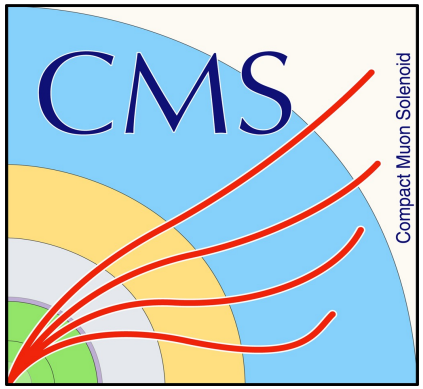
Search for new physics in multi-lepton final states with the ATLAS and CMS detectors

EPS-HEP CONFERENCE, VIENNA

July 22-29, 2015



Shilpi Jain,

NCU, Taiwan

On behalf of the ATLAS and CMS collaborations

Searches for new physics with multileptons

- Many interesting BSM physics phenomena can be searched for in multilepton final state
  - Observation of neutrino oscillation makes the following exciting:
    - Lepton flavour violation (LFV) decays of Z (Z–>eμ)
      - New physics like massive Dirac or Majorana neutrinos or R-parity SUSY
    - Lepton flavour violating decays of new heavy resonances
      - Resonant $\sim\nu_\tau$ LSP production in RPV SUSY
      - LFV gauge boson (Z'/a') exist and generate transitions between families
  - Compositeness in the lepton sector
  - Type III seesaw models
  - New phenomena with multi-photon

Lepton-flavor-violation in Z decays

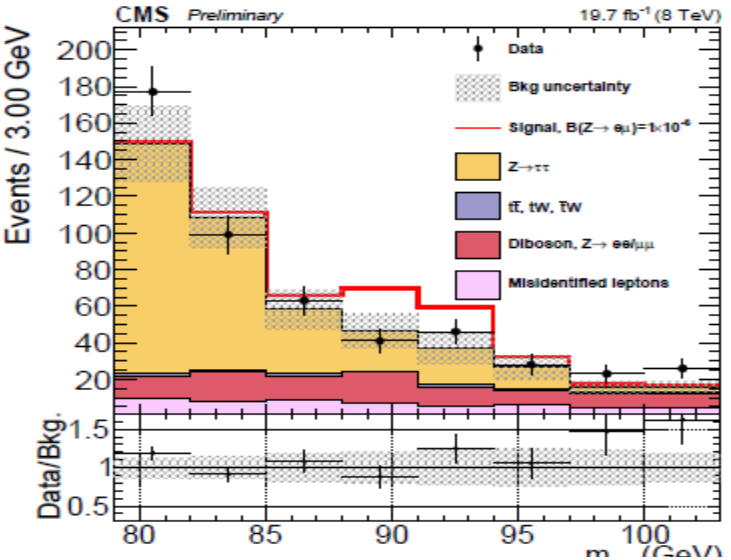
Limits from low energy experiment in μ–>3e channel already exist (BR(Z–>eμ)) < 5x10^{-13}

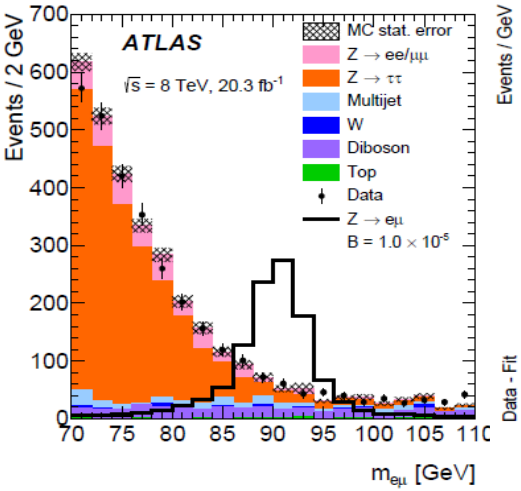
Nucl.Phys. B299(1988) 1

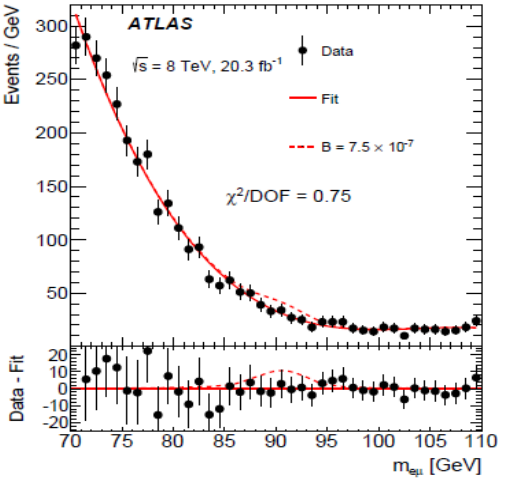
- Final state of eμ consistent with Z decays in $M_{e\mu}$ spectrum
- oppositely charged e, μ
- Dominant background: Z–>ττ
- CMS: Multi-lepton background: data-driven technique
- ATLAS: background estimated by **fit to data excluding the Z region, extrapolate**
- Upper limits:
  - **CMS: 7.3X10^{-7}**
  - **ATLAS: 7.5X10^{-7}**

  At 95% CL

CMS NEW!







CMS: EXO-13-005

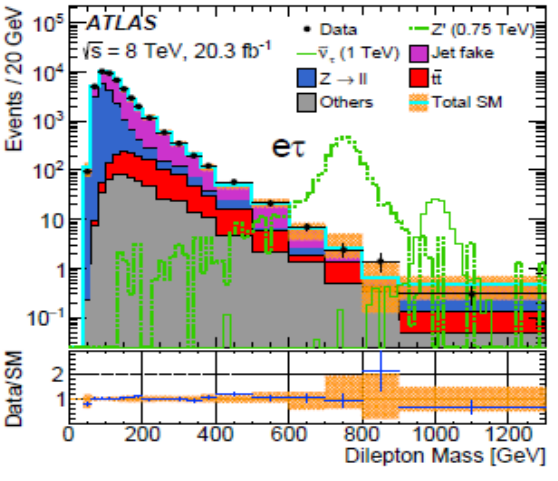
Everything Consistent with the SM

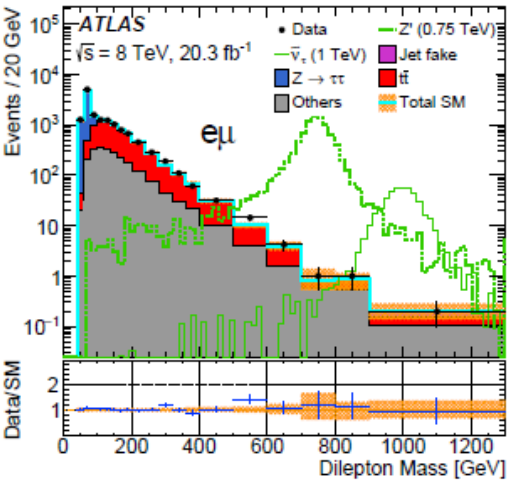
ATLAS: PRD 90, 072010 (2014)

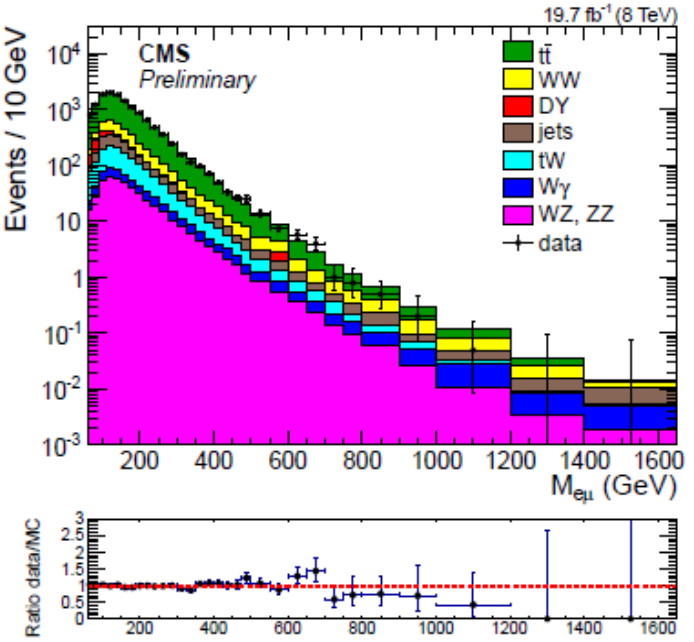
Lepton-flavour-violating decays of heavy resonances

- CMS: eμ, ATLAS: eμ,eτ or μτ
- Final state of ll' in broad range spectrum of $M_{ll'}$
- Oppositely charged e, μ
- ATLAS: collinear neutrino approximation used to reconstruct $m_{ll'}$ in the final state of τ_{had}
  - τ_{had} coming from decay of heavy resonance
  - ν and jets are collinear. 4-p vector of ν can be reconstructed
  - **Significantly improves the mass resolution**

LVF neutral gauge boson! (Z') ***QBH!*** ***RPV SUSY!***



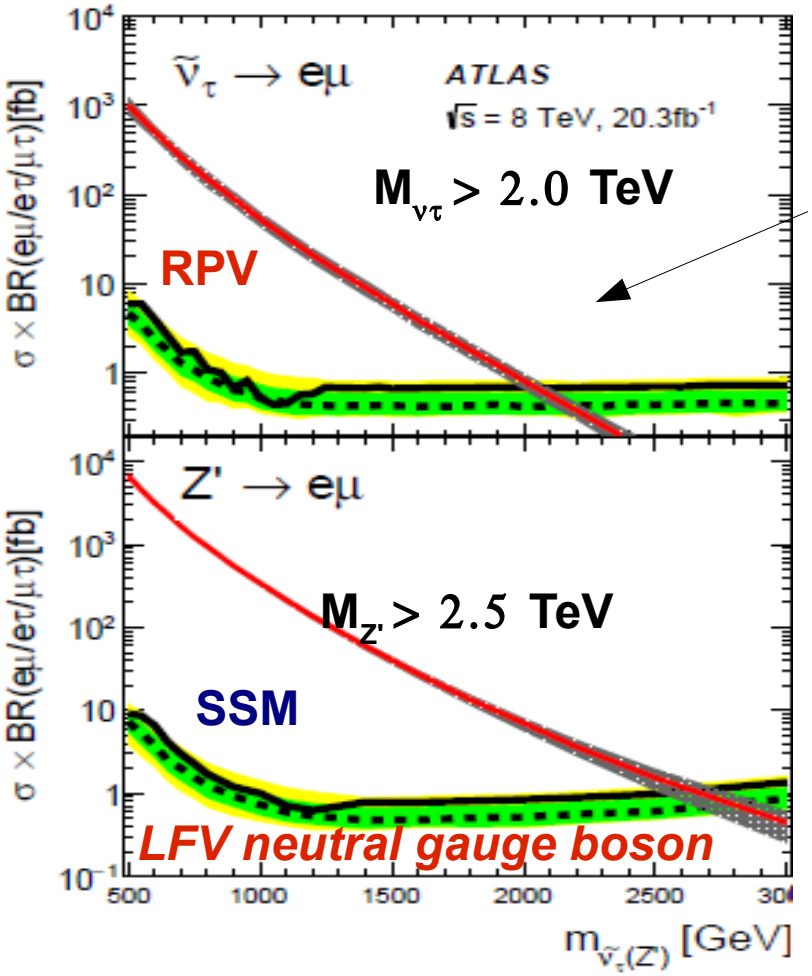




CMS: PAS EXO-13-002

ATLAS: arXiv: 1503.04430

Results and limits



RPV coupling parameters

ATLAS:

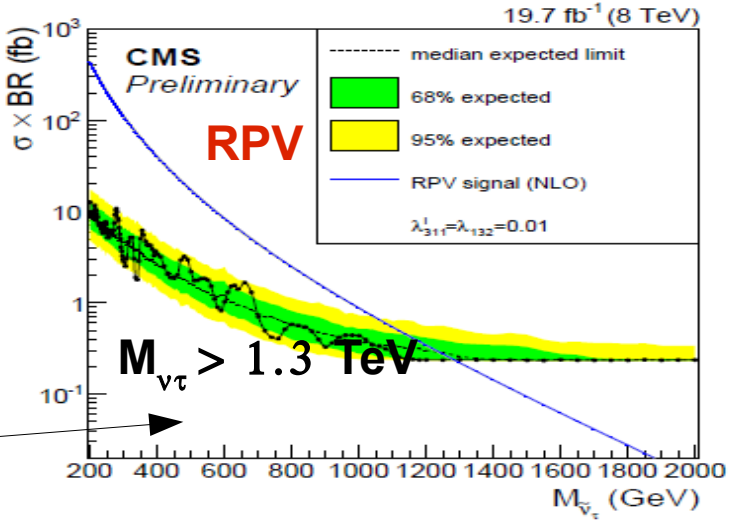
$\Lambda'_{311} = 0.11$ and

$\Lambda_{132} = 0.07$

CMS:

$\Lambda'_{311} = 0.01$ and

$\Lambda_{132} = 0.01$

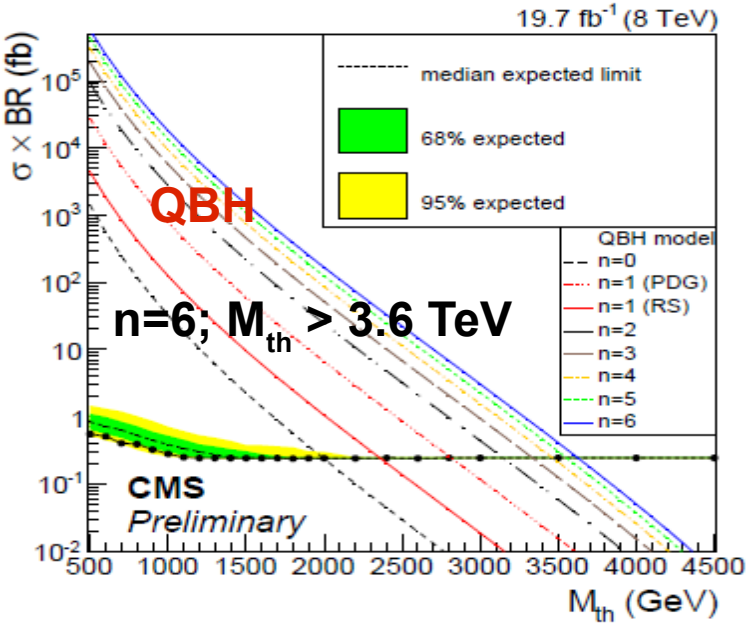


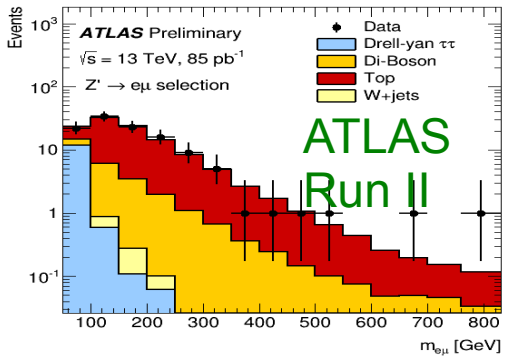
For different parameters, CMS has:

$\Lambda'_{311} = 0.1$ and

$\Lambda_{132} = 0.05$

$M_{\nu\tau} > 2.11$ TeV





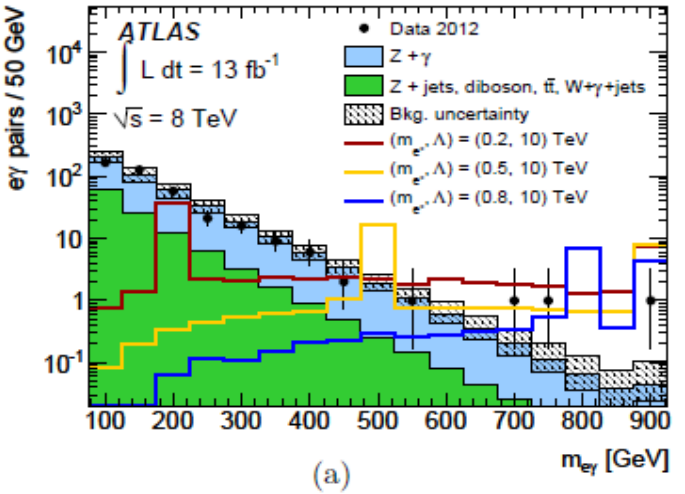
Λ_{132}: coupling of ν_τ with $e\mu$ Λ_{311}: coupling of ν_τ with d quarks

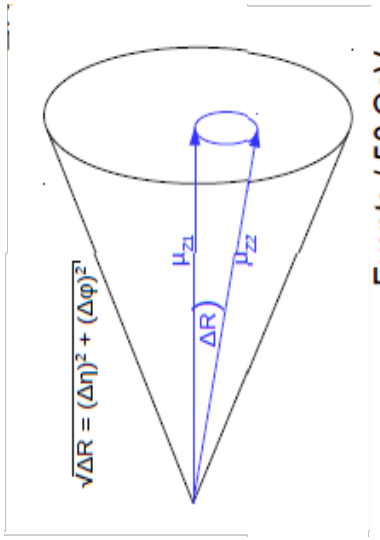
At 95% CL

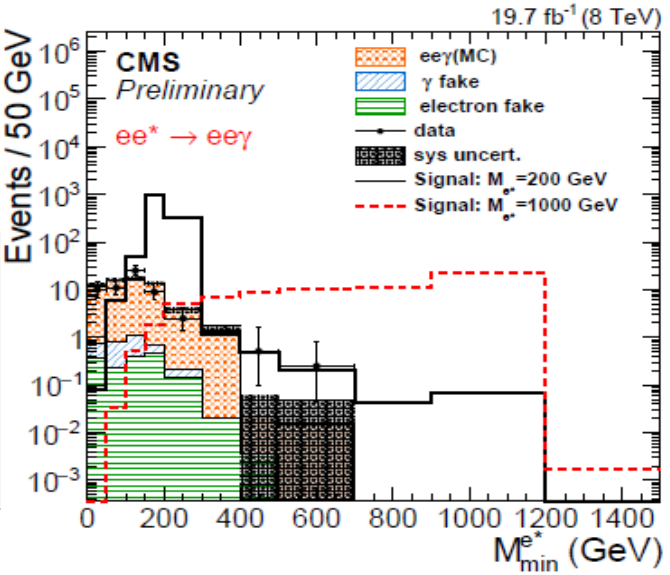
Non-LFV Multi-lepton searches

Search for excited leptons

- Look for single production of ℓ^*
  - ATLAS: pp–>$\ell^*\ell$–>$\ell\ell\gamma$
  - CMS: pp–>$\ell^*\ell$–>$\ell' V\ell$ (V=Z,γ)
    - Depending on the decay mode, final states can be:
      - $\ell\ell\gamma$ (ℓ=e,μ)
      - ***$\ell\ell$Z (For the first time at LHC from CMS!)***
        - **Z–>$\ell\ell$ (ℓ=e,μ) - A similar kind of decay topology is probed by ATLAS in the context of typeIII seesaw and vector-like leptons**
        - **Z–>dijet**
- pp–>$\ell^*\ell$–>$\ell\ell$Z in CMS: Z boson is boosted
  - Leptons from Z decay are collinear
  - Relaxed isolation is applied
- Two leptons in the final state,
  - Two possible combinations: $M_{\ell V}^{Min}$ and $M_{\ell V}^{Max}$



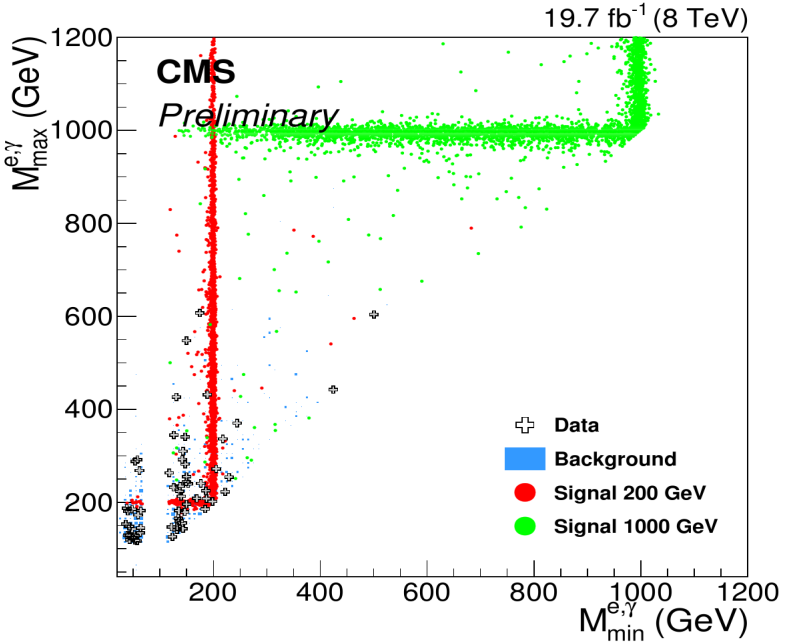


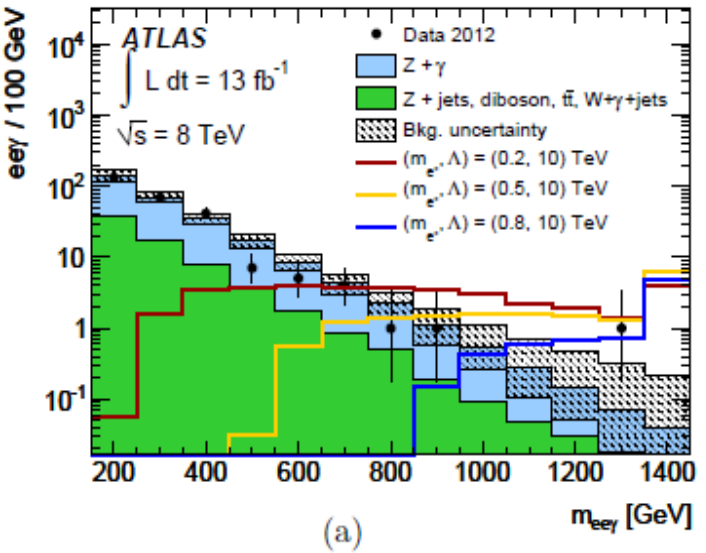


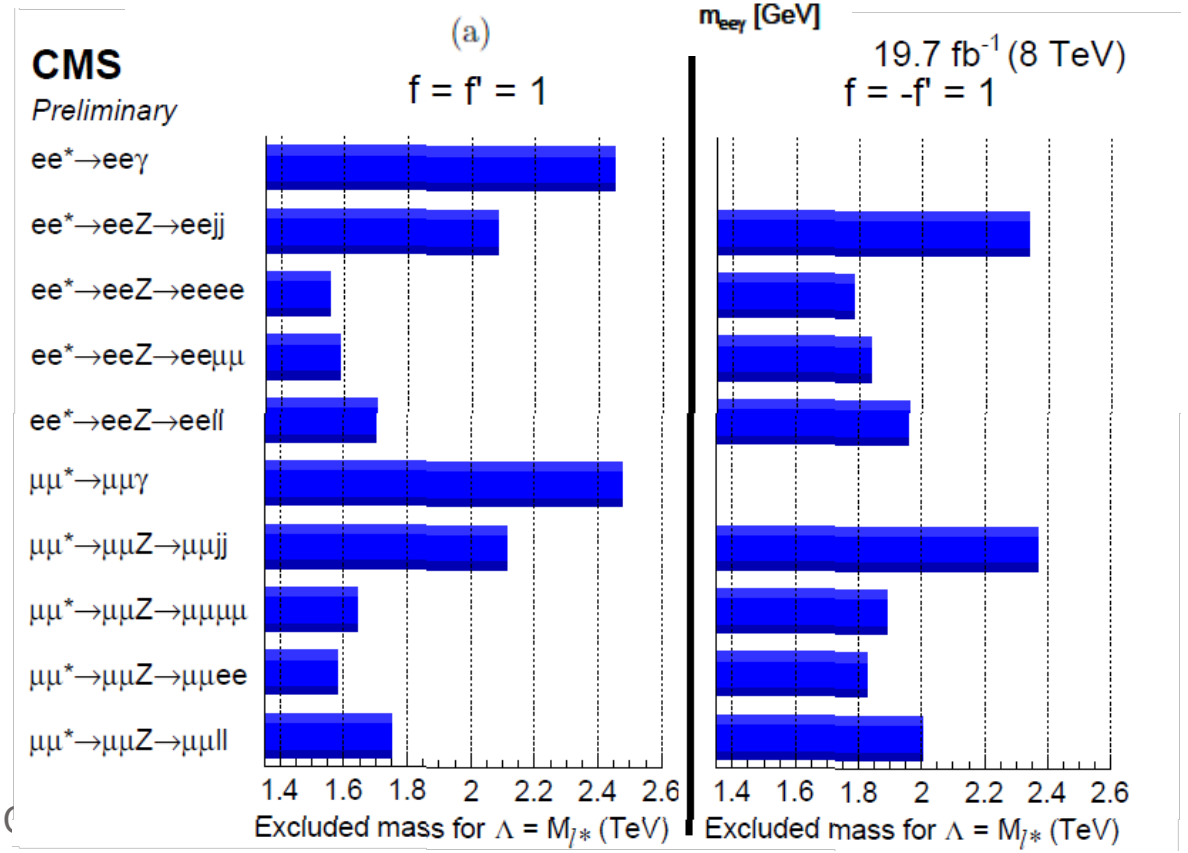
ATLAS: NJP 15 (2013) 093011

CMS: EXO-14-015

Results and Limits





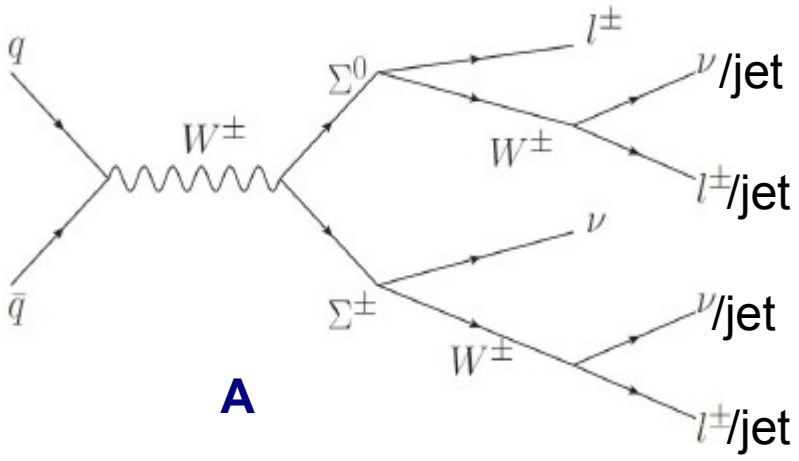


- ATLAS: applies cut on $M_{\ell\ell\gamma}$ for the search
- CMS: Apply a 2-D cut in the invariant mass plane of $M_{\ell\nu}^{Min}$ and $M_{\ell\nu}^{Max}$ - **improves the sensitivity**
- ATLAS: M_{ℓ^*}<2.2 TeV excluded
- CMS:
  - f=f' in $\ell\ell\gamma$ final state: M_{ℓ^*}<2.45(2.48) TeV for e(μ)
  - f=-f' in $\ell\ell Z$: M_{ℓ^*}<2.35(2.38) TeV for e(μ)

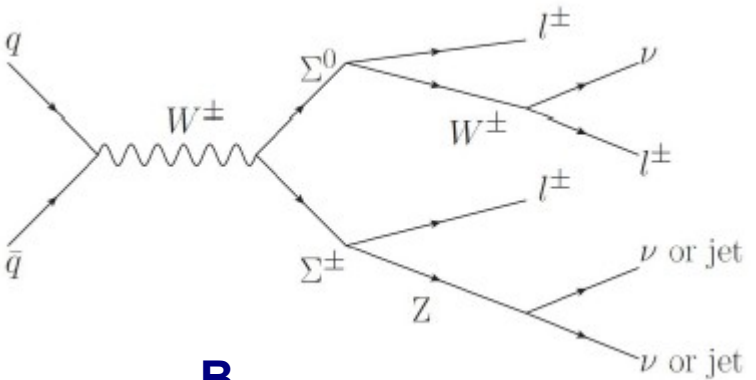
At 95% CL

Heavy-lepton partners of neutrinos (type III seesaw)

Can explain the neutrino masses and their smallness



A



B

- Look for triplet state: Σ^0, $\Sigma^{+/-}$
- In the Final state of:
  - CMS: 3 isolated leptons and MET (diag. A and B)
  - ATLAS: 2 isolated leptons and atleast 2 jets and MET (diag. A)
- Parameters of the theory: V_e, V_μ, V_τ: mixing angles between the SM and triplet state

ATLAS+CMS NEW!

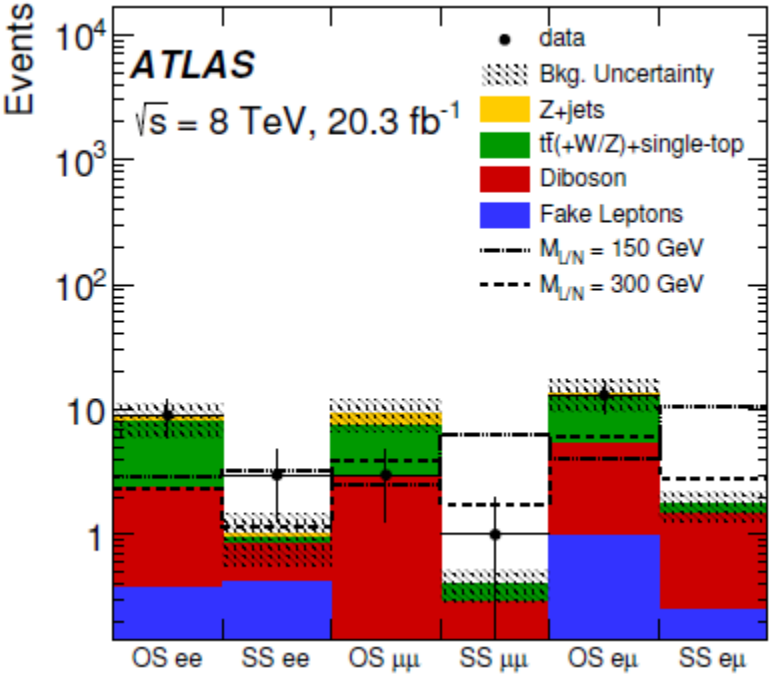
ATLAS: 4l final state with 5.8 fb-1 at 8 TeV: **ATLAS-CONF-2013-019**

CMS PAS: EXO-14-001

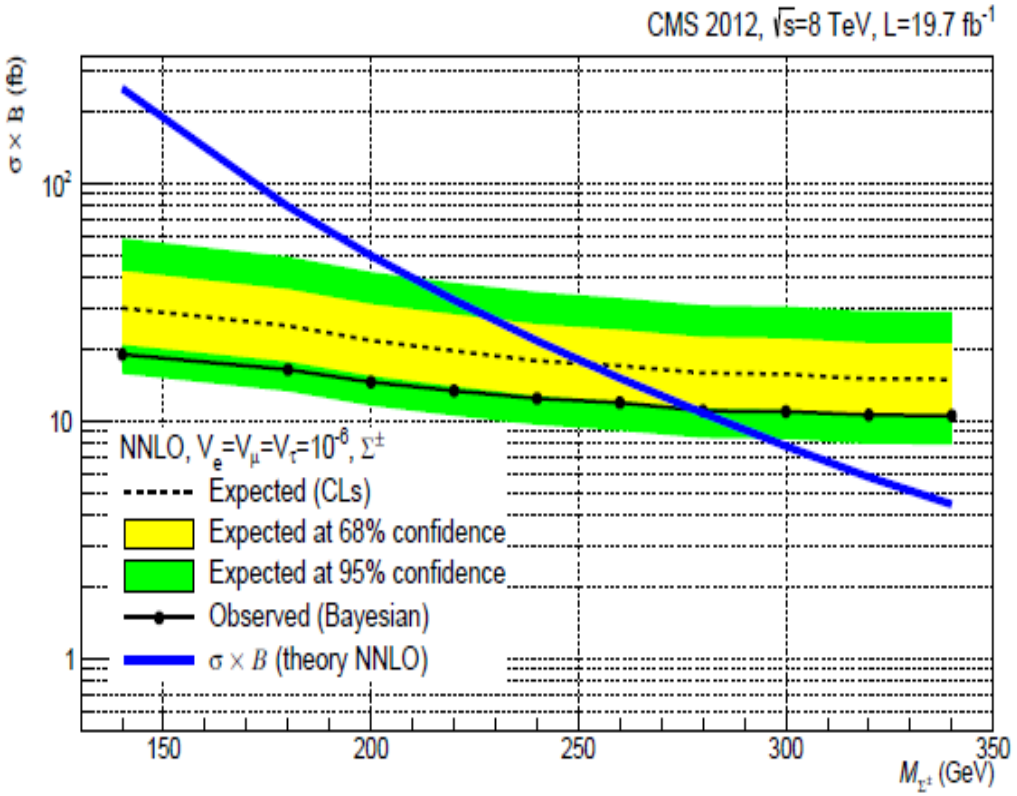
ATLAS: arxiv:1506.01839

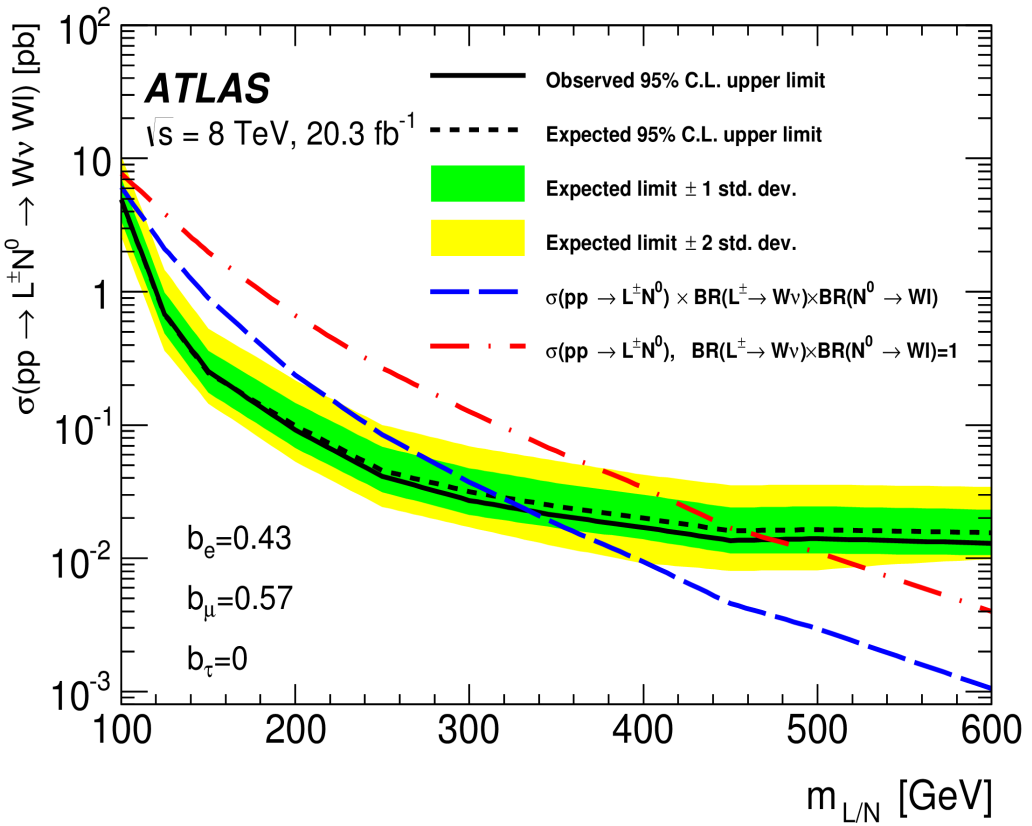
Heavy lepton partners of neutrinos (type III seesaw)

- ATLAS divides its analysis into OS and SS leptons (2 lepton final state)
- CMS categorizes in 12 categories:
  - 6 with total + and 6 with total – charge(e.g: $\mu+\mu-\mu+$, e+e+e- etc)
- Dalitz background:
  - In CMS, asymmetric photon conversion is a source of background: $Z\gamma \rightarrow lll$
    - One of the leptons from photon conversion takes most of the momentum – thus other goes undetected (low p_T)
    - Rejection by vetoing M_{lll} in the Z window



Limits





CMS excludes masses ($M_{\Sigma^{+/-}}$) below 280 GeV with $V_e=V_\mu=V_\tau = 10^{-6}$

Assuming only τ-e mixing, the mass limit 320 GeV

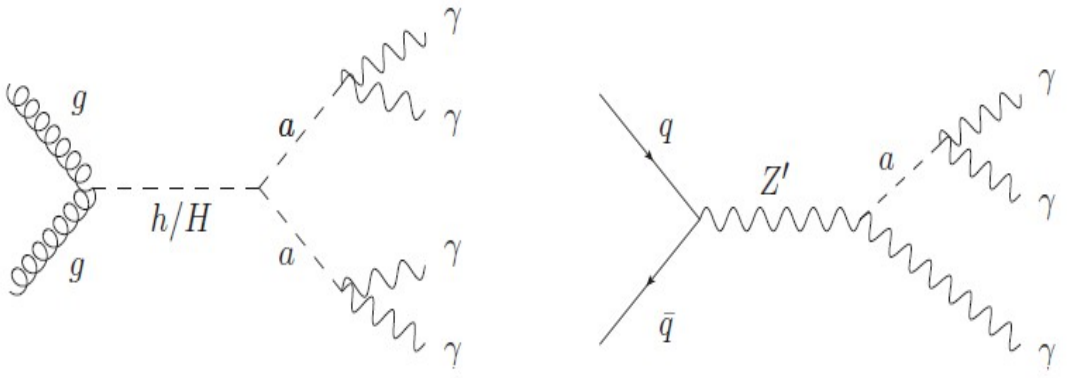
ATLAS excludes masses ($M_{L/N}$) below 335 GeV for $V_\tau = 0$; $V_e/V_\mu = 0.87$

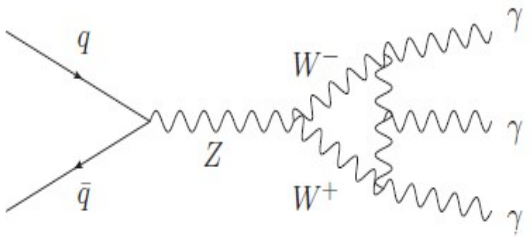
$$b_\alpha = |V_\alpha|^2/(|V_e|^2 + |V_\mu|^2 + |V_\tau|^2)$$

$L^{+/-} = \Sigma^{+/-}$ and $N = \Sigma^0$

At 95% CL

New phenomena with multi-photon





Brand new!

ATLAS: EXOT-2013-24: to be published

	Inclusive signal region	80 GeV < $m_{3\gamma}$ < 100 GeV
Total SM exp.	1370 ± 140	233 ± 28
Observed	1290	244

	Obs. (exp.) 95% C.L. upper limit	
N_{sig}	240 $\left(273^{+83}_{-66}\right)$	—
$BR(Z \to 3\gamma)$	—	2.2 (2.0) $\times 10^{-6}$
$\sigma_{fid} \times \mathcal{A}$ [fb]		
$H \to aa \to 4\gamma$		
300 GeV < m_H < 900 GeV		
m_a = 100 GeV	18 $\left(21^{+6}_{-5}\right)$	—
$Z' \to a + \gamma \to 3\gamma$		
200 GeV < $m_{Z'}$ < 1 TeV		
m_a = 100 GeV	19 $\left(22^{+7}_{-5}\right)$	—

Five times stronger than the previous results from LEP!

At 95% CL

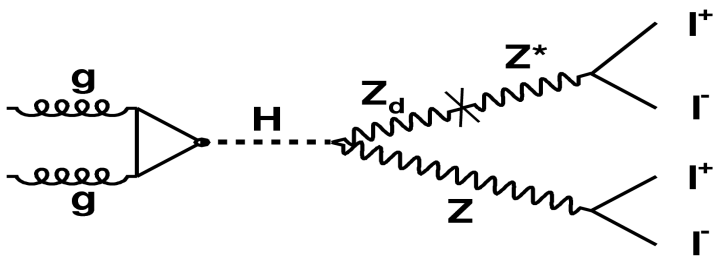
Summary

- Many new searches for BSM physics have been searched for in the final state of multileptons/photons
  - Most recent have been presented today
  - More can be found here:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
- Limits on LFV decays to Z, heavy resonances, type III seesaw mechanism, excited leptons, multi-photons have been put
- Exciting times ahead for the search of new physics with the new energy frontier at the LHC

....and who knows tomorrow may turn out to be yet another day for celebration...

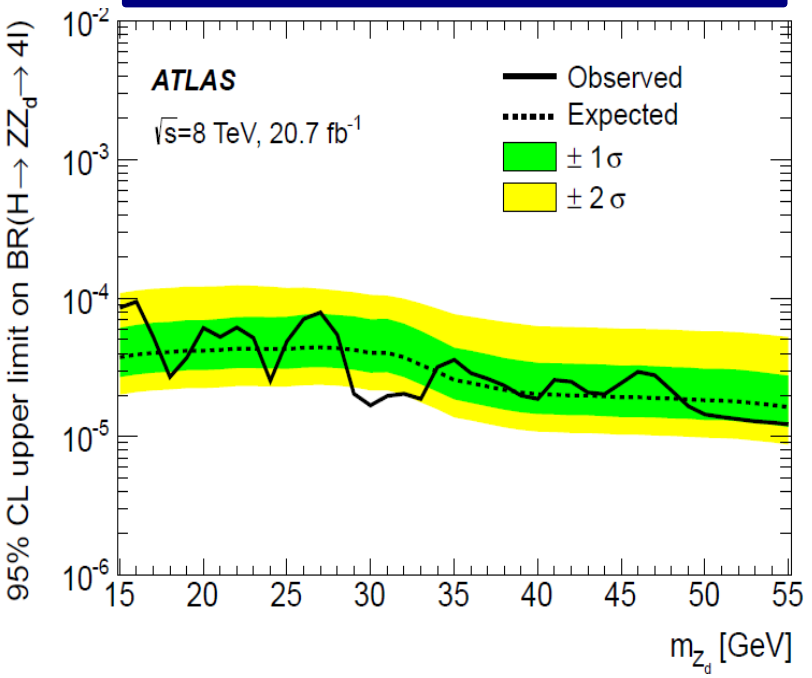
backup

Window to the hidden sector



ATLAS NEW!

ATLAS: arXiv:1505.07645



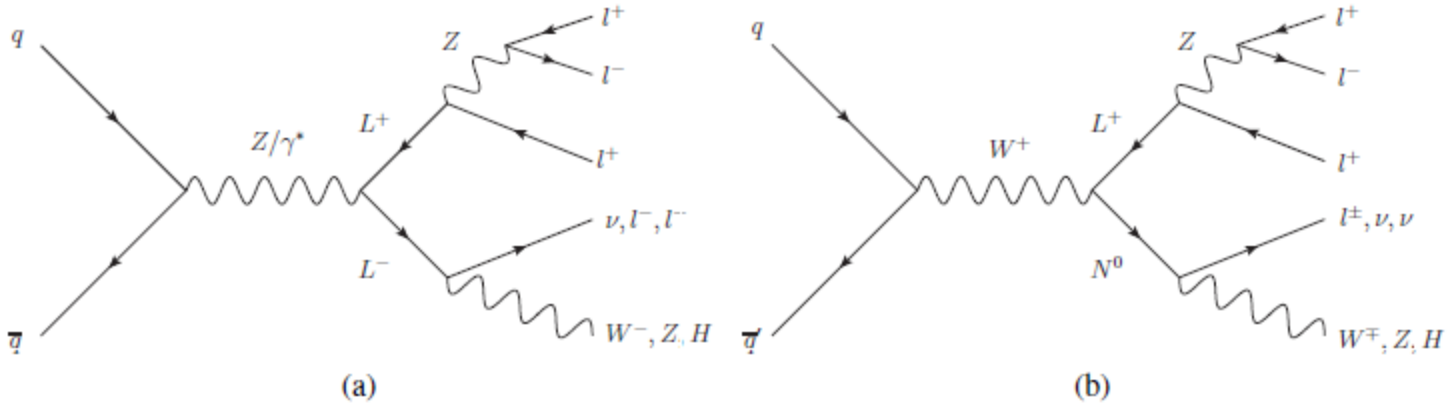
- Presence of a dark sector
  - Dark vector boson (Z_d) with the following parameters in the theory:
    - ε: coupling strength between Z_d and SM particles
    - δ: coupling strength between Z_d and SM Z boson
    - M_{Zd}: mass of Z_d
- H–>ZZ_d–>4l
  - H–>ZZ_d–>4l: covers the parameter space of ε and M_{Zd} or δ and M_{Zd}
- Final states of 4e, 4μ, 2e2μ are considered

For 15 <Z_d < 35 GeV,
Limits on BR(H–>ZZ_d–>4l): (1-9)x10^{-5}

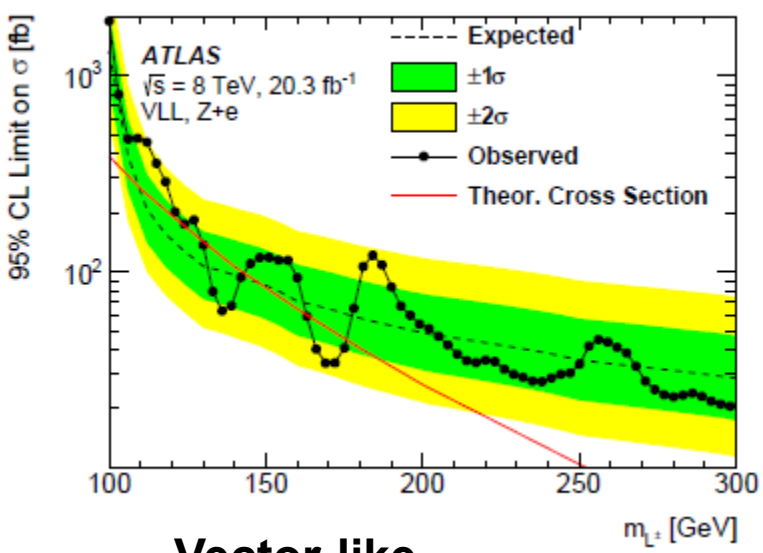
CMS: arXiv:1506.00424: Look for hidden sectors via γ_D as well in the multi-lepton final state

At 95% CL

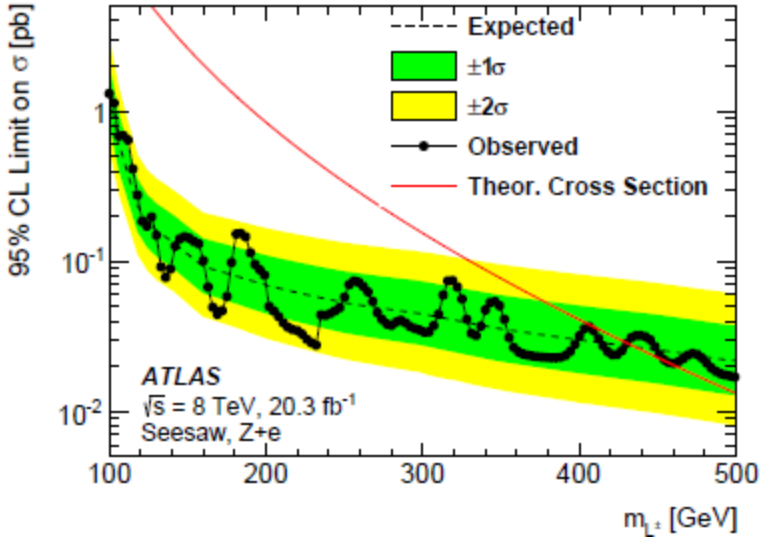
Heavy lepton resonances decaying to a Z boson and a lepton



ATLAS NEW!



Vector-like



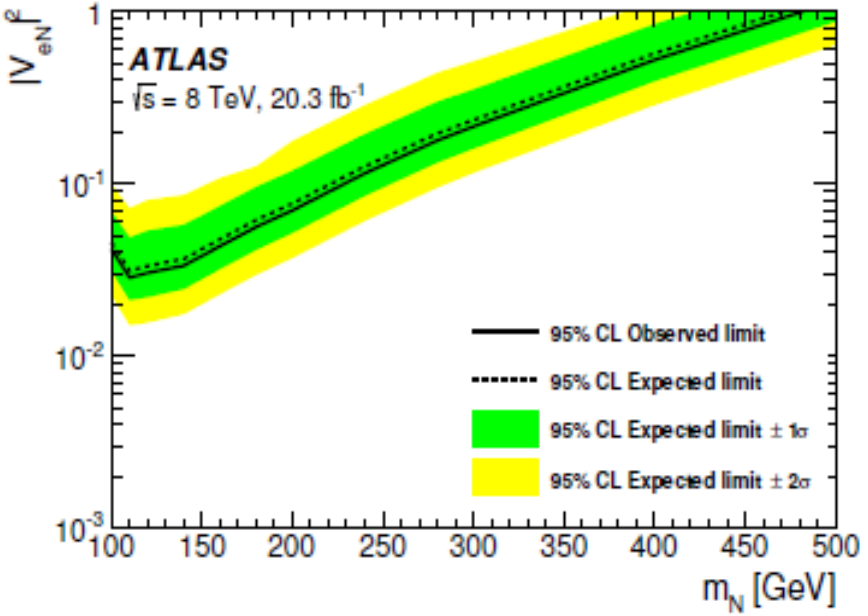
Type-III seesaw

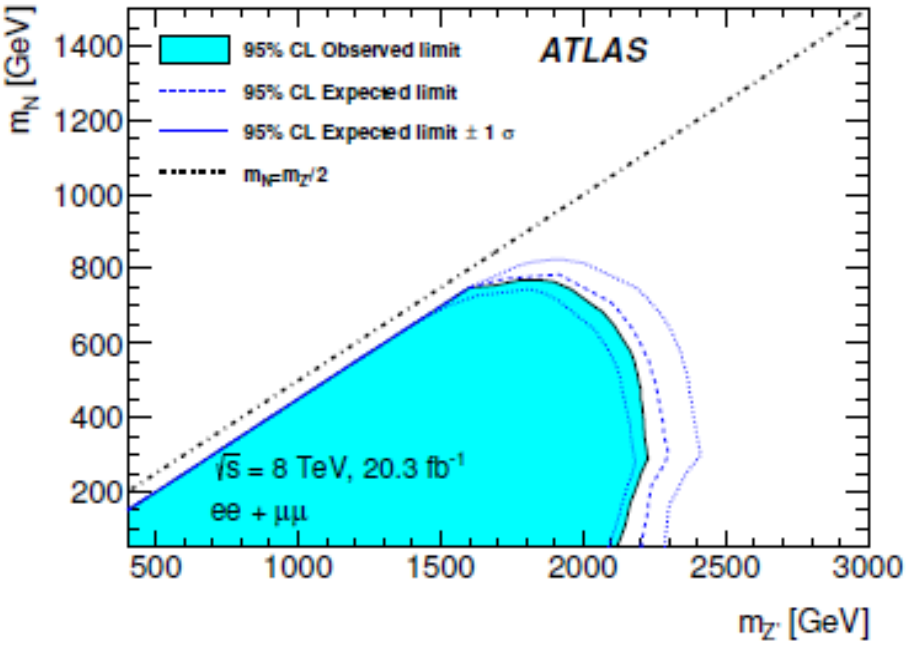
- Results are interpreted as vector-like leptons and tupe-III seesaw
- Limits on vector like: 129-176 GeV(114-168 GeV)
- Limits on typeIII seesaw: 100-430 GeV(100-468 GeV)

ATLAS: arXiv:1506.01291

Heavy Majorana neutrinoes

- Looks for a pair of same sign high-p_T leptons and high p_T jets
- Limits are set in the context of:
  - Minimal extension of the SM
    - Limit on mixing between SM neutrinoes and Majorana neutrinoes: couplings below $|V_{\mu N}|^2 = 0.0028$; $|V_{eN}|^2 = 0.029$ are excluded
  - Left-right symmetric extension of the SM
    - Heavy gauge boson masses beow 400 GeV are excluded



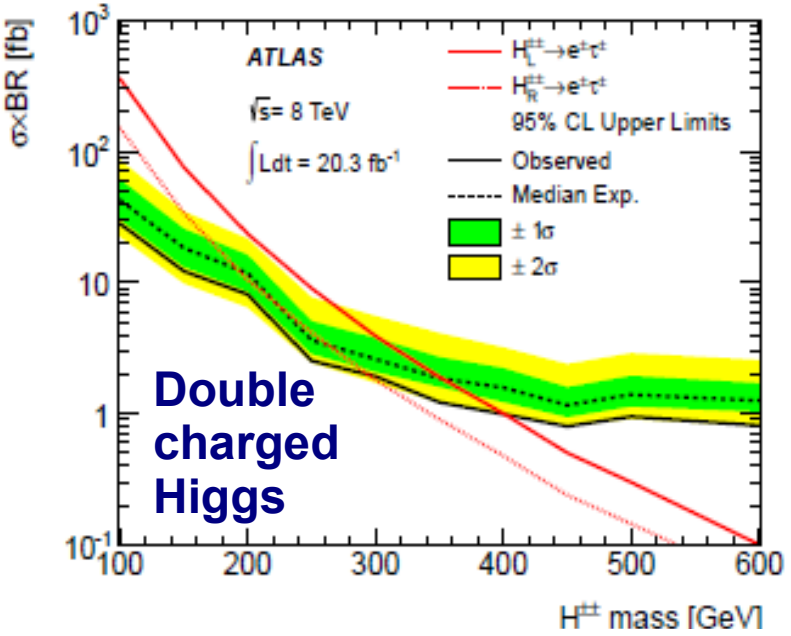


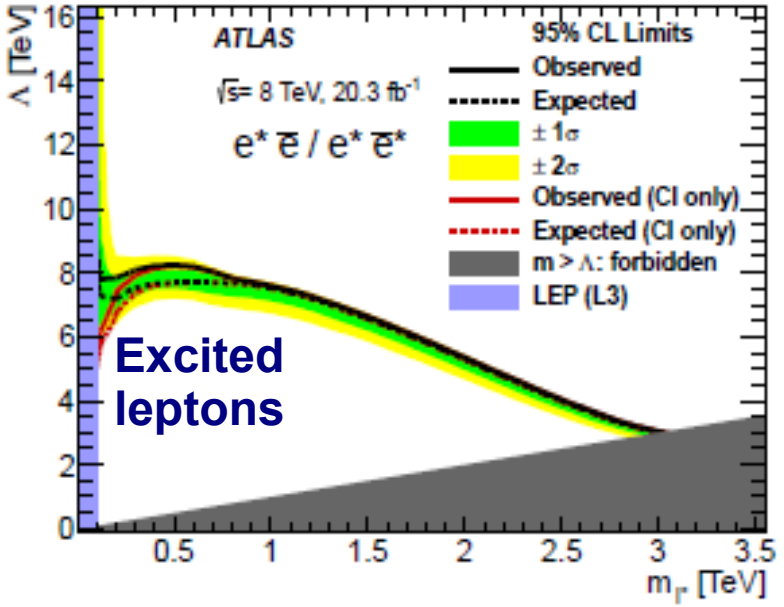
ATLAS: arXiv:1506.06020

Final state of 3 or more charged leptons

- Search for events with atleast 3 leptons, 2 of them atleast – e's or μ's, 3rd may be τ_{had}
- Limits put in the context of:
  - Doubly charged Higgs boson
    - For decay to eτ or μτ, mass limit is 400 GeV
  - Excited leptons
    - For Λ=M*,
      - M_{e^*} and M_{μ^*} < 3 TeV
      - M_{τ^*} < 2.5 TeV
      - M_{ν^*} < 1.6 TeV

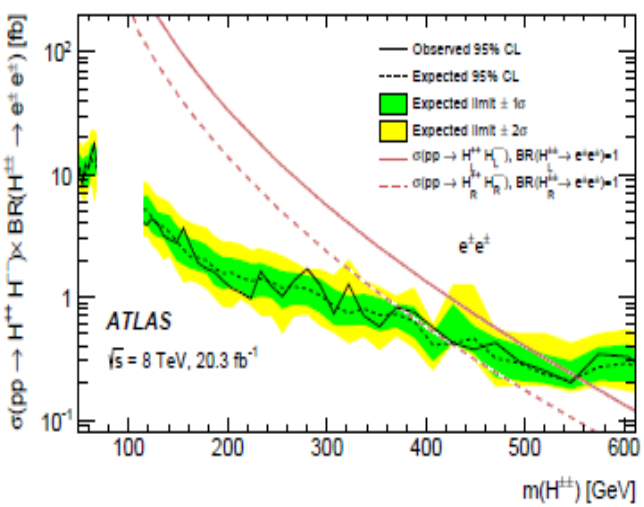
ATLAS: arXiv:1411.2921

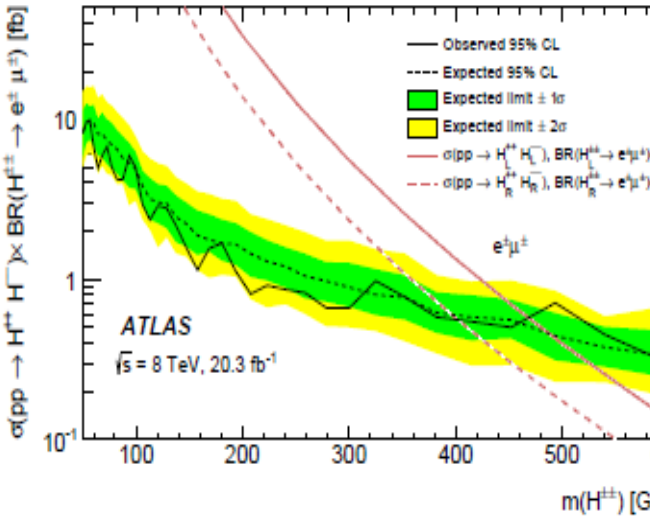


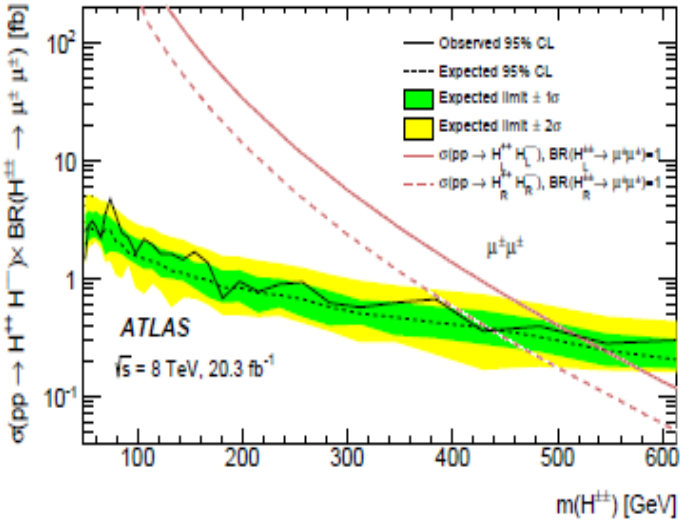


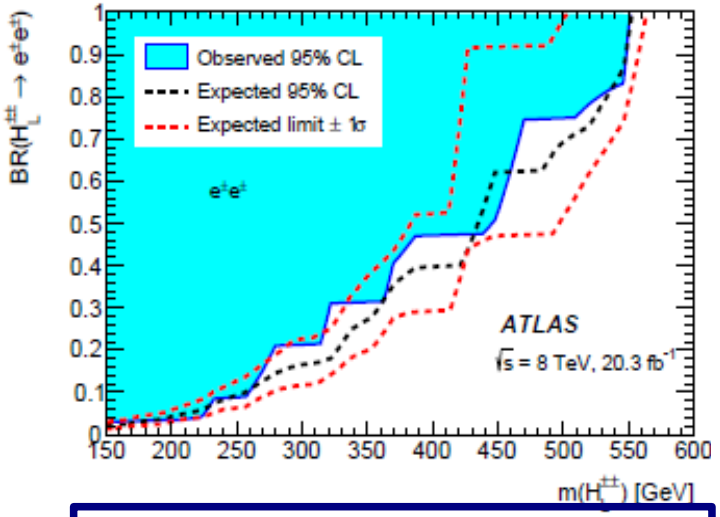
Anomalous same-sign lepton pairs and a pair of doubly charged Higgs bosons

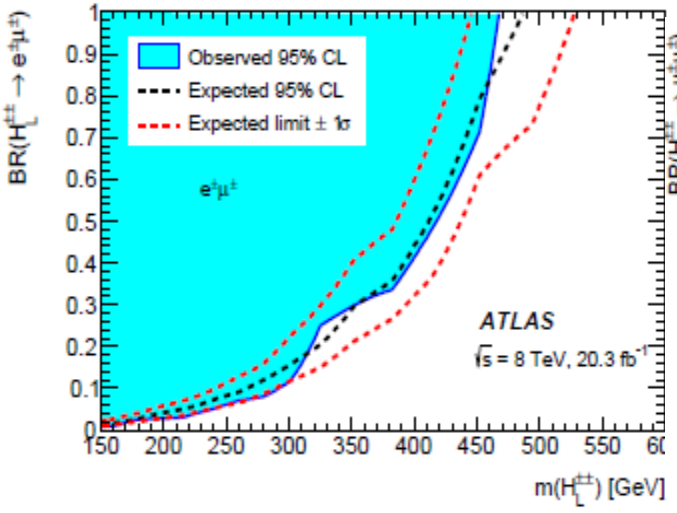
- Search for same sign dileptons: e^+e^+, $\mu^+\mu^+$, $e^+\mu^+$

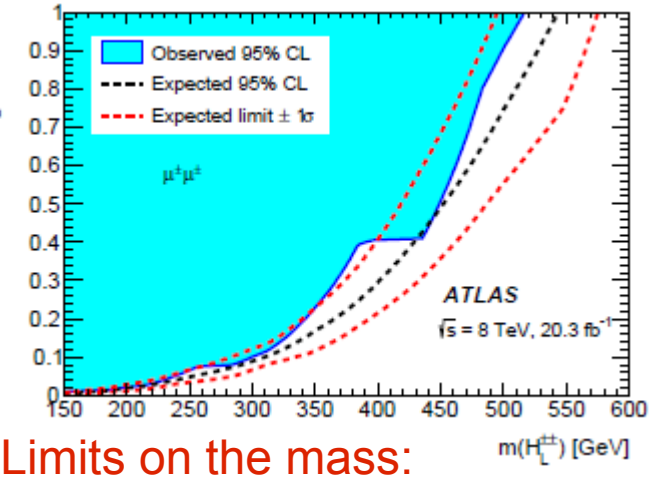








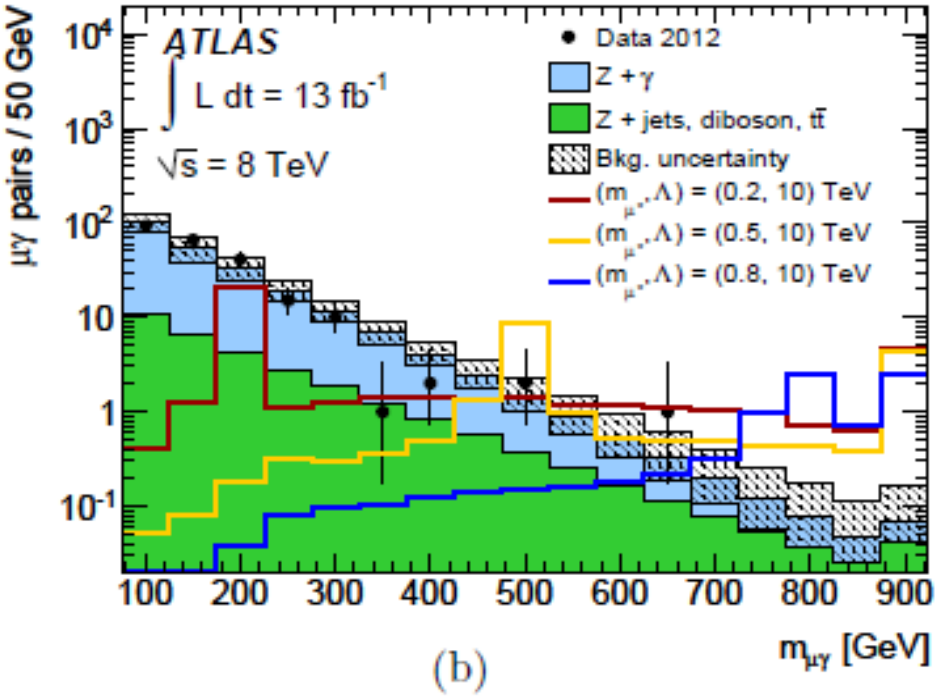




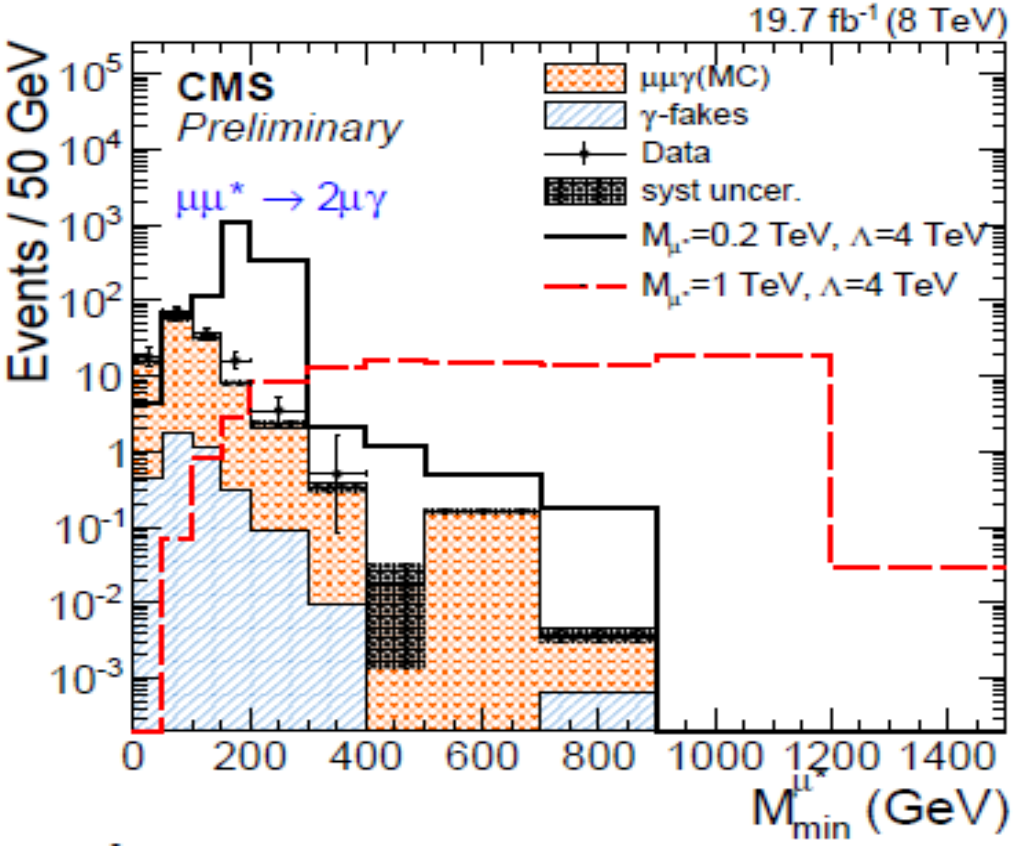
ATLAS: arXiv:1412.0237

Limits on the mass:
H_L – 465-550 GeV
H_R – 370-435 GeV

Excited leptons



(b)

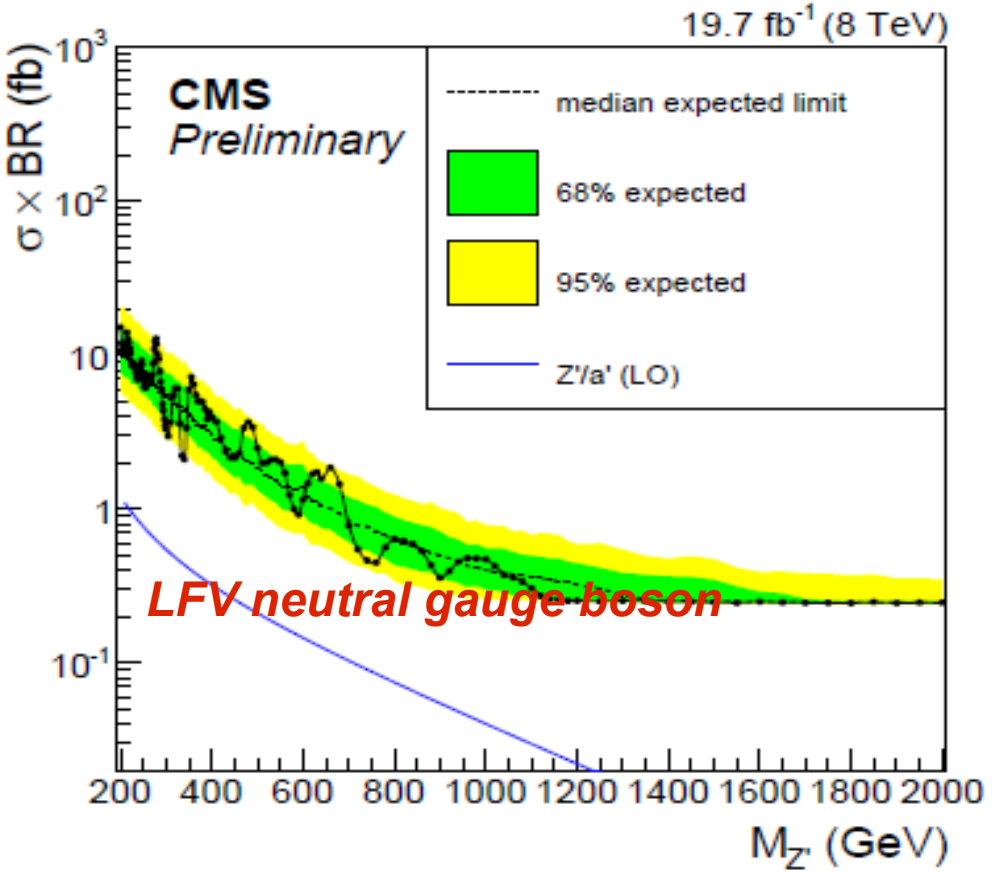


Type III seesaw - ATLAS

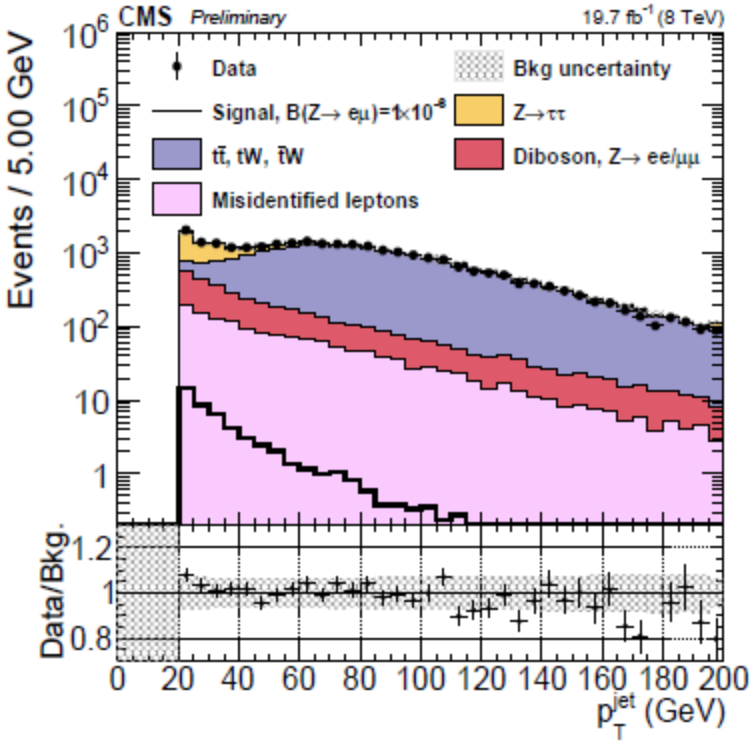
TABLE I. Event yields for opposite-sign (OS) and same-sign (SS) selection for predicted backgrounds, data, and type-III seesaw lepton pair-production with masses of 150 and 300 GeV. The reported errors include both the statistical and systematic uncertainties.

	OS	SS
Fake Leptons	1.4 ± 0.9	0.67 ± 0.42
Z+jets	2.4 ± 1.2	0.06 ± 0.23
$WW/WZ/ZZ$	9.2 ± 2.9	1.95 ± 0.58
$t\bar{t}$ $(+W/Z)$ and single top	17.9 ± 6.9	0.47 ± 0.25
Total	31.0 ± 7.7	3.15 ± 0.80
Data	25	4
Signal $m_{L/N} = 150$ GeV	9.5 ± 1.6	20.3 ± 2.3
Signal $m_{L/N} = 300$ GeV	12.2 ± 0.6	5.7 ± 0.5

CMS: LFV decays of heavy resonances (extra dimension)



LVF -Z

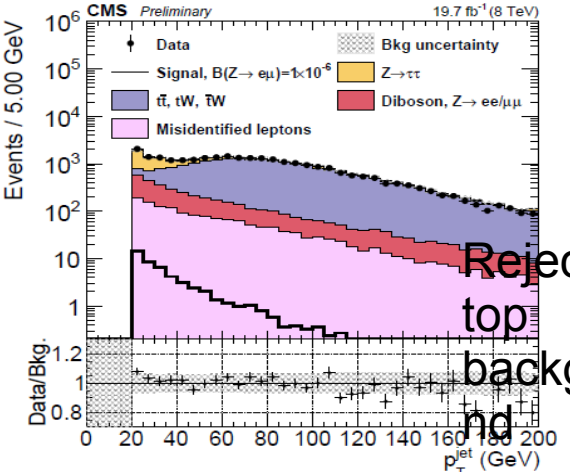


- *Z decays*
  - BR of Z->emu < 4.10^-60 via one loop decays with flavour-oscillating neutrinoes in the SM (QUES: is it really SM??)
  - New physics (eg, massive Dirac or Majorana netrinoes) can change the BR to 10-9)
  - Direct probe of new physics

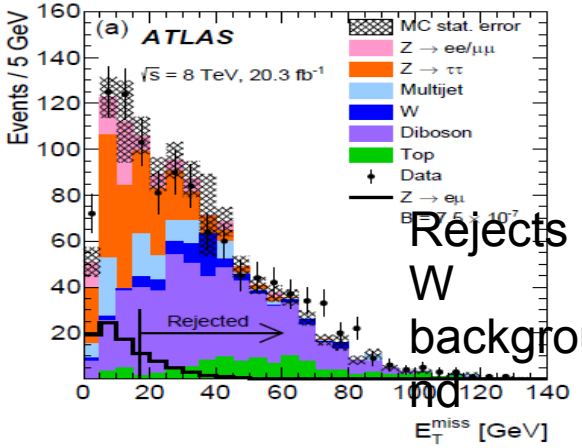
Figure 1: The leading jet p_T for events where a well-identified electron and muon are selected, the trigger requirement is met and that satisfy $60 < m_{e\mu} < 120\,\text{GeV}$. The signal is drawn on the bottom (not stacked). The background uncertainty band includes only uncertainties from statistical precision and systematic effects on the normalization.

LVF in Z decays: Backgrounds and Selection

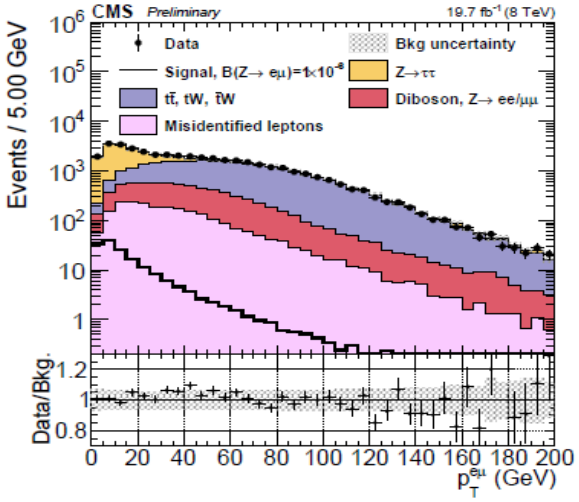
- Backgrounds: z->tautau, leptonic decays of WW, ttbar, tW, WZ, ZZ, mis-identified leptons from W+jets and Z+jets
- Z: oppositely charged μ and e
- Events vetoed: third lepton passinng loose criteria (rejects multi-lepton backgrounds e.g., WZ or ZZ)
- 60 (70) < Memu < 120 (110) in CMS(ATLAS)
- Top background (eg, tW, tt) rejection: PTjet < 40 (
- Reject WW, trasnverse mass < 60
- PT of the Z candidate < 10 GEV
-



Rejects top background



Rejects W background



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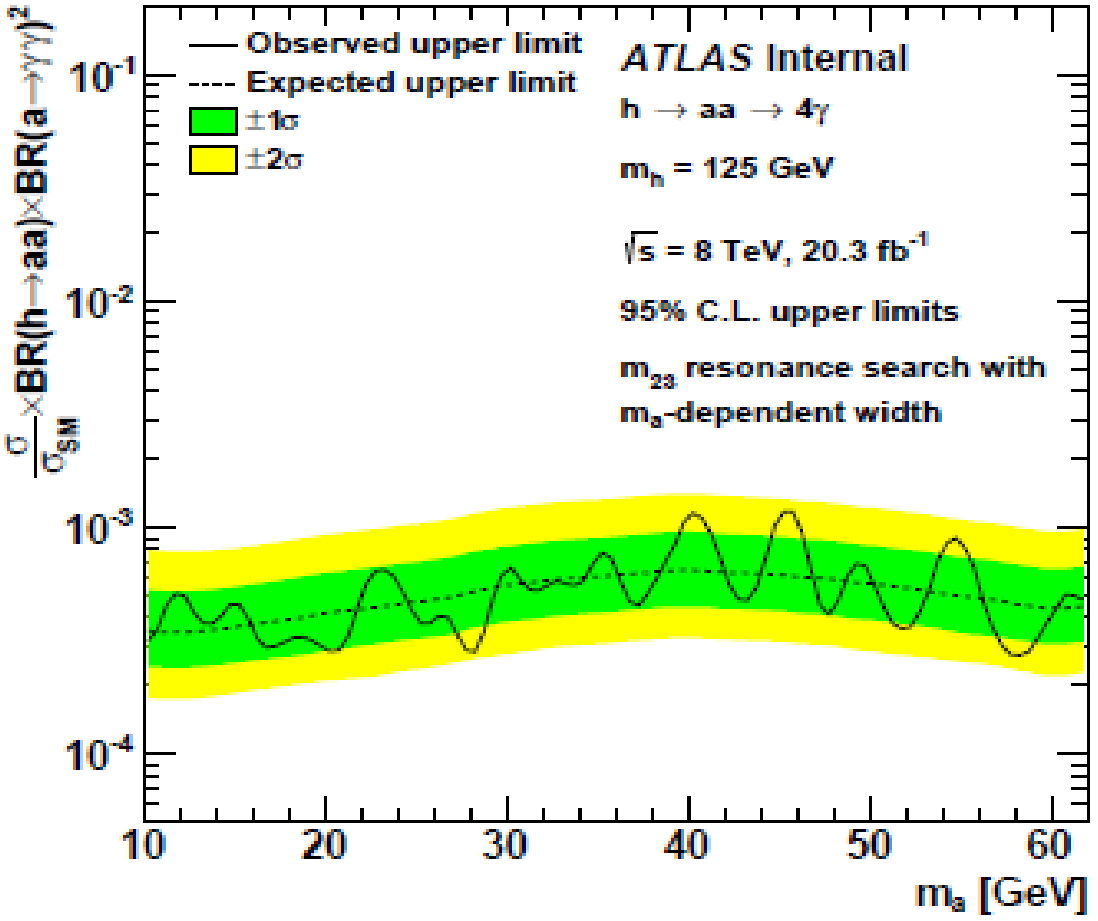
Type III seesaw - CMS

Table 2: Predicted background yields with systematic uncertainties and observed data yields for all event categories. The values for three signal mass points are listed. For the EWK prompt and fake background sources, the statistical uncertainties are given in parenthesis.

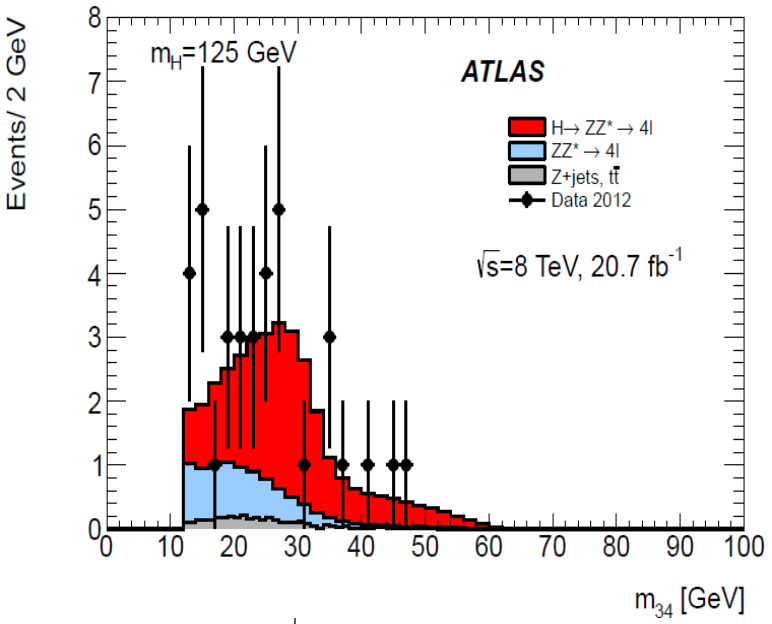
Category	EWK prompt	Fake	Total background	Data	Signal mass M_Σ (GeV)		
					180	240	340
$\mu^+\mu^+\mu^-$	4.7±1.2 (0.4)	0.4±0.5 (0.4)	5.0±1.3	9	4.3±0.3	2.0±0.1	0.55±0.04
$e^+e^+e^-$	2.9±0.8 (0.3)	1.4±1.1 (0.8)	4.3±1.4	6	2.8±0.3	1.4±0.1	0.39±0.04
$\mu^+\mu^+e^-$	0.6±0.2 (0.1)	2.1±1.3 (0.7)	2.7±1.3	1	6.7±0.4	2.4±0.2	0.56±0.04
$\mu^+e^+\mu^-$	7.1±1.8 (0.6)	3.5±1.9 (0.7)	10.6±2.6	8	9.8±0.6	4.2±0.3	1.06±0.08
$e^+e^+\mu^-$	0.7±0.2 (0.1)	2.8±1.5 (0.6)	3.6±1.6	1	5.9±0.5	2.2±0.2	0.51±0.04
$\mu^+e^+e^-$	4.8±1.2 (0.4)	1.0±0.8 (0.6)	5.7±1.4	6	8.7±0.7	3.7±0.3	0.97±0.08
Total sign +	20.7±2.6 (0.9)	11.2±3.1 (1.6)	31.9±4.0	31	38.2±1.2	15.8±0.5	4.04±0.14
$\mu^-\mu^-\mu^+$	2.4±0.6 (0.3)	0.2±0.5 (0.5)	2.6±0.8	2	2.1±0.2	0.96±0.07	0.24±0.02
$e^-e^-e^+$	2.4±0.7 (0.3)	2.7±1.6 (0.9)	5.1±1.8	5	1.4±0.1	0.66±0.07	0.17±0.02
$\mu^-\mu^-e^+$	0.5±0.2 (0.1)	1.6±1.0 (0.6)	2.1±1.0	2	3.4±0.2	1.09±0.08	0.24±0.02
$\mu^-e^-\mu^+$	3.4±0.9 (0.4)	2.1±1.2 (0.7)	5.5±1.5	2	5.0±0.4	1.86±0.14	0.46±0.04
$e^-e^-\mu^+$	0.6±0.2 (0.1)	2.3±1.3 (0.7)	2.9±1.4	1	2.8±0.2	0.96±0.08	0.22±0.02
$\mu^-e^-e^+$	3.4±0.8 (0.4)	2.0±1.2 (0.7)	5.4±1.5	4	4.5±0.4	1.71±0.15	0.42±0.04
Total sign -	12.6±1.5 (0.7)	10.9±2.9 (1.6)	23.5±3.3	16	19.2±0.7	7.2±0.25	1.75±0.07
Total	33.3±3.9 (1.2)	22.1±5.2 (1.7)	55.4±6.5	47	57.5±1.4	23.1±0.6	5.78±0.16

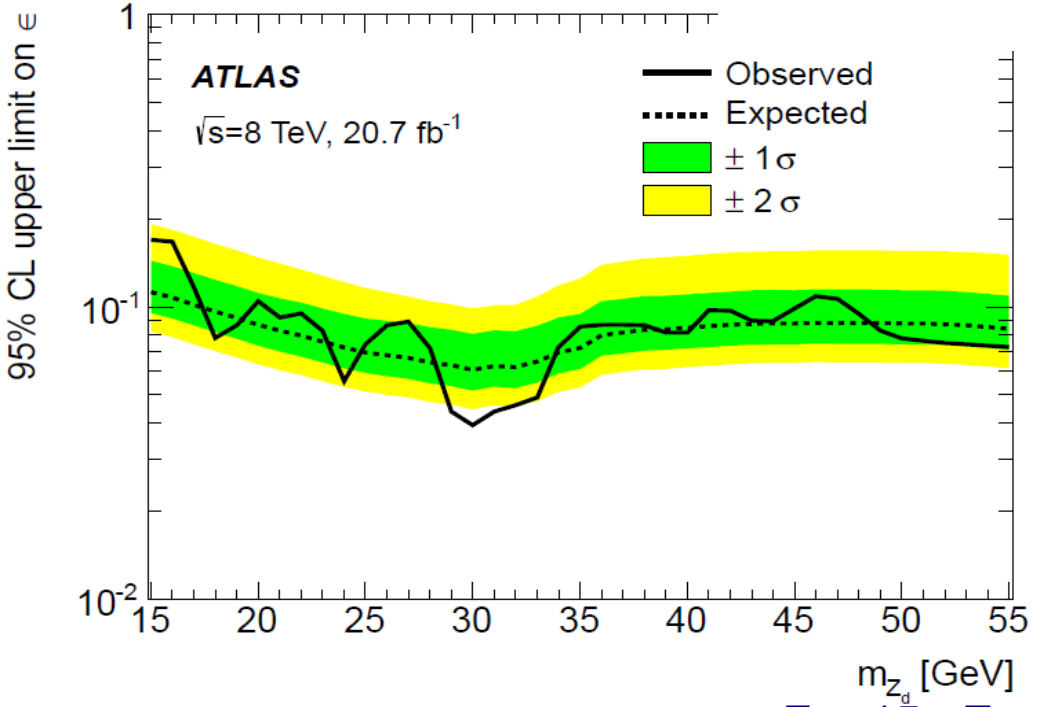
Multi-photon search - ATLAS



H–>ZZ$_d$–>4l: Results and Limits

- Possible combination of same flavour, opposite charge leptons are made
- m_{12}: pair closest to Z mass, m_{34}: other pair
- Search is performed in m_{34} mass spectrum
  - Template fit of m_{34} is used for local access using signal and background templates from the MC



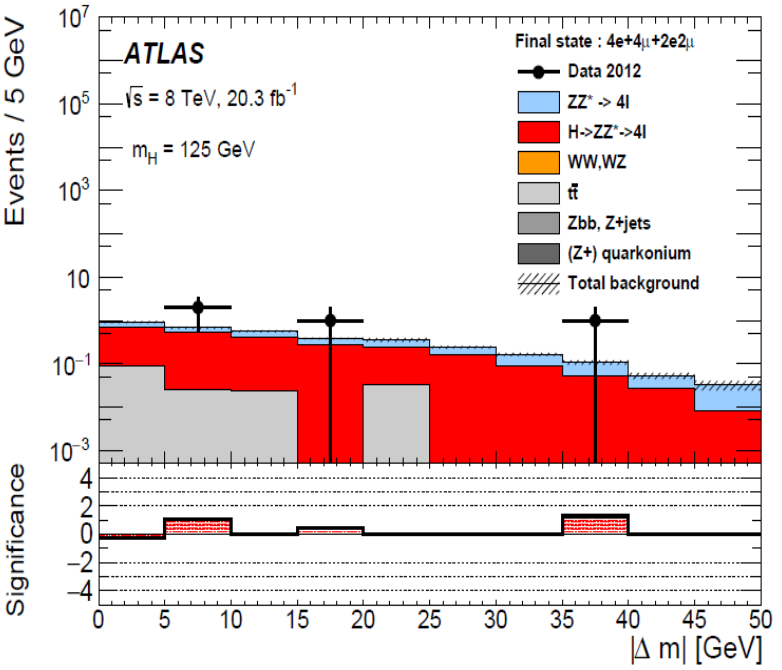


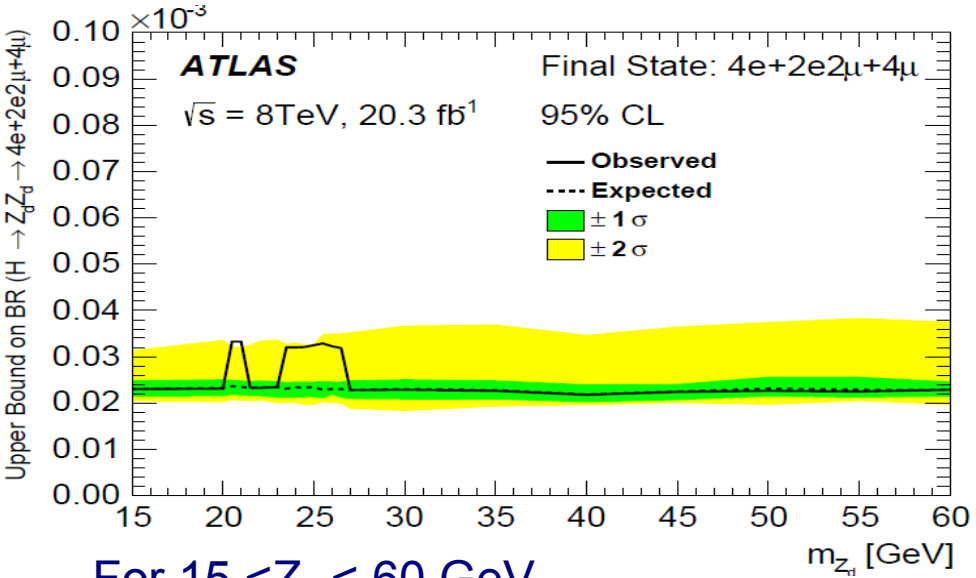
For 15 <Z_d < 35 GeV,

Limits on ε: (1.5-8.7)x10^{-4}

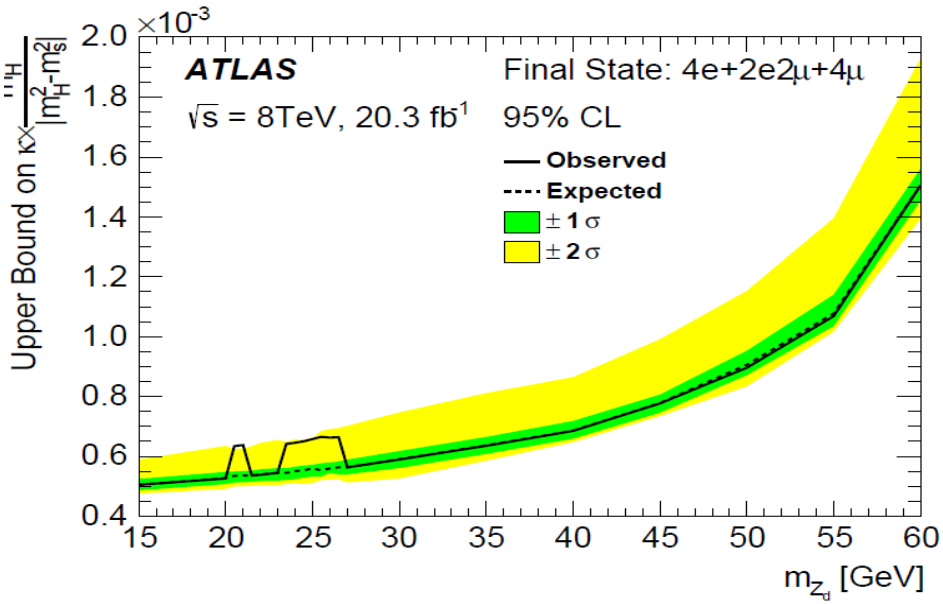
$H \to Z_d Z_d \to 4l$: Results and Limits

- Possible combination of same flavour, opposite charge leptons are made
- Pairs which have minimum $\Delta m = |m_{12} - m_{34}|$ are chosen
- Require:
  - $115 < m_{4l} < 130$
  - Veto Z, J/ψ, γ
  - Loose signal region: $m_{12} < m_H/2$ and $m_{34} < m_H/2$
  - Tight signal: $|M_d - m_{12}| < \delta m$



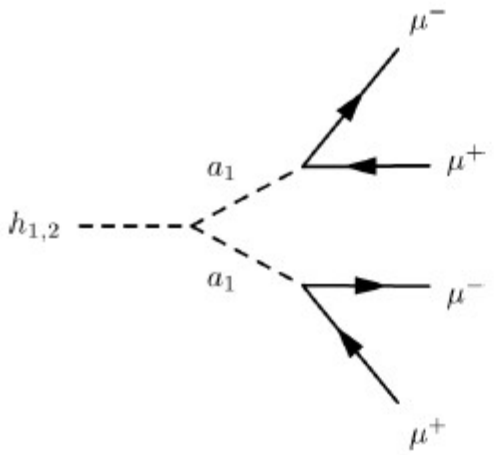


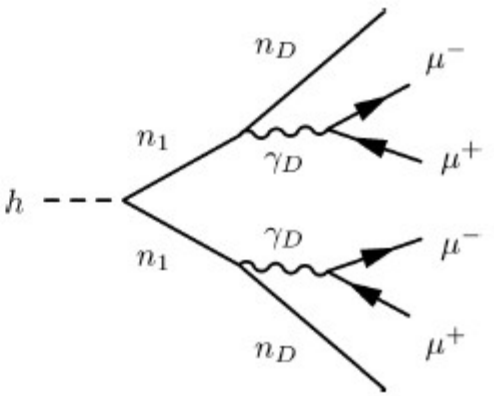
For $15 < Z_d < 60$ GeV,
Limits on $BR(H \to ZZ_d \to 4l)$: $(2\text{-}3)\times10^{-5}$



For $15 < Z_d < 60$ GeV,
Limits on κ: $(1\text{-}10)\times10^{-4}$

New light gauge bosons in Higgs boson decays to 4-μ final states

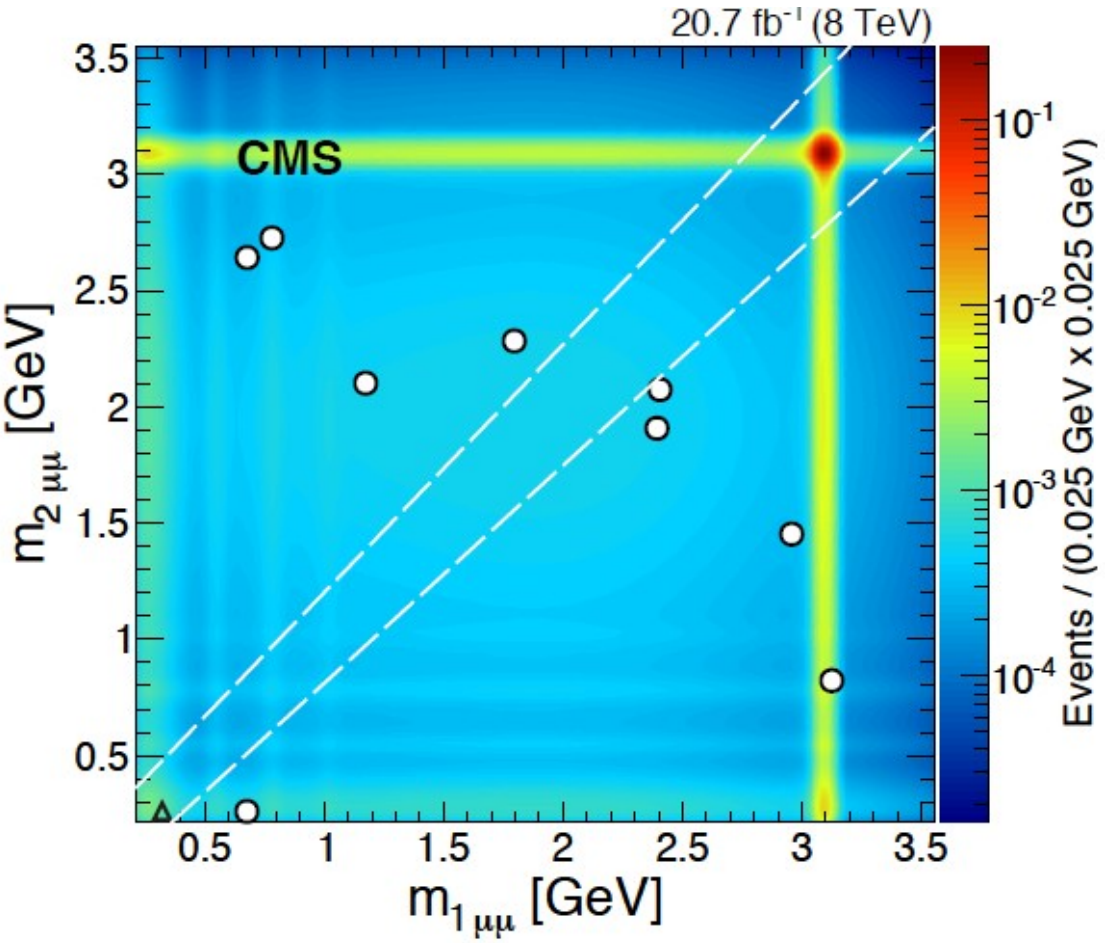




CMS: arXiv:1506.00424

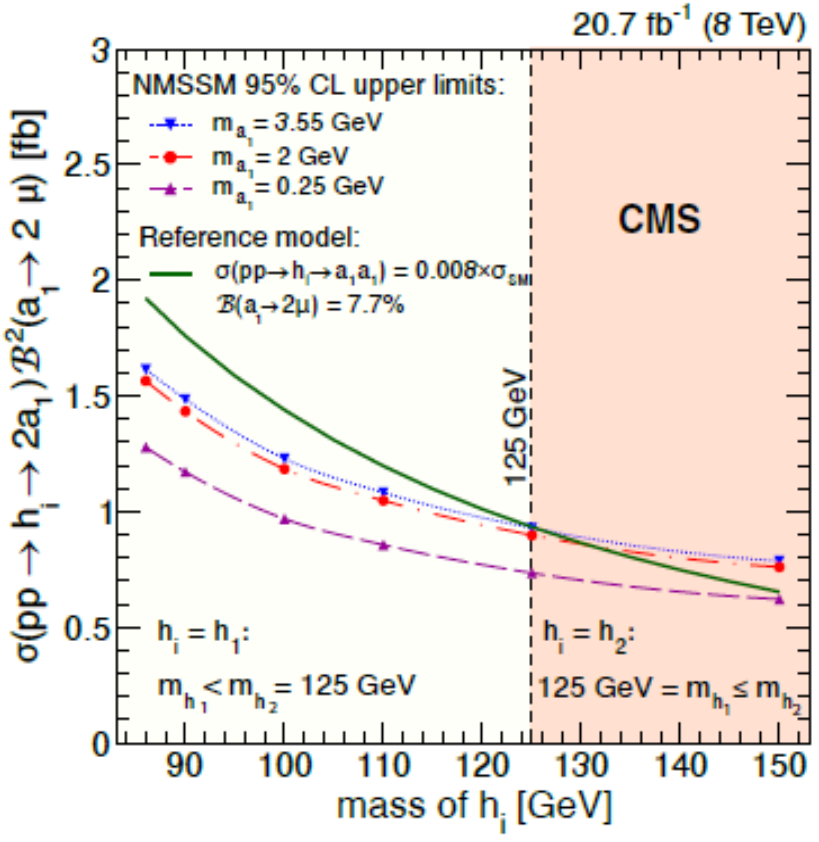
- Looks in the final state of 4 muons
- Models considered: NMSSM and Dark SUSY
- Require two pairs of dimuons
  - coming from a common vertex OR
  - $m_{\mu\mu} < 5$ GeV
  - Near in dR (<0.01)
- Require the invariant mass of two dimuons to be compatible with each other within the detector resolution
- To maintain model independence – no restriction on the 4μ invariant mass
- Dominated backgrounds are bb~ and J/psi

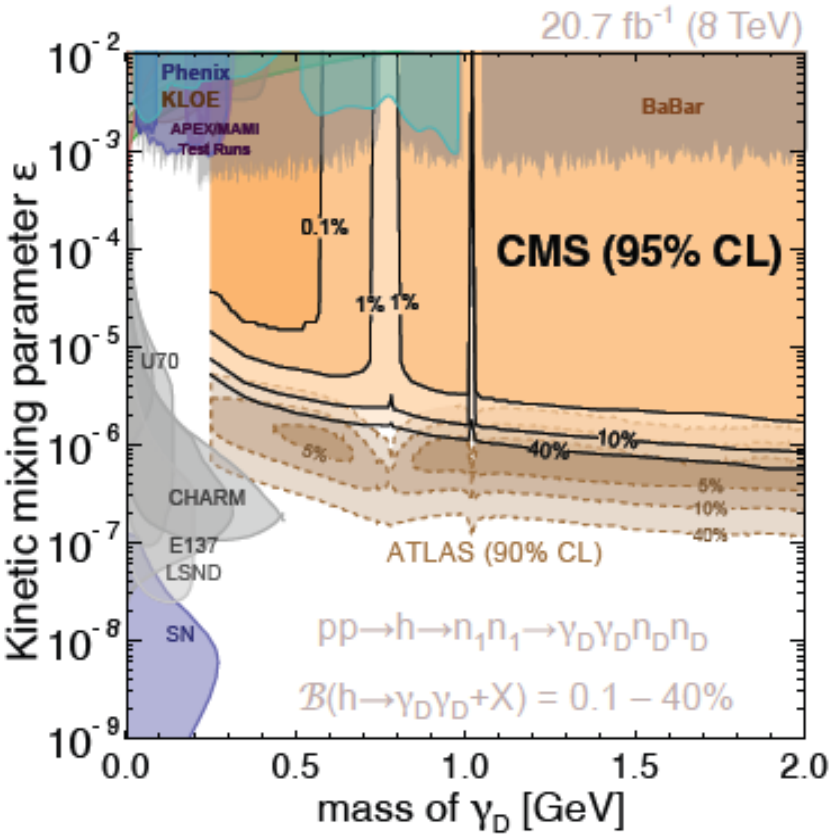
Estimation of the main background



- bb~
  - Modeled as a 2-D template $B_{bb\sim}(m1,m2)$ in invariant mass plane of the two dimuons
  - Construct the template as: $B_{17+8}(m1)$ X $B_{8+8}(m2)$
  - B17x8(m1): estimated from bb~ events rich sample:
    - One dimuon (with one muon p_T > 17 GeV) and one orphan (ungrouped) muon (with p_T > 8 GeV)
  - B8x8(m2): estimated from bb~ events rich sample:
    - One dimuon (with both muons p_T > 8 GeV) and one orphan (ungrouped) muon (with p_T > 17 GeV)
  - Both templates fitted with Crystall ball and Bernstein polynomials
- J/ψ pair: using simulation

Results





- After ublinding the signal region, one event was observed in the signal region (m1~m2)
- Limit is valid for new light boson masses in the range: $0.25 < m_a < 3.55$ and $m_h > 86$ GeV