Search for high-mass resonances decaying into leptonic final states using the ATLAS detector

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On behalf of the ATLAS Collaboration

Introduction

- The resonance search is the most standard way to find a new particle.
- There are many physics models beyond the Standard Model (SM) that predict new heavy particles decaying into lepton final states:

Spin-0 scalar (H)

- Minimal Supersymmetric SM (MSSM)

Spin-2 excited states of graviton

- Randall-Sundrum model with a warped extra dimension

Spin-1 vector (Z', W')

- E6-motivated Grand Unification model
- Left-Right symmetry models
- Little Higgs models
- Models with extra dimensions

- ATLAS experiment took good data for physics analyses of 139 fb^{-1} with 13 TeV pp colliding energy at LHC during Run2 (2015 ~ 2018).

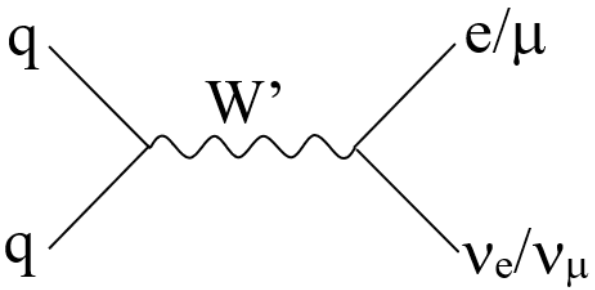
New spin-1 vector bosons (W', Z') were explored in the ATLAS experiment with a full Run2 dataset. ([arXiv:1906.05609], [arxiv1903.06248])

Benchmark models

- 3 benchmark models were used in this search:

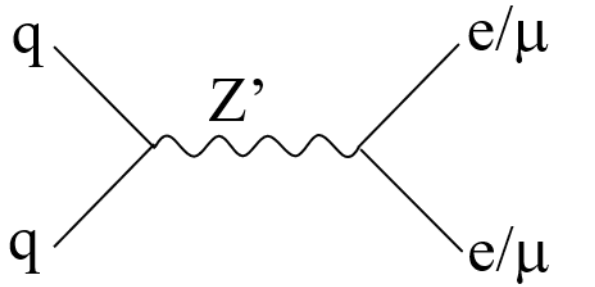
Sequential Standard Model (SSM)

- W'/Z' couples to fermions with the same strength as SM W/Z.
- Couplings to W/Z are ignored.



E6-motivated Grand Unification model

- Two Z's (Z'_χ, Z'_ψ) are predicted.



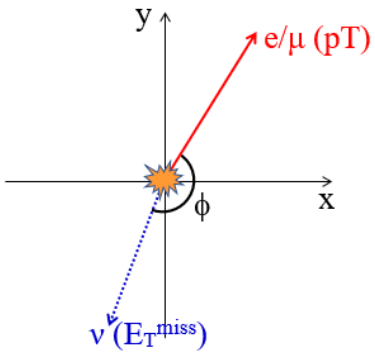
Heavy Vector Triplet (HVT) model

- Provides generic framework with couplings of W'/Z' to fermions and Higgs.

- W'/Z' can decay into a single/two charged lepton final states.
- No interference effect between W'/Z' and W/Z was taken into account.

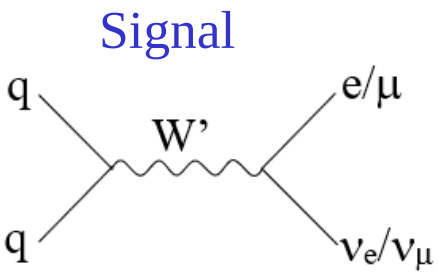
Signal selection

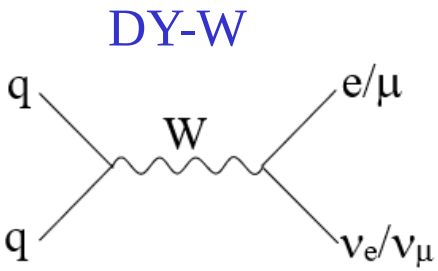
- A single and two isolated electron(s) or muon(s) with high-p_T were selected as the signal candidates.



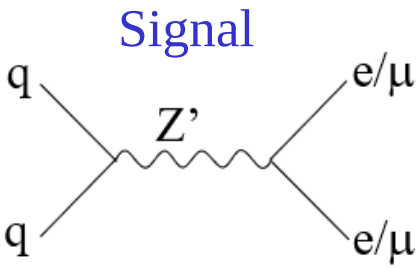
- Final discriminants to be fit for the signal extraction:
  - Single charged lepton (W'): Transverse mass (m_T)

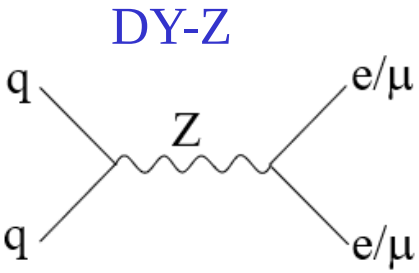
$$m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos \varphi_{\ell\nu})}$$





  - Two charged leptons (Z'): Di-lepton invariant mass ($m_{\ell\ell}$)





Background estimation

Single charged lepton final states (W')

- DY W, Z/γ*, top pair, single top and diboson were modeled with MC.
- Fake electrons/muons originated from multi-jet production were extracted from data using the matrix method.
- Top-quark, diboson and fake backgrounds were extrapolated to high m_T by using smoothly falling functions due to short of statistics in MC samples at high m_T.

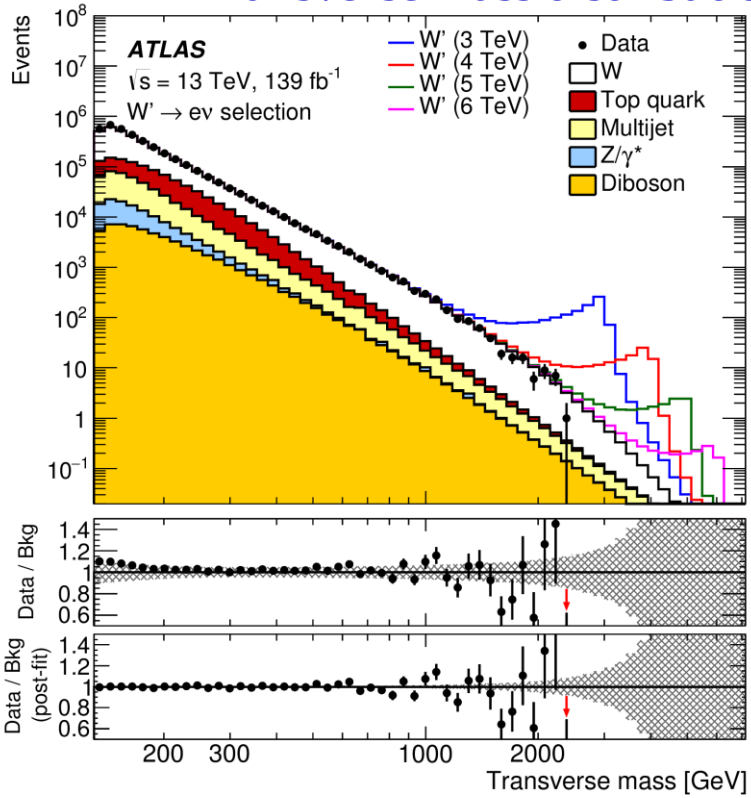
Two charged lepton final states (Z')

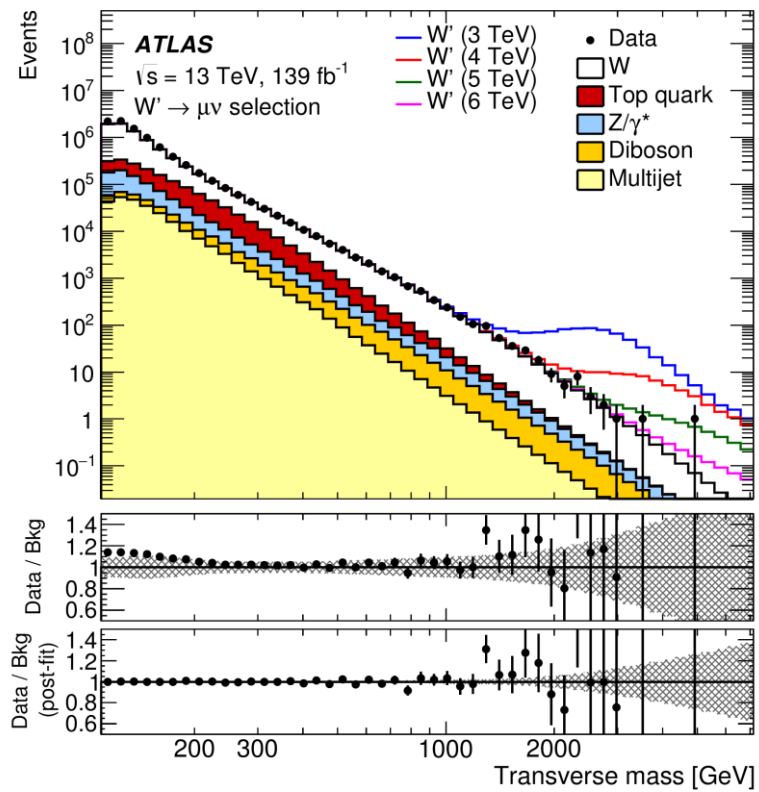
- A functional form fit was used to evaluate the background inclusively for all of DY, top pair, single top, diboson and fakes.
- The fit function was optimized, based on performance studies on a MC background template.

Transverse mass distribution (W')

- Transverse mass distributions were created after all selection cuts.
- No excess from SM expectation was observed.
- Possible reason of deviation at low m_T is mis-modeling of jet energy resolution and E_T^{miss} track soft term, but it is covered by uncertainty.

Transverse mass distributions for electron and muon channels

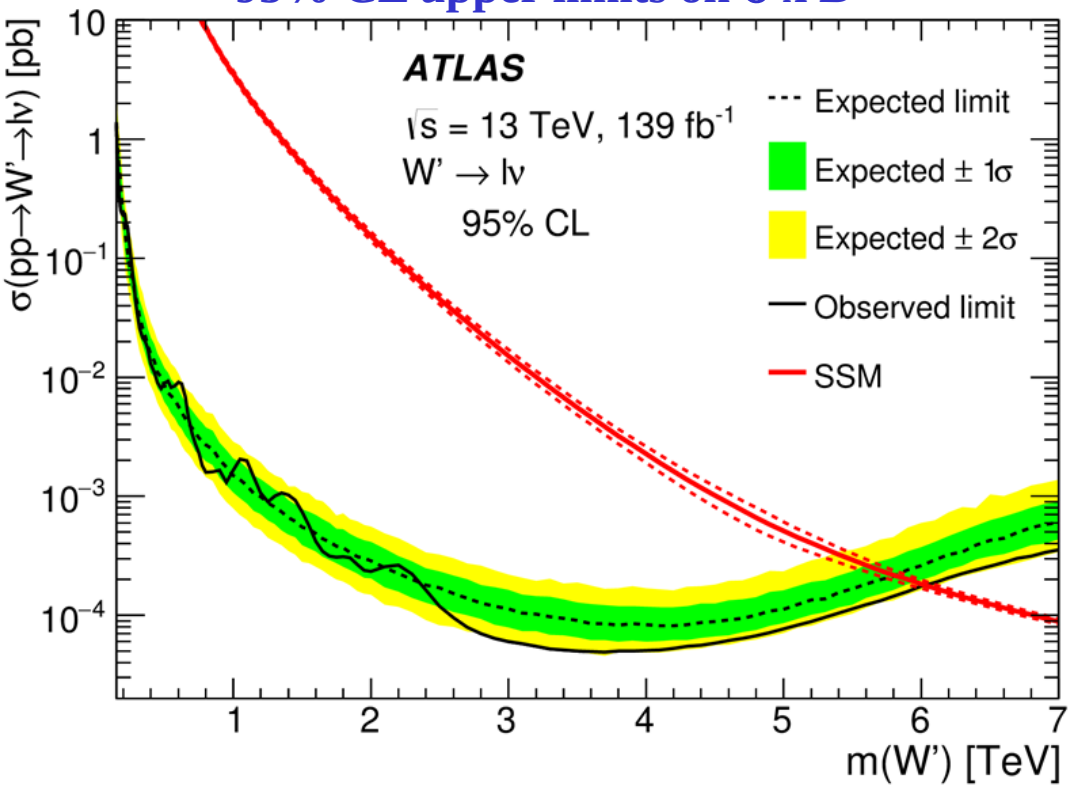




Cross-section limit (W')

- The cross-section limit was investigated as a function of mass, based on SSM.
- The mass limits were improved significantly from the previous results with 36.1 fb^{-1}.

95% CL upper limits on σ x B



36.1 fb^{-1}

Decay	$m_{W'}$ lower limit [TeV] Expected	Observed
$W' \to e\nu$	5.1	5.2
$W' \to \mu\nu$	4.7	4.5
$W' \to \ell\nu$	5.2	5.1

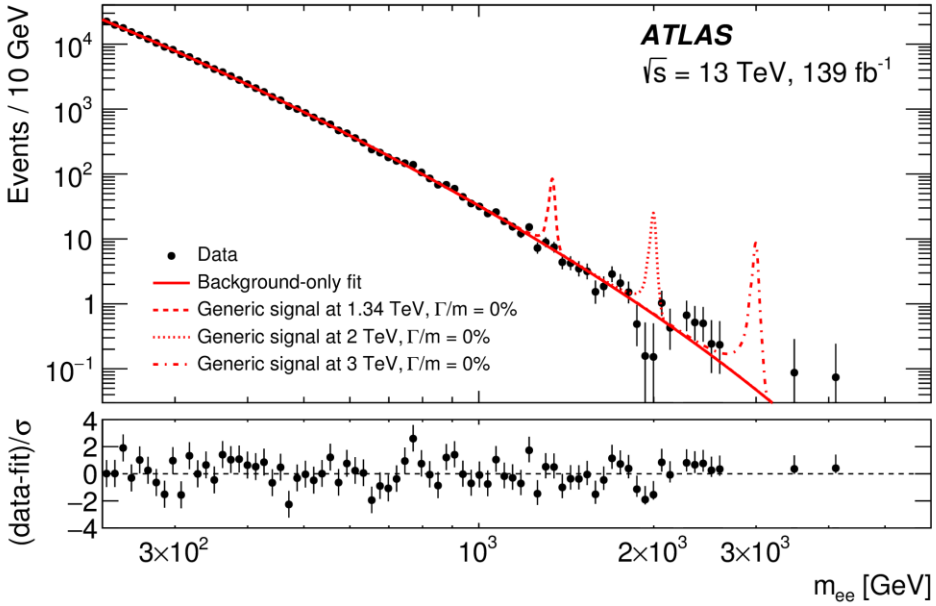
139 fb^{-1}

Decay	$m(W')$ lower limit [TeV] Observed	Expected
$W' \to e\nu$	6.0	5.7
$W' \to \mu\nu$	5.1	5.1
$W' \to \ell\nu$	6.0	5.8

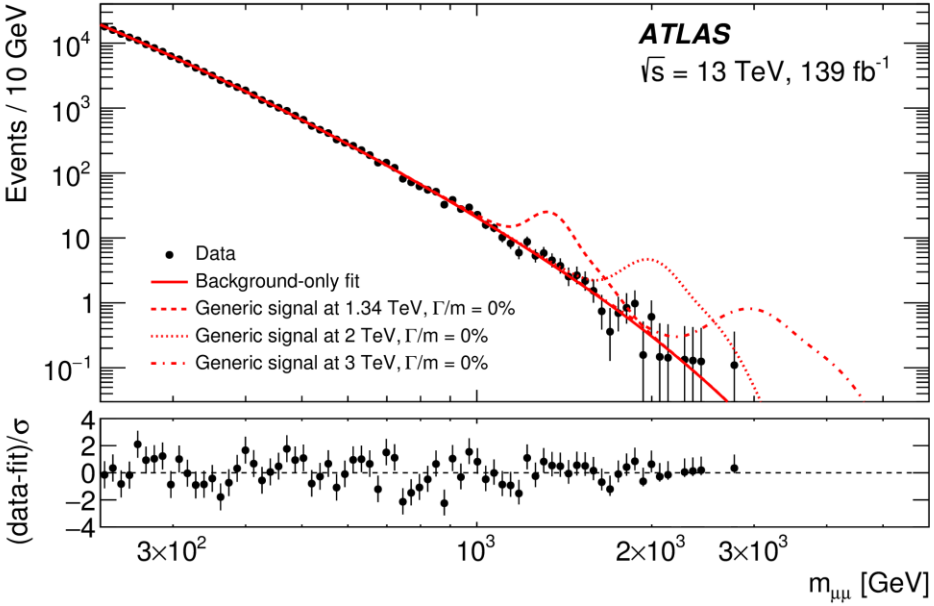
Di-lepton mass distribution (Z')

- Di-lepton invariant mass distributions were created with events after all selection cuts.
- Highest di-lepton mass: 4.06 TeV for m_{ee} and 2.75 TeV for $m_{\mu\mu}$
- The distributions are consistent with the smoothly falling background expectations.

Di-electron mass distribution



Di-muon mass distribution



Cross-section limit (Z')

The fiducial cross-section limits was calculated, taking account of only signal peak region in Breit-Wigner shape.

→ Can be supposed as model independent result

36.1 fb^{-1}

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	3.6	3.6	3.3	3.2	3.8	3.7
Z'_χ	3.9	3.9	3.6	3.6	4.1	4.0
Z'_{SSM}	4.3	4.3	4.0	3.9	4.5	4.5

139 fb^{-1}

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
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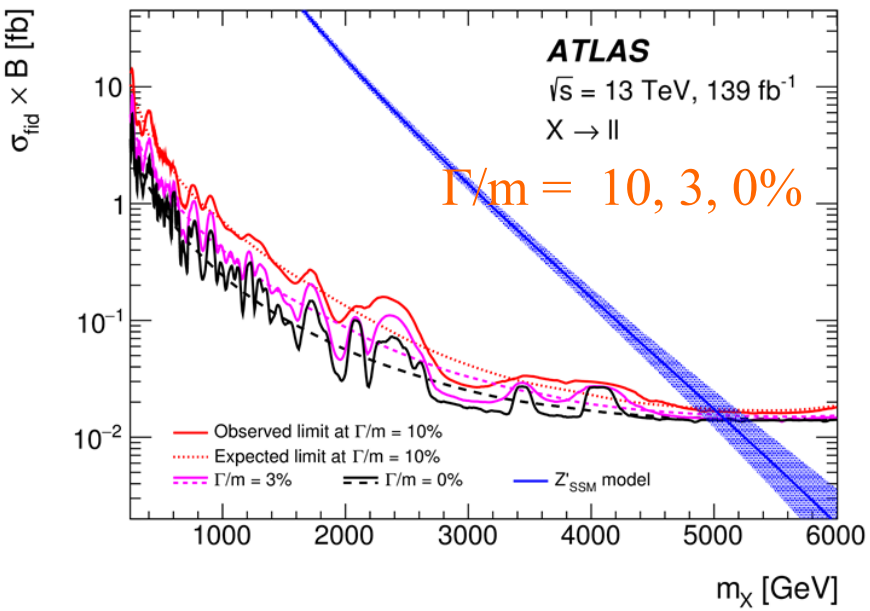
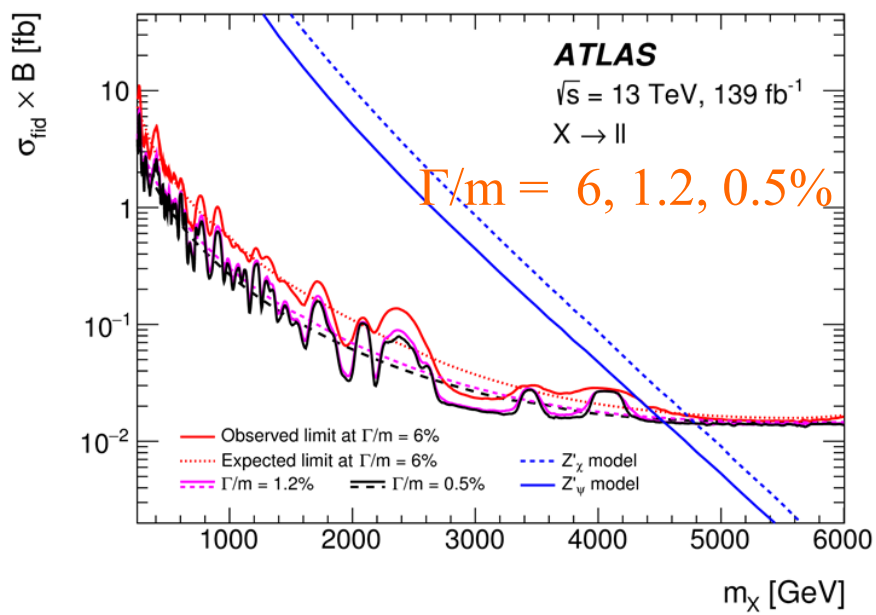
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

95% CL upper limits on fiducial σ x B





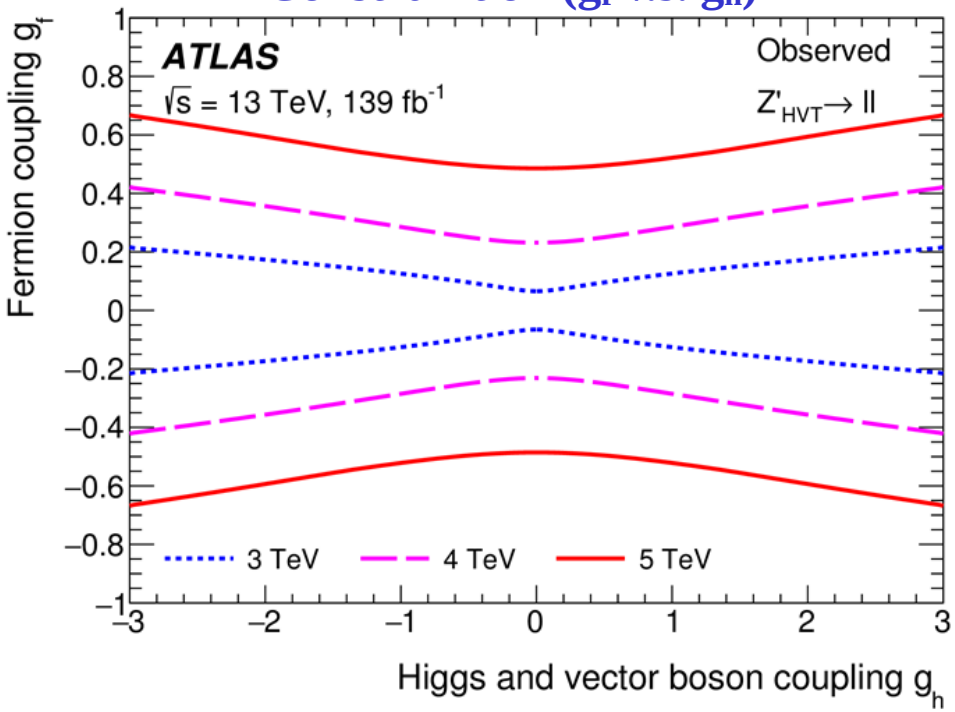
Coupling constraint in HVT (Z')

The constraint on couplings was studied, based on HVT model.

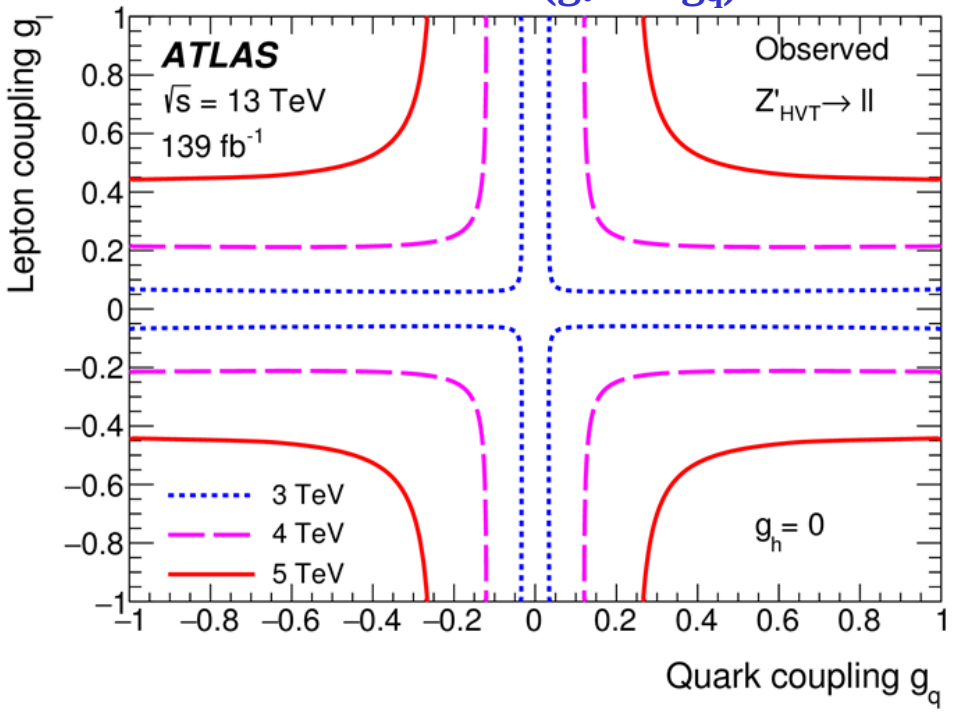
- (g_f, g_h) with $g_f = g_\ell = g_q$
- (g_ℓ, g_q) with $g_h = 0$

$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -\boxed{g_q}\mathcal{W}_\mu^a \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - \boxed{g_\ell}\mathcal{W}_\mu^a \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - \boxed{g_H}\left(\mathcal{W}_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.}\right)$$

Constraint on (g_f v.s. g_h)



Constraint on (g_ℓ v.s. g_q)

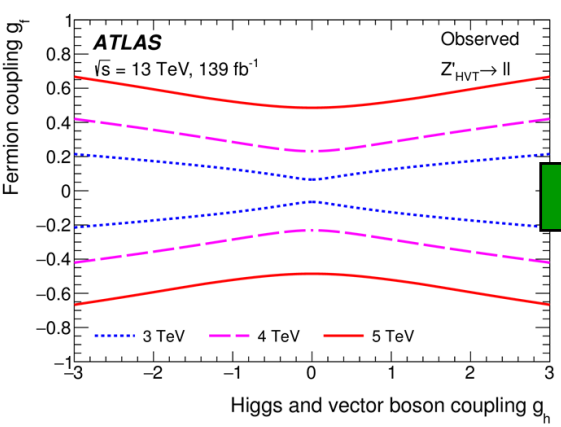


Comparison with combination analysis (1)

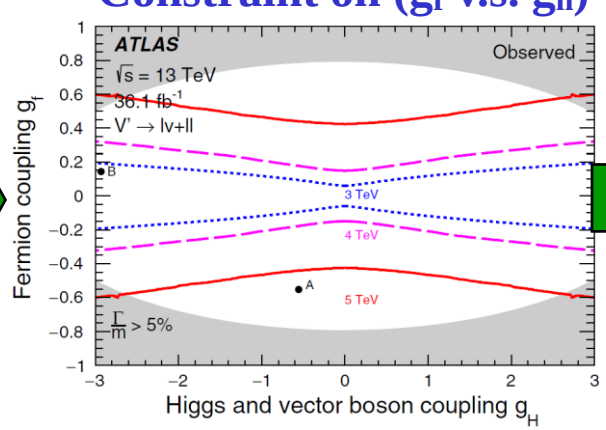
- The constraint on HVT couplings was studied by using 36.1 fb^{-1}, combining single/two charged lepton final states and di-boson final states. [arXiv:1808.02380]
- The combination with 36.1 fb^{-1} gives stronger constraint than Z'→ℓℓ only result with 139 fb^{-1}.
  - W'→ℓν result gives the strongest constraint.

Addition of ℓν results with 139 fb^{-1} and a further combination will provide the strongest limit on the couplings.

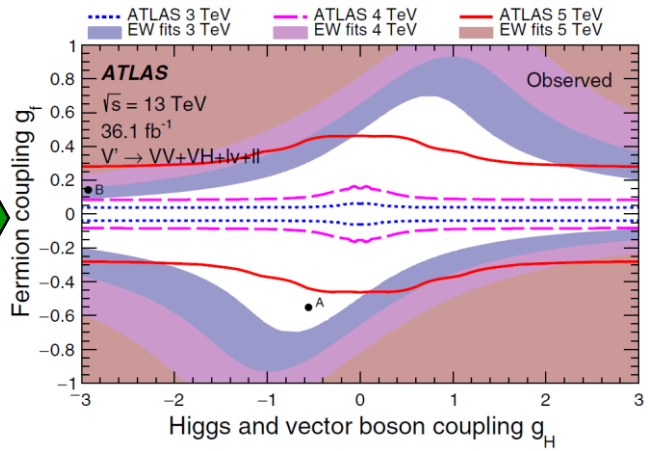
Constraint on (g_f v.s. g_h)



Z'→ℓℓ only (139 fb^{-1})



ℓν/ℓℓ comb. (36.1 fb^{-1})



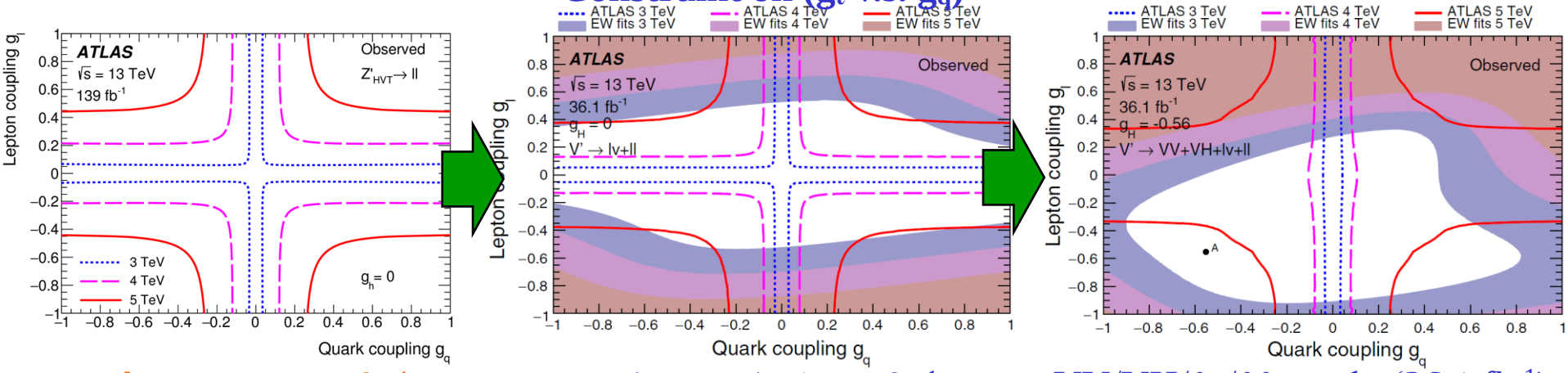
VV/VH/ℓν/ℓℓ comb. (36.1 fb^{-1})

Comparison with combination analysis (2)

- The constraint on HVT couplings was studied by using 36.1 fb^{-1}, combining single/two charged lepton final states and di-boson final states. [arXiv:1808.02380]
- The combination with 36.1 fb^{-1} gives stronger constraint than Z'→ℓℓ only result with 139 fb^{-1}.
  - W' result gives the strongest constraint.

The combination analysis with a full Run2 dataset (139 fb^{-1}) is the next important step.

Constraint on (g_ℓ v.s. g_q)



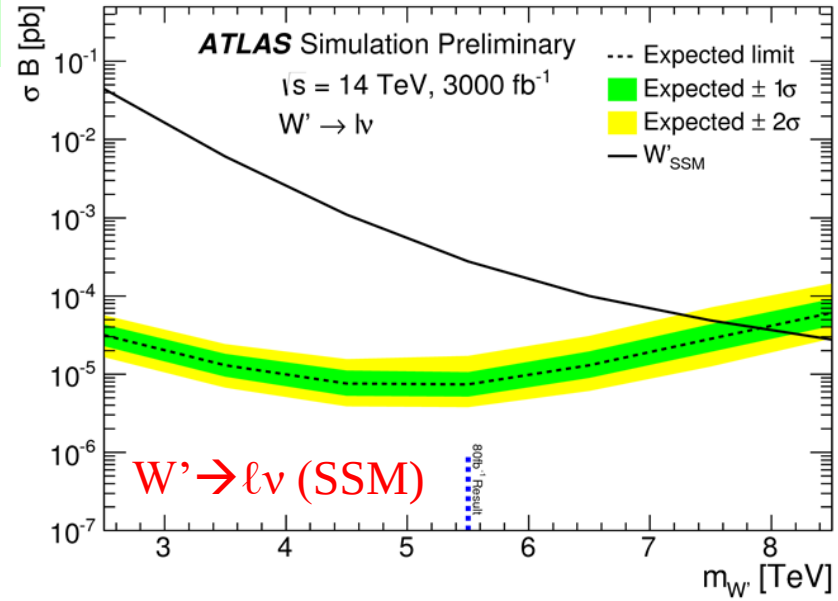
Z'→ℓℓ only (139 fb^{-1}) | ℓν/ℓℓ comb. (36.1 fb^{-1}) | VV/VH/ℓν/ℓℓ comb. (36.1 fb^{-1})

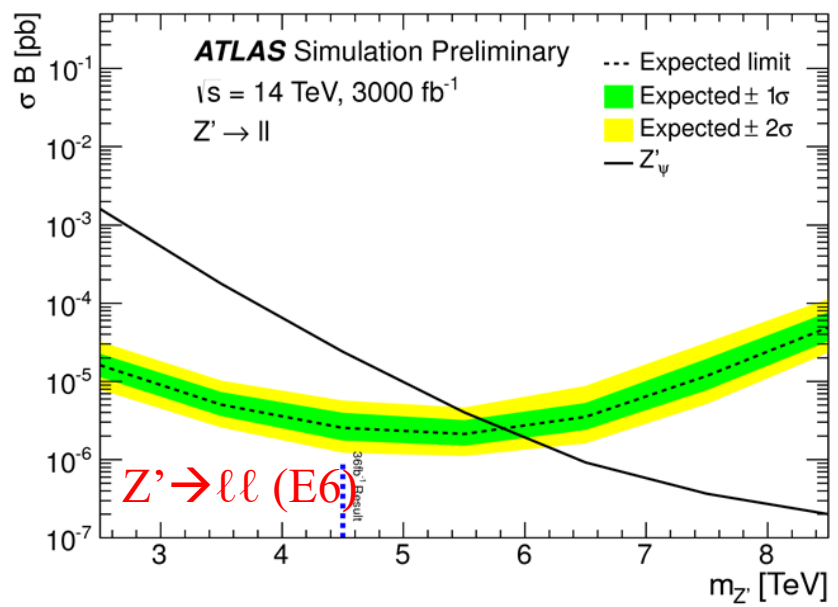
Prospect at HL-LHC

- LHC will be upgraded to High Luminosity LHC (HL-LHC) in ~2026.
- The sensitivity to W'/Z' masses will be improved drastically.
  - 1.5~2 TeV improvements at 3000 fb^{-1} from Run2 with 139 fb^{-1}.

The resonance searches with lepton final states are important also at HL-LHC!

Expected upper limits on σ x B @ 3000 fb^{-1}





Decay	Exclusion [TeV]	Discovery [TeV]
$W'_{\rm SSM} \to e\nu$	7.6	7.5
$W'_{\rm SSM} \to \mu\nu$	7.3	7.1
$W'_{\rm SSM} \to \ell\nu$	7.9	7.7

	$\sqrt{s} = 13$ TeV		$\sqrt{s} = 14$ TeV		$\sqrt{s} = 15$ TeV	
Decay	Exclusion	Discovery	Exclusion	Discovery	Exclusion	Discovery
$Z'_{\rm SSM} \to ee$	6.0 TeV	5.9 TeV	6.4 TeV	6.3 TeV	6.7 TeV	6.6 TeV
$Z'_{\rm SSM} \to \mu\mu$	5.5 TeV	5.4 TeV	5.8 TeV	5.7 TeV	6.0 TeV	5.9 TeV
$Z'_{\rm SSM} \to \ell\ell$	6.1 TeV	6.1 TeV	6.5 TeV	6.4 TeV	6.7 TeV	6.7 TeV
$Z'_{\psi} \to ee$	5.3 TeV	5.3 TeV	5.7 TeV	5.6 TeV	6.1 TeV	6.0 TeV
$Z'_{\psi} \to \mu\mu$	4.9 TeV	4.6 TeV	5.2 TeV	5.0 TeV	5.5 TeV	5.2 TeV
$Z'_{\psi} \to \ell\ell$	5.4 TeV	5.4 TeV	5.8 TeV	5.7 TeV	6.1 TeV	6.1 TeV

Summary and Conclusions

- New resonance searches are powerful probes to explore physics beyond the Standard Model.
- Searches for high mass resonance with lepton final states have been performed in the ATLAS experiment by using a full Run2 dataset (139 fb^{-1}).
- No excess from the SM expectation was observed.
- The cross-section and mass limits were improved, compared to the previous analysis results with 36.1 fb^{-1}.
- The combination analysis with a full Run2 dataset is the next important step.
- The resonance searches with lepton final states are important also at HL-LHC.

Backup

Estimation of multi-jet backgrounds (W')

The matrix method is used to estimate backgrounds from fake leptons.

Measurable quantities

- T: passes "signal" selection
- L: passes "loose" selection

Truth quantities

- R: real leptons
- L: fake leptons

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} r & f \\ (1-r) & (1-f) \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix}$$

(for W' analysis)

- r: fraction of real leptons passing signal selection (evaluated with MC W sample)
- f: fraction of fake leptons passing signal selection (evaluated with jet enriched data sample)

$$N_T^{\text{Multijet}} = f\,N_F = \frac{f}{r-f}\left(r\,(N_L + N_T) - N_T \right)$$

Systematic uncertainties (W')

Source	Electron channel		Muon channel	
	Background m_T = 2 (6) TeV	Signal m_T = 2 (6) TeV	Background m_T = 2 (6) TeV	Signal 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%)

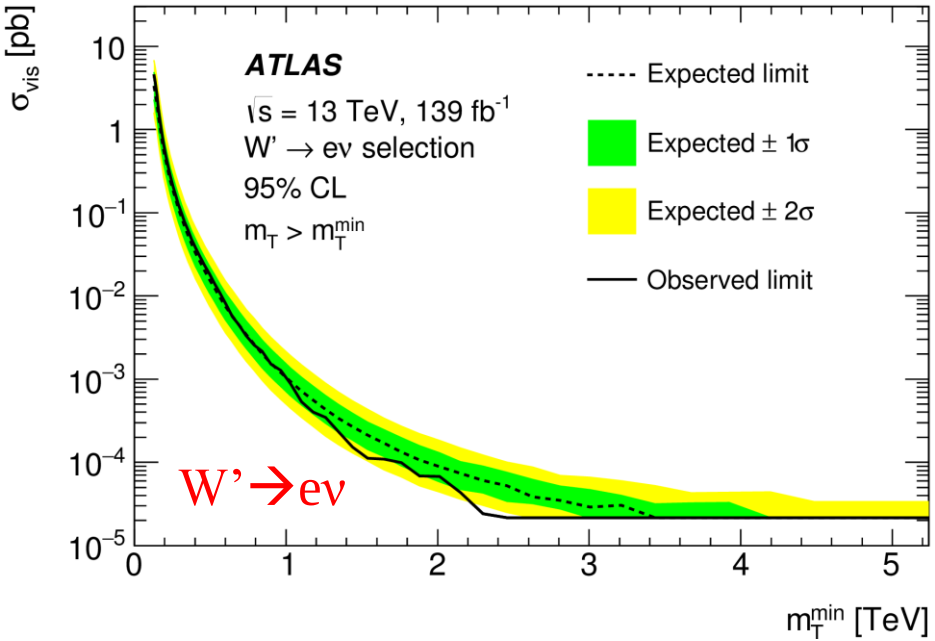
Systematic uncertainties (Z')

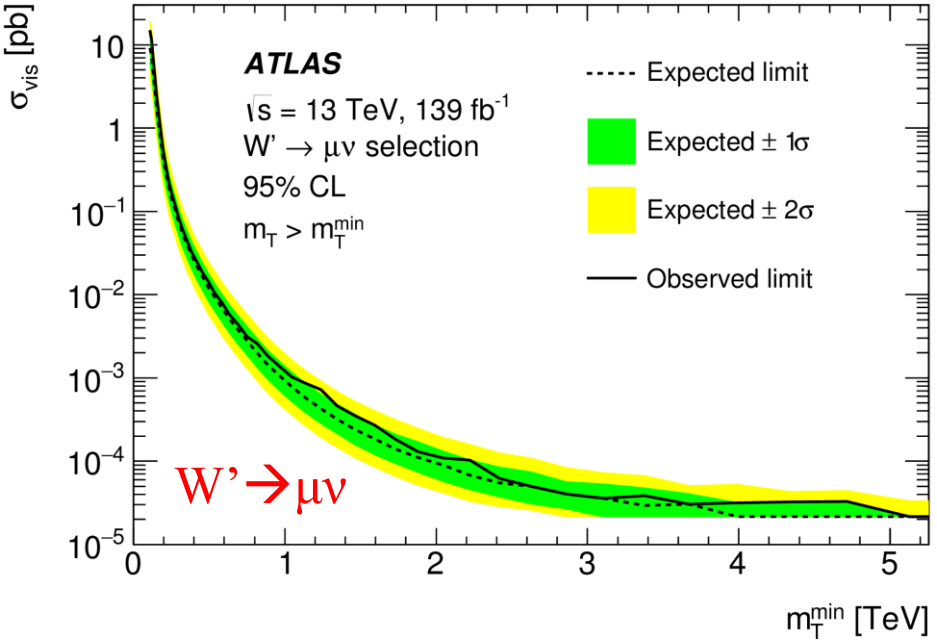
Uncertainty source for m_X [GeV]	Dielectron 300	Dielectron 5000	Dimuon 300	Dimuon 5000
Spurious signal	± 12.5 (12.0)	± 0.1 (1.0)	± 11.7 (11.0)	± 2.1 (2.2)
Lepton identification	± 1.6 (1.6)	± 5.6 (5.6)	± 1.8 (1.8)	$^{+25}_{-20}$ $\left(^{+25}_{-20}\right)$
Isolation	± 0.3 (0.3)	± 1.1 (1.1)	± 0.4 (0.4)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

Model-independent cross-section limit (W')

- The model-independent upper limits of the cross-section were also provided by varying the minimum m_T value (m_T^{min}).

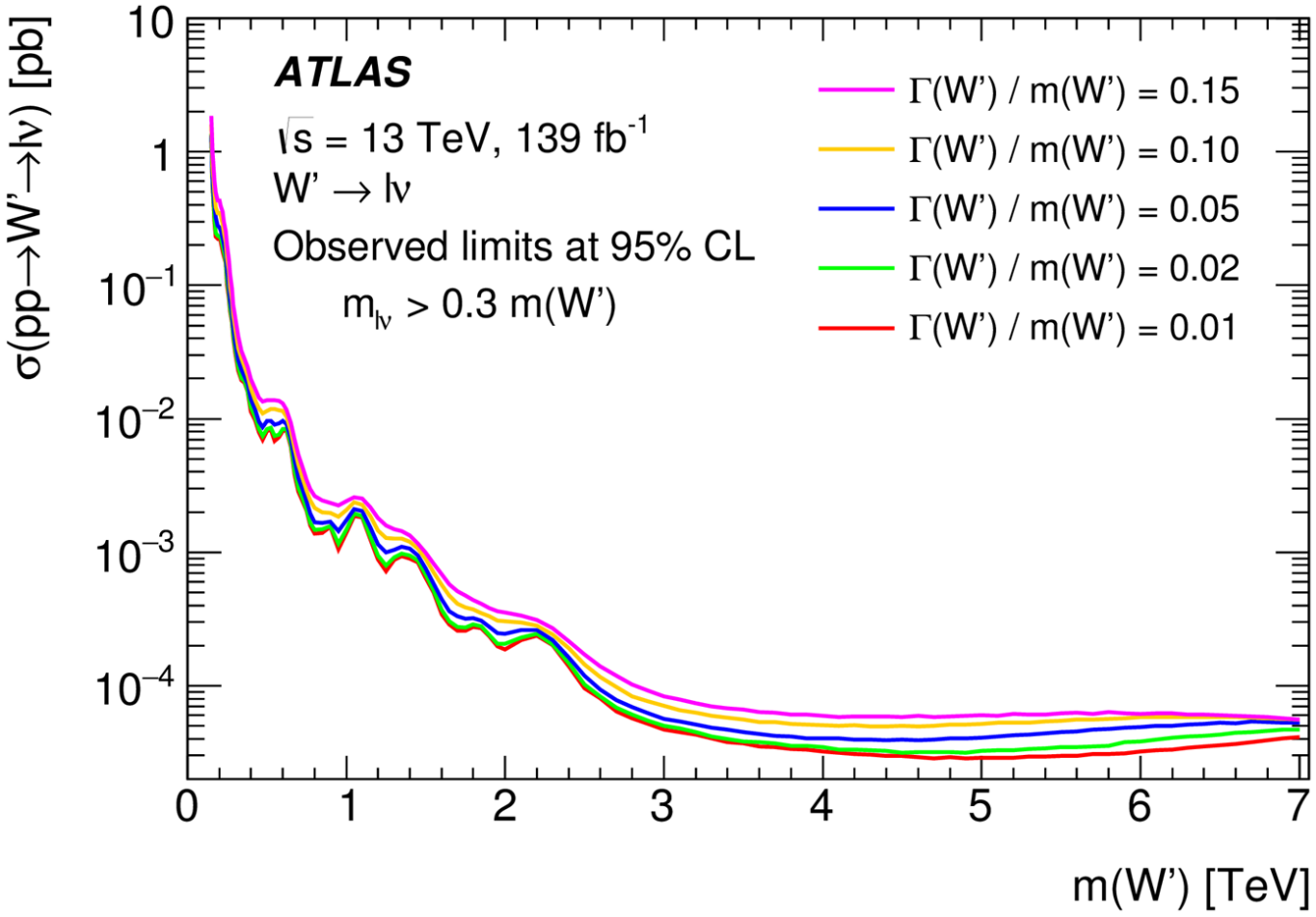
95% CL cross-section limit v.s. m_T threshold





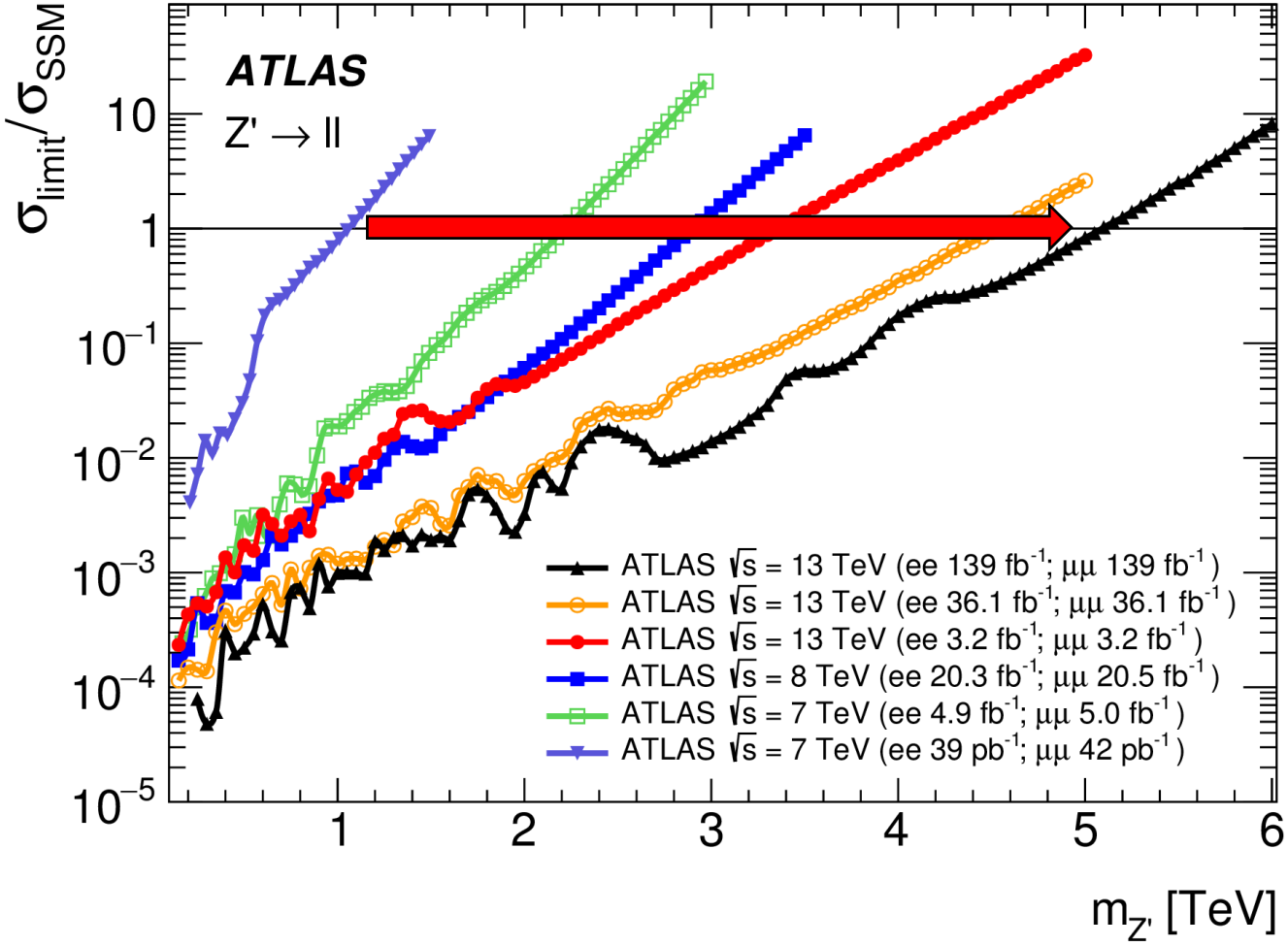
Cross-section limit with different Γ (W')

- The variation of cross-section limit was checked with different W' mass width.

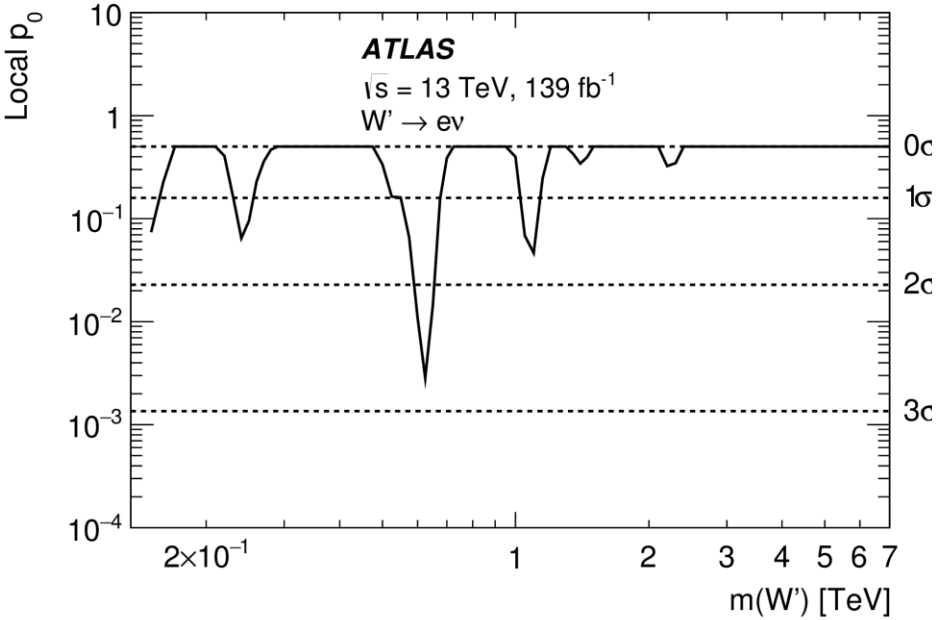


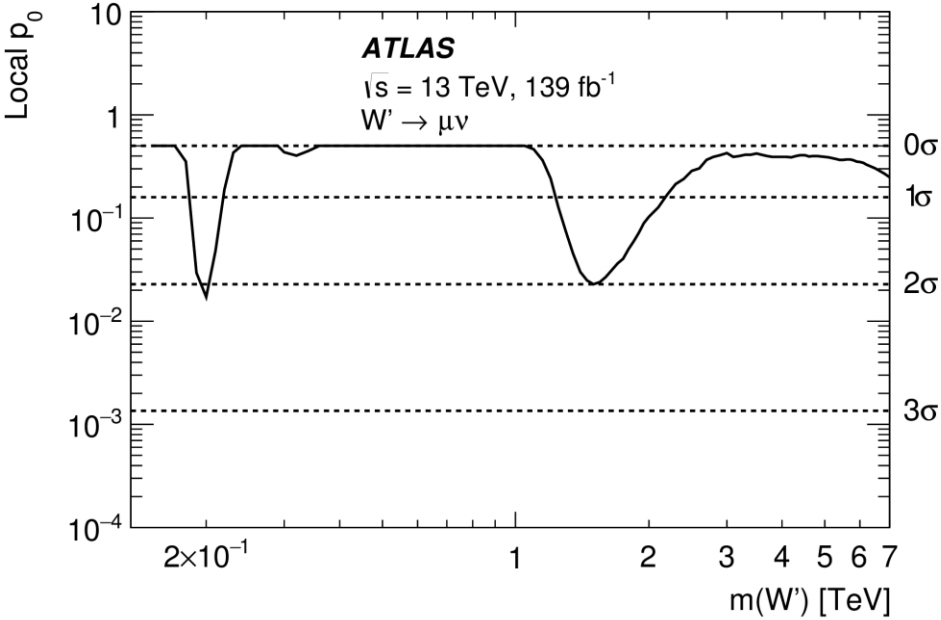
Improvement of cross-section limit (Z')

The cross-section limits were improved by higher pp colliding energy at LHC and larger statistics.

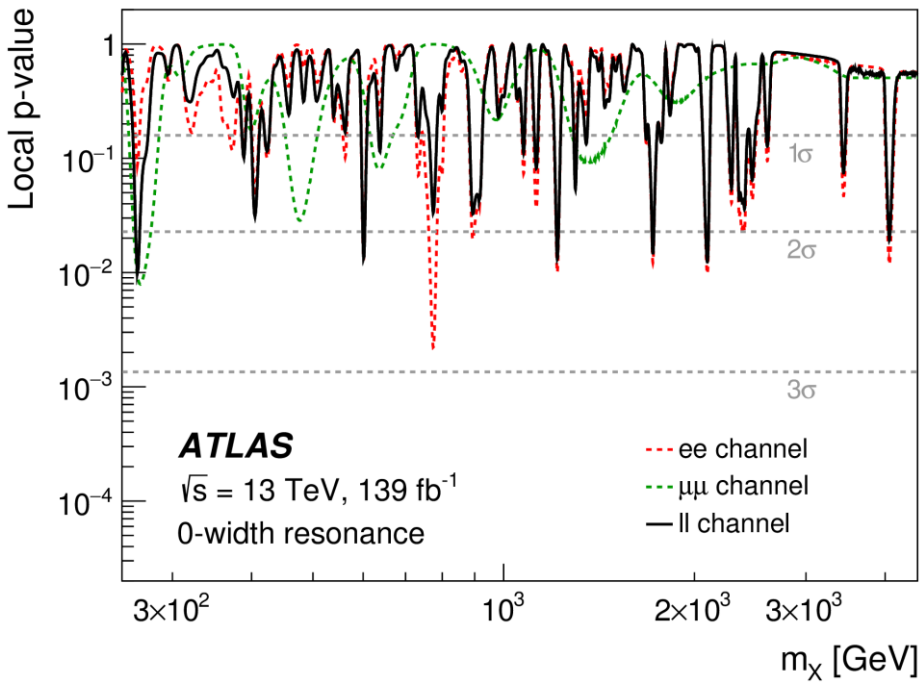


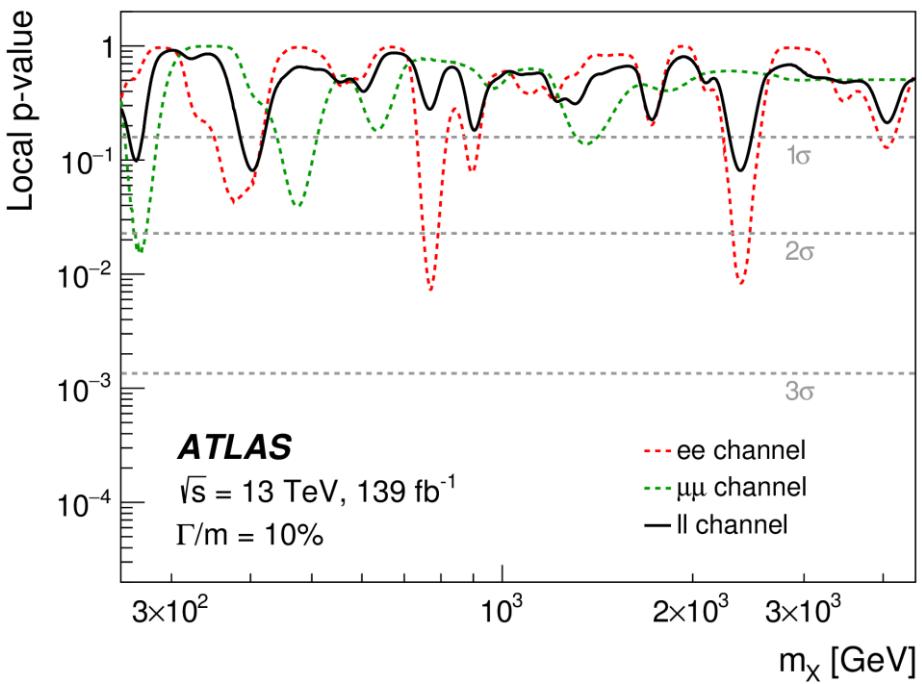
Local p-value (W')



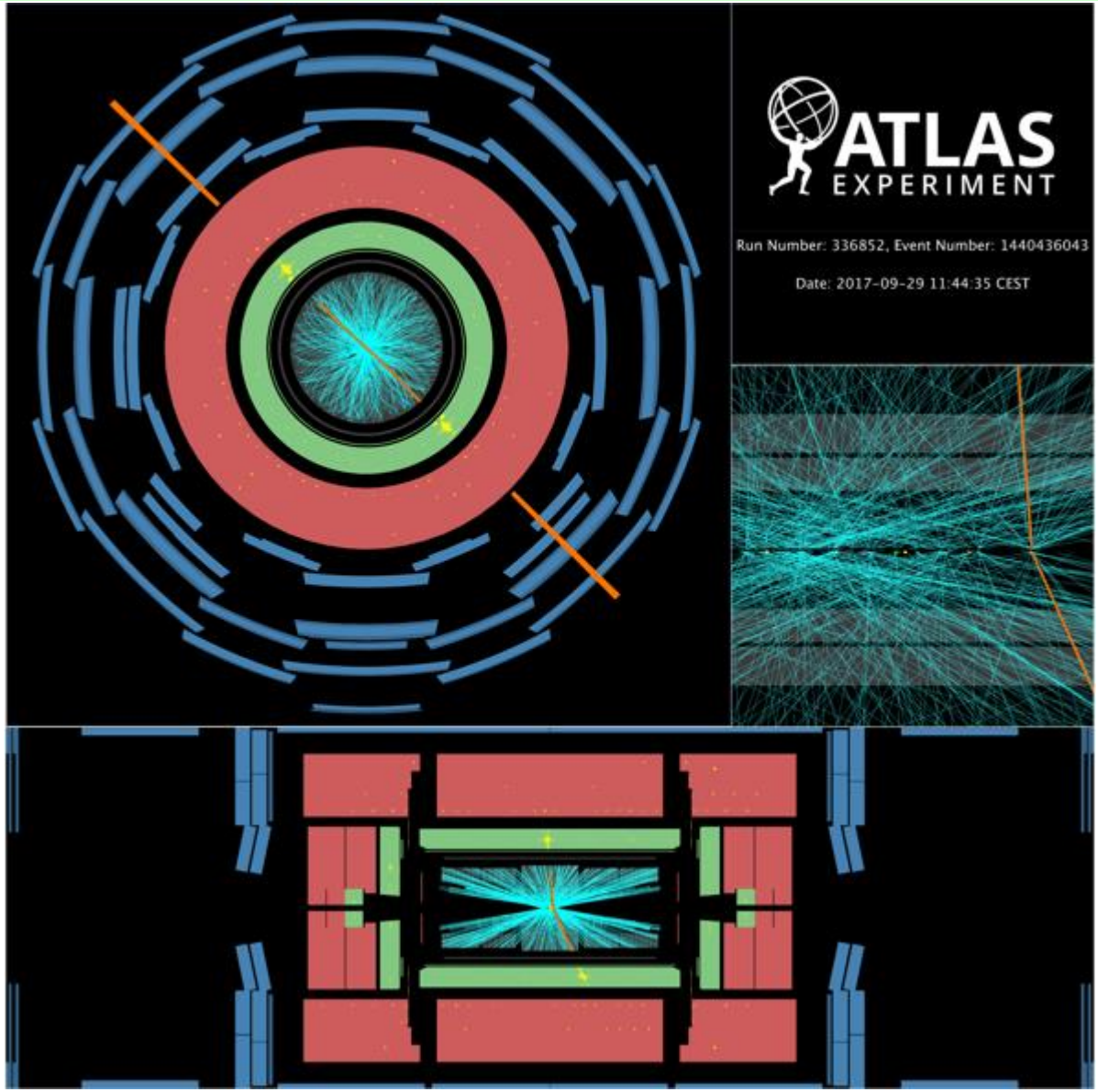


Local p-value with different Γ (Z')





Di-electron candidate with m_{ee} = 4.06 TeV



Di-muon candidate with m_{ee} = 2.75 TeV