

# Search for Exotics (and Higgs) Physics beyond the Standard Model with the ATLAS Detector

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on behalf of the ATLAS Collaboration



University  
of Victoria

# Plan of this talk

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- LHC and ATLAS detector.
- Signature based search strategy.
- Dileptons/Multi-leptons signature
- Lepton(s) + jet(s) signature
- Dijets/Multi-jets signature
- Top quarks signature
- Vector bosons signature
- Other signatures
- Conclusions.

# Other topics

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- BSM Higgs:
  - “Beyond the Standard Model Higgs Physics Using the ATLAS Detector” (Guillermo Hamity).
- Dark Matter:
  - “Searches for Dark Matter with the ATLAS Detector” (Ketevi Assamagan).
- Supersymmetry (SUSY):
  - “SUSY Searches in the ATLAS Detector” (Lawrence Lee JR).

# LHC

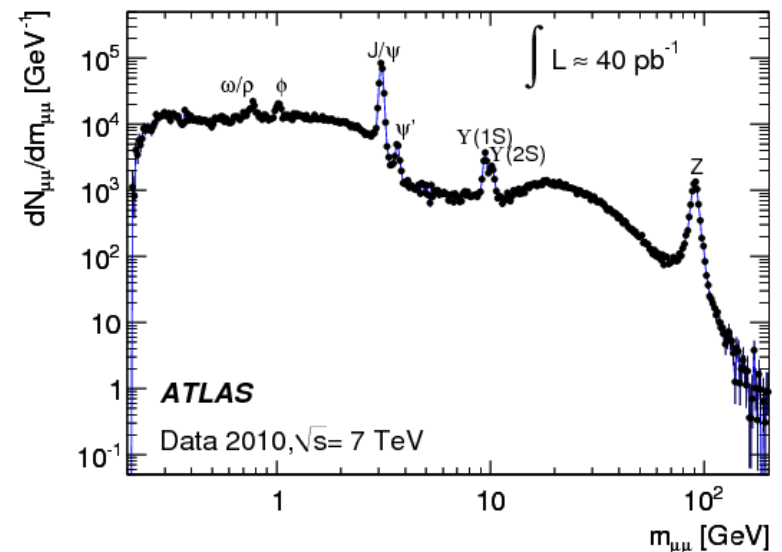
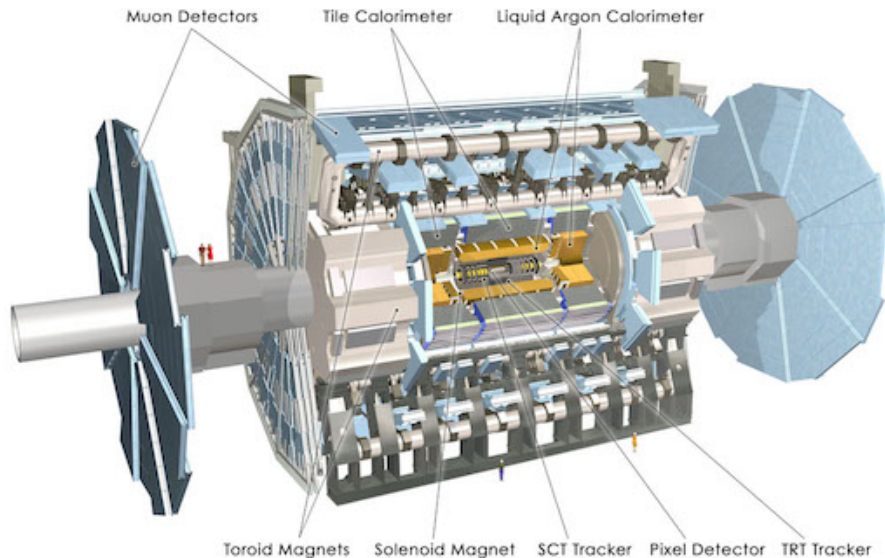
- Large Hadron Collider (LHC)
  - Collide two protons (pp-collision).
  - Center of mass energy:
    - Run1: 2011, 7 TeV,  $\sim 5 \text{ fb}^{-1}$ ; 2012, 8 TeV,  $\sim 20 \text{ fb}^{-1}$
    - Run2 (2015  $\sim$ ): 13 TeV or 14 TeV



- Only recent results with 8TeV data are presented in this talk.
- Selection is based on my preference.

# ATLAS Detector

- From inside to outside
  - Inner tracker: reconstruct charged tracks.
  - Calorimeter: detect particle energies.
    - Electromagnetic calorimeter: electrons and photons
    - Hadronic calorimeter: charged and neutral hadrons.
  - Muon detector: detect muons.



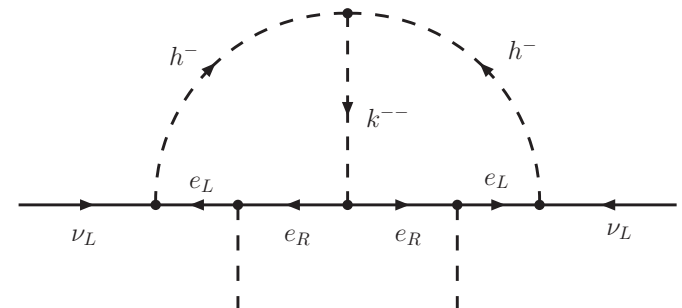
# Need for BSM physics

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- There are many problems with the Standard Model (SM).
  - Hierarchy Problem
  - Neutrino mass term
  - Dark matter
  - Gravity
  - ...
- Possible solution is a Beyond the Standard Model (BSM) physics?
  - Supersymmetry?
  - Extra dimensions?
  - Higher symmetry/Unified model?
  - Seesaw mechanism?
  - ...

# Signature based search (1)

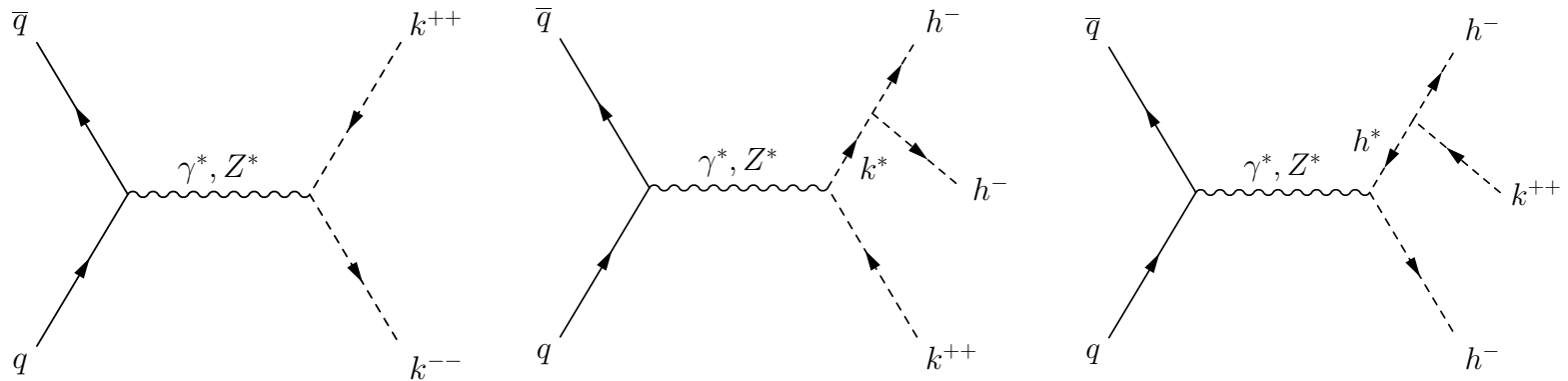
- To search for a new physics, experimentalists look for **particles in final states** produced by the new physics.
- An example: Zee-Babu model
  - Physics point of view:
    - A model to generate small neutrino mass with a two loop diagram.
    - Introduce **two new scalar particles**:  $h^+$ ,  $k^{++}$
    - Lepton flavor violation is also introduced.
  - Experimental point of view:
    - Look for the new particles.
    - **How they are produced** in pp-collisions?
    - **How they decay**?



ArXiv:0711.0483

# Signature based search (2)

- Production



- The new particle  $k$  is either pair produced or produced along with  $h$ .
- Decay
  - $k^{++} \rightarrow e^+e^+, e^+\mu^+, \mu^+\mu^+, \text{ etc.}$
- Look for **same-sign lepton pair(s)** in final states.

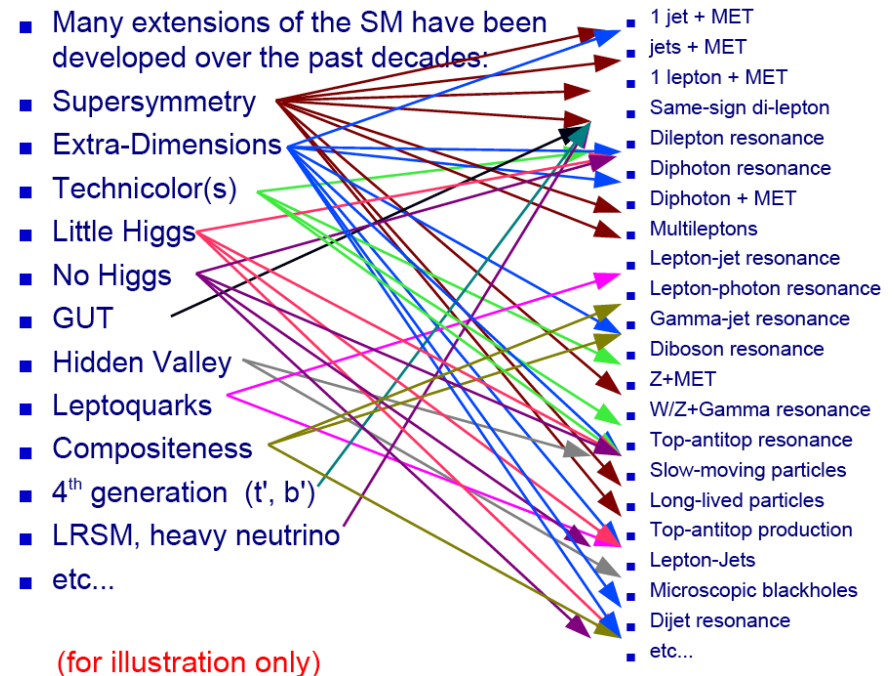


# Signature vs Physics models

- Many new physics models can be searched by same signature.
  - (Example) Same-sign dilepton signature:
    - SUSY, Universal Extra Dimensions, Left-right symmetric models, neutrino mass models, Doubly charged Higgs, Vector-like quarks.

- A new model can be probed by many signatures.

- (Example) Type III seesaw model:
  - 2 leptons + 2 jets
  - 3 leptons
  - 4 leptons



# Dileptons/Multi-leptons

More details on  
[Blue](#) analysis

- Dileptons
  - Opposite-sign same flavor
    - [High mass resonance search](#) (arXiv:1405.4123, PRD90,052005(2014))
      - Heavy gauge boson  $Z'$ , Excited boson  $Z^*$ , Spin-2 graviton, Quantum Black Holes, Technicolor
    - Non-resonant dileptons (arXiv:1407.2410, EPJC)
      - Contact Interaction (llqq), Large Extra Dimensions
  - Opposite-sign mixed flavor
    - [Lepton Flavor Violation:  \$Z \rightarrow e \mu\$](#)  (arXiv:1408.5774, PRD90,072010(2014))
  - [Same-sign dileptons](#) (arXiv:1412.0237, JHEP)
    - SUSY, Extra dimension, Neutrino mass models, Doubly-charged Higgs
- [3 or more leptons](#) (arXiv:1411.2921)
  - SUSY, Neutrino mass models, Doubly-charged Higgs

# Dileptons/Multi-leptons (2)

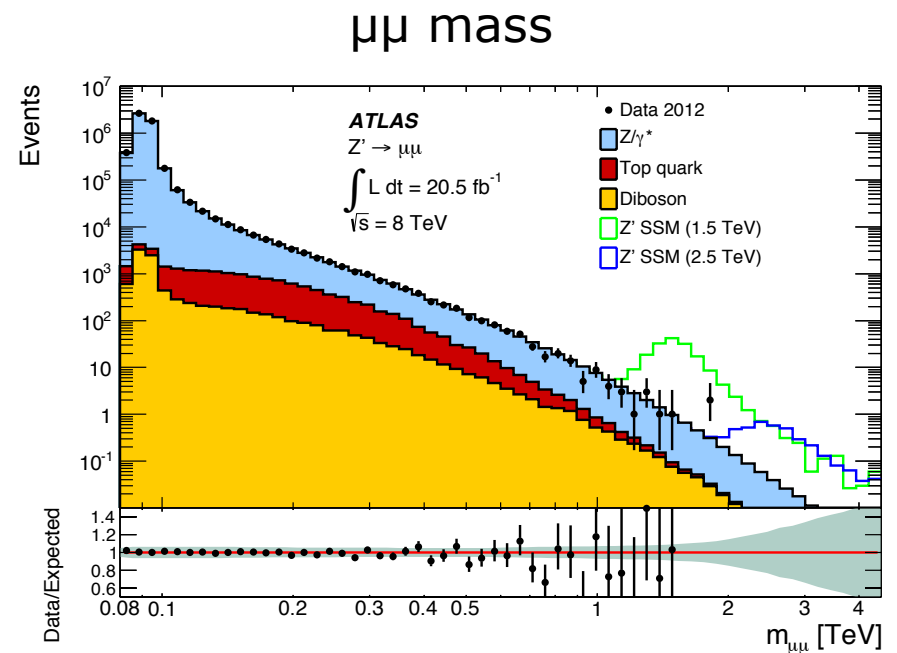
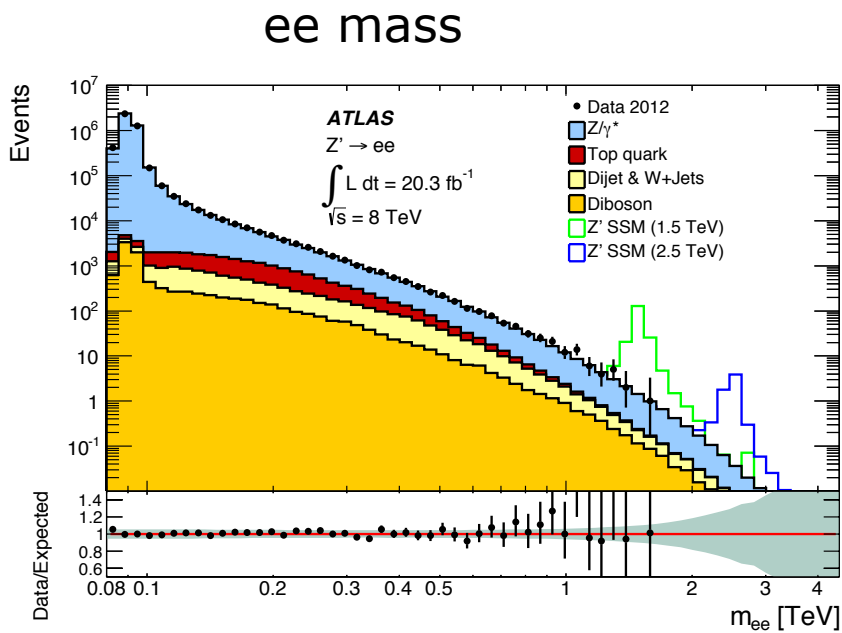
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- Diphoton resonance (arXiv:1210.8389, NJP15,242(2013))
  - KK Graviton (Extra dimensions)

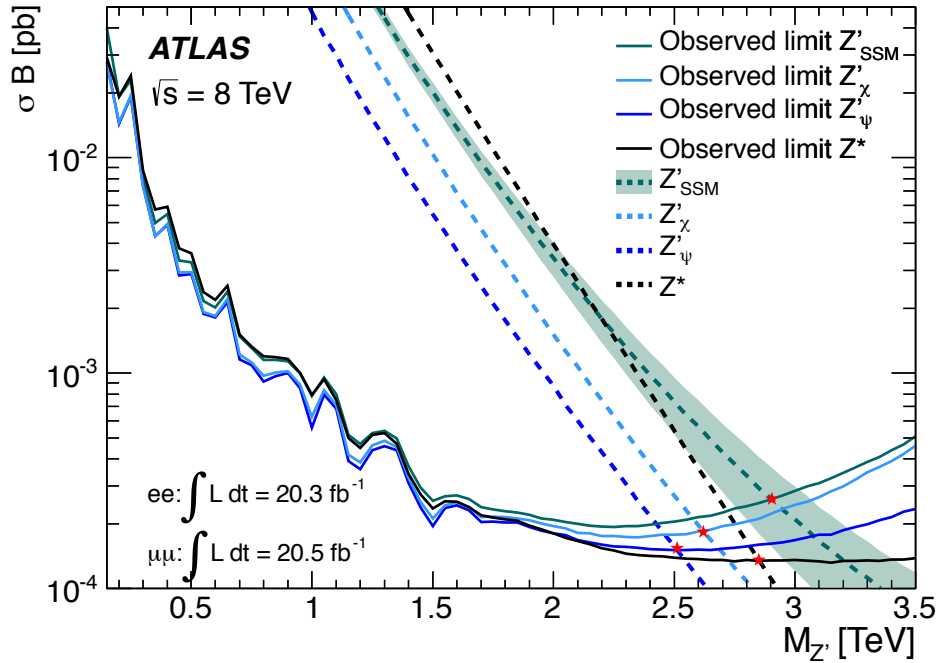
# Dilepton resonance (arXiv:1405.4123, PRD90,052005(2014))

- $Z'$  and  $Z^* \rightarrow l^+l^-$

- Two isolated opposite-charge same-flavor leptons.
- Electron: leading  $E_T > 40\text{GeV}$ , subleading  $E_T > 30\text{GeV}$
- Muon  $p_T > 25\text{GeV}$



# Dilepton Resonance (2)



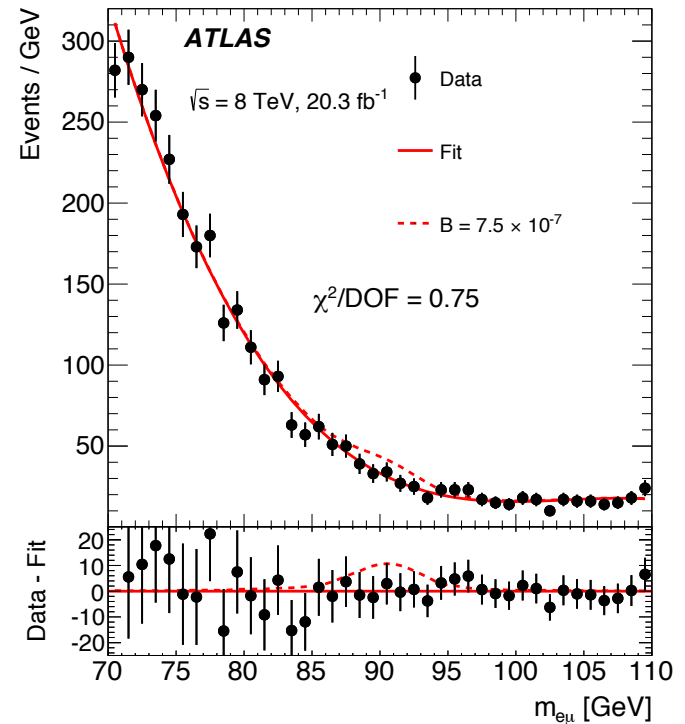
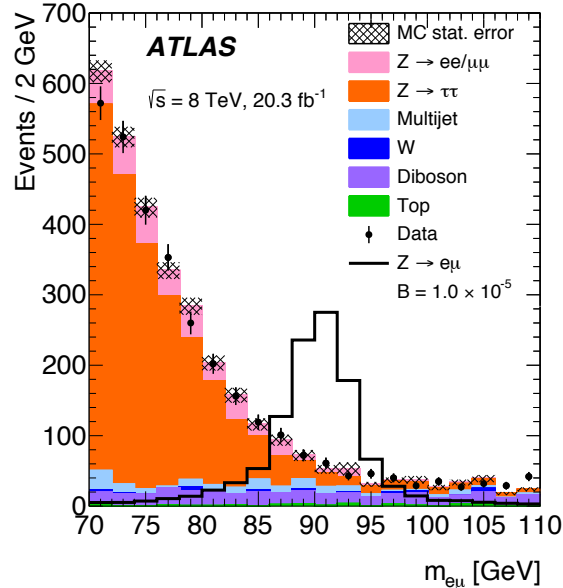
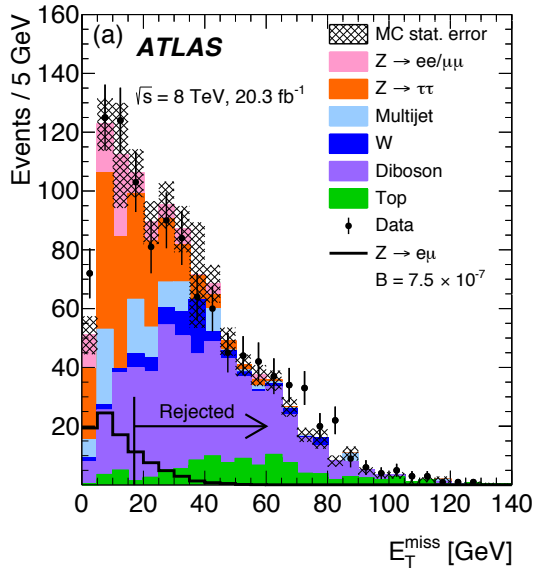
Mass limits

Model	Width [%]	Observed Limit [TeV]	Expected Limit [TeV]
$Z'_{SSM}$	3.0	2.90	2.87
$Z'_{\chi}$	1.2	2.62	2.60
$Z'_{\psi}$	0.5	2.51	2.46
$Z^*$	3.4	2.85	2.82

# LFV $Z \rightarrow e \mu$ (arXiv:1408.5774, PRD90,072010(2014))

- Lepton Flavor Violation (LFV) decay  $Z \rightarrow e \mu$ .

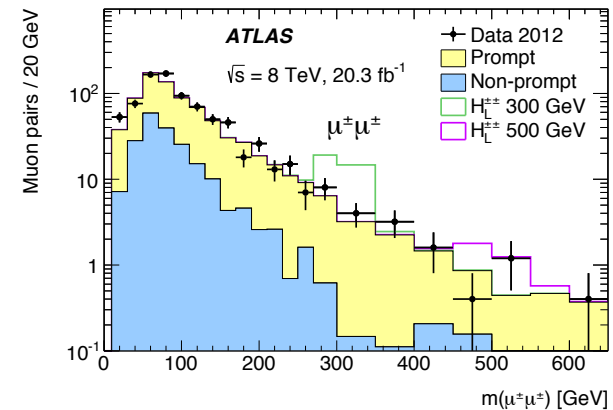
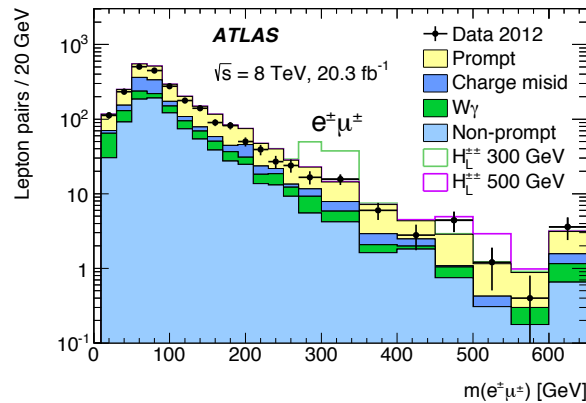
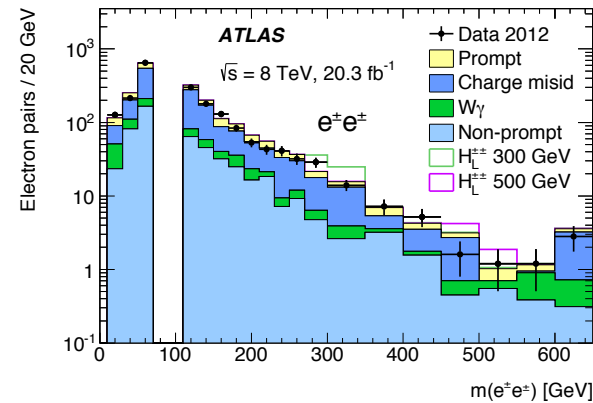
Isolated  $e$  with  $E_T > 25 \text{ GeV}$   
 Isolated  $\mu$  with  $p_T > 25 \text{ GeV}$   
 Missing  $E_T < 15 \text{ GeV}$



$$B(Z \rightarrow e \mu) < 7.5 \times 10^{-7}$$

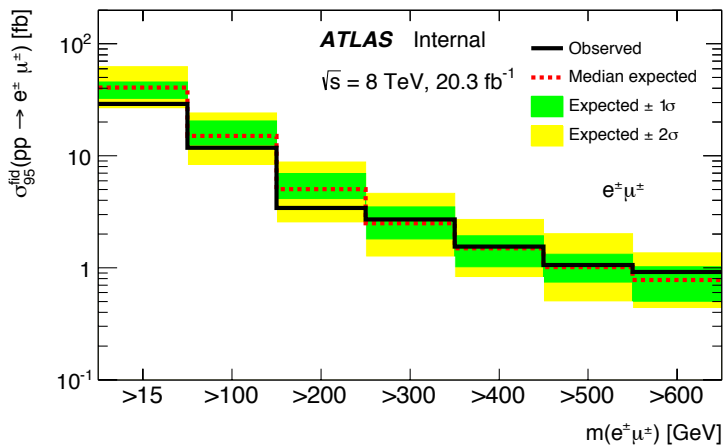
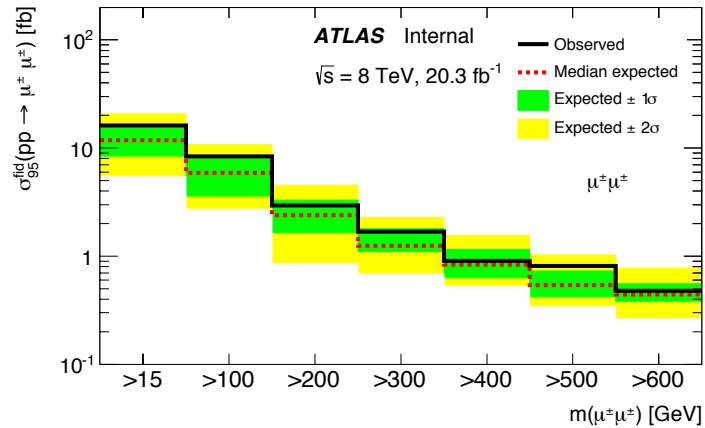
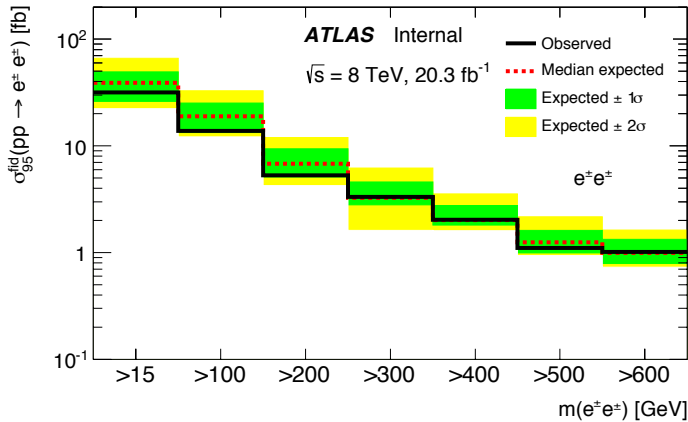
# Same-sign dilepton (arXiv:1412.0237, JHEP)

- Two isolated same-sign leptons:
  - Electron leading  $p_T > 12 \text{ GeV}$ , others  $p_T > 6 \text{ GeV}$
  - Muon leading  $p_T > 18 \text{ GeV}$ , others  $p_T > 12 \text{ GeV}$
- Z-veto



# Same-sign dilepton (2)

- Fiducial cross section limits



## Doubly-charged Higgs mass limits:

Signal	95% CL lower limit [GeV]					
	$e^\pm e^\pm$		$e^\pm \mu^\pm$		$\mu^\pm \mu^\pm$	
	Expected	Observed	Expected	Observed	Expected	Observed
$H_L^{\pm\pm}$	$553 \pm 30$	551	$487 \pm 41$	468	$543 \pm 40$	516
$H_R^{\pm\pm}$	$425 \pm 30$	374	$396 \pm 34$	402	$435 \pm 33$	438



# 3 or more charged leptons (arXiv:1411.2921)

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- Event selection

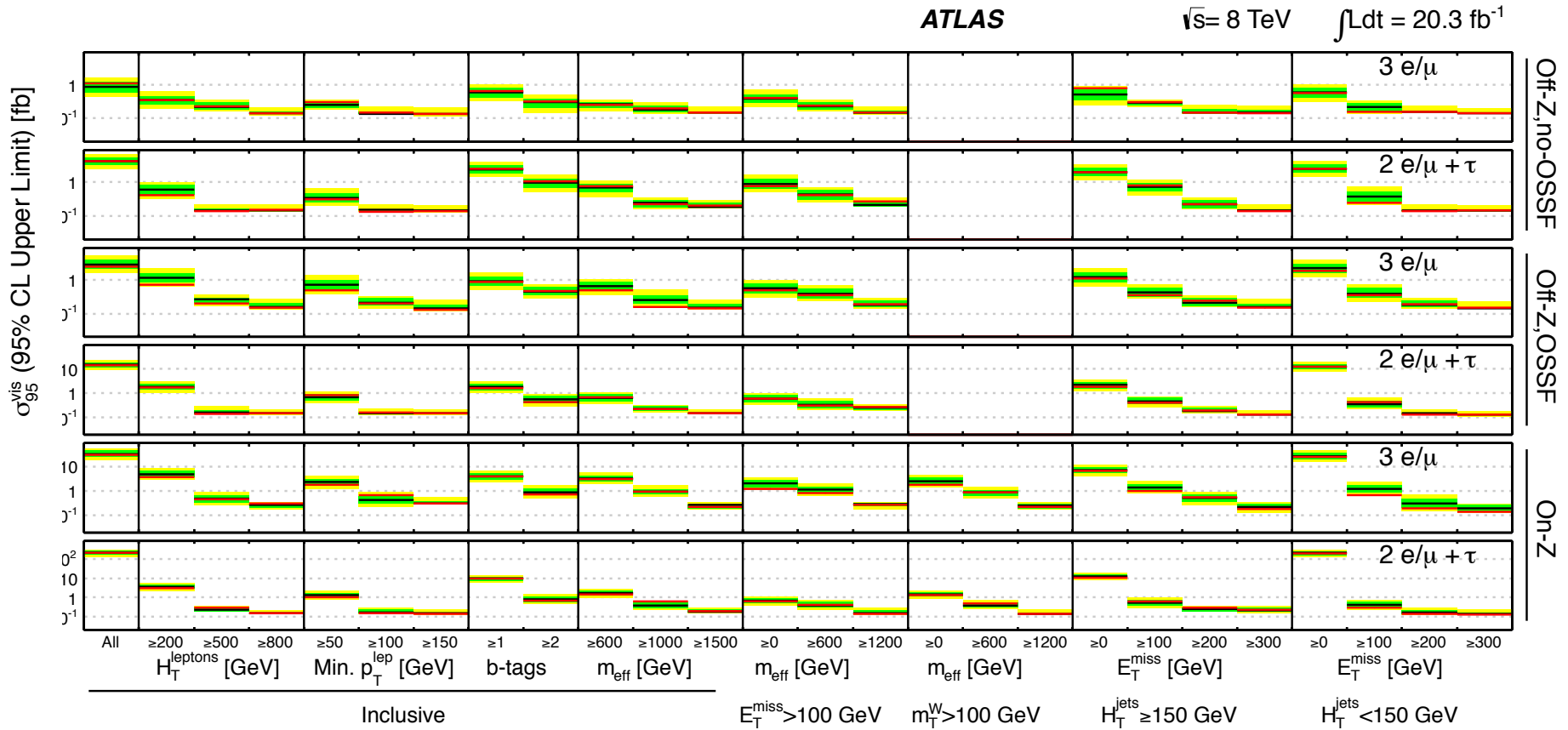
- 3 or more isolated leptons
- Leading lepton: electron or muon with  $p_T > 26\text{GeV}$
- Second lepton: electron or muon with  $p_T > 15\text{GeV}$
- Third lepton: electron or muon with  $p_T > 15\text{GeV}$   
or tau with  $p_T > 20\text{GeV}$

- This is a generic search and include multiple Signal Regions depending on

- On-Z, Off-Z
- MET = missing transverse energy
- $H_T$  = scalar sum of  $p_T$
- $m_{\text{eff}}$  = scalar sum of missing  $E_T$ , jet  $H_T$  and lepton  $p_T$

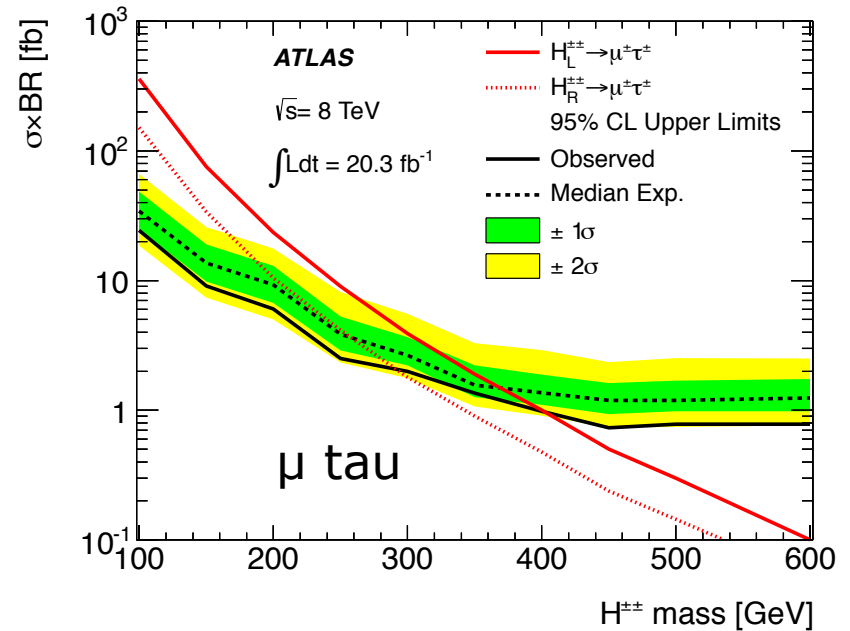
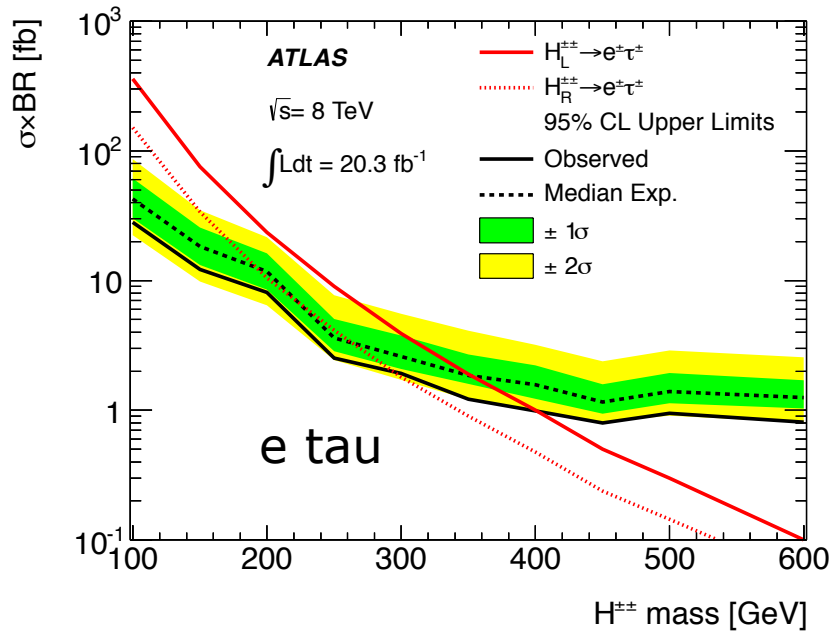
# 3 or more leptons (2)

- Cross section limits in various signal regions:



# 3 or more leptons (3)

- Doubly-charged Higgs in **tau decay mode**:



Mass limit :  $H_L^{++} > 400 \text{ GeV}$

# Lepton + X

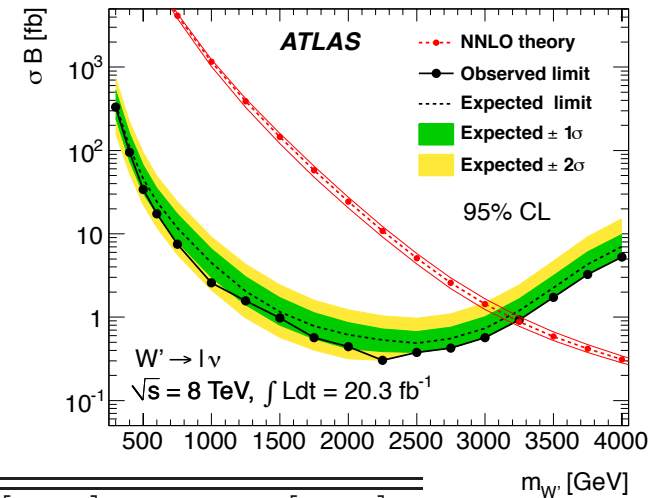
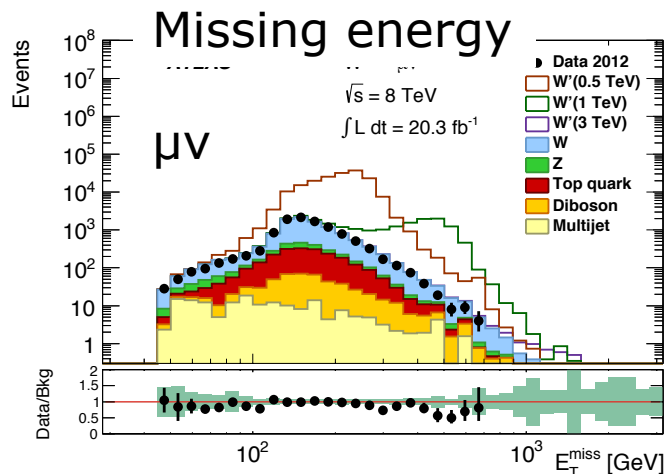
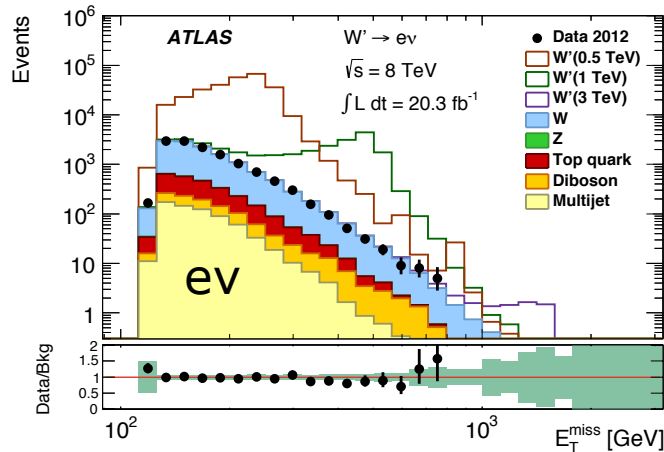
More details on  
Blue analysis

- Lepton + X general search (ATLAS-CONF-2014-006)
  - Events with isolated electrons, photons, muons, jets.
- **Lepton + MET (neutrino)** (arXiv:1407.7494, JHEP09(2014)037)
  - Heavy gauge boson  $W'$ , Excited boson  $W^*$ .
- Lepton + jet
  - Scalar Leptoquarks:
    - 1st generation (arXiv:1112.4828, PLB709(2012)158-176)
    - 2nd generation (arXiv:1203.3172, EPJ C72(2012)2151)
    - 3rd generation (arXiv:1303.0526, JHEP06(2013)033)
  - Microscopic Black Holes (arXiv:1405.4254, JHEP08(2014)103)
  - Quantum Black Holes (arXiv:1311.2006, PRL112,091804(2014))
  - Excited Leptons (arXiv:1308.1364, NJP15(2013)093011)

# L + Missing energy (arXiv:1407.7494, JHEP09(2014)037)

## W' and W\* → l + ν

- One isolated electron with  $E_T > 125 \text{ GeV} + \text{MET} > 125 \text{ GeV}$
- Or one muon with  $p_T > 45 \text{ GeV} + \text{MET} > 45 \text{ GeV}$
- No additional lepton with  $p_T > 20 \text{ GeV}$



## Mass limits

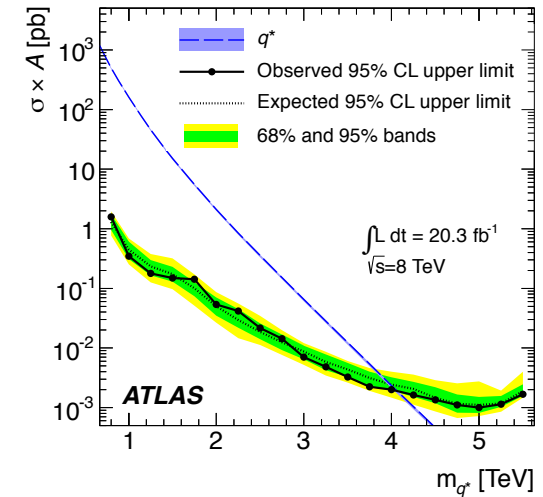
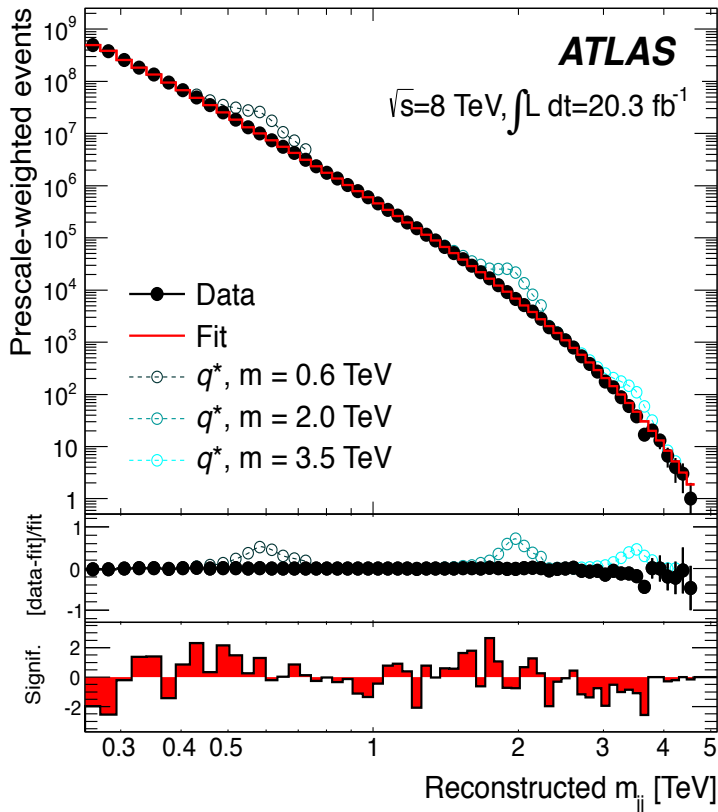
Decay	$m_{W'}$ [TeV]		$m_{W^*}$ [TeV]	
	Exp.	Obs.	Exp.	Obs.
$e\nu$	3.13	3.13	3.08	3.08
$\mu\nu$	2.97	2.97	2.83	2.83
Both	3.17	3.24	3.12	3.21

# Dijets/Multi jets

- **Dijet resonance** (arXiv:1407.1376, PRD)
  - Excited quarks, Color octet scalars, Heavy and excited W bosons, Quantum black holes,
- **Multi jets**
  - Resonant Higgs Pair Production (ATLAS-CONF-2014-005)
    - $X \rightarrow HH \rightarrow bbbb$
    - Two Higgs doublet models, KK graviton
- **Photon + jet** (arXiv:1309.3230, PLB728,562(2013))
  - Quantum Black Holes, Excited quarks
- **Dark matter search:**
  - “Searches for Dark Matter with the ATLAS Detector” (Ketevi Assamagan).

# Dijet resonance (arXiv:1407.1376, PRD)

- Two well measured jets with  $p_T > 50\text{GeV}$
- $m_{jj} > 250\text{GeV}$

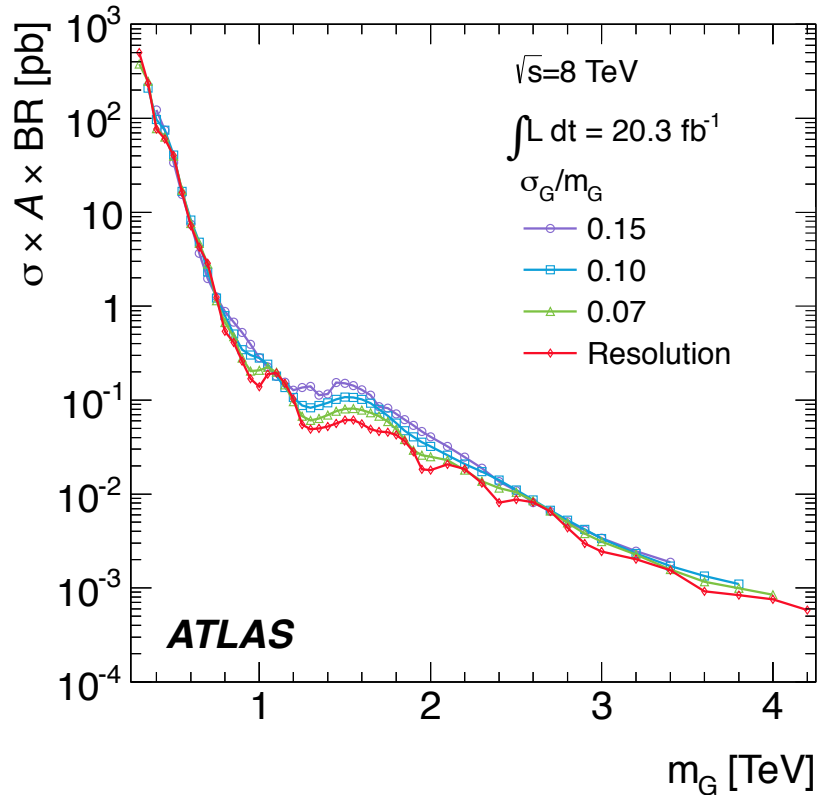


## Mass limits

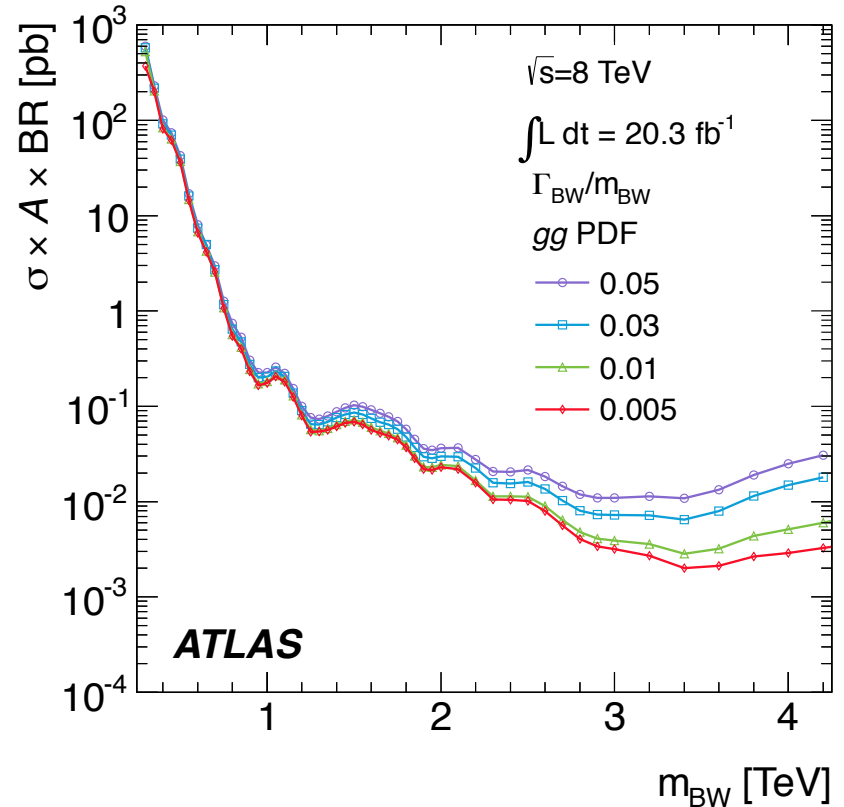
Model and Final State	95% CL Limits [TeV]	
	Expected	Observed
$q^* \rightarrow qq$	3.99	4.09
$s\bar{s} \rightarrow gg$	2.83	2.72
$W' \rightarrow q\bar{q}'$	2.51	2.45
Leptophobic $W^* \rightarrow q\bar{q}'$	1.93	1.75
Leptophilic $W^* \rightarrow q\bar{q}'$	1.67	1.66
QBH black holes ( $q$ and $g$ decays only)	5.82	5.82
BLACKMAX black holes (all decays)	5.75	5.75

# Dijet resonance (2)

## Gaussian resonance limits



## B-W narrow resonance limits





# Top quark final states

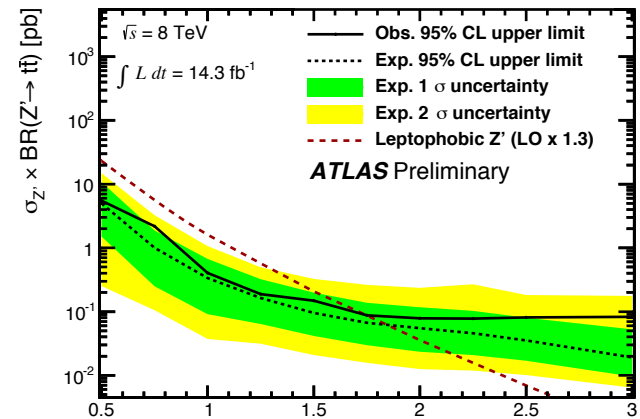
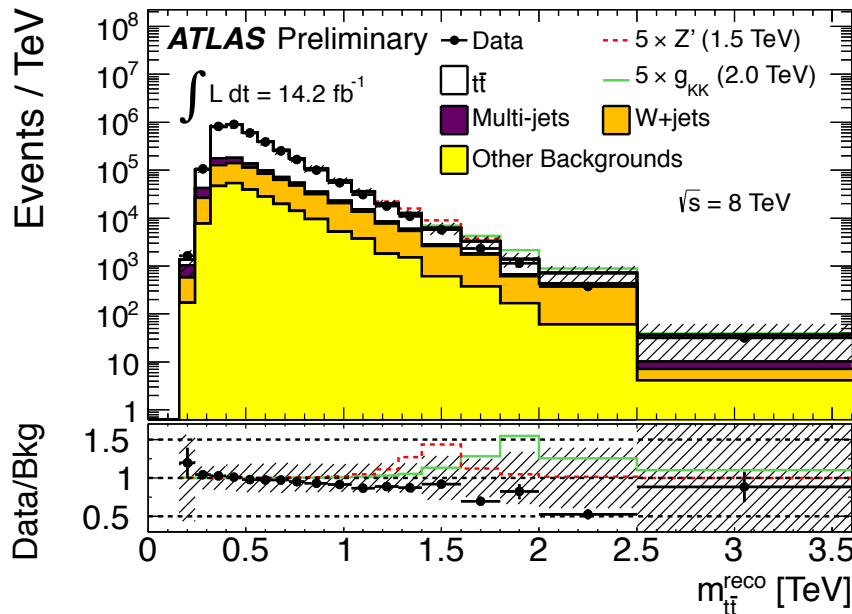
More details on  
Blue analysis

- **ttbar resonance** (ATLAS-CONF-2013-052)
  - Leptophobic topcolor  $Z'$ , Kaluza-Klein gluons
- **Same-sign top etc.** (ATLAS-CONF-2013-051)
  - 4<sup>th</sup> generation down-type chiral quarks ( $b'$ ), Vector Like Quarks, Composite top partners ( $T_{5/3}$ ), Same-sign top pairs, Contact interactions.
- **Vector Like Quarks (VLQ)**
  - Little Higgs, Composite Higgs.
  - $VLQ \rightarrow H + t$  (ATLAS-CONF-2013-018)
  - $VLQ \rightarrow W + b$  (ATLAS-CONF-2013-060)
  - **$VLQ \rightarrow Z + t/b$**  (arXiv:1409.5500, JHEP)
- **$W' \rightarrow t b$ :**
  - **$l + jets$  final states** (arXiv:1410.4103, PLB)
  - qqbb final states (arXiv:1408.0889, EPJC)

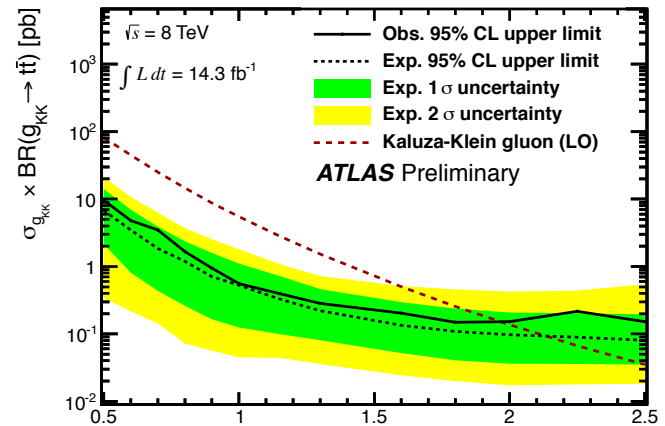
# ttbar resonance (ATLAS-CONF-2013-052)

## ■ ttbar → b l + bbar l

- Isolated lepton ( $p_T > 25 \text{ GeV}$ ) + well defined b-jet
- e+jets: MET > 30 GeV,  $m_T > 30 \text{ GeV}$
- $\mu$ +jets: MET > 20 GeV, MET +  $m_T > 60 \text{ GeV}$
- Angular distance between l and j < 1.5



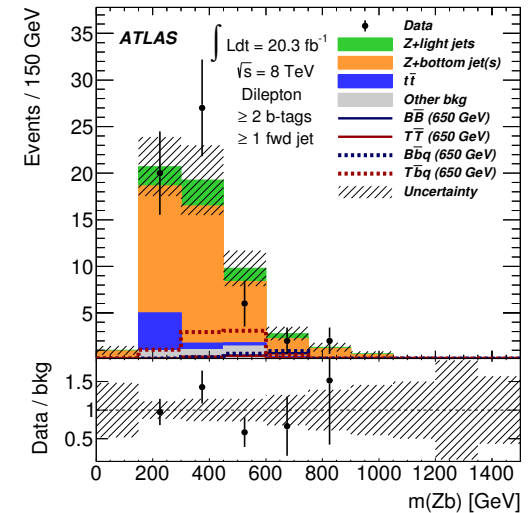
Topcolor  $Z'$  mass < 1.9 TeV



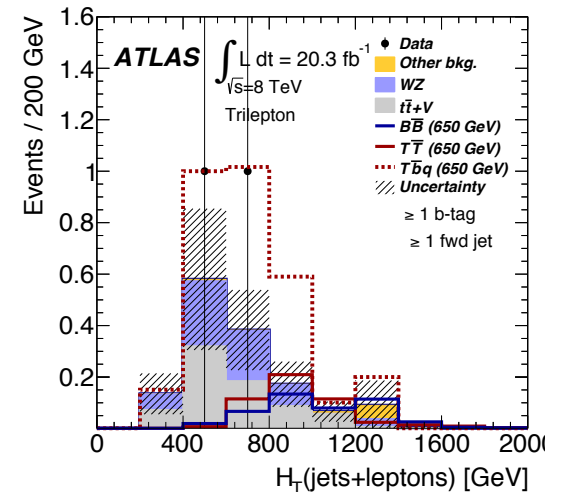
KK gluon mass < 2.1 TeV

# VLQ $\rightarrow$ Zt/b (arXiv:1409.5500, JHEP)

- $T \rightarrow Zt \rightarrow \ell\ell b/\nu, B \rightarrow Zb \rightarrow \ell\ell b$
- Isolated electrons and muons
- Well defined b-jet
- Z candidate: opposite-charge, same -flavor leptons with  $|m(\ell\ell) - m(Z)| < 10\text{GeV}$



Event selection			
Z boson candidate preselection			
$\geq 2$ central jets			
$p_T(Z) \geq 150 \text{ GeV}$			
Dilepton channel		Trilepton channel	
= 2 leptons		$\geq 3$ leptons	
$\geq 2$ b-tagged jets		$\geq 1$ b-tagged jet	
Pair production	Single production	Pair production	Single production
$H_T(\text{jets}) \geq 600 \text{ GeV}$	$\geq 1$ fwd. jet	-	$\geq 1$ fwd. jet
Final discriminant			
$m(Zb)$		$H_T(\text{jets+leptons})$	

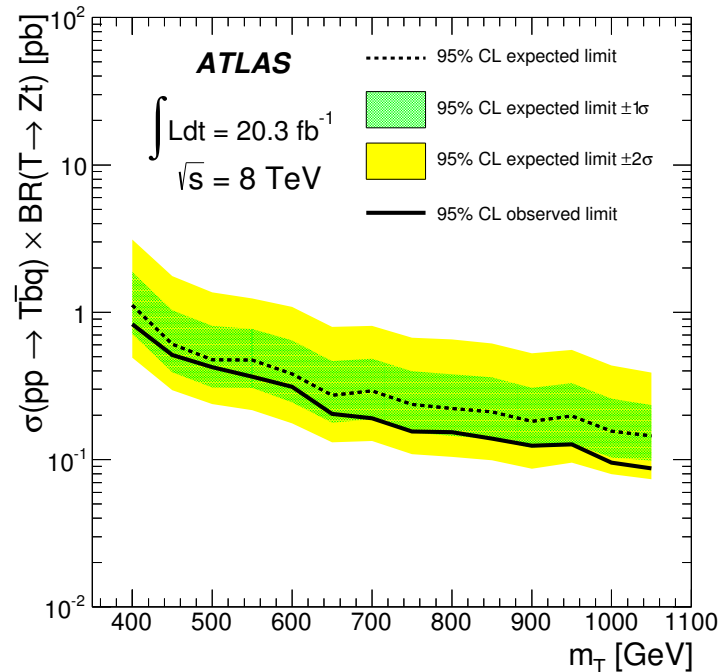
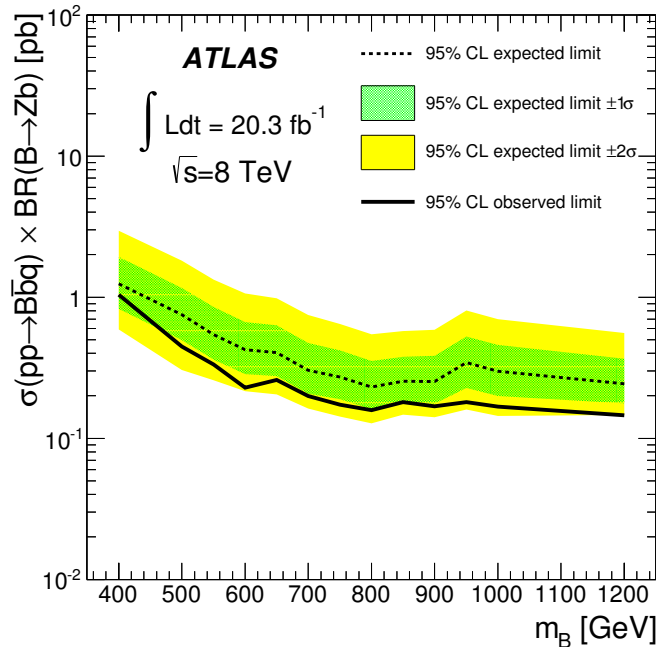


# VLQ $\rightarrow$ Zt/b (2)

Pair production mass limits:

Hypothesis	Singlet mass limit [GeV]			Doublet mass limit [GeV]		
	Dilepton	Trilepton	Comb.	Dilepton	Trilepton	Comb.
$B\bar{B}$	690 (665)	610 (610)	685 (670)	765 (750)	540 (530)	755 (755)
$T\bar{T}$	620 (585)	620 (620)	655 (625)	705 (665)	700 (700)	735 (720)

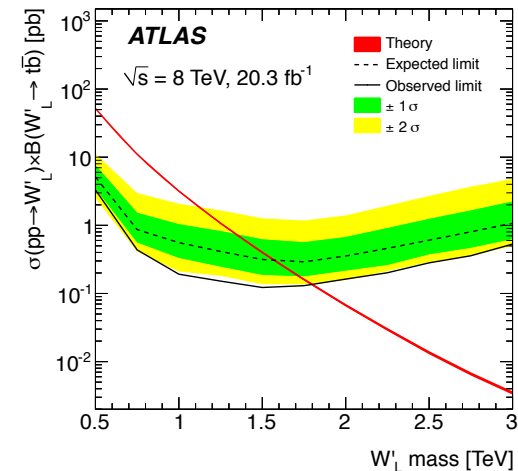
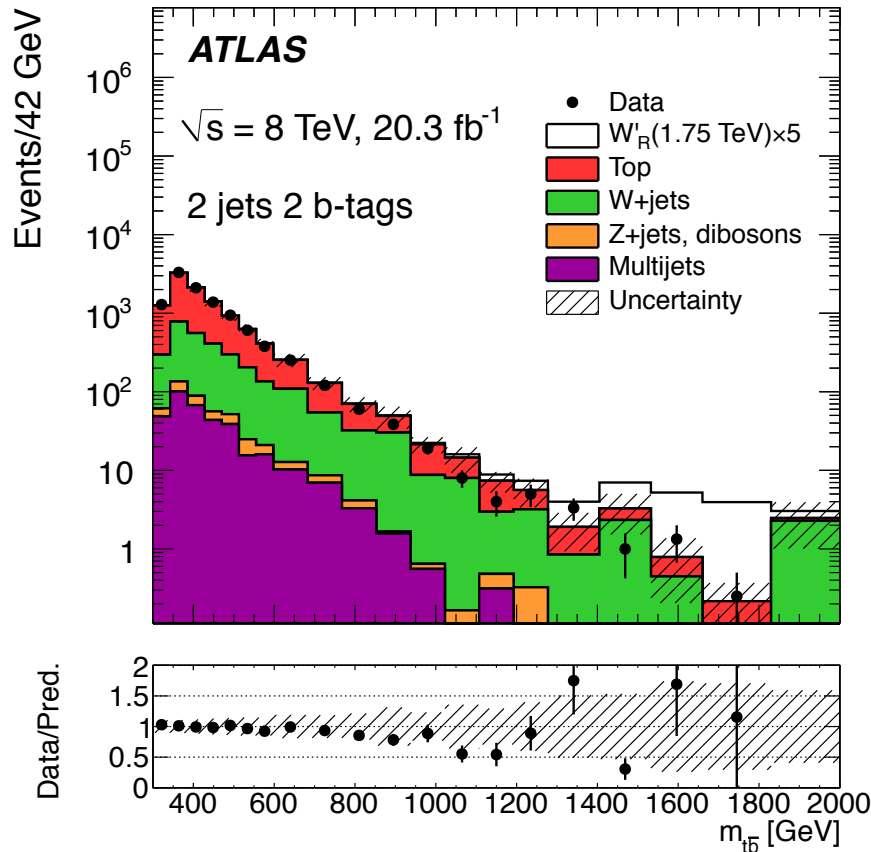
Single production cross section limits:



# $W' \rightarrow tb$ (L+jets) (arXiv:1410.4103, PLB)

- Isolated leptons with  $p_T > 30 \text{ GeV}$
- Well measured jets with  $p_T > 25 \text{ GeV}$

- $W' \rightarrow t \text{ bbar} \rightarrow W(\text{lv})b \text{ bbar}$
- 1 lepton + 2 b-jets (+ jet)
- $\text{MET} > 35 \text{ GeV}$
- $m_T(W) + \text{MET} > 70 \text{ GeV}$



**$W'_L > 1.70 \text{ TeV}$**

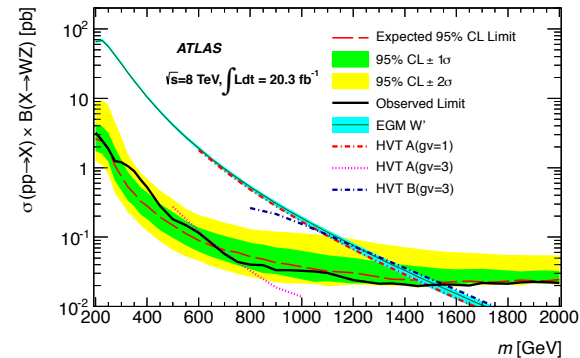
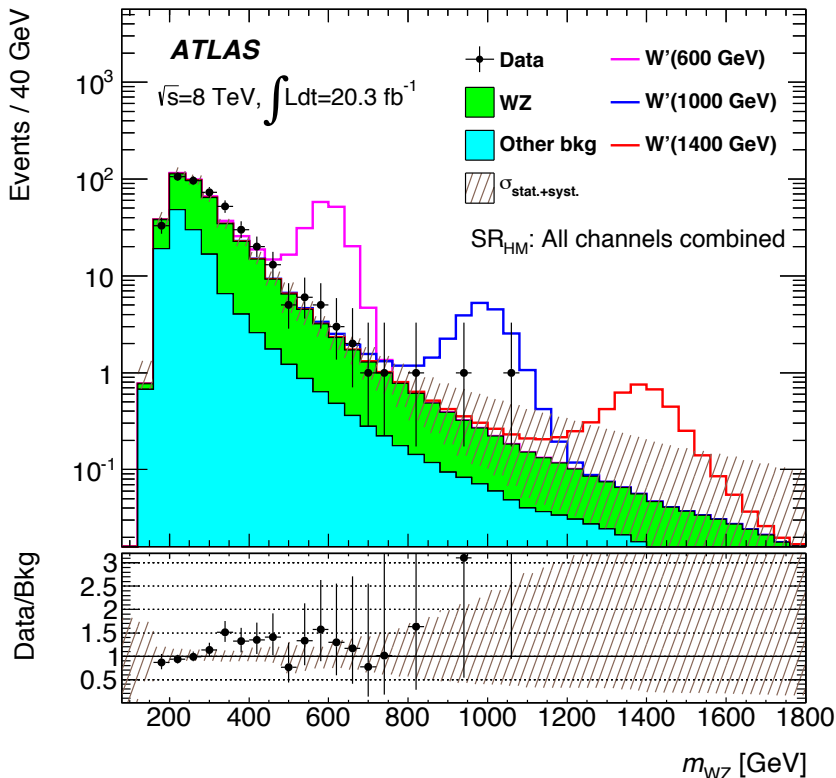
# Vector boson final states

More details on  
[Blue](#) analysis

- Diboson resonances ( $V = Z$  or  $W$ )
  - GUT, Little Higgs, Technicolor, Composite Higgs, Extra dimensions.
  - $WZ \rightarrow l\nu l$  (full leptonic) (arXiv:1406.4456, PLB737,223(2014))
  - $ZZ/ZW \rightarrow lljj$  (arXiv:1409.6190, EPJC)
  - $W\gamma$  and  $Z\gamma$  (arXiv:1407.8150, PLB738,428(2014))
  - $WH/ZH \rightarrow Wjj/Zjj$  (ATLAS-CONF-2013-074)
- Heavy lepton search
  - Heavy neutrino  $\rightarrow W\nu$  (ATLAS-CONF-2012-139)
    - Left-right symmetric model
  - Heavy lepton  $\rightarrow Zl$  (ATLAS-CONF-2013-019)
    - Type III seesaw model

# $WZ \rightarrow |v\bar{v}|$ (full leptonic) (arXiv:1406.4456, PLB737,223(2014))

- Exactly 3 isolated leptons with  $p_T > 25\text{GeV}$
- $\text{MET} > 25\text{GeV}$
- Z candidate: opposite-charge same-flavor leptons with  $|m(\ell\bar{\ell}) - m(Z)| < 20\text{GeV}$



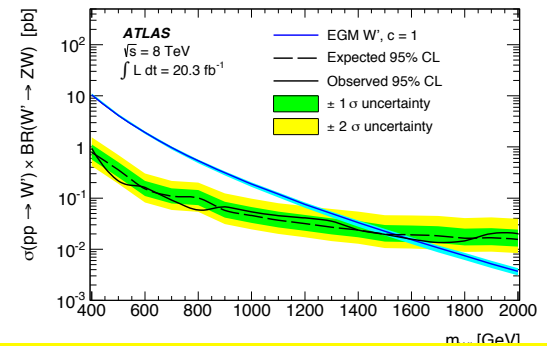
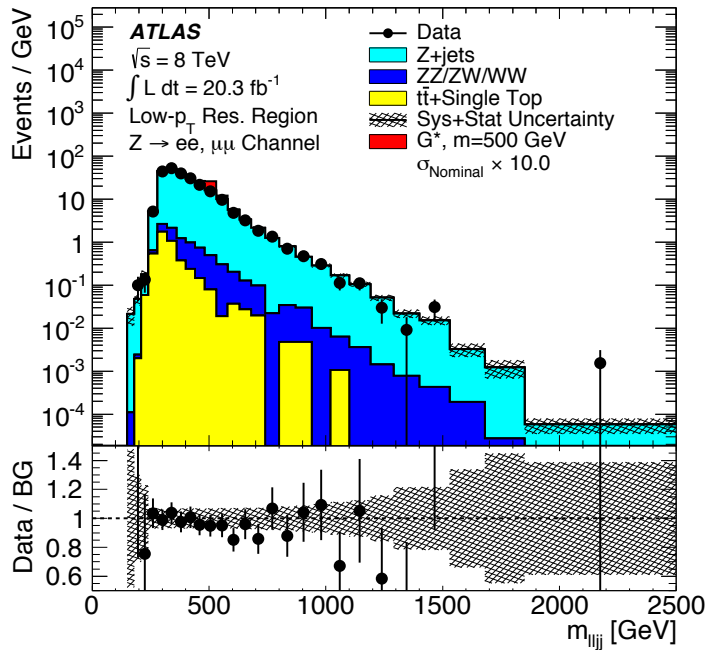
## Extended Gauge Model W' mass limits

	Excluded EGM W' lower mass [TeV]				
	<i>ee</i>	$\mu e$	$e\nu\mu$	$\mu\nu\mu$	combined
Expected	1.21	1.16	1.17	1.16	1.49
Observed	1.20	1.19	1.06	1.17	1.52

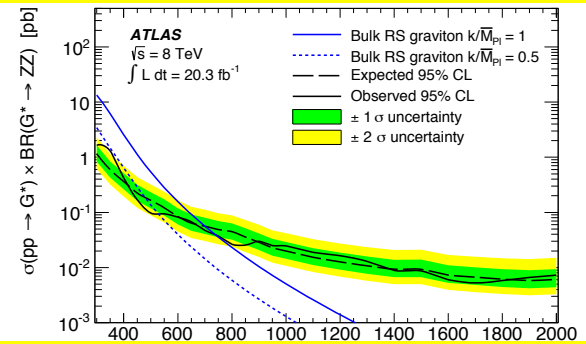
# $ZZ/ZW \rightarrow llqq$ (arXiv:1409.6190, EPJC)

- Exactly two isolated opposite-charge, same-flavor leptons with  $66\text{GeV} < |m(ll) - m(Z)| < 116\text{GeV}$
- qq side: two well measured jets or one large-R jet. Mass agrees with Z or W.

- Extended Gauge Model  $W' \rightarrow WZ$
- KK Graviton  $G^* \rightarrow ZZ$



**EGM  $W'$  mass  $> 1590\text{ GeV}$**



**Bulk RS  $G^*$  mass  $> 740\text{ GeV}$**



# Other Signatures

More details on  
[Blue](#) analysis

- Exotic charges
  - Highly ionizing particles (arXiv:1207.6411, PRL109(2012)261803)
    - Magnetic monopoles
- Long Lived Particles (LLP)
  - LLP decays away from the pp interaction point.
  - Look for displaced decay point (vertex).
  - Special trigger is required.
  - Displaced lepton-jets (LJ):
    - $H \rightarrow$  dark photon (arXiv:1409.0746, JHEP)
  - Displaced jets:
    - Heavy scalar  $\rightarrow$  Hidden Valley LLP pair (ATLAS-CONF-2014-041)
- BSM Higgs specific searches:
  - “Beyond the Standard Model Higgs Physics Using the ATLAS Detector” (Guillermo Hamity).

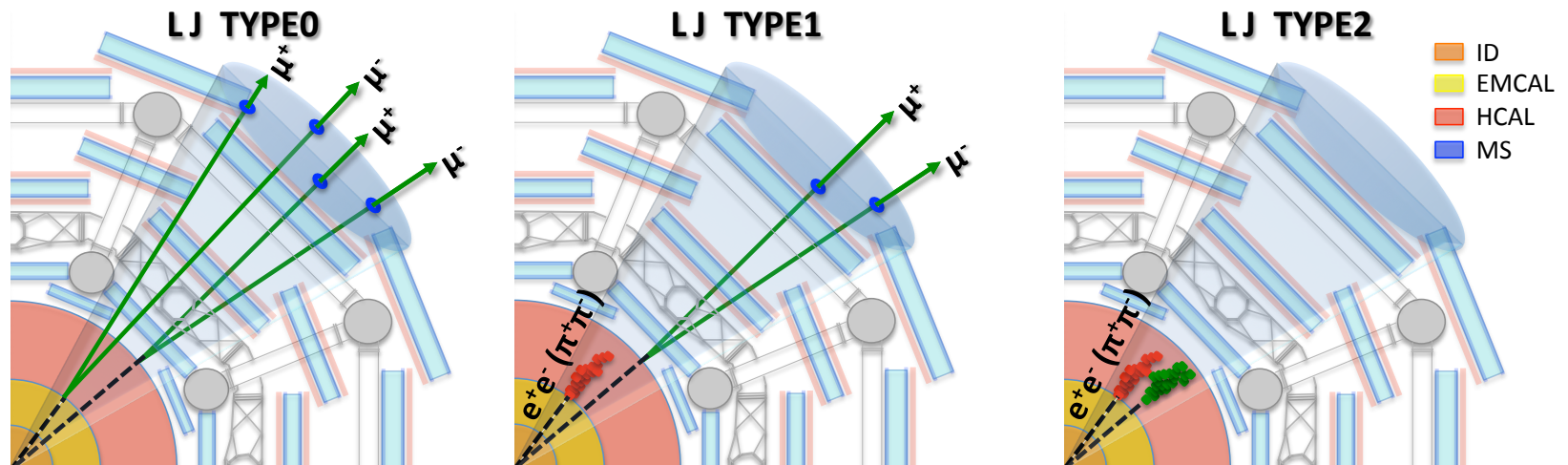
# Other Signatures

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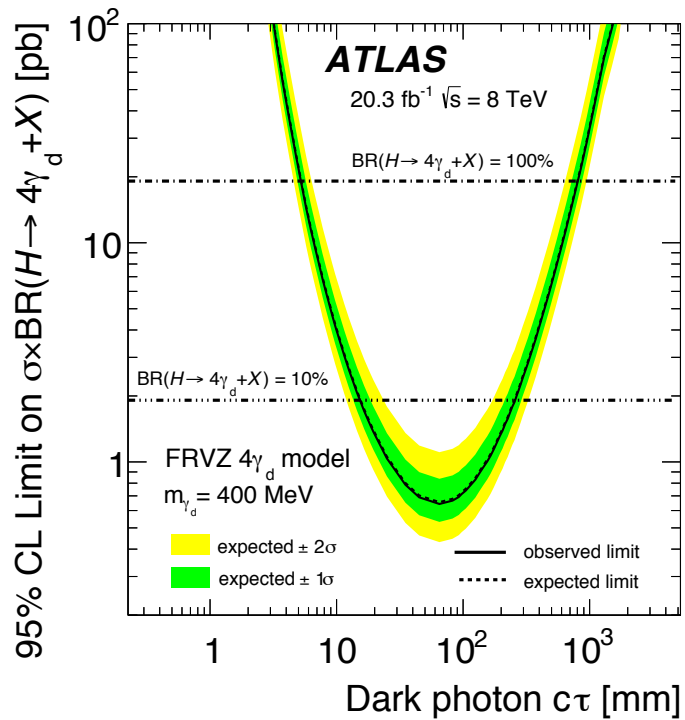
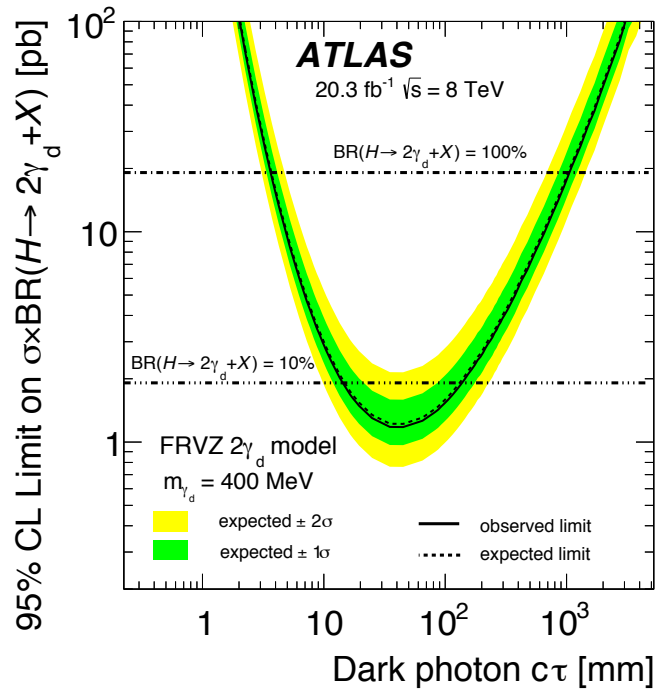
# LLP $\rightarrow$ lepton-jets (arXiv:1409.0746, JHEP)

- $pp \rightarrow 2(4)$  dark photons  $\rightarrow 2(4)$  lepton-jets (LJ)
- Dark photons decay in the calorimeter.



- LJ signature:
  - $\mu\mu$ : two muons in the muon detector and no near-by jets.
  - $ee$ : one jet in the calorimeter.
  - No matching tracks in the inner tracker.
  - Type0 (muons), Type1 (muons and jets), Type2 (jets)
- Two LJs with back-to-back (large angular separation)

# LLP $\rightarrow$ lepton-jets (2)



FRVZ model	Excluded $c\tau$ [mm] BR(10%)
$H \rightarrow 2\gamma_d + X$	$14 \leq c\tau \leq 140$
$H \rightarrow 4\gamma_d + X$	$15 \leq c\tau \leq 260$

# Conclusions

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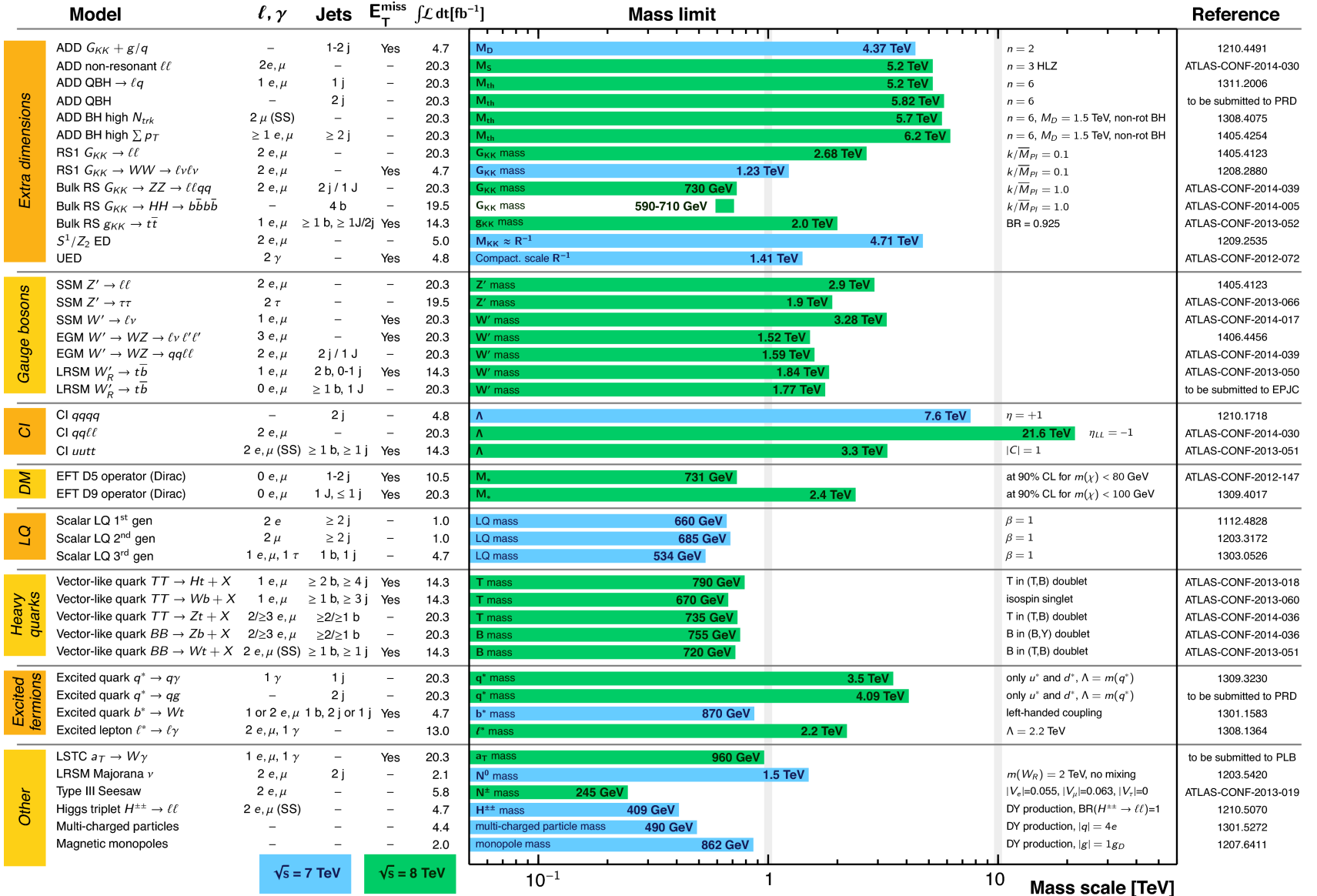
- Signature based search was done to look for physics Beyond the Standard Model (BSM).
- Recent results with 2012, 8TeV data are presented.
- No significant deviation from the Standard Model.
- Limits are set for new physics models/particles.
- Please see other talks for BSM Higgs, Dark Matter and SUSY.

# ATLAS Exotics Searches\* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

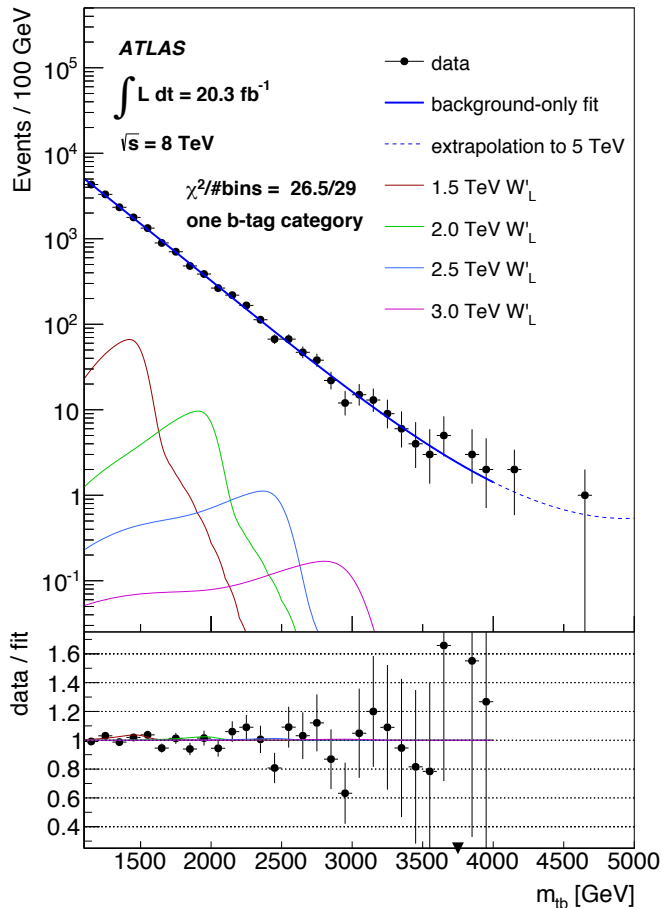
$\int \mathcal{L} dt = (1.0 - 20.3) \text{ fb}^{-1}$   $\sqrt{s} = 7, 8 \text{ TeV}$



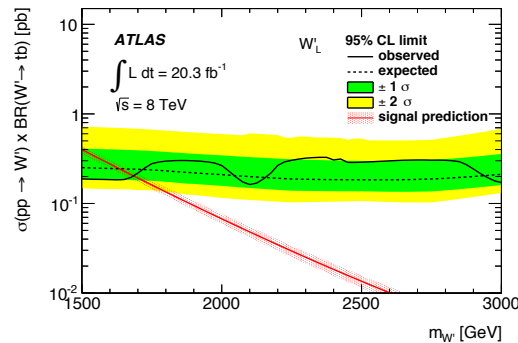
\*Only a selection of the available mass limits on new states or phenomena is shown.

# $W' \rightarrow tb$ (qqbb) (arXiv:1408.0886, EPJC)

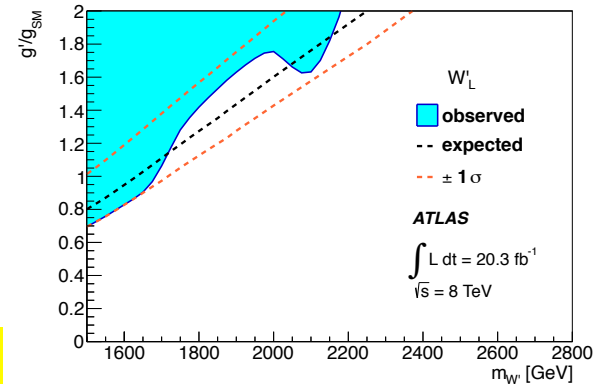
- $W' \rightarrow t b\bar{b} \rightarrow W(qq)b b\bar{b}$



- One large-R jet with  $p_T > 350 \text{ GeV}$
- Large-R jet is widely distributed and include  $W(qq)$  and  $b$ .
- One b-jet with  $p_T > 350 \text{ GeV}$
- Angular distance between large-R jet and b-jet  $> 2.0$

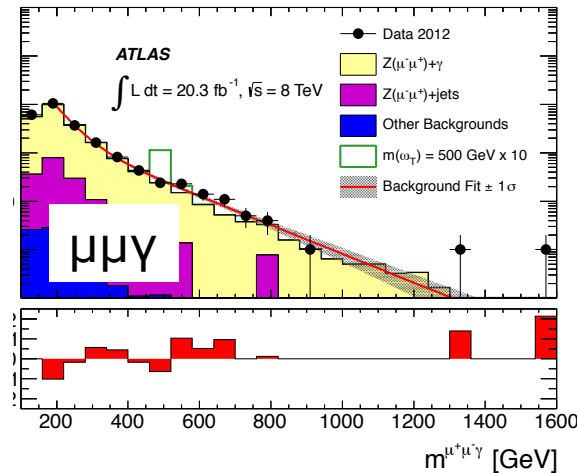
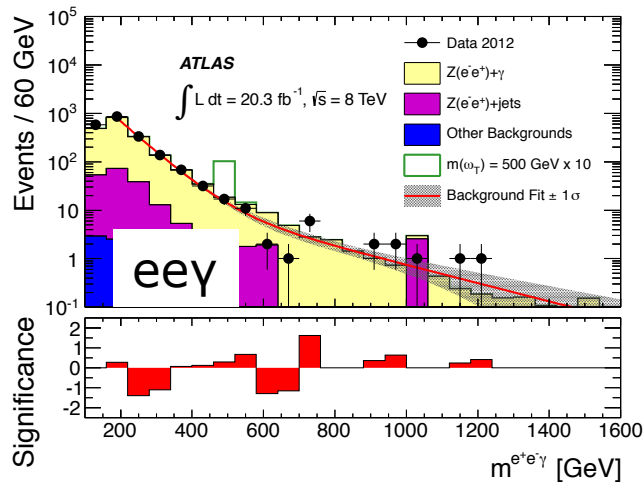
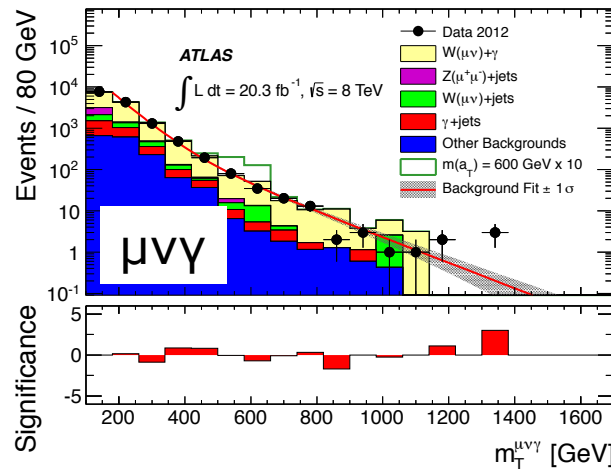
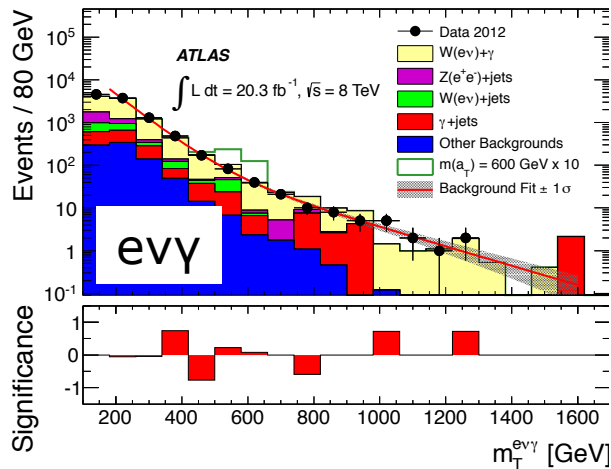


**$M(W') > 1.68 \text{ TeV}$**



# $W\gamma$ and $Z\gamma$ (arXiv:1407.8150, PLB738,428(2014))

## ■ $W \rightarrow l\nu, Z \rightarrow ll$ mode



$l\nu\gamma$  mode:

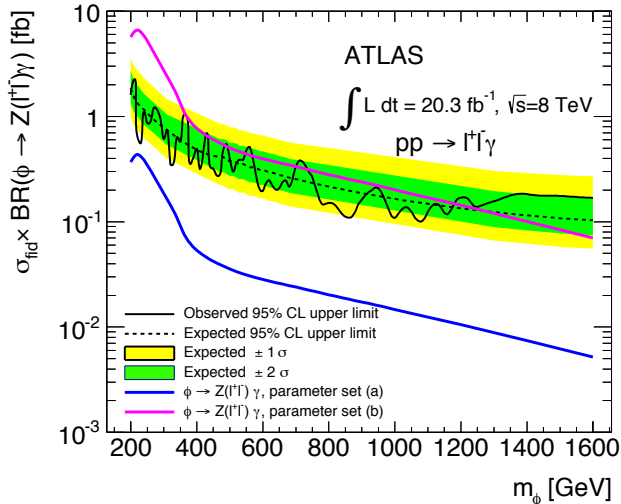
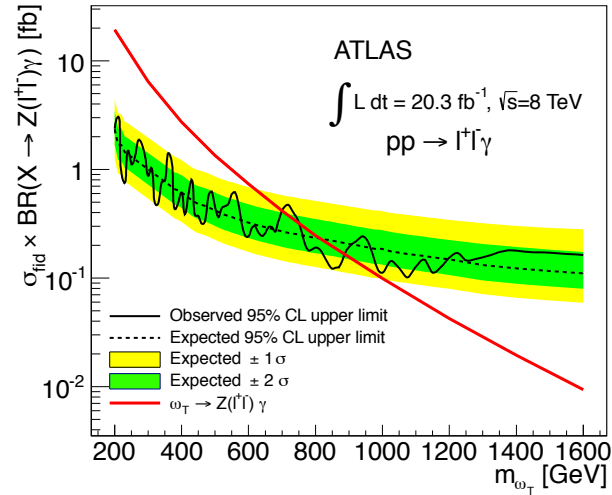
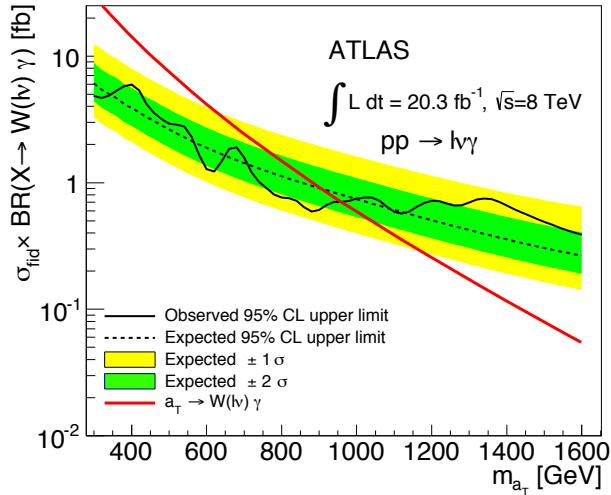
- Lepton  $p_T > 25 \text{ GeV}$
- Photon  $E_T > 45 \text{ GeV}$
- $\text{MET} > 35 \text{ GeV}$

$ll\gamma$  mode:

- $65 < |m(ll) - m(Z)| < 115 \text{ GeV}$
- Photon  $E_T > 40 \text{ GeV}$



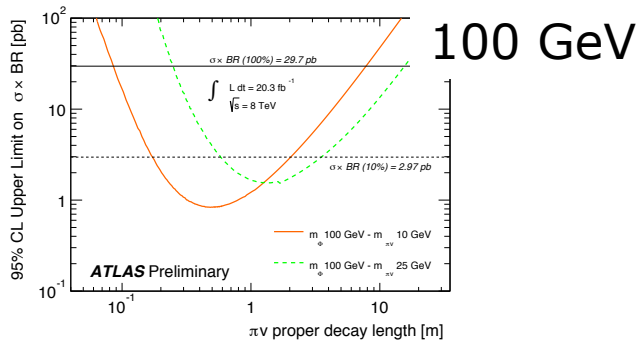
# W $\gamma$ and Z $\gamma$ (2)



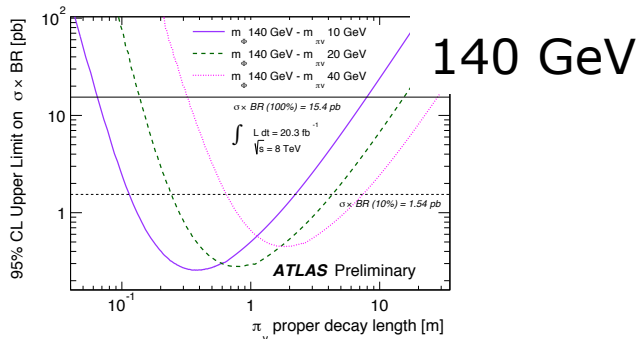
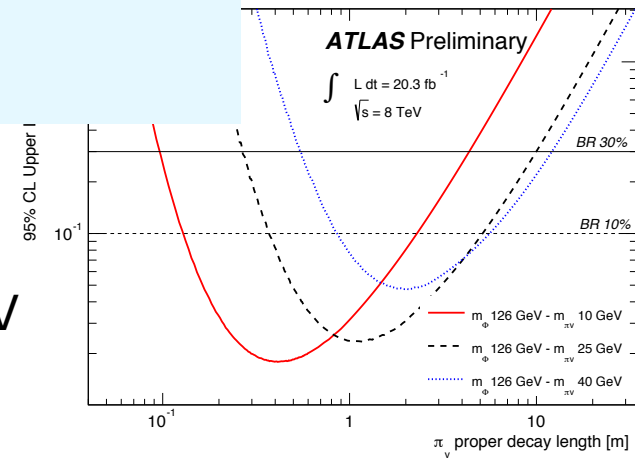
- Low Scale Technicolor model:
  - $M(a_T) > 960 \text{ GeV}$
  - $M(\omega_T) > 890 \text{ GeV}$
- Singlet scalar resonance:
  - $M(\phi) > 1180 \text{ GeV}$

# LLP pair (ATLAS-CONF-2014-041)

- Heavy scalar boson ( $\Phi_{HS}$ )  $\rightarrow$  LLP ( $\pi_\nu$ ) pair
- LLP candidate:
  - Narrow jet in hadronic calorimeter
  - Small energy deposit in EM calorimeter.
  - No matching track in the inner tracker.



126 GeV



Excluded proper decay length

MC sample $m_\Phi, m_{\pi_\nu}$ [GeV]	excluded range 30% BR $\Phi_{HS} \rightarrow \pi_\nu \pi_\nu$ [m]	excluded range 10% BR $\Phi_{HS} \rightarrow \pi_\nu \pi_\nu$ [m]
126, 10	0.10 - 4.38	0.13 - 2.30
126, 25	0.27 - 10.01	0.37 - 5.12
126, 40	0.54 - 12.11	0.86 - 5.62