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

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On behalf of the ATLAS Collaboration

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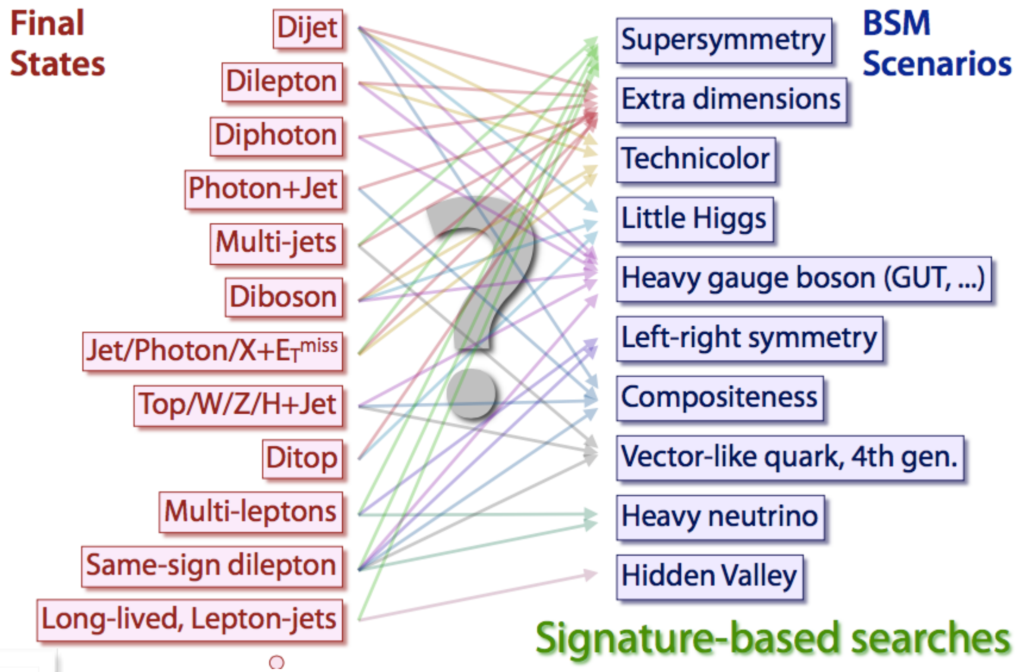
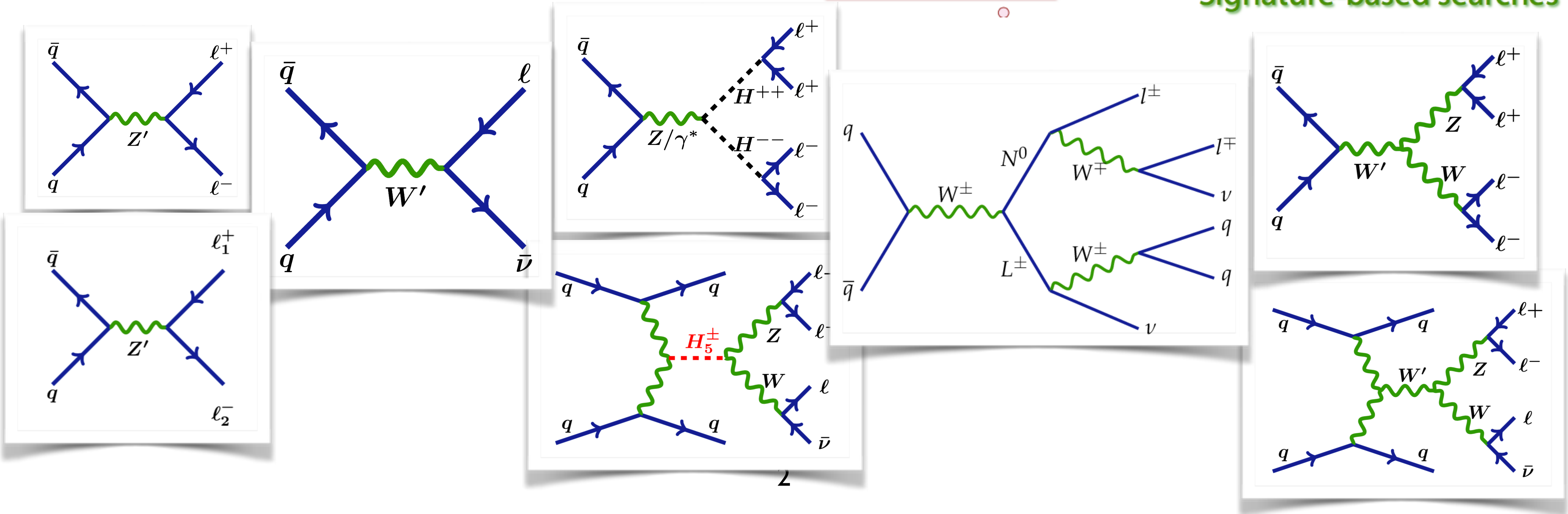
Why look for leptons in final states?

ATLAS EXPERIMENT

- **Theoretical motivation:**
  - Such states a clear signature for interactions predicted by a wide range of new physics models:
  - **Signature of new particles** such as heavy gauge boson (W', Z'), and heavy lepton multiplets, predicted by:
    - Sequential Standard Model,
    - Type I-III seesaw models,
    - Left-Right Symmetric Model,
    - Two-Higgs-doublet model,
    - Higgs triplet, dark sector extensions, …
  - **Lepton Flavor Violating (LFV) coupling is a clear and direct signature of new physics.**

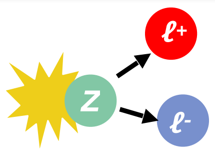


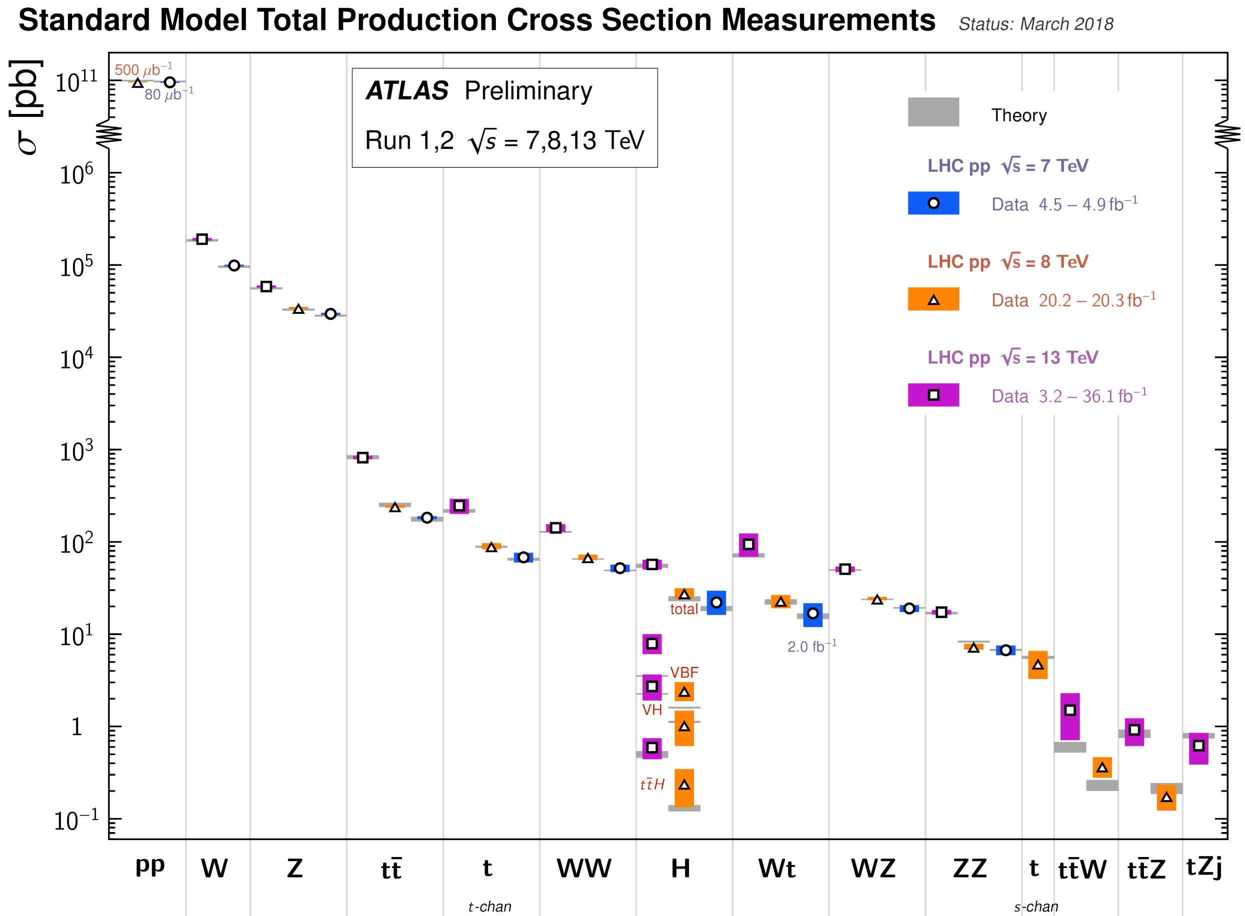


Why look for leptons in final states?

- **Experimental motivation:**
  - Distinct experimental signatures.
  - Can be efficiently triggered on and recorded (lepton trigger, MET trigger).
  - **Precisely measured and modeled backgrounds.**

Prompt (true) leptons





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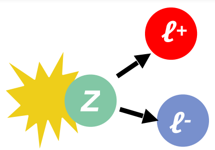

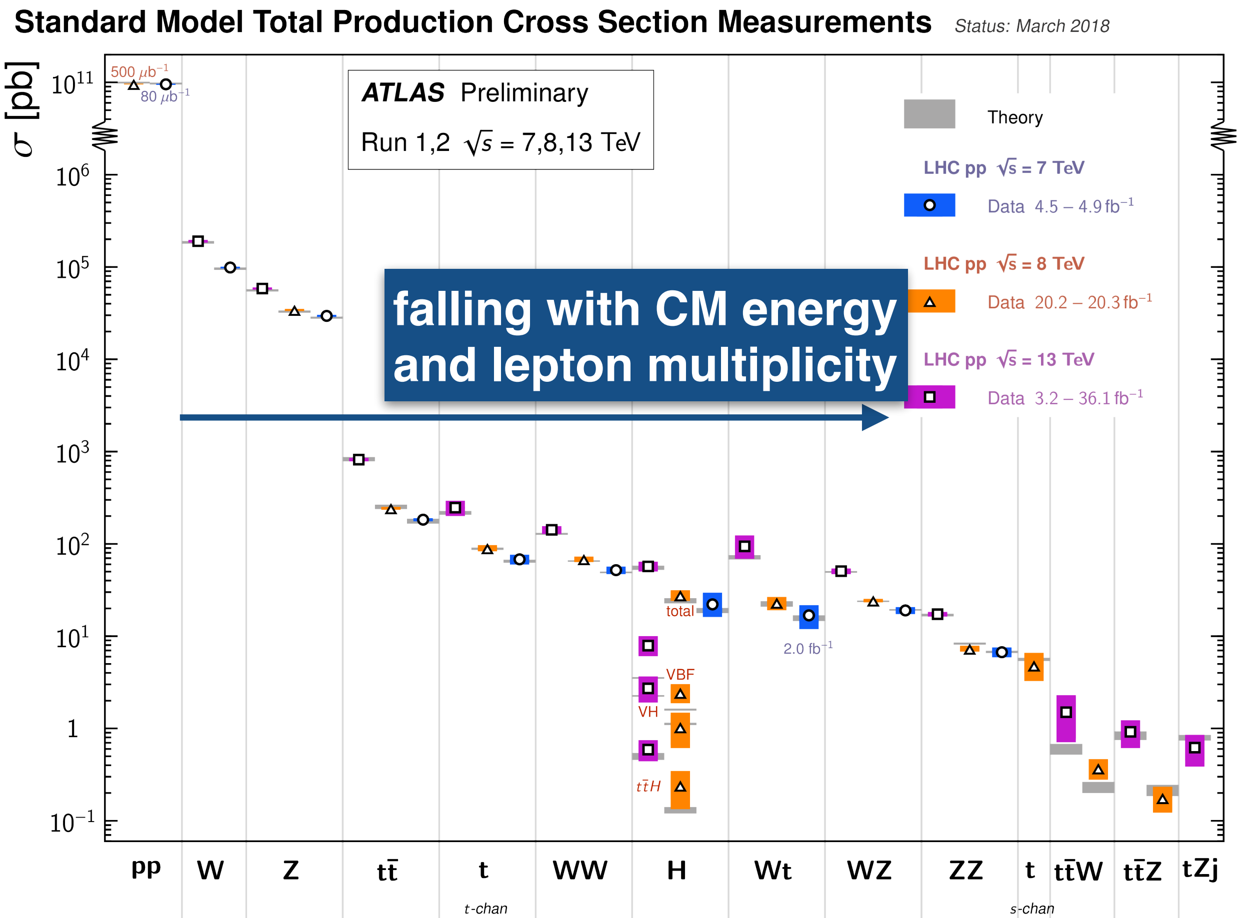

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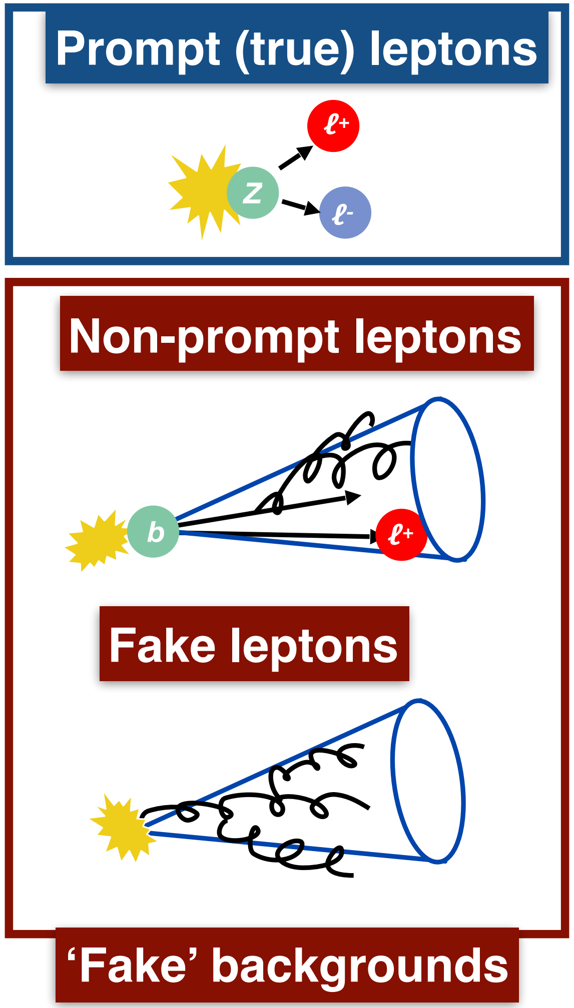

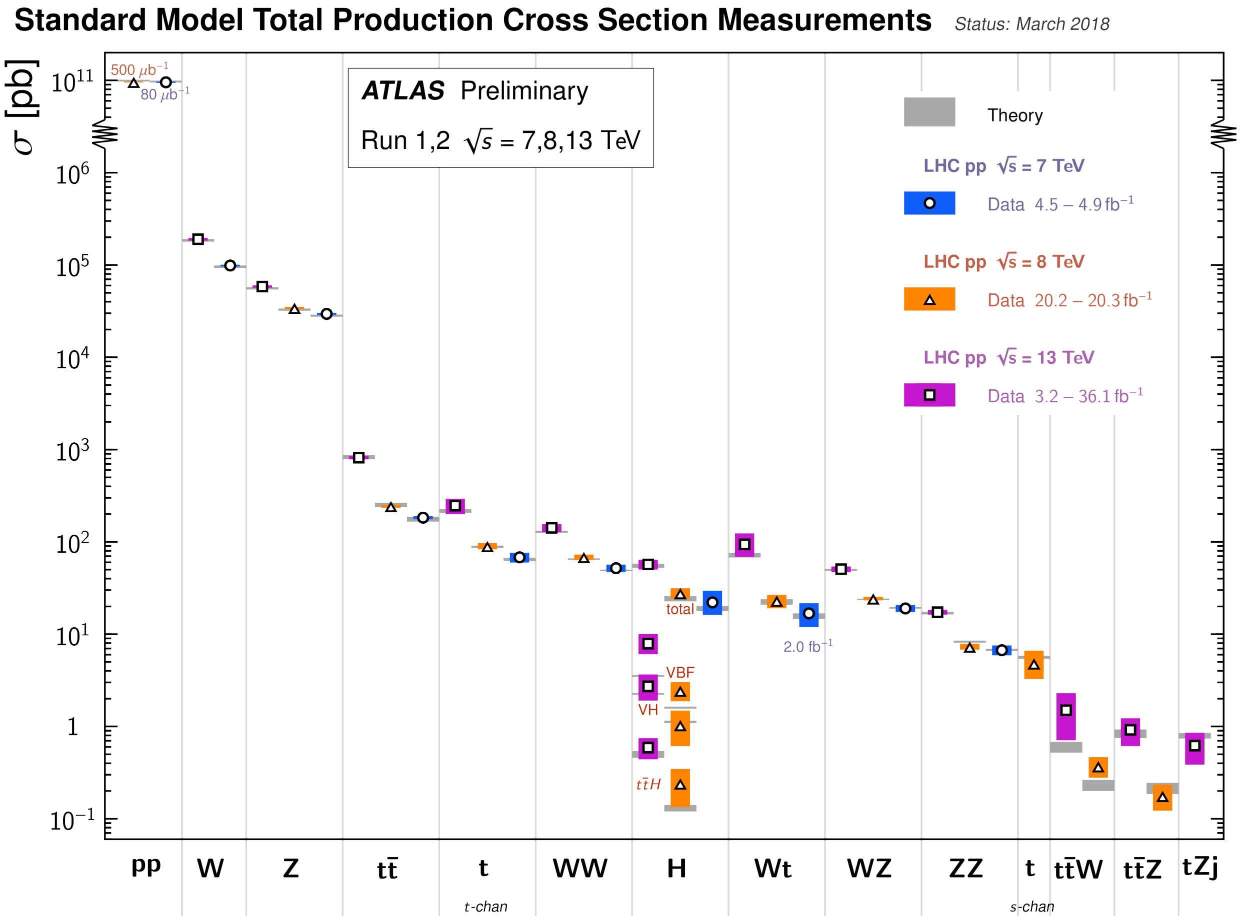

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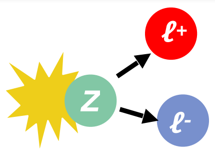
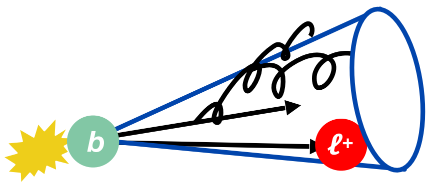
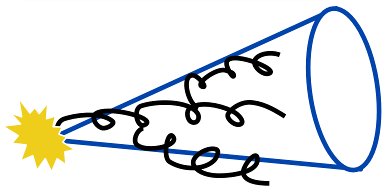


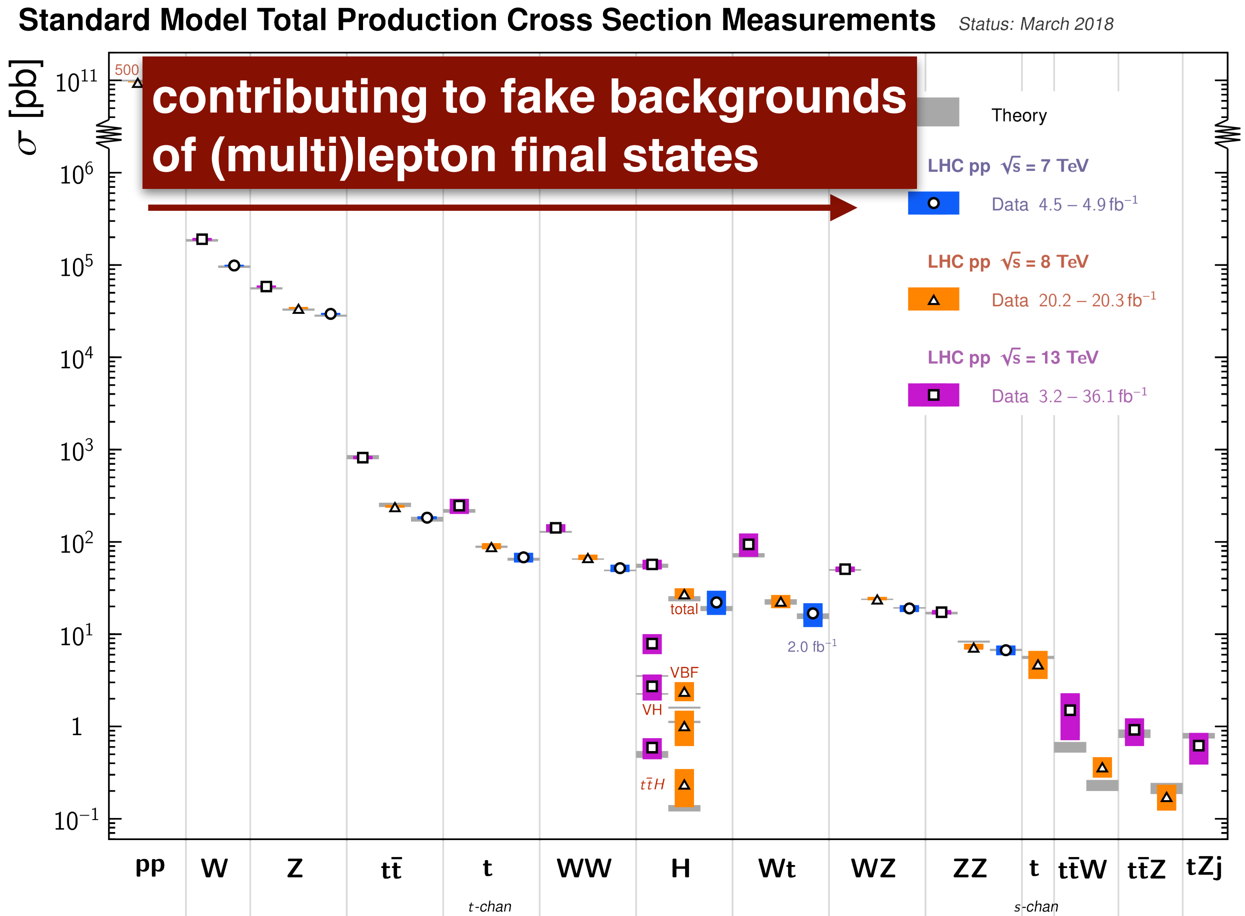
Non-prompt leptons



Fake leptons



'Fake' backgrounds



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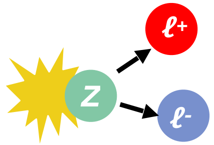

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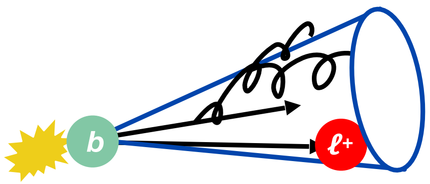

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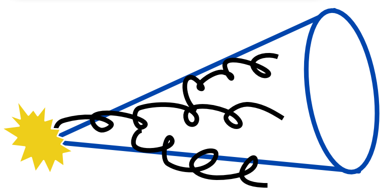

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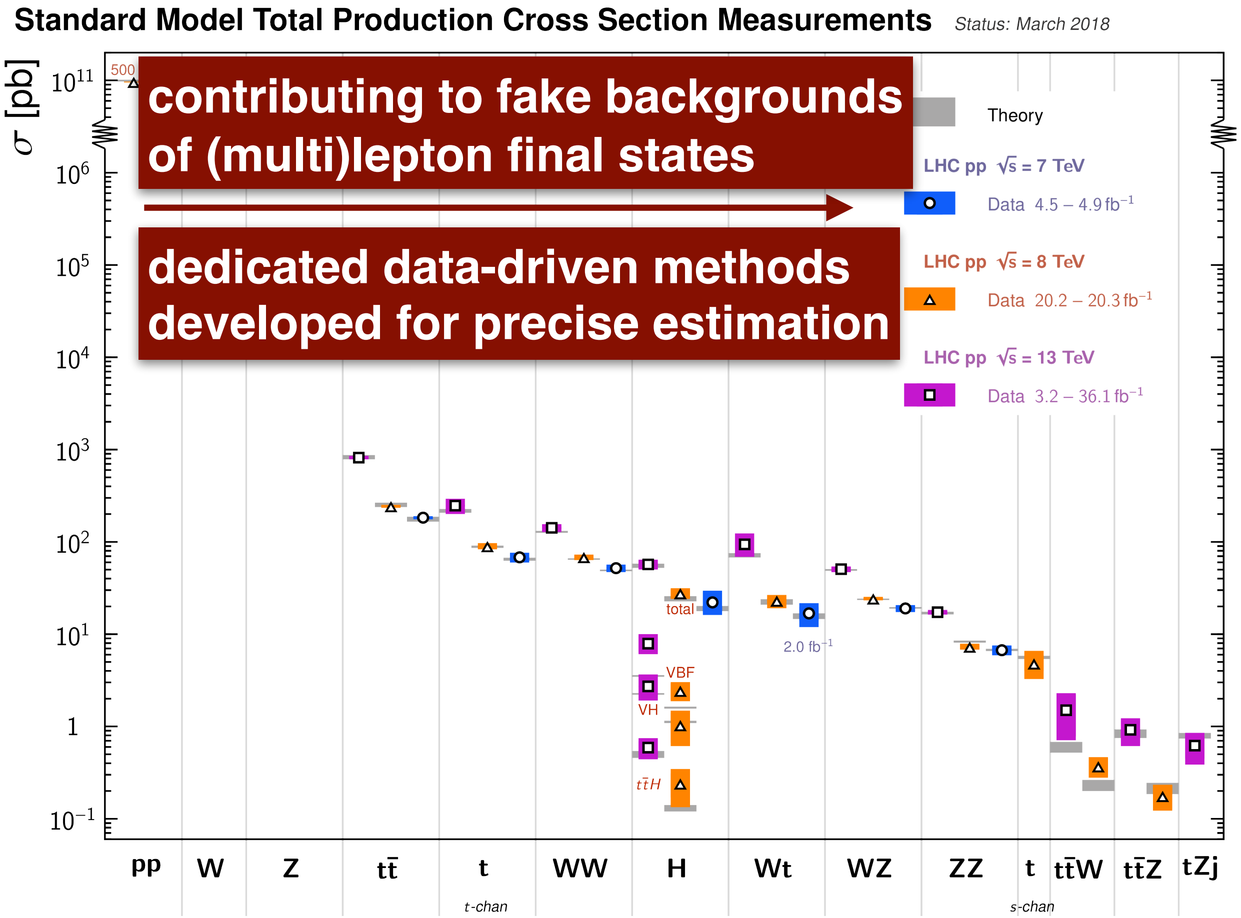
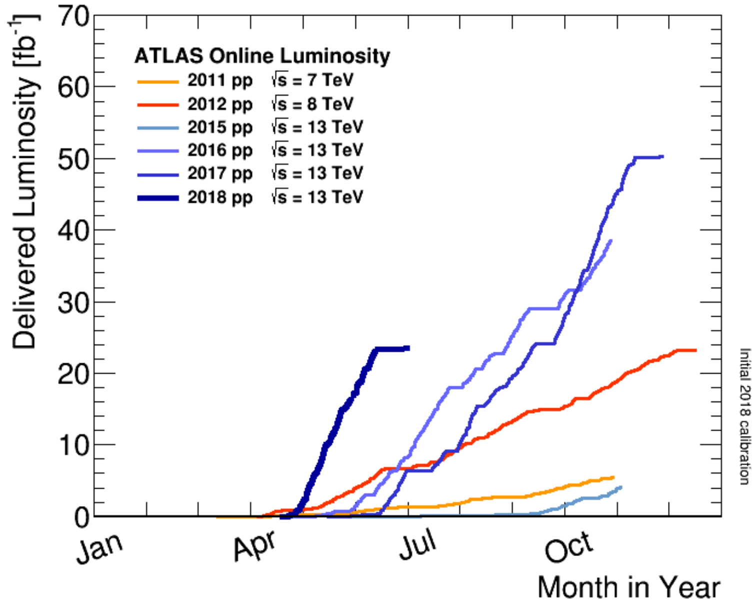


contributing to fake backgrounds of (multi)lepton final states

dedicated data-driven methods developed for precise estimation

Presented results

Four new results of BSM searches in leptonic final states!



New (with 2017 data)

- Search for W' in eν and μν decays (80/fb)

New (with 2017 data)

- Heavy lepton triplet search motivated by Type III seesaw mechanism (80/fb)

New result

- Search for high mass dilepton Z' resonance with Lepton Flavor Violating (LFV) final state (36/fb)

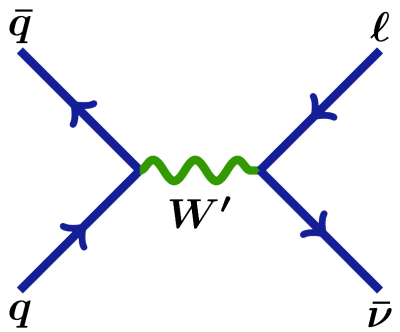
New result

- $X \rightarrow WZ$ resonance decay to lνll (l =e or μ) final states (36/fb)

All public results can be found @ https://twiki.cern.ch/twiki/bin/view/AtlasPublic

ATLAS-CONF-2018-17

$W' \to e\nu$, $W' \to \mu\nu$



Theoretical motivation:

- Look for straightforward extensions of the SM with new gauge bosons:
  - predicted in LRSM, in the little Higgs model …
  - Conceptually, these particles are heavier versions of the SM *W* and *Z* bosons.
  - Generically referred to as W' and Z' bosons.
- **ATLAS uses the Sequential Standard Model (SSM) : predicts a W' boson with couplings to fermions that are identical to the SM.**

Experimental Signature is a hard lepton + MET

- Single e/μ trigger
- lepton p_T> 60(e), 55(μ) GeV and MET > 60(e), 55(μ) GeV
- Careful selection on muons to guarantee a controlled resolution at high p_T

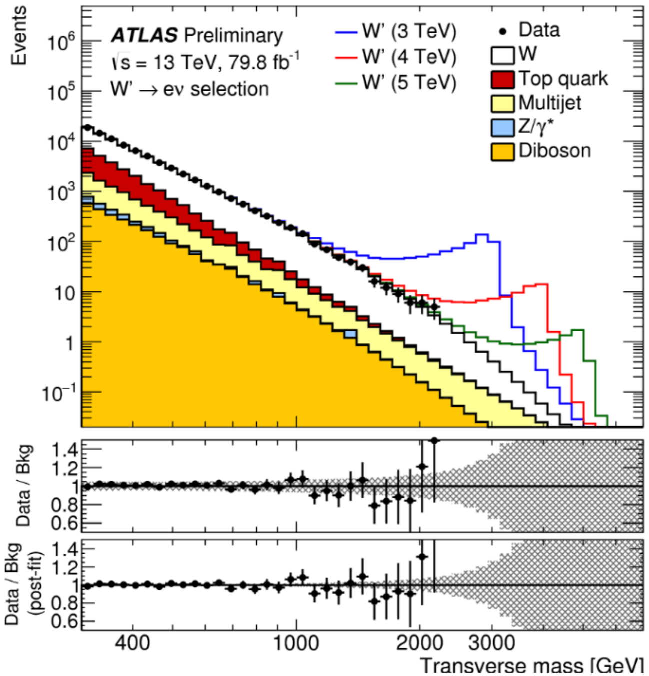
Backgrounds

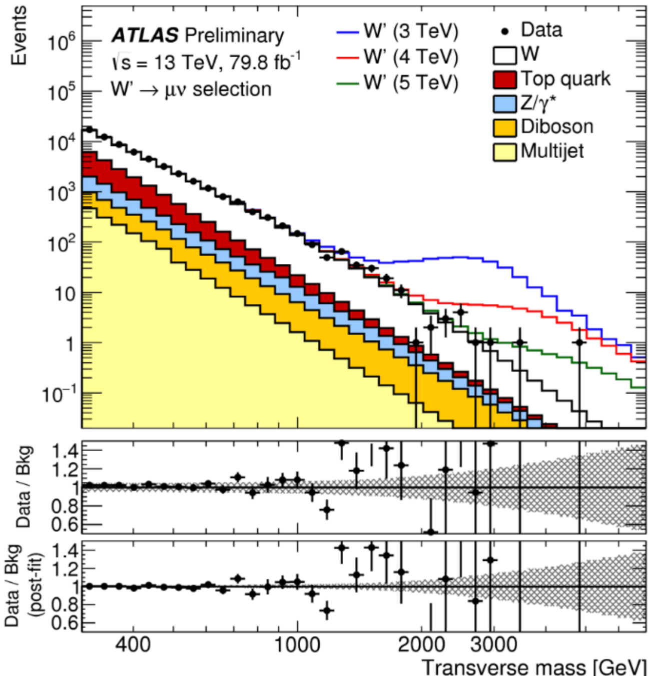
- Off-shell $W \to l\nu$
- Top pair
- Multi-jet (reducible)
  - **Fake leptons**

Signal extraction:

- Fit on $m_T(l,\nu)$ for $m_T(l,\nu)$ > 300 GeV

$$m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos\phi_{\ell\nu})}$$





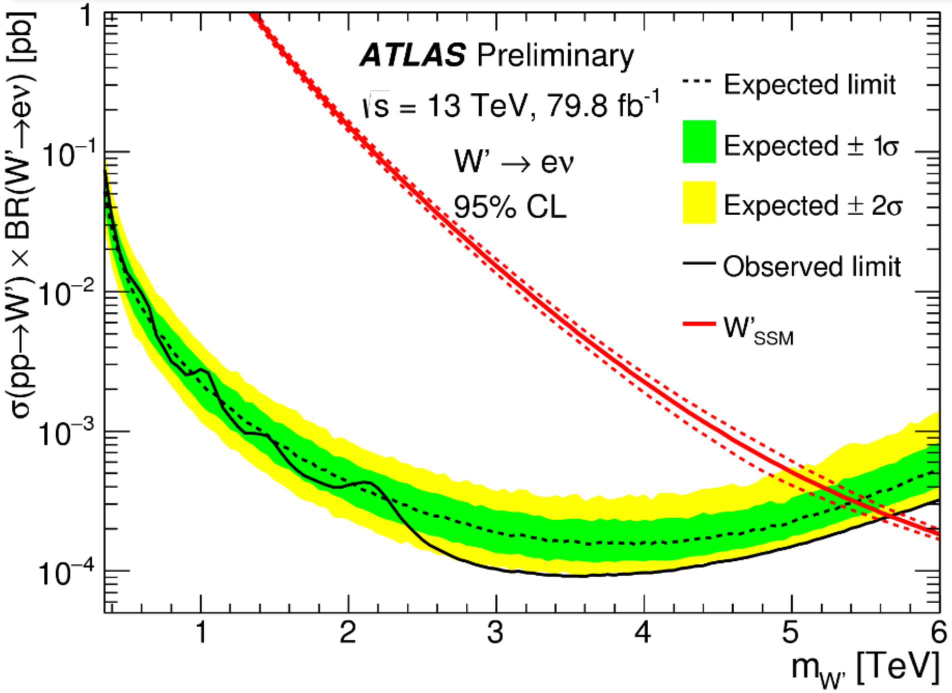
ATLAS-CONF-2018-17

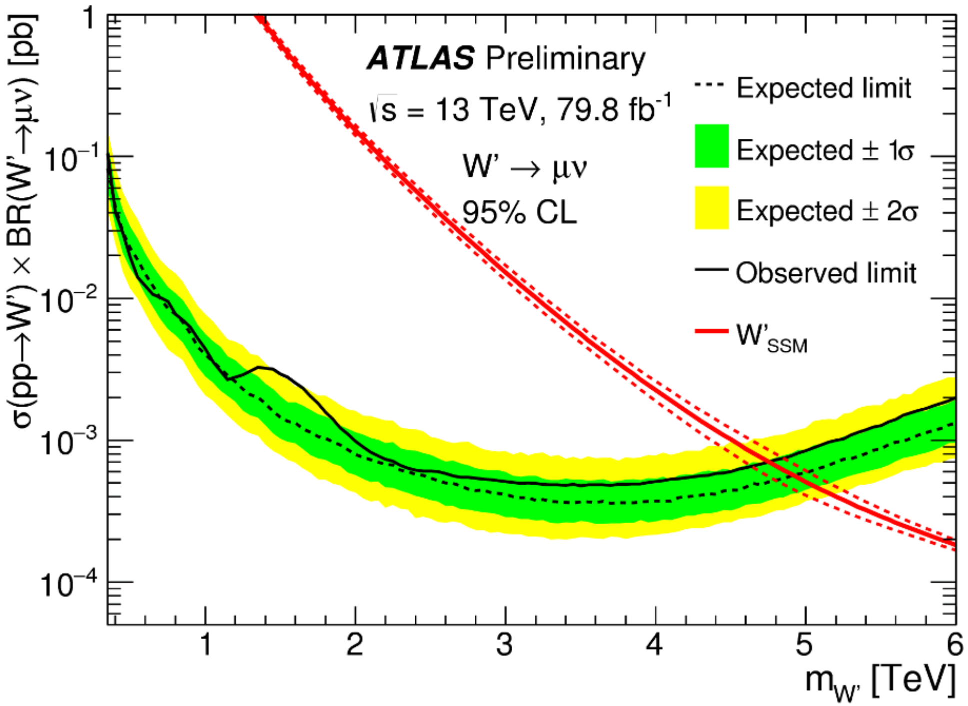
$W' \rightarrow e\nu$, $W' \rightarrow \mu\nu$

- **Production rate exclusion in 300<M<6000 GeV**
  - $\sigma \times BF < 10^{-1} - 9 \times 10^{-5}$ pb ($e\nu$)
  - $\sigma \times BF < 10^{-1} - 4 \times 10^{-4}$ pb ($\mu\nu$)
- **SSM W' mass exclusion**
  - $M_{W'} < 5.7$ TeV ($e\nu$)
  - $M_{W'} < 4.8$ TeV ($\mu\nu$)

Decay	$m_{W'}$ lower limit [TeV] Expected	Observed
$W' \rightarrow e\nu$	5.4	5.7
$W' \rightarrow \mu\nu$	4.9	4.8
$W' \rightarrow \ell\nu$	5.5	5.6

... bottom line, no excess observed.
Pushing the exclusion towards 6 TeV!



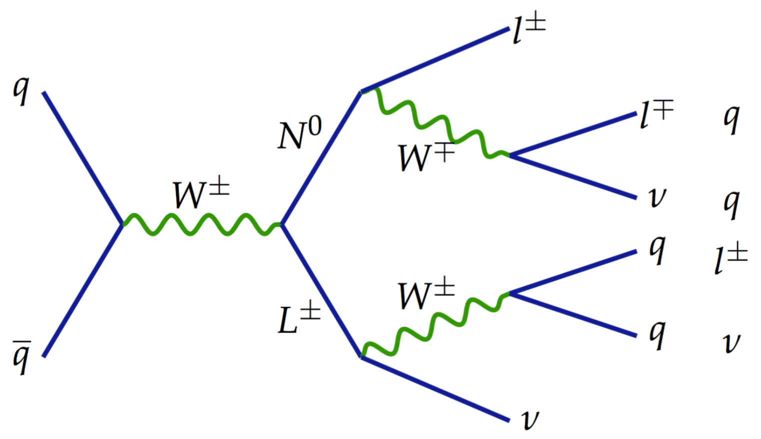


ATLAS-CONF-2018-20

Heavy lepton (Type III seesaw)

Theoretical motivation:

- Explanation of very light neutrino masses.
- SU(2) symmetry giving a heavy fermion triplet: $L^{\pm}$ (heavy Dirac charged leptons) and N^{0} (heavy Majorana neutrinos):
  - Couple to leptons and Higgs(es), neutrino masses occur via the seesaw mechanism.



Signal signature: final state lepton pair with

-

Experimental Signature: dilepton (OS/SS) + jets + Missing E_T

Analysis strategy:

- Focusing on the dilepton final state with charged current interactions.
- *$L^{\pm}$* and *N^{0}* couples to e, μ, τ equally.
- Main selections:
  - Dilepton trigger (ee, eμ)
    Single lepton trigger (μμ)
  - 2 leptons (ee, eμ, μμ) with OS/SS with M_{ll} > 110 GeV
  - 2 jets with M_{jj} consistent to W mass in +/- 20 GeV
  - Missing E_T (MET) significance > 10 (OS), 7.5 (SS)

Leading backgrounds

- OS: Top pair, Di-boson+jets
- SS: Di-boson+jets, Fake leptons, **electron charge flip**

ATLAS-CONF-2018-20

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ATLAS EXPERIMENT

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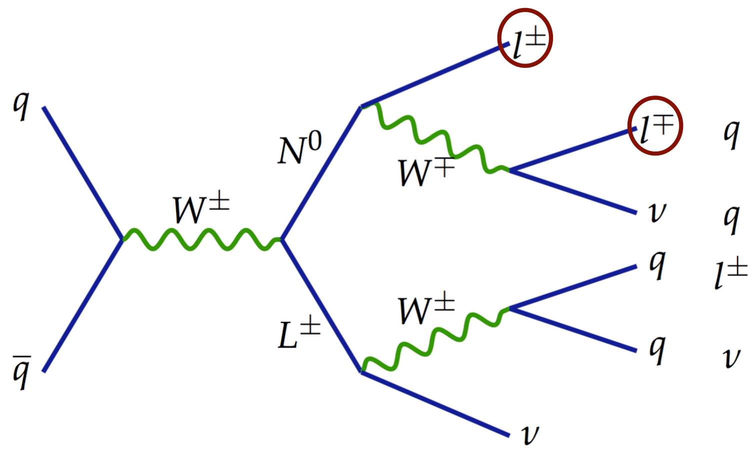

Signal signature: final state lepton pair with

- Opposite-sign charge
-

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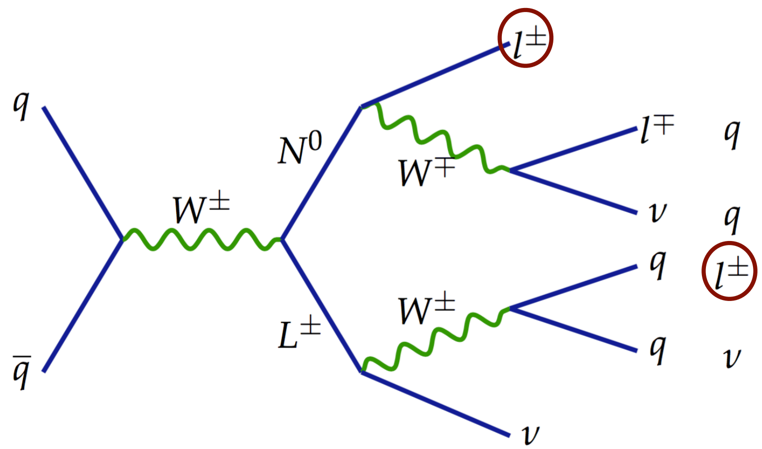


Signal signature: final state lepton pair with

- Opposite-sign charge
- Same-sign charge

Experimental Signature: dilepton (OS/SS) + jets + Missing E_T

Analysis strategy:

- Focusing on the dilepton final state with charged current interactions.
- $L^{\pm}$ and N^0 couples to e, μ, τ equally
- Main selections:
  - Dilepton trigger (ee, eμ)
    Single lepton trigger (μμ)
  - 2 leptons (ee, eμ, μμ) with OS/SS with M_{ll} > 110 GeV
  - 2 jets with M_{jj} consistent to W mass in +/- 20 GeV
  - Missing E_T (MET) significance > 10 (OS), 7.5 (SS)

Leading backgrounds

- OS: Top pair, Di-boson+jets
- SS: Di-boson+jets, Fake leptons, **electron charge flip**

ATLAS-CONF-2018-20

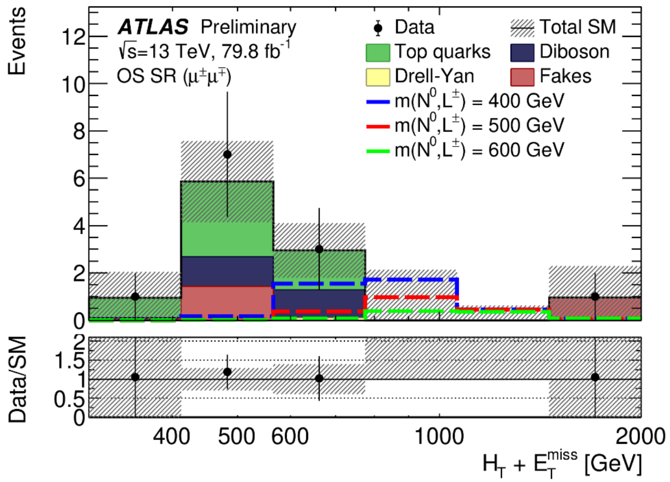
Heavy lepton (Type III seesaw)

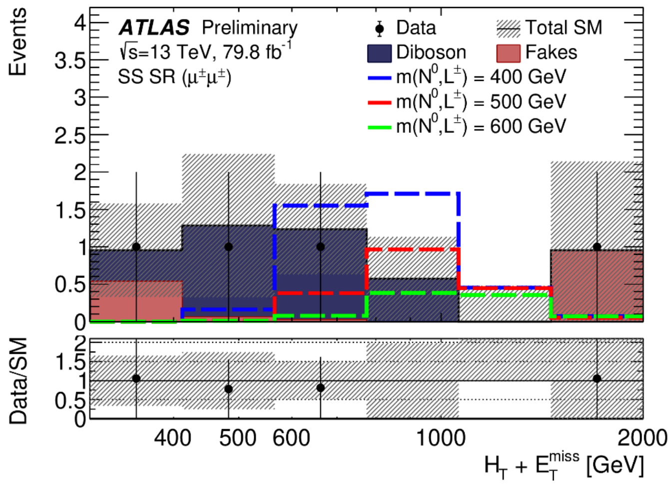
- Signal exclusion up to 560 GeV
  - Upper limit on cross-section σ~100 - 2 fb for 200-700 GeV

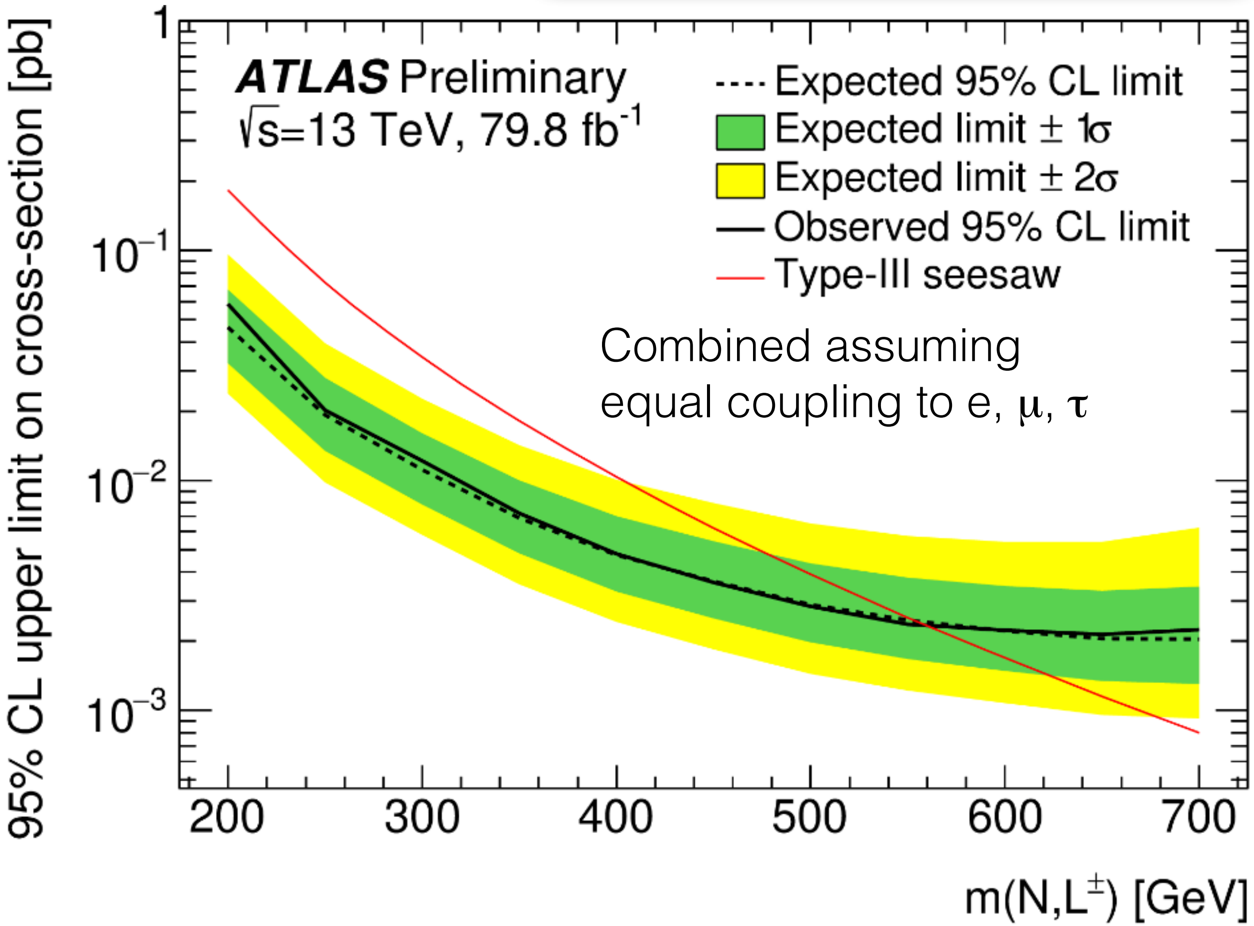
Signal extraction:

- Simultaneous fit on H_T + MET

…bottom line, no excess observed. Pushing the exclusion upwards.







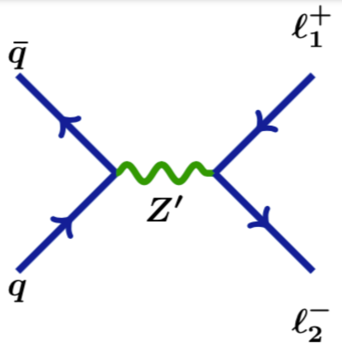
ATLAS-EXOT-2016-09

LFV Z' resonance

ATLAS EXPERIMENT

Theoretical motivation:

- Additional U(1) gauge symmetry: $Z' \to e\mu, e\tau, \mu\tau$
- Quantum black holes: RS (n=1 extra dimension) or ADD (n=6) : giving LFV QBH $\to ll'$
- R-parity violating SUSY



LFV $e\mu$, $e\tau$, $\mu\tau$ high mass resonance search

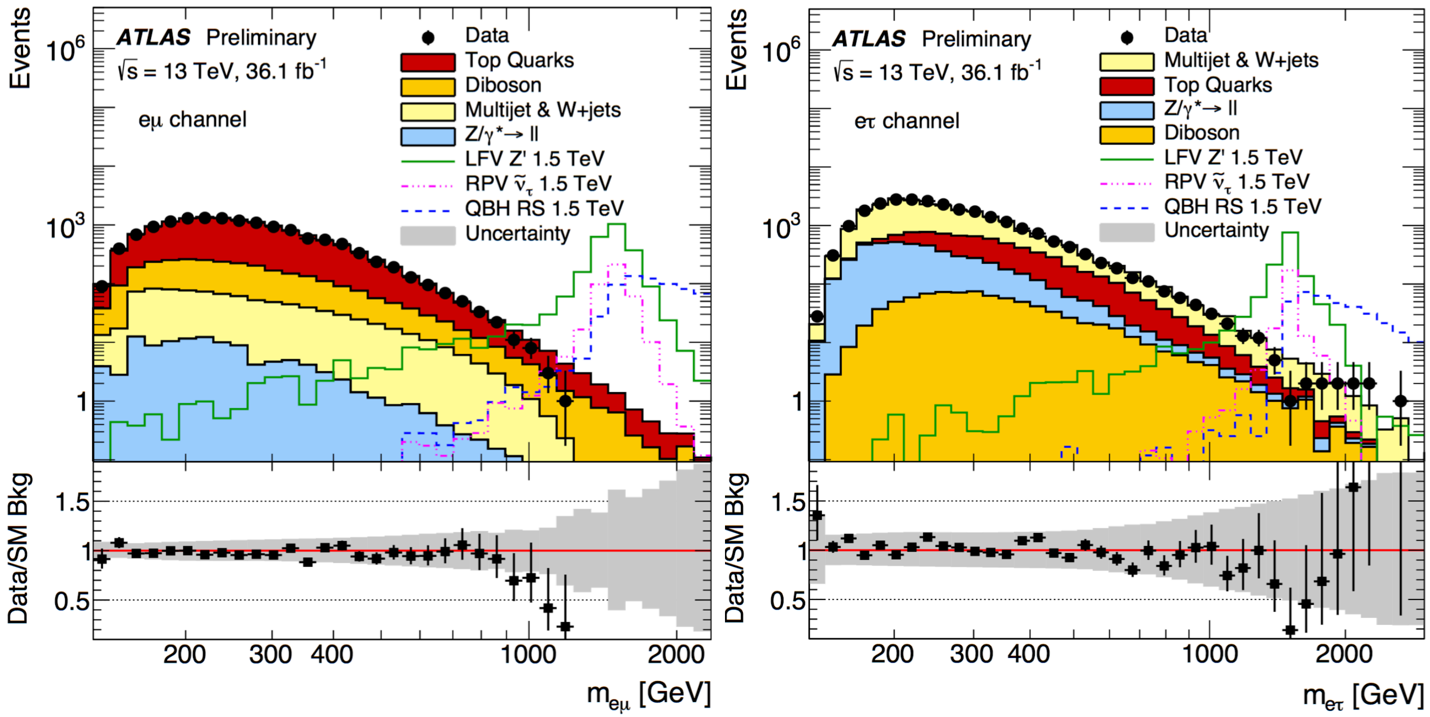
- Single e/μ trigger without isolation
- Different flavor leptons p_T > 65 GeV

Backgrounds

- $e\mu$: top pair
- $e\tau$, $\mu\tau$: fake τ
  - W+jets
  - multi-jet

Signal extraction:

- Fit on $M_{ll'}$

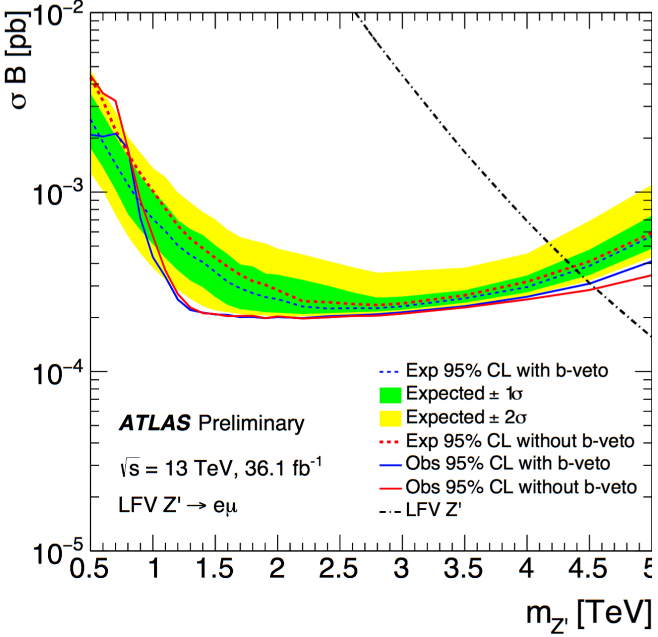


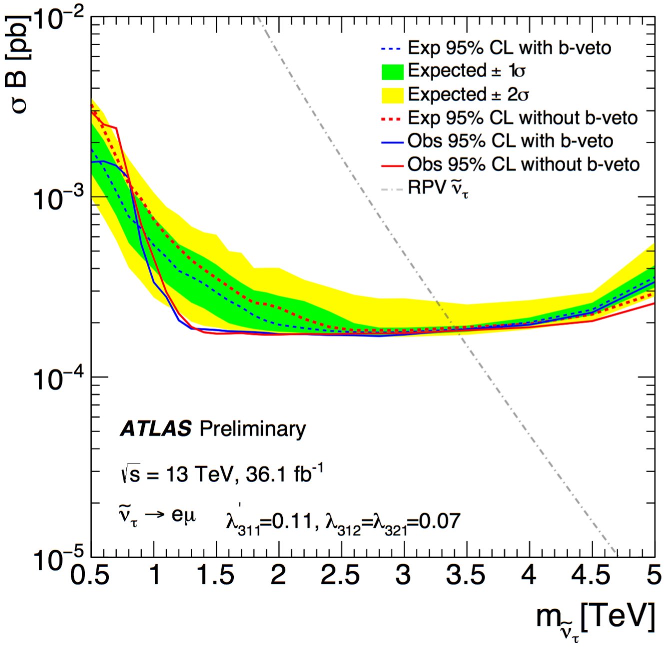
ATLAS-EXOT-2016-09

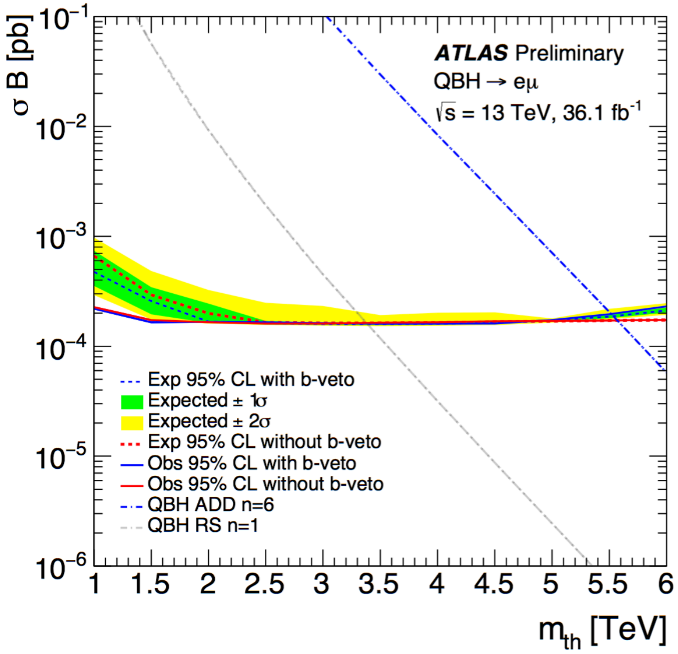
LFV Z' resonance

Model-dependent lower mass limits derived for the three classes of new physics models:

- Z' with an LFV coupling
- RPV scalar neutrino
- and QBH production tested







4.5 (eμ), 3.7(eτ), 3.5 (μτ) TeV

3.4 (eμ), 2.9(eτ), 2.6 (μτ) TeV

5.5 (eμ), 4.9(eτ), 4.5 (μτ) TeV

3.4 (eμ), 2.9(eτ), 2.6 (μτ) TeV

… no excess observed. Giving mass limits at 2.6-5.5 TeV scale!

EXOT-2016-09

ATLAS-EXOT-2016-11

$X \to WZ$ resonance

ATLAS EXPERIMENT

Theoretical motivation:

- Use Parameterized Lagrangians with a heavy vector triplet (HVT) for a generic vector resonance search:
  - **The benchmark model used in ATLAS assumes resonance couples to gauge bosons ($W' \to WZ$). Can vary suppression of couplings to fermions (models A/B for VBF).**
- The Georgi–Machacek model (GM) is used as a benchmark for a singly charged scalar resonance.
  - **Assuming a light fermiophobic fiveplet H_5 ($H^{++}, H^{+}, H^{0}, H^{-}, H^{--}$) coupling to gauge bosons ($H_5 \to WZ$ produced through VBF).**

$WZ \to l\nu ll$ (l =e or μ) high mass resonance search:

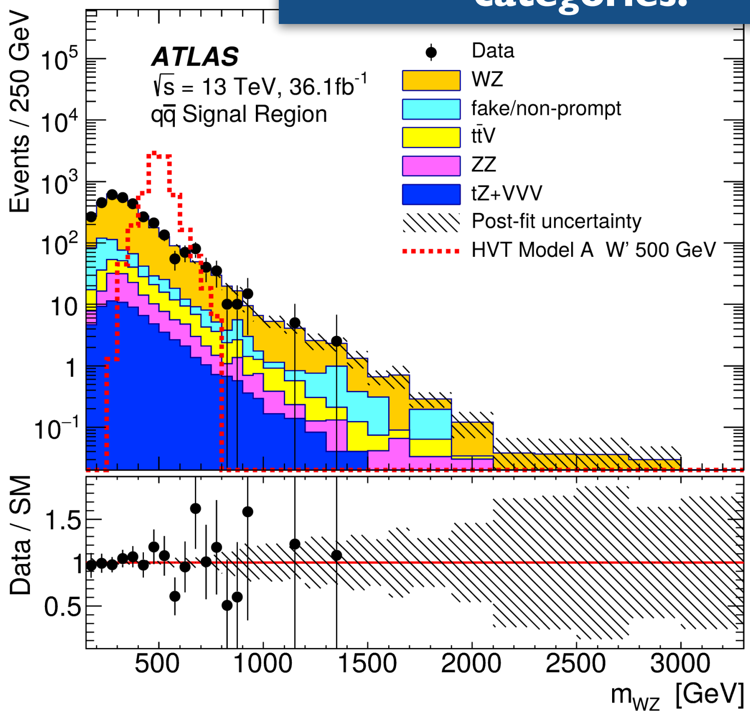
- Single e/μ trigger.
- Three leptons with Lepton p_T > 27 GeV.
- Two OS SF leptons | m_{ll} - m_Z | < 20 GeV.
- **Special selections for VBF and qq categories.**

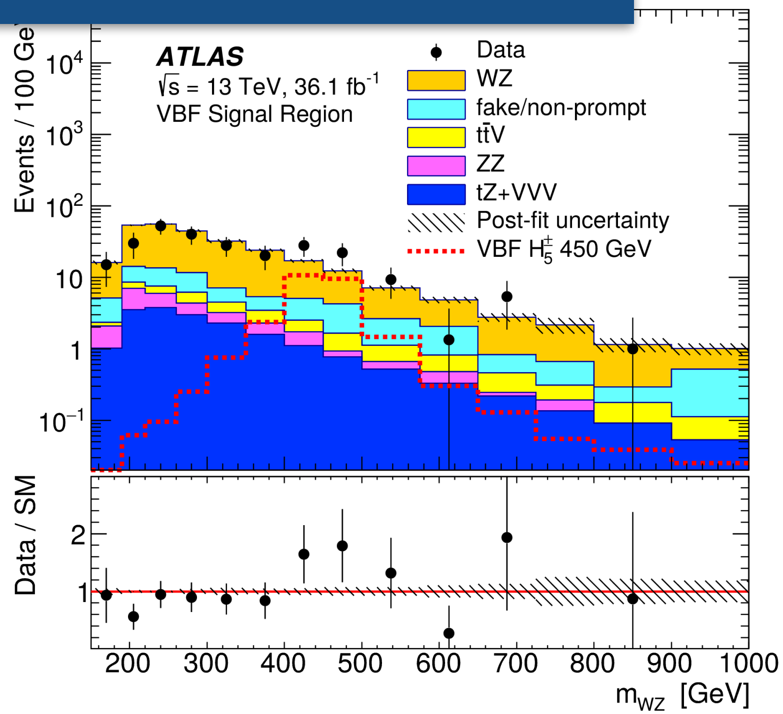
Backgrounds

- multi-boson (*VV*,*VVV*)
- single t, tt, ttV …
- fake backgrounds:
  - *Z*+jets, *Z*+γ
  - *W*+jets, multi-jet

Signal extraction:

- Constrained fit on M_{WZ}.
- M_{WZ} derived from lepton momenta and MET.





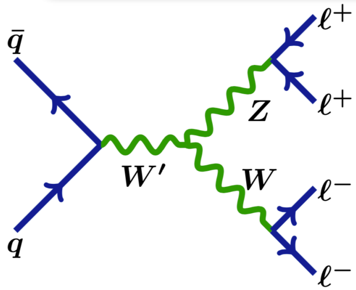
ATLAS-EXOT-2016-11

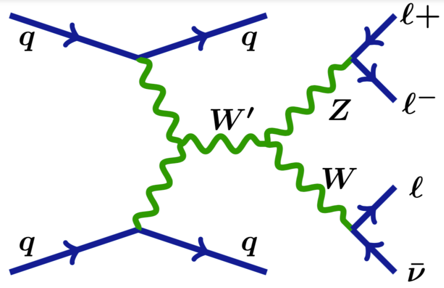
$X \rightarrow WZ$ resonance

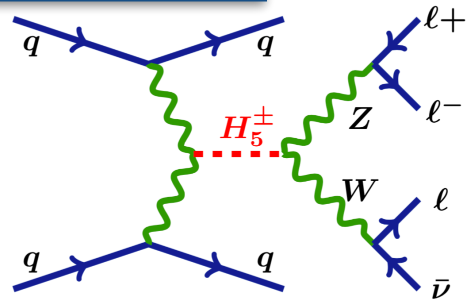
ATLAS EXPERIMENT

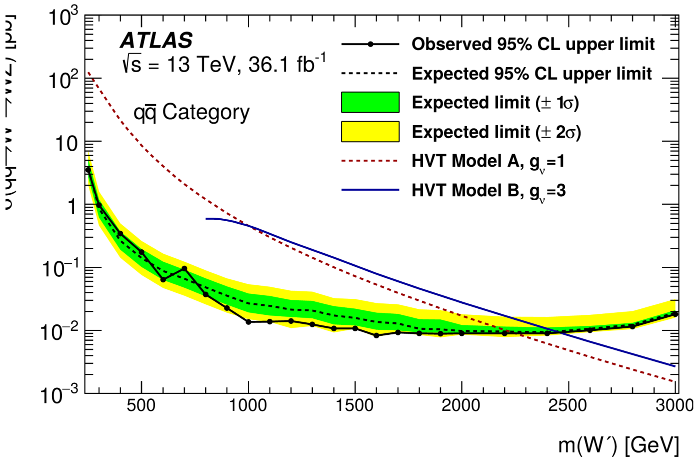
Model-dependent lower mass limits derived for three new physics models:

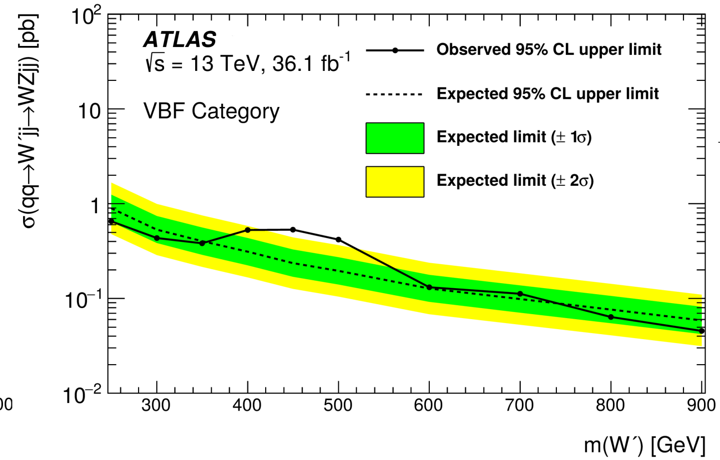
- W' in Heavy Vector Triplet benchmark Model A (Model B) with coupling constant $g_V = 1$ ($g_V = 3$) in qq and VBF categories.
- Fermion coupling suppressed in the VBF category ($c_F = 0$).
- H_5 in the Georgi–Machacek model in the VBF category.

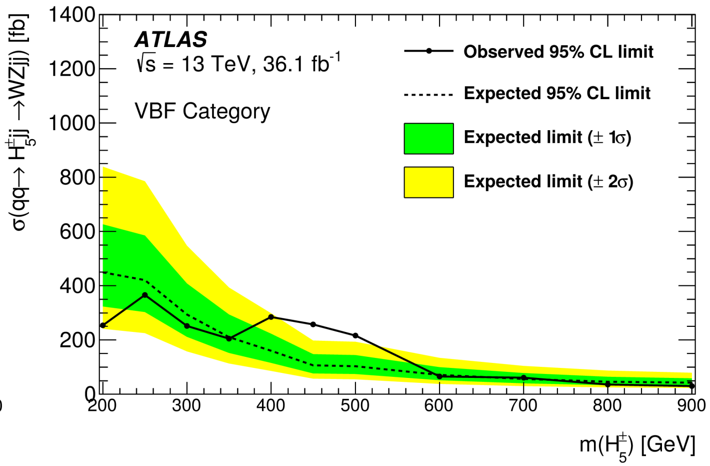












qq category: 2260 (2460) GeV for $g_V = 1$ ($g_V = 3$)

95% CL upper limits W' VBF

significance 2.9 (local) and 1.6 (global, LEE)

95% CL upper limits H_5 VBF

significance 3.1 (local) and 1.9 (global, LEE)

A local excess visible @ 450 GeV in VBF category

ATLAS-EXOT-2016-11

$X \to WZ$ resonance

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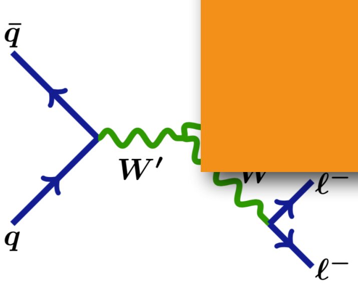
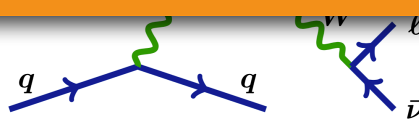
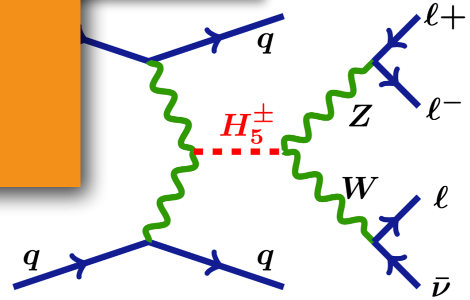
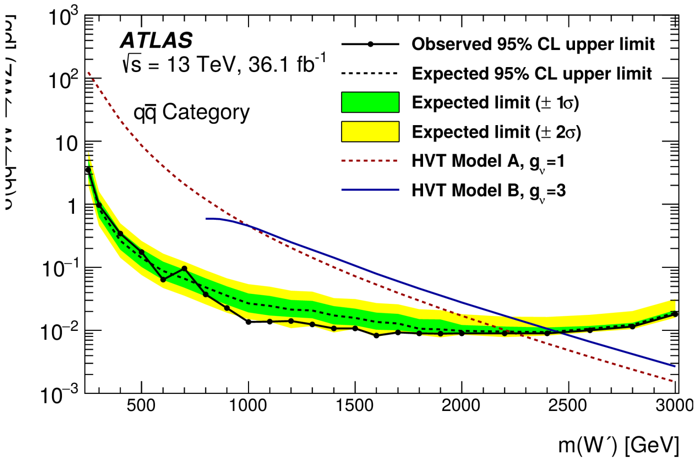
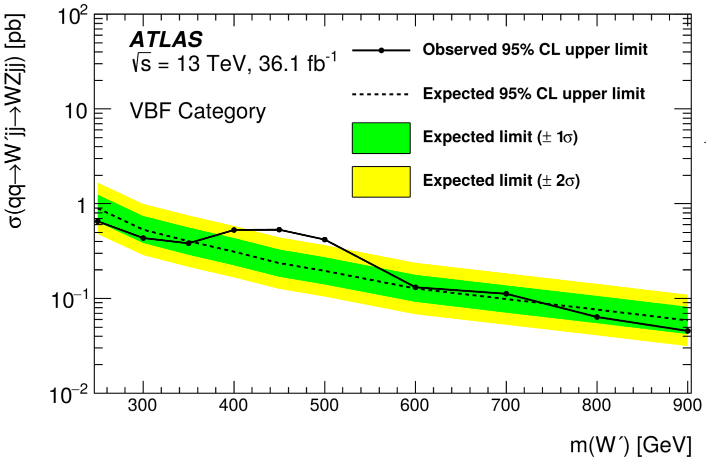
More on charged Higgs boson searches in the MSSM in the talk by Lluïsa-Maria Mir

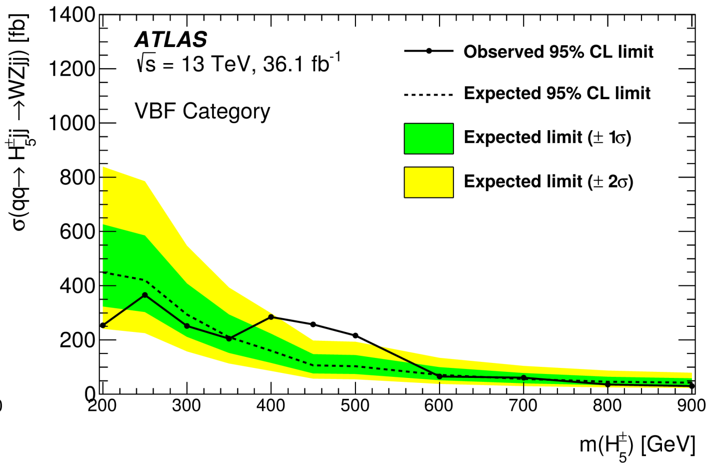












qq category: 2260 (2460) GeV for $g_V = 1$ ($g_V = 3$)

95% CL upper limits W' VBF

significance 2.9 (local) and 1.6 (global, LEE)

95% CL upper limits H_5 VBF

significance 3.1 (local) and 1.9 (global, LEE)

A local excess visible @ 450 GeV in VBF category

Conclusions

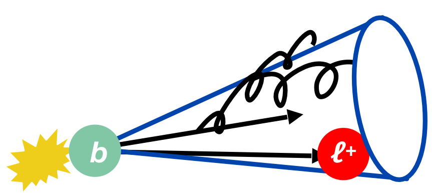
- **A rich program is being conducted searching for new physics in final states with leptons in the ATLAS collaboration:**
  - heavy resonance (vector boson and scalar) searches,
  - heavy lepton searches,
  - LFV signature searches,
  - and many more are coming!
- **The first results using the 2017 data were shown**
  - **Demonstrating readiness for the full Run-2 analyses!**
    - For fakes, charge flip, high pT muons, high mass l and ν modeling in the hard pileup condition in 2017.
- **Stay tuned for more results!**
  - No new physics is found yet…
  - … but we are only half way through our data and full of new ideas!

Backup

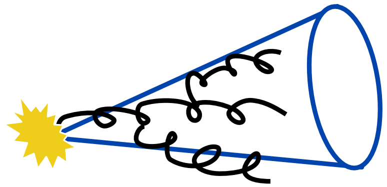
ATLAS-CONF-2018-17

Estimation of the fake background

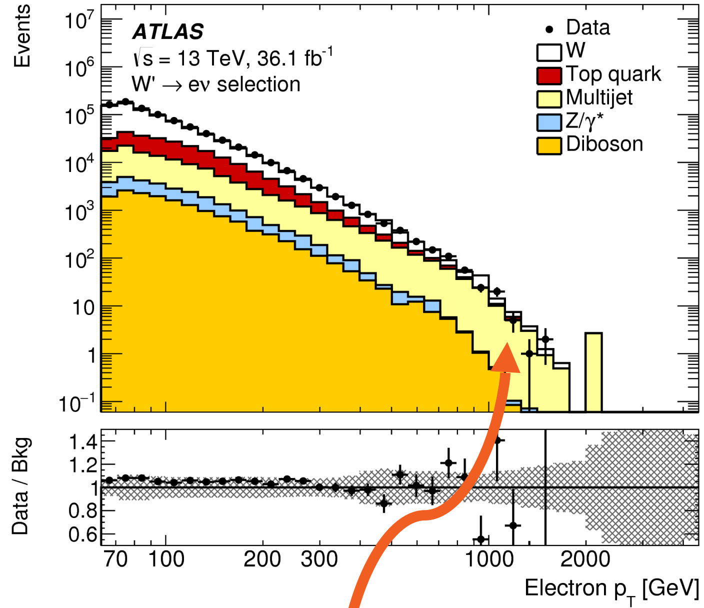
Non-prompt leptons

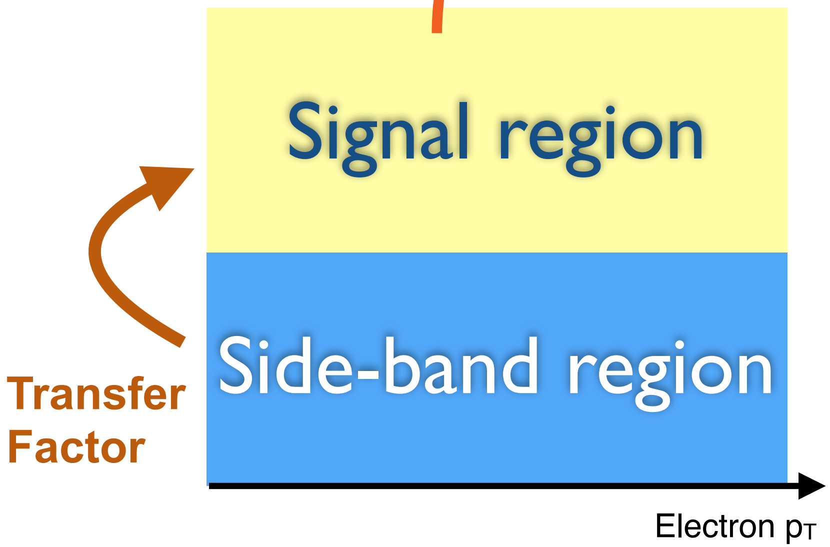


Fake leptons



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

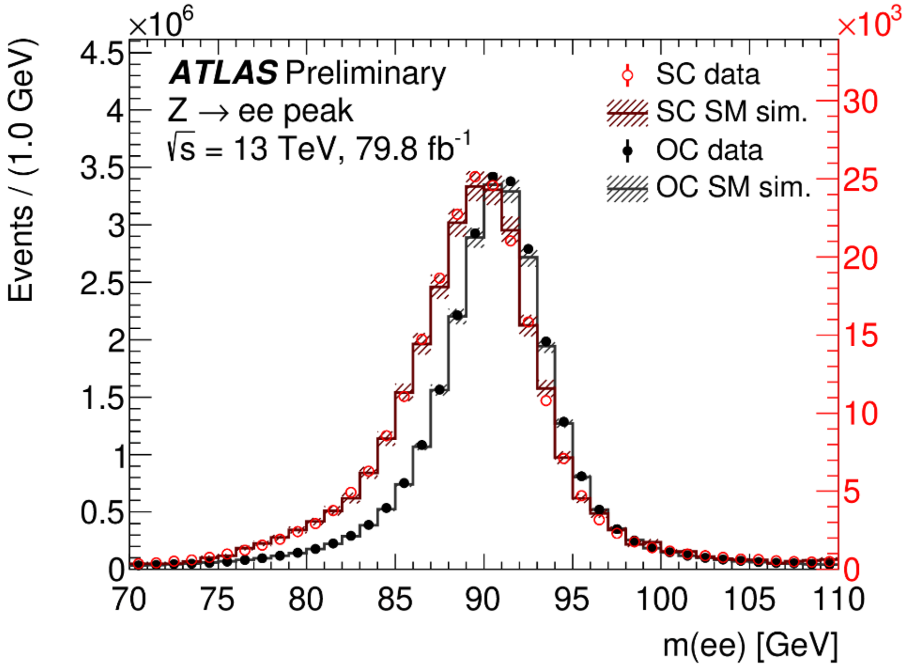




ATLAS-CONF-2018-20

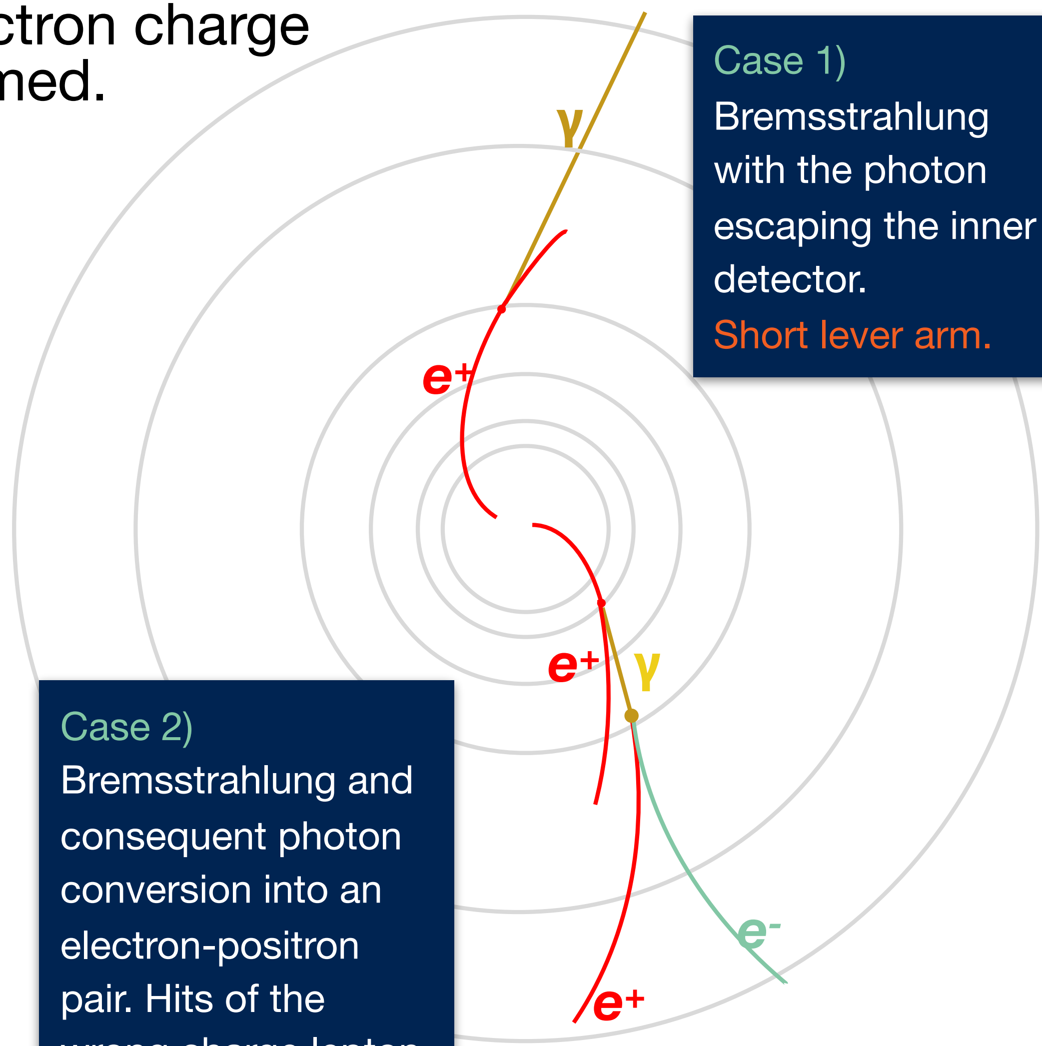
Electron charge misidentification

- **In type III seesaw analysis the same-sign charge final state is a distinct signature.**
- Calibration and validation of electron charge misid. modeling in MC is performed.



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

The probability is about 1% at the Z peak.

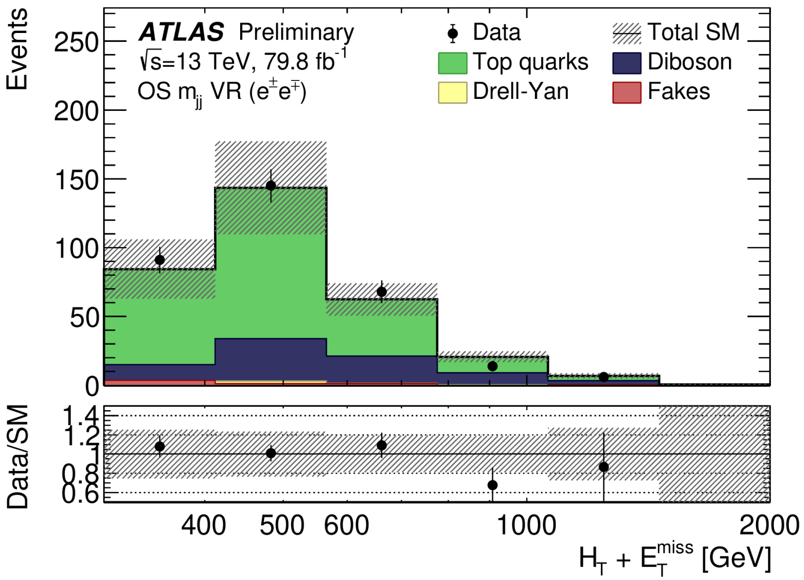


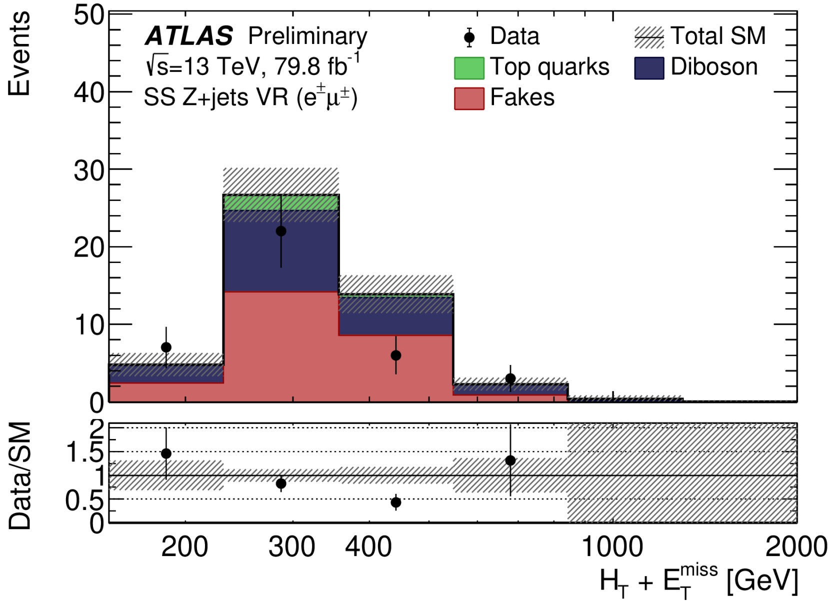
Case 1)
Bremsstrahlung with the photon escaping the inner detector.
Short lever arm.

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

ATLAS-CONF-2018-20

Heavy lepton (Type III seesaw)





Normalization of leading backgrounds in dedicated control regions

- Top pairs (CR with b-tag)
- SS: diboson+jets (M_{jj} sideband)

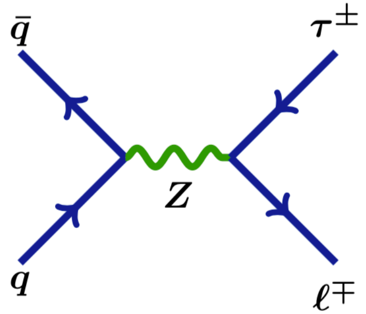
Detector related backgrounds especially important in same-sign charge final state:

- validation of data-driven fake estimation

Signal regions	OS ee	OS $e\mu$	OS $\mu\mu$	SS ee	SS $e\mu$	SS $\mu\mu$
Observed events	11	13	12	13	19	4
Total background	9.9 ±3.2	15.7 ±2.7	10.7 ±3.7	12.5 ±4.4	13.4 ±2.8	5.0 ±1.9
Top quarks	6.1 ±2.7	9.1 ±2.5	5.7 ±2.9	3.1 ±1.5	2.3 ±2.7	
Diboson	3.2 ±0.9	4.3 ±1.2	2.5 ±1.5	5.7 ±1.5	9.5 ±1.9	3.4 ±1.3
Drell–Yan	0.2 ±0.2	< 0.001	0.1 ±1.0	0.1 ±0.1	0.1 ±0.1	< 0.001
Fakes	0.5 ±2.0	2.3 ±1.5	2.4 ±1.3	3.6 ±4.8	1.4 ±1.7	1.6 ±1.6

LFV Z boson decay

ATLAS-EXOT-2016-36, arXiv:1804.09568



Theoretical motivation:

- Lepton-flavor-violating (LFV) Z boson decays are predicted by models with:
  - heavy neutrinos,
  - extended gauge models and
  - supersymmetry (among others).
  - The most stringent bounds on such decays with a τ-lepton in the final state are set by the LEP experiments.

LFV search for Z (91 GeV) → eτ, μτ decay

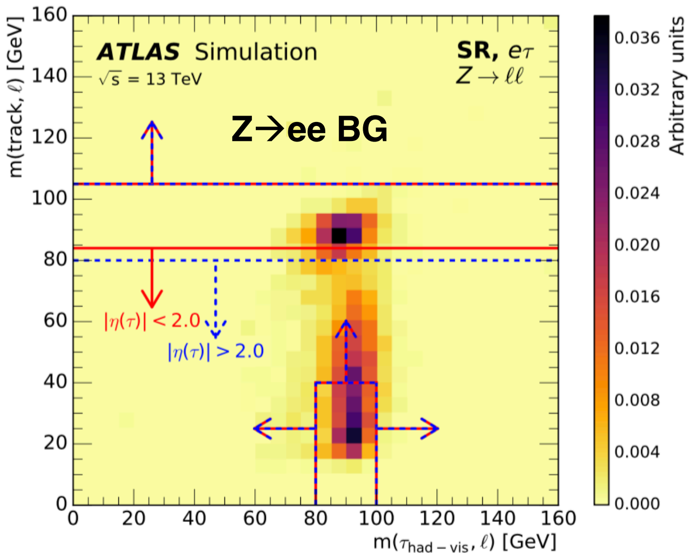
- Single e/μ trigger with isolation
- Exactly one e/μ with p_T > 30 GeV
- At least hadronic τ with visible p_T > 20 GeV

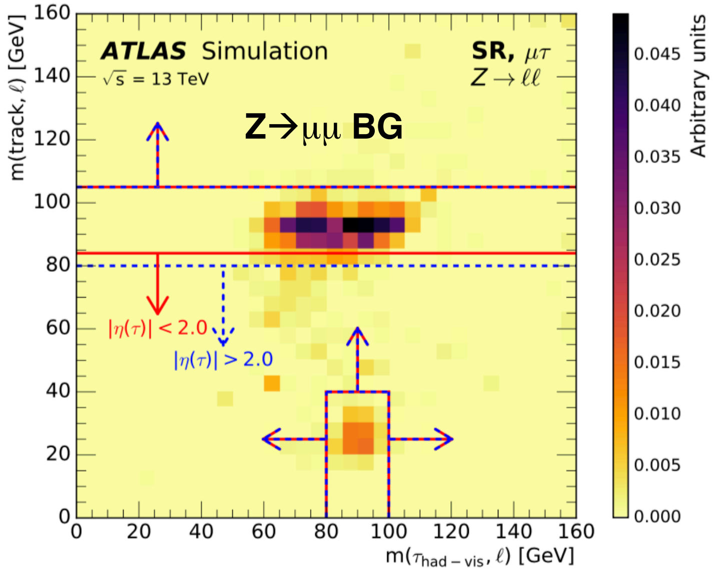
Backgrounds

- Careful veto for Z→ee, μμ backgrounds (unique challenge)
- Overlap removal between τ and e/μ
- Z mass veto with M(tau & e) and M(track of tau & μ)
  - handles lepton inefficiency or uncovered regions

Signal efficiency:

- 3.2% for eτ
- 3.5% for μτ





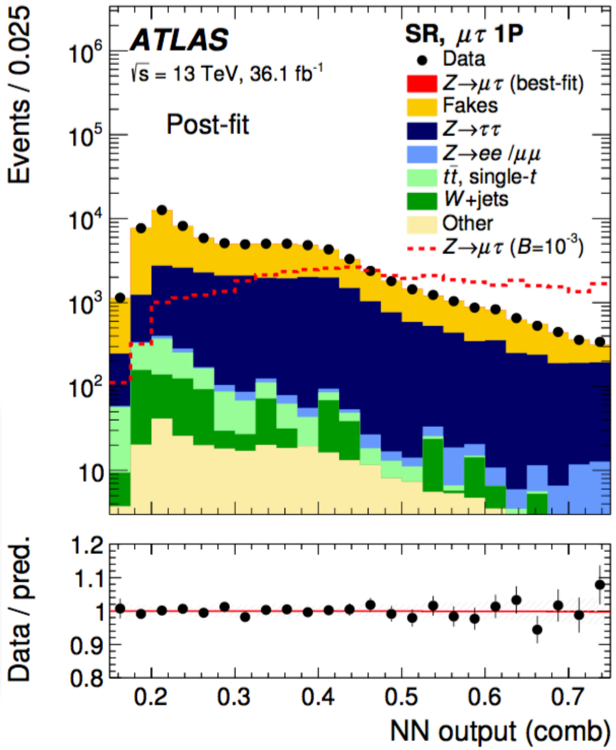
ATLAS-EXOT-2016-36,
arXiv:1804.09568

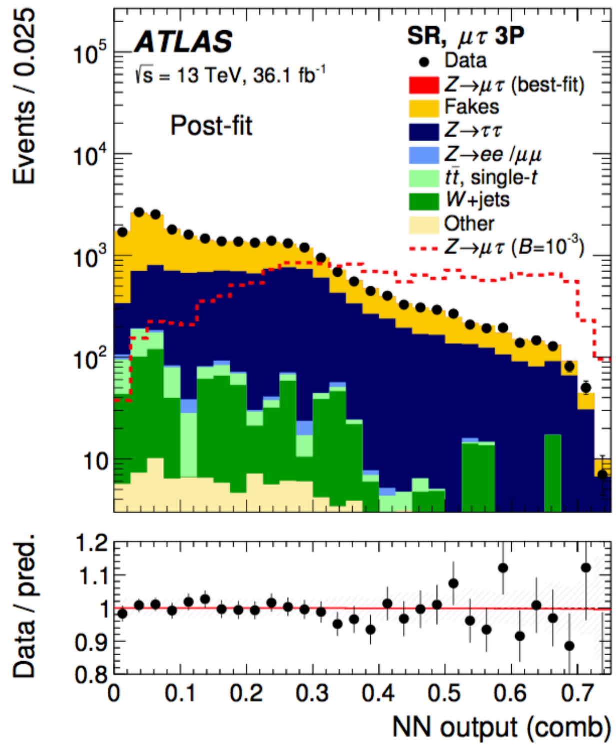
LFV Z boson decay

ATLAS EXPERIMENT

Backgrounds
- Fake tau backgrounds
- Multi-jet
- W+jets
- $Z \rightarrow \tau\tau$

Signal selection using a neural network:
- NN trained to classify:
  - signal vs $Z \rightarrow \tau\tau$
  - signal vs W+jets
  - signal vs $Z \rightarrow ee/\mu\mu$





Signal extraction:
- $Z \rightarrow \tau e$, $Z \rightarrow \mu\tau$ signals extracted by a fit to NN distribution

	$e\tau$	$\mu\tau$
$\mathcal{B}(Z \rightarrow \ell\tau)$	$(3.3^{+1.5}_{-1.4}) \times 10^{-5}$	$(-0.1^{+1.2}_{-1.2}) \times 10^{-5}$
Observed (expected) upper limit at 95% CL	$5.8(2.8) \times 10^{-5}$	$2.4(2.4) \times 10^{-5}$

Run1 combination

$$\mathcal{B}(Z \rightarrow \mu\tau) < 1.3 \times 10^{-5}$$

(compatible with LEP)

…bottom line, no deviation observed.