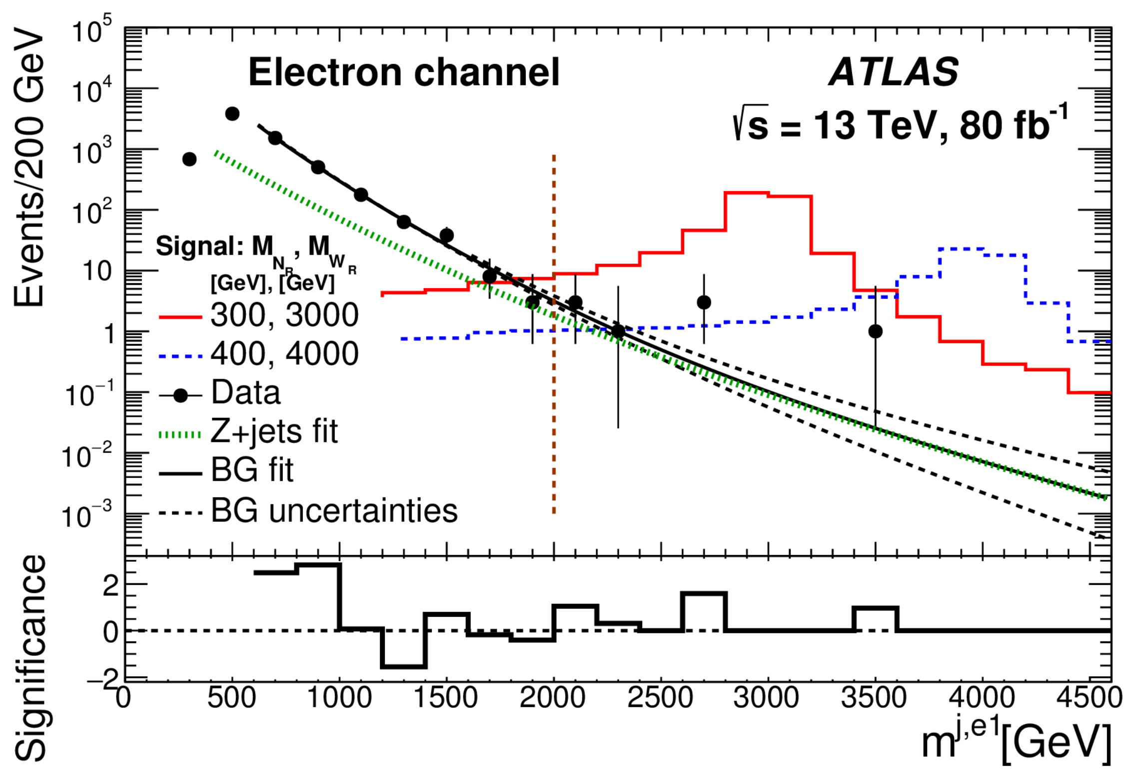
Boosted topology

1904.12679

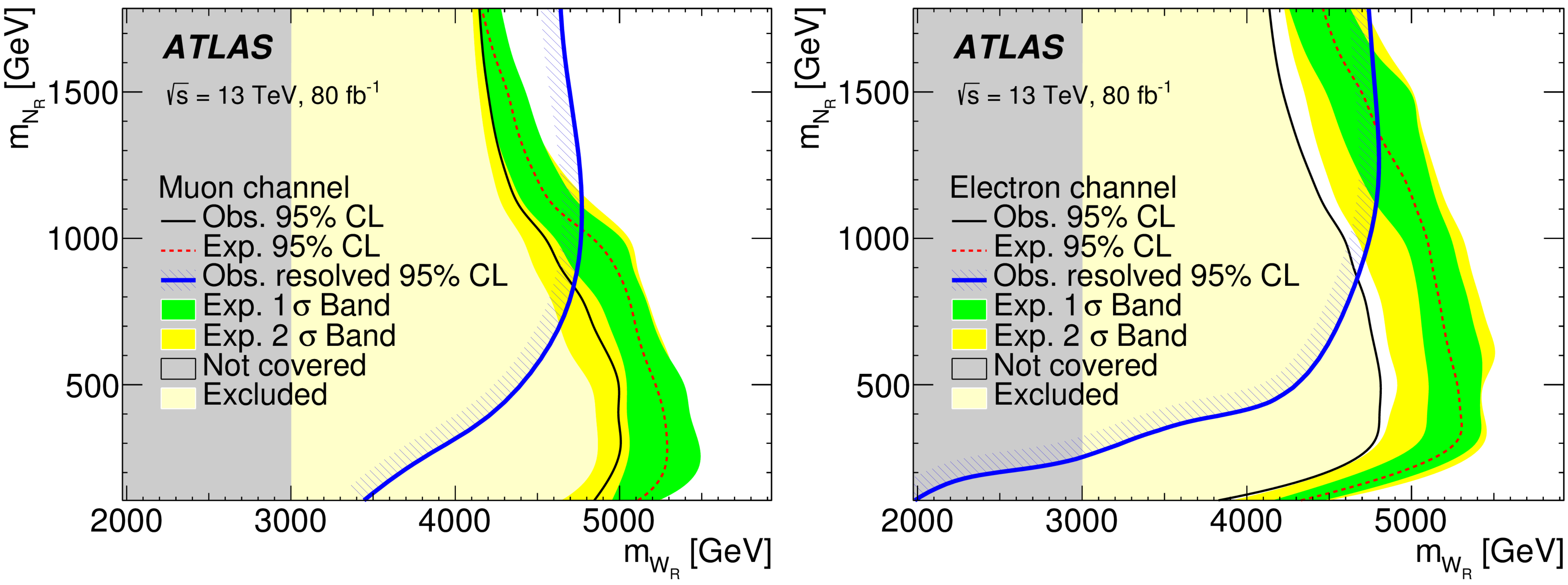


- Heavy neutrinos with large transverse momenta.
- Two same-flavour leptons and one large-R jet (R=1.0) with $p_T(J)$ > 200 GeV.
- The large-R jet should contain the subleading lepton.
- Isolated lepton back-to-back in azimuth wrt the large-R jet.
- $m(\ell,\ell)$ > 200 GeV to suppress Z+jets.





Boosted topology



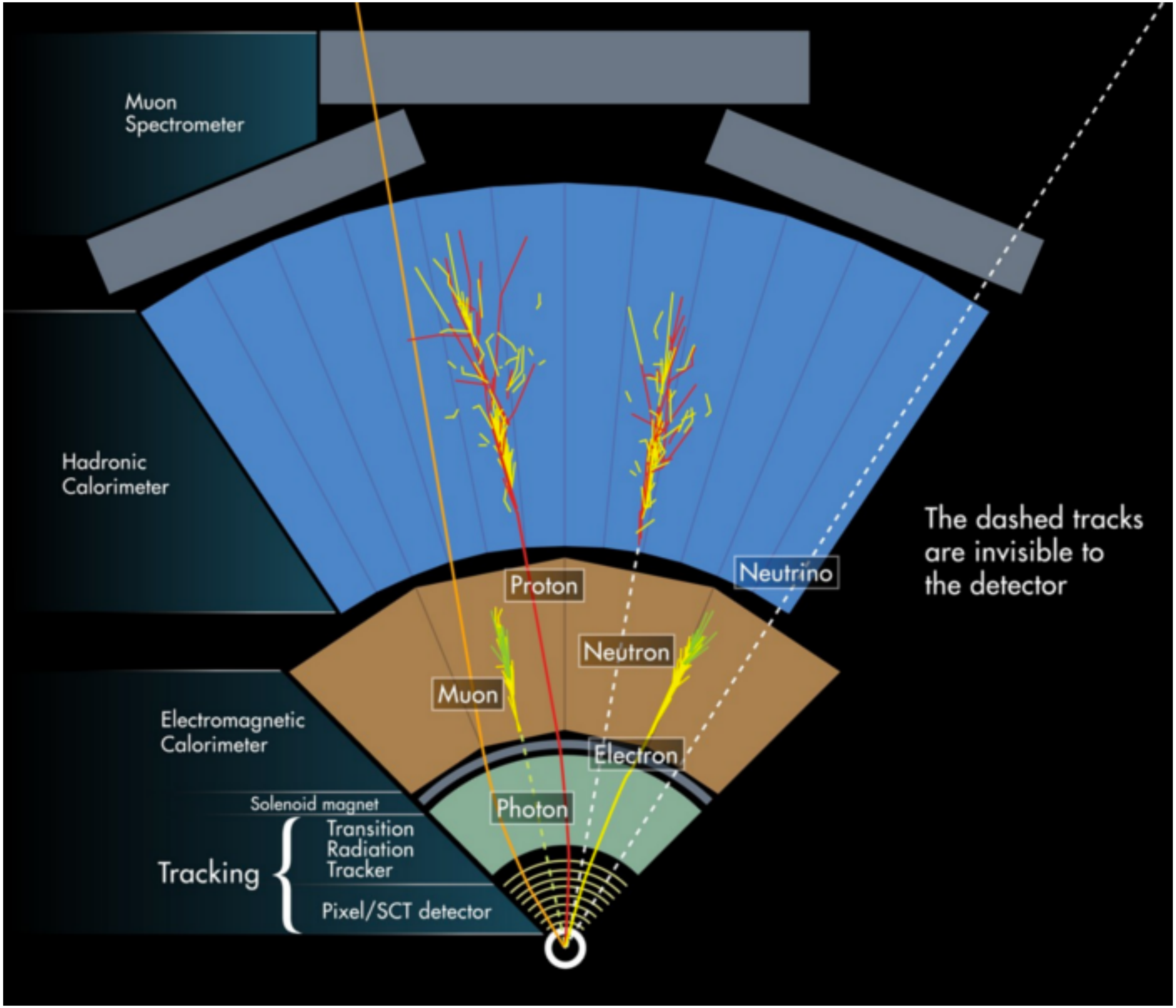
- Limits obtained from single-bin poissonian experiments show little dependence on the particle masses and are only sensitive to the signal efficiencies.

Conclusions

- The see-saw mechanism is a promising scenario for neutrino mass generations embedded in many theories of new physics.
- Collider experiments do have access to different incarnations of it: Type-I/II/III.
- ATLAS Run-II searches will be updated with the final dataset.
- Many updates in program: new channels/techniques.

Backup

ATLAS

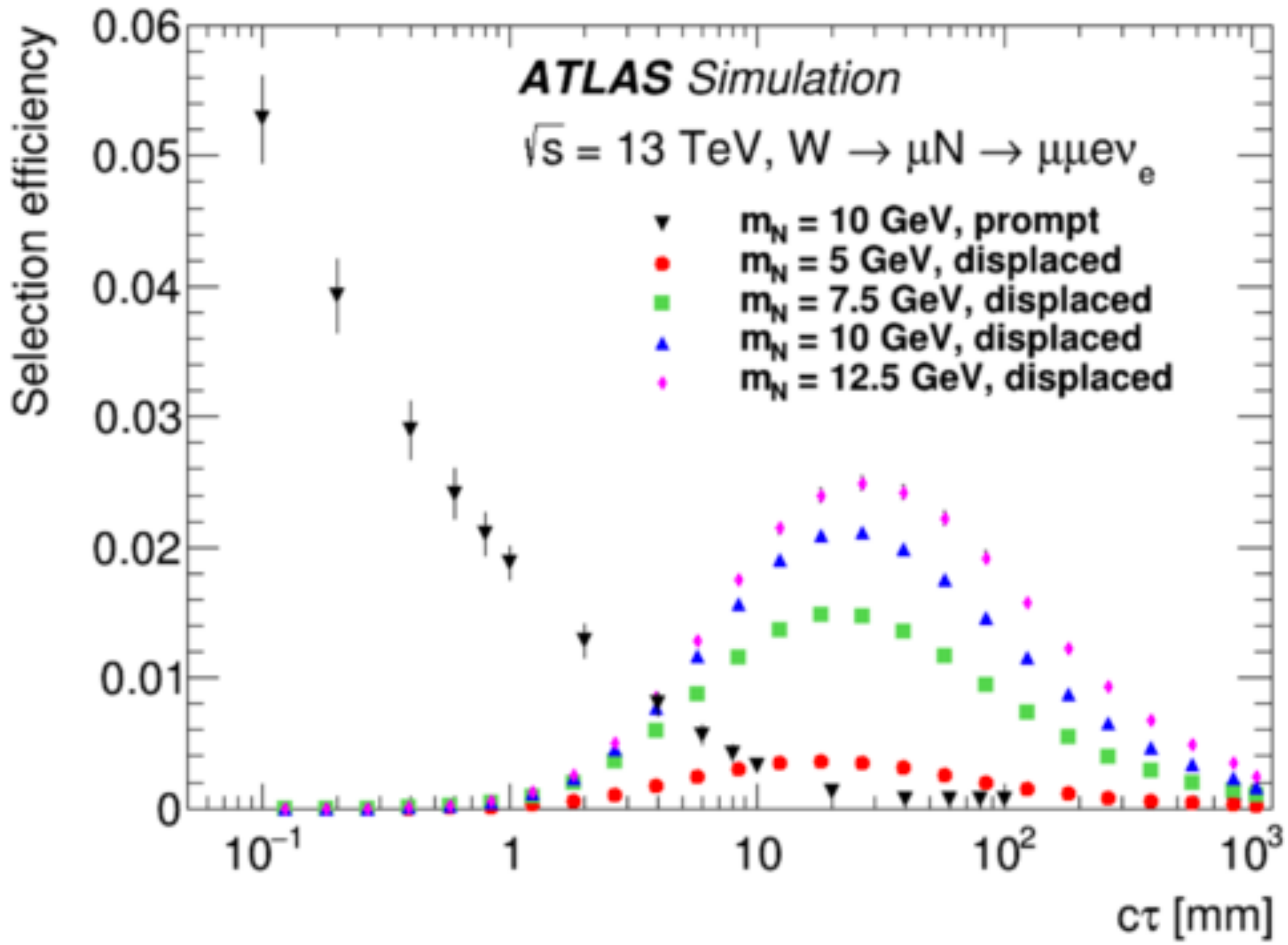

Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT detector
Proton
Neutron
Muon
Electron
Photon
Neutrino
The dashed tracks
are invisible to
the detector

Multi-leptonic Type-I search

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

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

- 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.

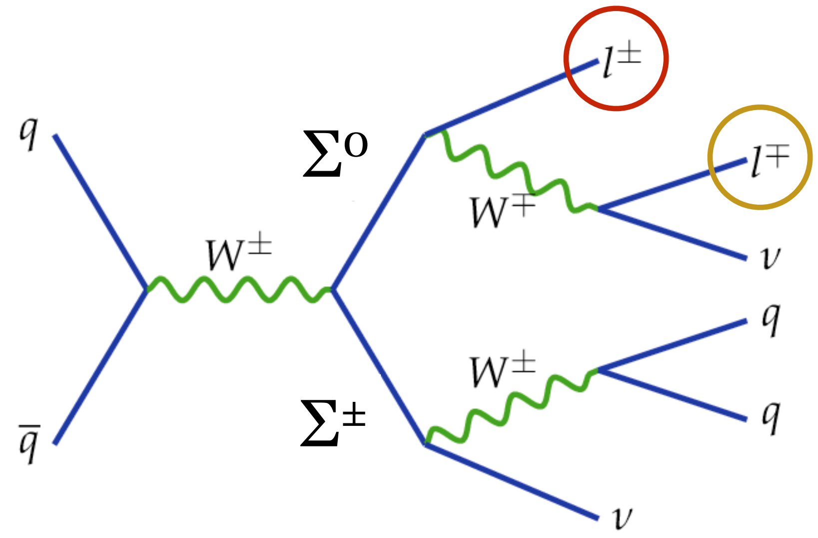


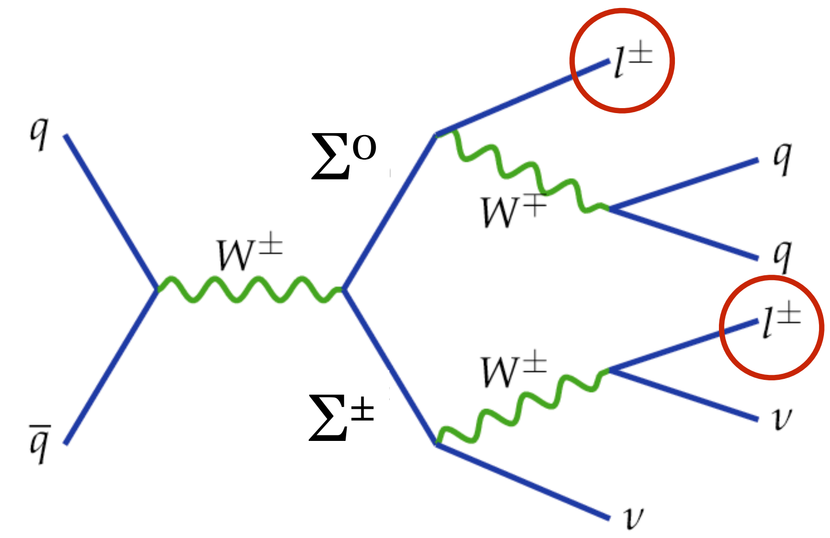
Multi-leptonic Type-I search

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	$40 < m(\ell,\ell,\ell') < 90\,\mathrm{GeV}$	$m(\ell,\ell,\ell') \leq 40\,\mathrm{GeV} \;\|\|\; m(\ell,\ell,\ell') \geq 90\,\mathrm{GeV}$	$p_{\mathrm{T}}(\ell')$
2	b-jet veto	at least one b-jet	$p_{\mathrm{T}}(\ell')$
3	$E_{\mathrm{T}}^{\mathrm{miss}} < 60\,\mathrm{GeV}$	$E_{\mathrm{T}}^{\mathrm{miss}} \geq 60\,\mathrm{GeV}$	$p_{\mathrm{T}}(\ell')$

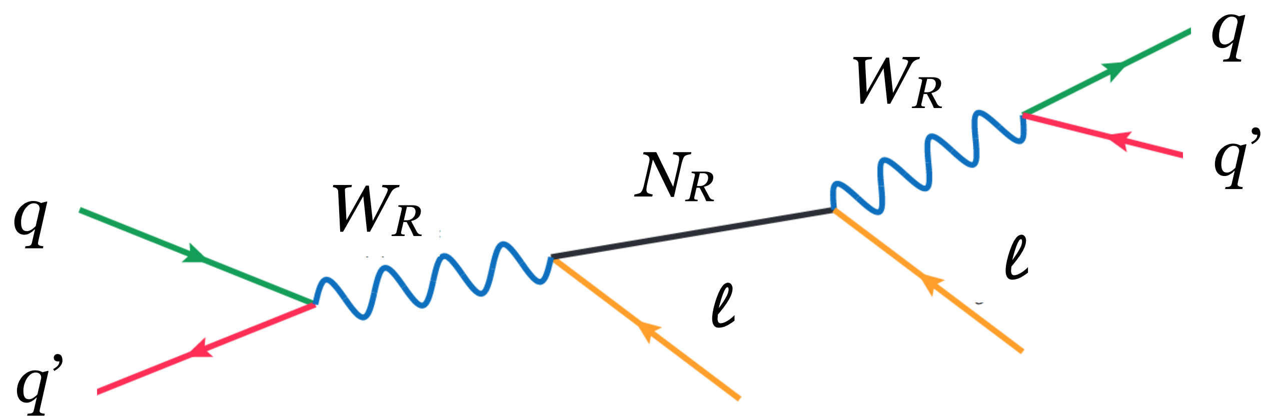
Type-III search





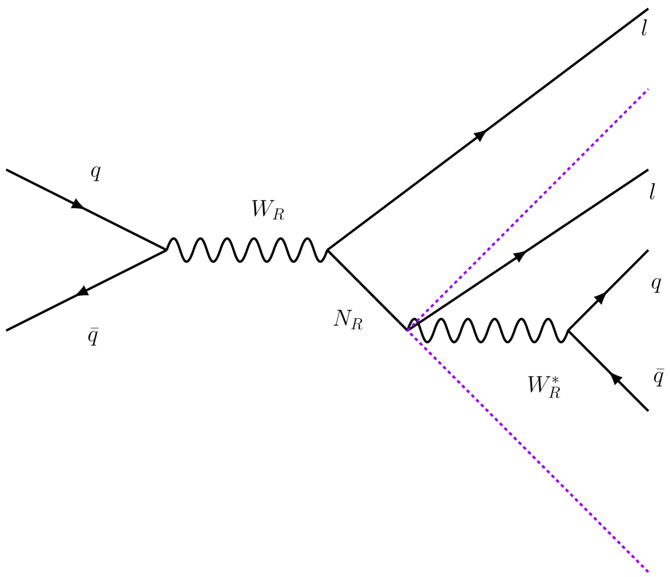
	OS ($\ell^+\ell^- = e^+e^-$, $e^{\pm}\mu^{\mp}$, $\mu^+\mu^-$)				**SS** ($\ell^{\pm}\ell^{\pm} = e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$)			
	Top CR	Z+jets VR	m_{jj} VR	SR	Z+jets VR	m_{jj} VR	m_{jj} CR	SR
N(jet)	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2
N(b-jet)	$\mathbf{\geq 2}$	0	0	0	0	0	0	0
m_{jj} [GeV]	$[60, 100)$	$[60, 100)$	$\mathbf{[35, 60) \cup [100, 125)}$	$[60, 100)$	$[60, 100)$	$\mathbf{[0, 60) \cup [100, 300)}$	$\mathbf{[0, 60) \cup [100, 300)}$	$[60, 100)$
$m_{\ell\ell}$[GeV]	$[110, \infty)$	$\mathbf{[70, 110)}$	$[110, \infty)$	$[110, \infty)$	$\mathbf{[70, 100)}$	$[100, \infty)$	$[100, \infty)$	$[100, \infty)$
Sig(E_T^{miss})	≥ 5	≥ 5	$\mathbf{\geq 10}$	$\mathbf{\geq 10}$	≥ 5	≥ 5	≥ 5	$\mathbf{\geq 7.5}$
$\Delta\phi(E_T^{miss}, l)_{min}$				$\mathbf{\geq 1}$				
$p_T(jj)$ [GeV]				$\mathbf{[100, \infty)}$				$\mathbf{[60, \infty)}$
$p_T(\ell\ell)$ [GeV]				$\mathbf{[100, \infty)}$				$\mathbf{[100, \infty)}$
$H_T + E_T^{miss}$ [GeV]	$[300, \infty)$	$[300, \infty)$	$[300, \infty)$	$[300, \infty)$		$\mathbf{[500, \infty)}$	$\mathbf{[300, 500)}$	$[300, \infty)$

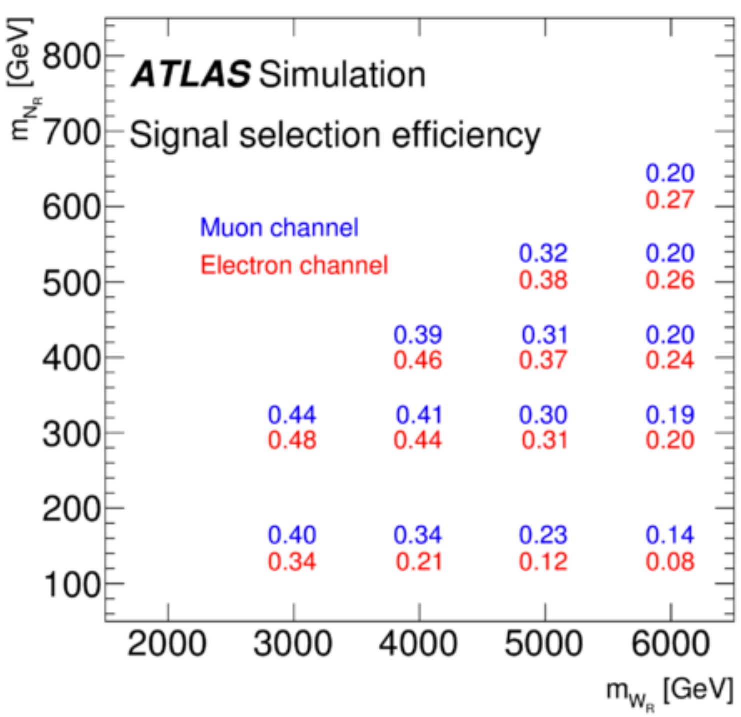
Resolved topology



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

Boosted topology

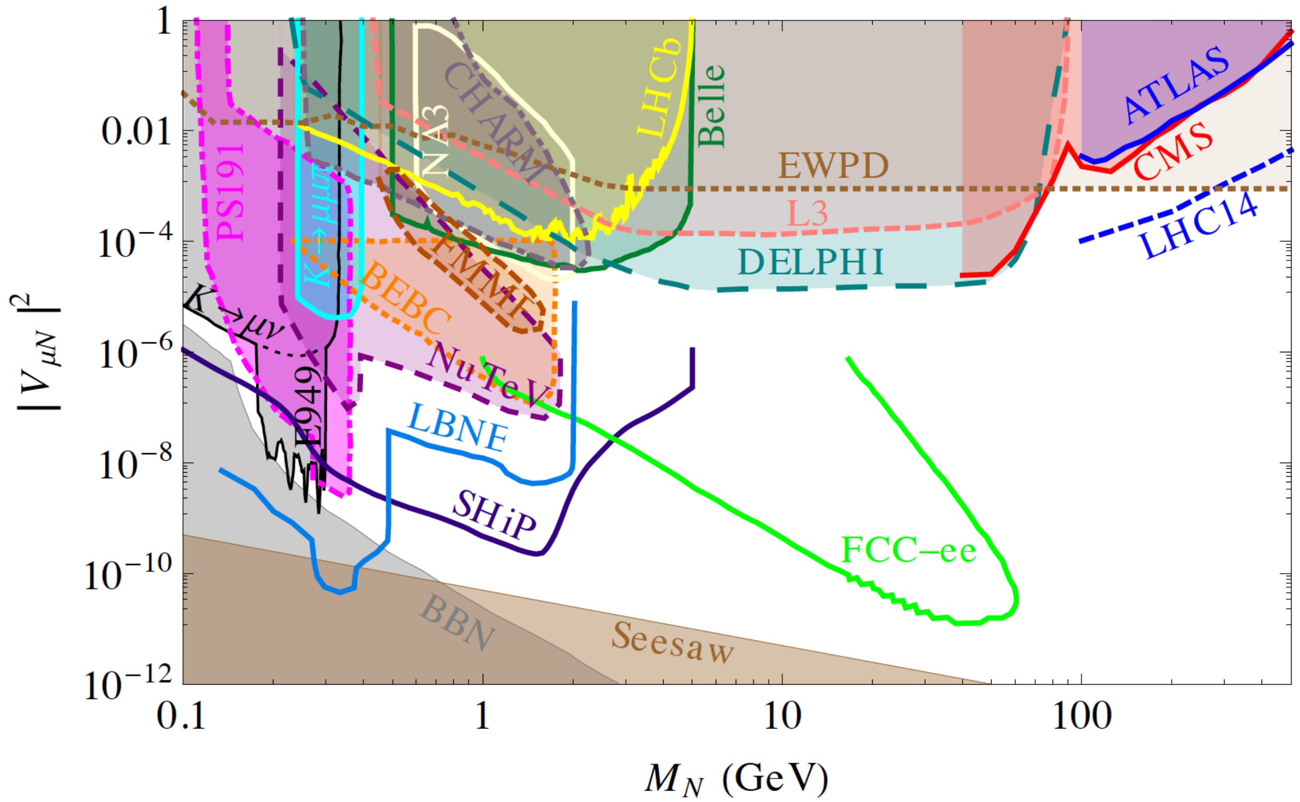


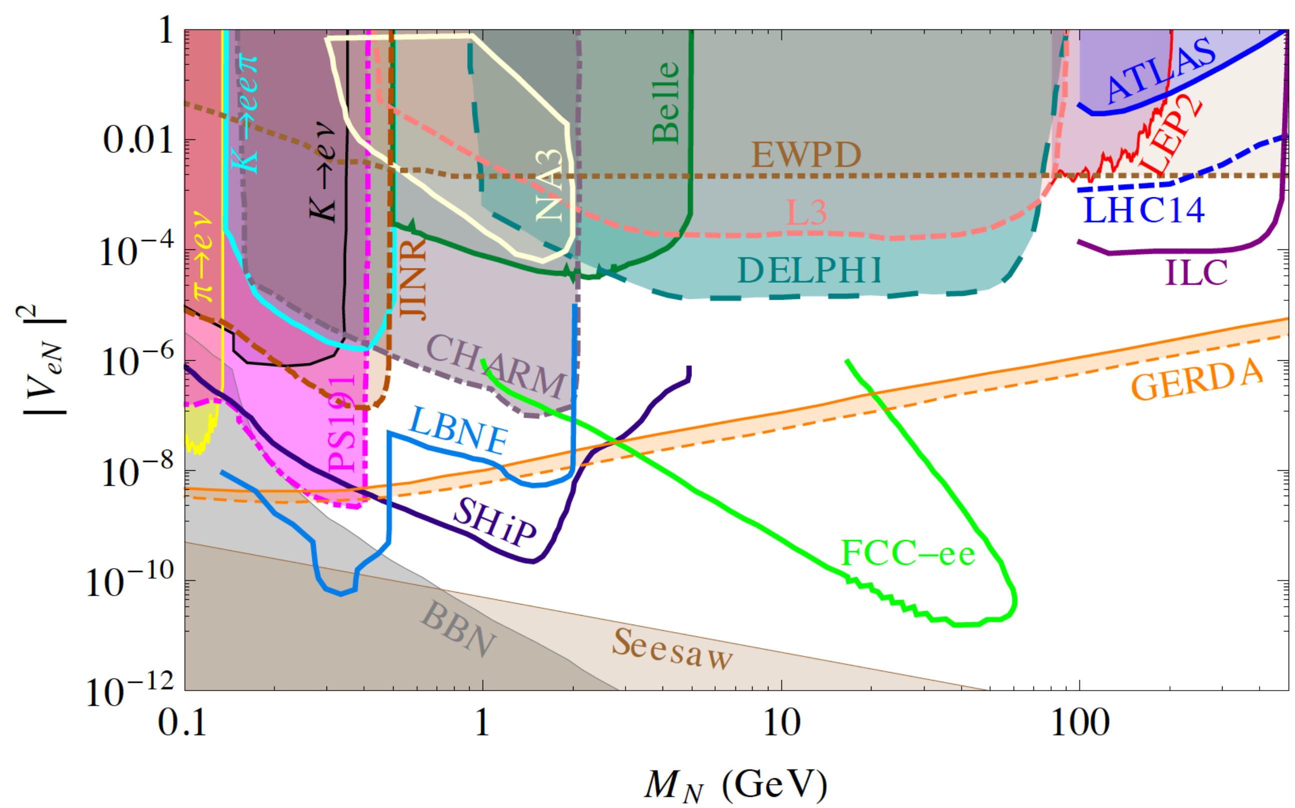


	Electron channel	Muon channel
Lepton:		
p_T	> 26 GeV	> 28 GeV
$\|\eta\|$	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	< 2.5
Leading lepton quality	Medium [61], isolated [61]	Medium [62], isolated [62]
Subleading lepton quality	Medium, no isolation	Medium, no isolation
Transverse impact parameter significance	$\|d_0\|/\sigma_{d_0} < 5.0$	$\|d_0\|/\sigma_{d_0} < 3.0$
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)

LHC sensitivity





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