Searches for resonances at the LHC,

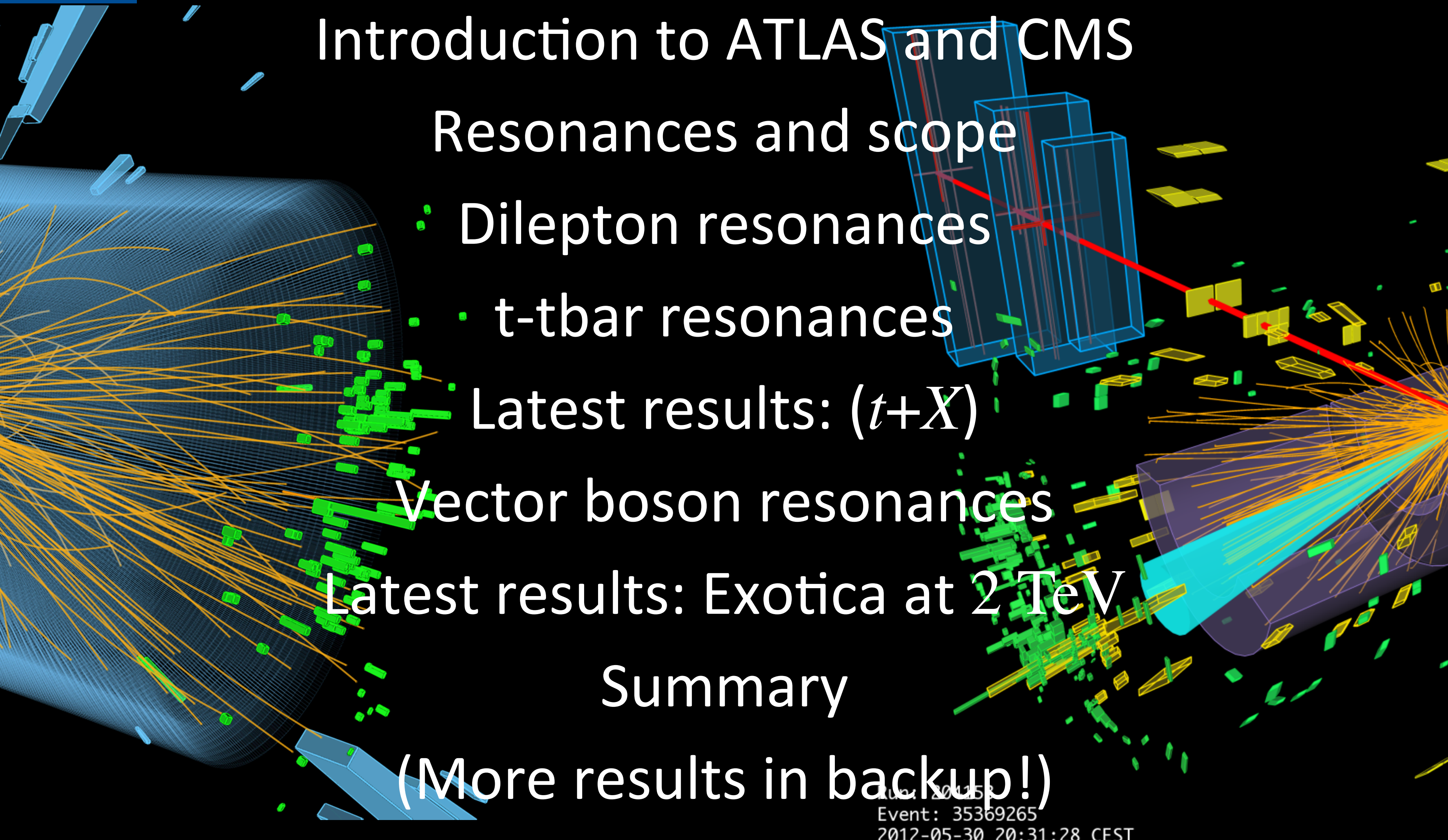
IAP Summer Solstice

Aidan Randle-Conde

Université Libre de Bruxelles (ULB)

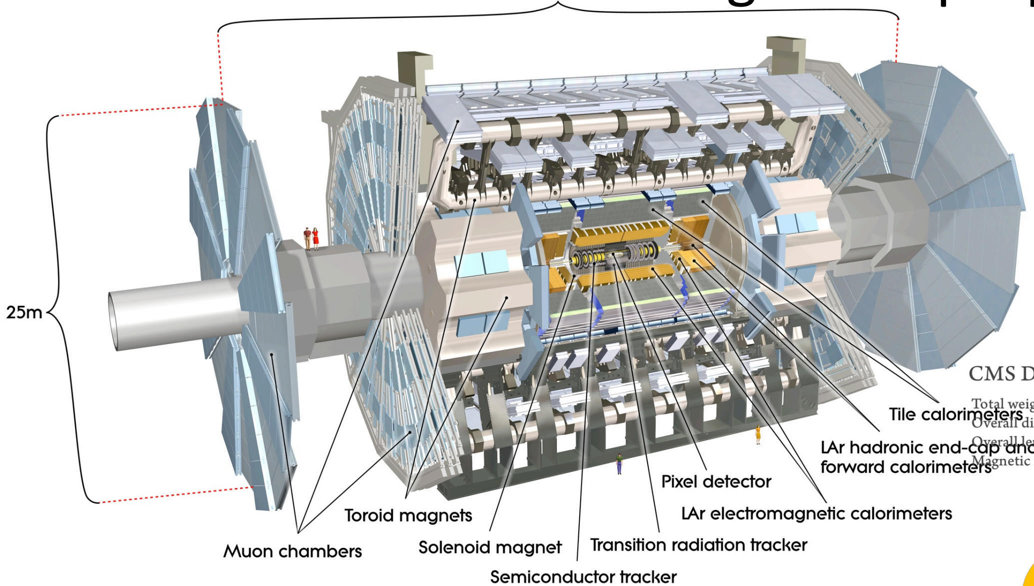
Overview

- Introduction to ATLAS and CMS
- Resonances and scope
  - Dilepton resonances
  - t-tbar resonances
  - Latest results: (t+X)
- Vector boson resonances
- Latest results: Exotica at 2 TeV
- Summary
- (More results in backup!)

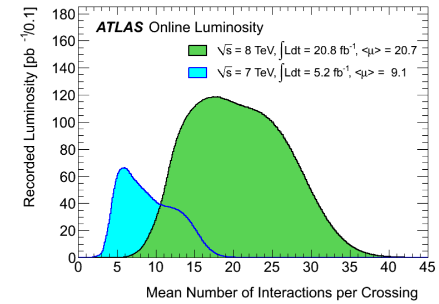


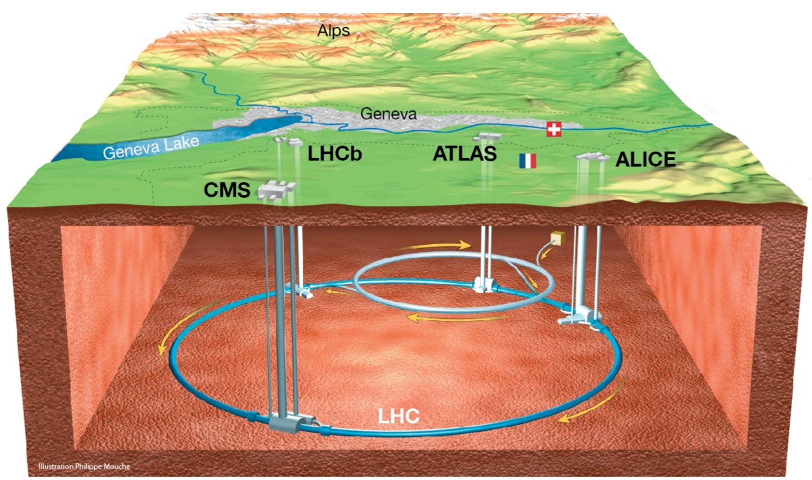
The LHC experiments

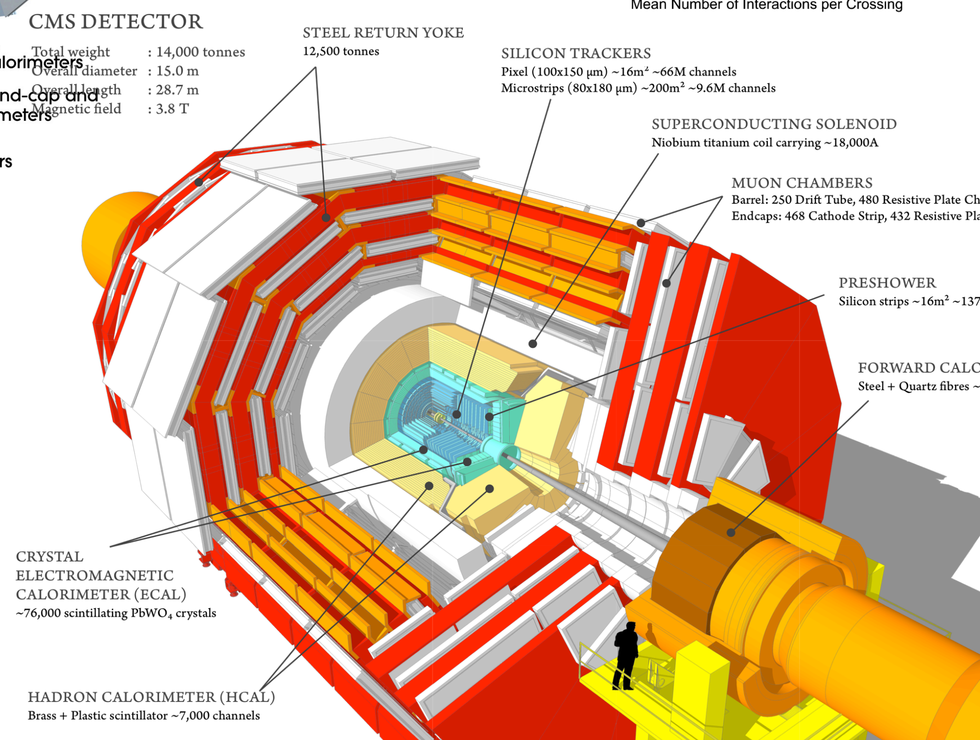
- ATLAS and CMS are two general purpose detectors at the LHC



LHC: *27 km, pp* collider with $\sqrt{s}=7, 8$ TeV

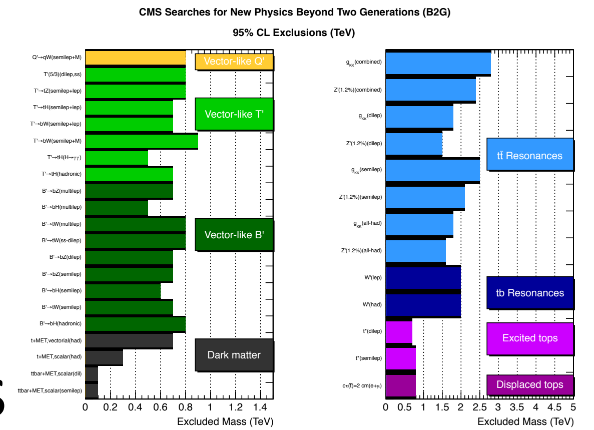


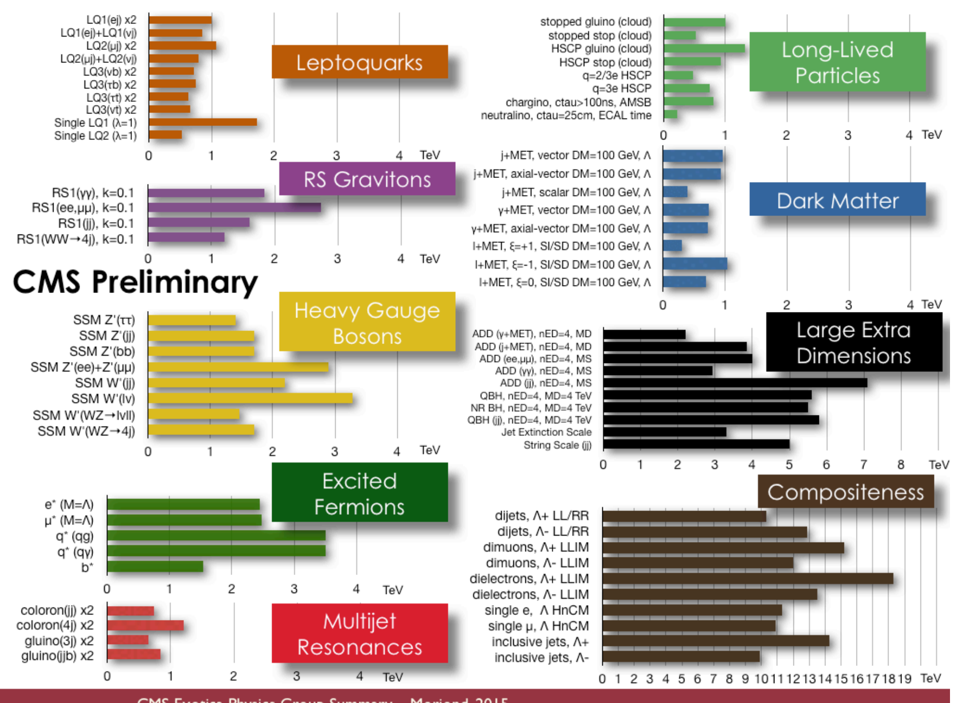


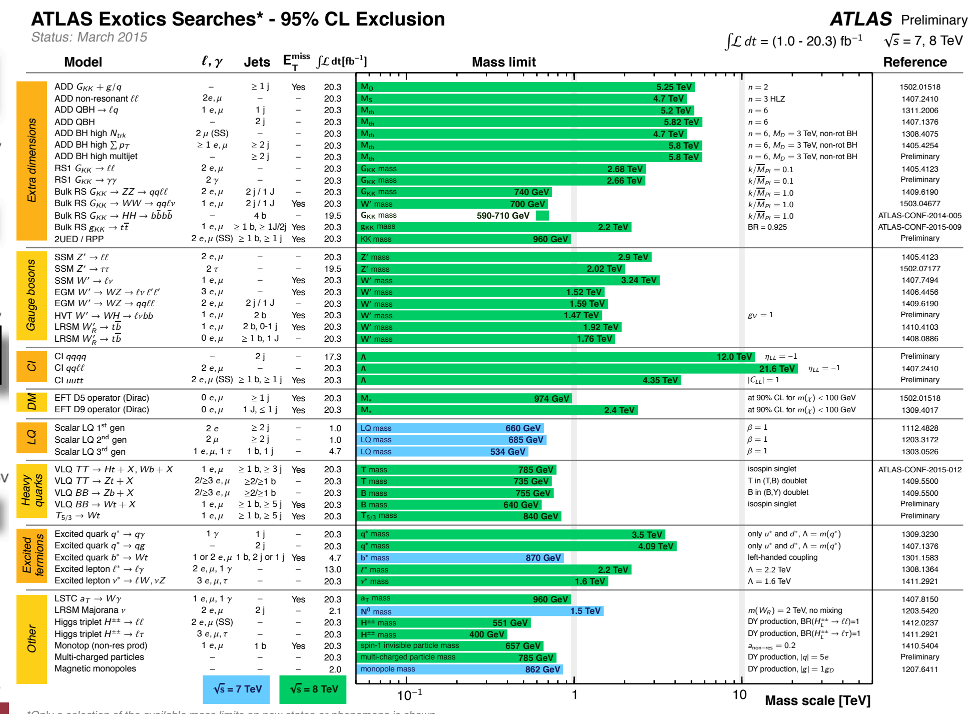


Resonances: scope

- A huge number of analyses fit into the topic "resonances"
- I can only cover a fraction of these!
- Mix of simple and complex final states







Dilepton resonances

- Both ATLAS and CMS have searched for dilepton resonances:
  - Simple final states, low backgrounds.
  - Look for peak above smoothly falling background.
- Main selections:

PRD 90, 052005

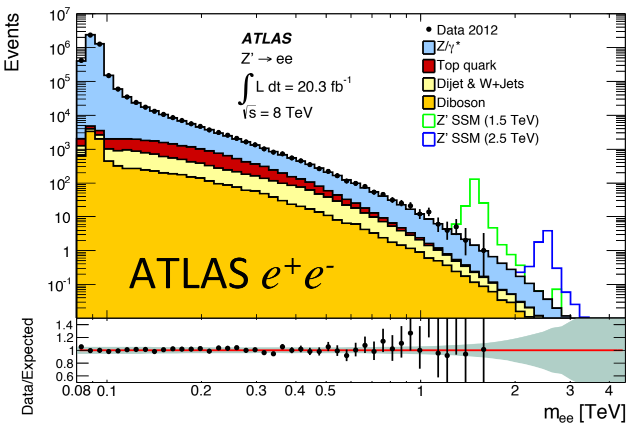
JHEP04(2015)025

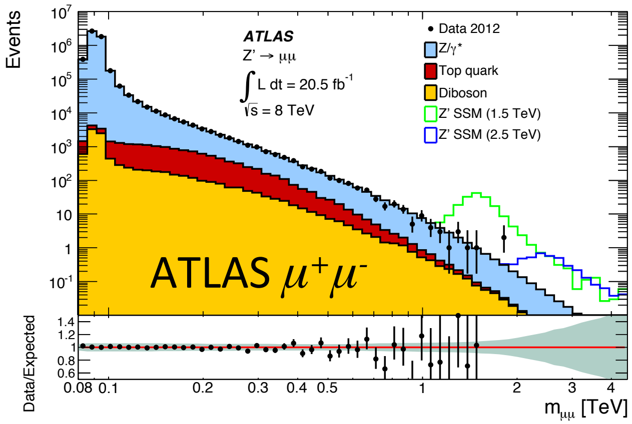
	ATLAS	CMS
ee	$E_{\mathrm{T}} > 40, 30$ GeV $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	$E_{\mathrm{T}} > 35, 35$ GeV $\lvert\eta\rvert < 1.442$ or $1.56 < \lvert\eta\rvert < 2.5$
$\mu\mu$	$p_{\mathrm{T}} > 25, 25$ GeV $\lvert\eta\rvert < 1.05$	$p_{\mathrm{T}} > 45, 45$ GeV $\lvert\eta\rvert < 2.4$ ($\lvert\eta\rvert < 2.1$ for triggering muon)

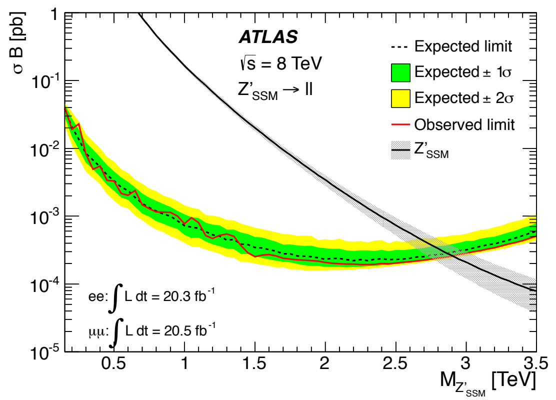
- Leading systematic uncertainties come from the PDFs for background modeling (more information in backup slides), and lepton scale factors (statistically limited at high transverse momentum.)
  - ATLAS: 4% for all channels.
  - CMS: 3% for dimuon, $4(6)\%$ for dielectron barrel-barrel (barrel-endcap) .
- (Ditau in backup- please ask if you want to see details.)

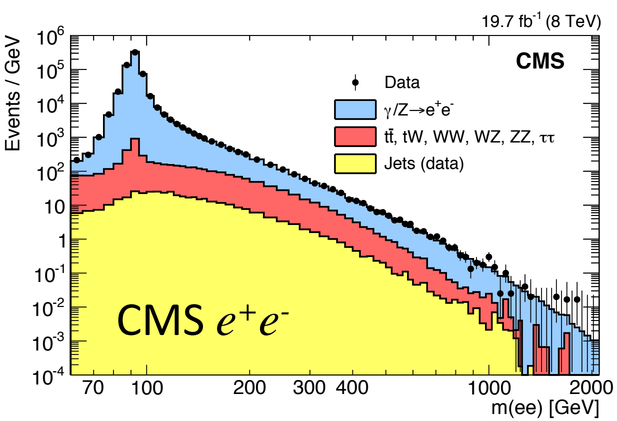
Dilepton resonances

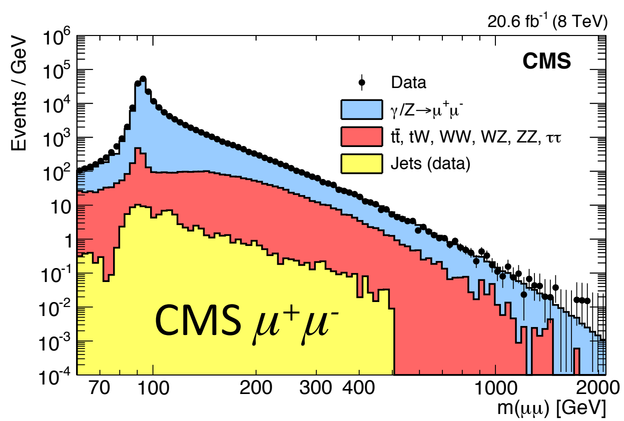
- Both ATLAS and CMS have searched for dilepton resonances:

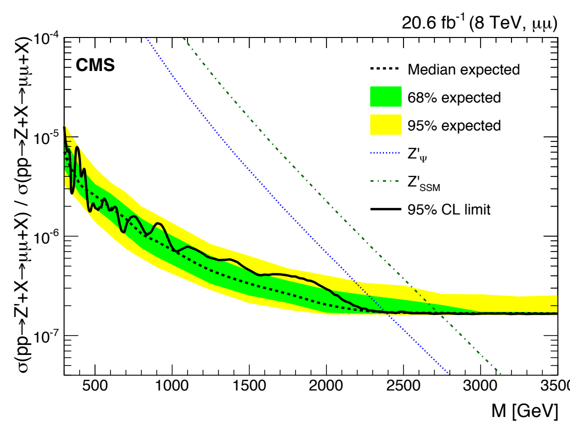












- Exclusion limits:

ATLAS: $m(Z'_{SSM}) > 2.90$ TeV   CMS: $m(Z'_{SSM}) > 2.90$ TeV

t-tbar resonances

- Both ATLAS and CMS search for t-tbar resonances.
- Many complex final states.
- Kinematic selections:

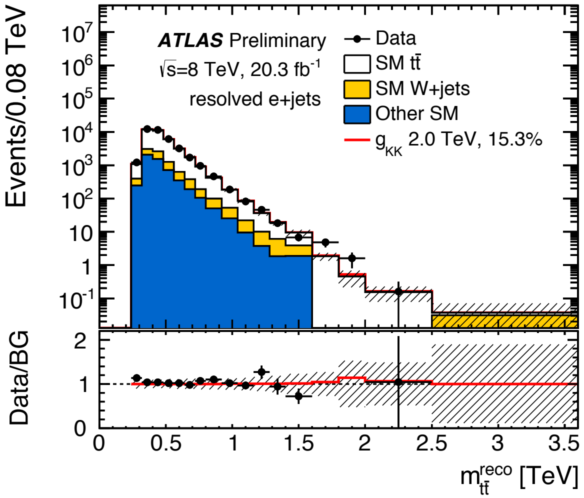
CMS-B2G-13-008

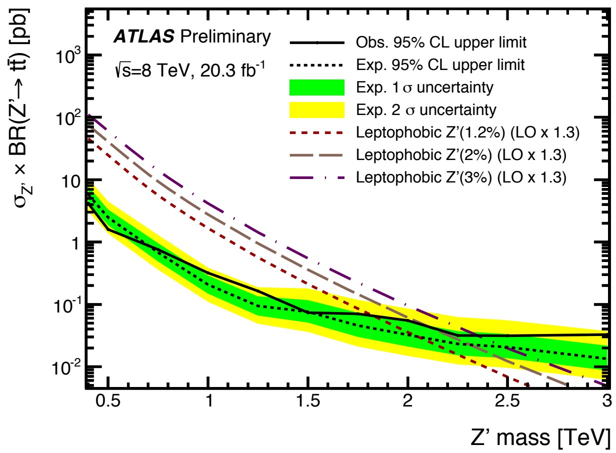
CERN-PH-EP-2015-090

	ATLAS	CMS
jets	anti-kT $\Delta R = 0.4$: $p_T(j) > 25$ GeV, $\lvert\eta(j)\rvert < 2.5$ anti-kT $\Delta R = 1.0$: $p_T(j) > 300$ GeV, $\lvert\eta(j)\rvert < 2.0$	$p_T(j) > 100, 50$ GeV $\lvert\eta(j)\rvert < 2.4$ Top-tagging
e	$E_T(e) > 25$ GeV $\lvert\eta(e)\rvert < 1.37$ or $1.52 < \lvert\eta(e)\rvert < 2.47$	$\lvert\eta(e)\rvert < 1.442$ or $1.56 < \lvert\eta(e)\rvert < 2.5$ $E_T(e) > 85, 20$ GeV (depending on final state)
μ	$p_T(\mu) > 25$ GeV $\lvert\eta(\mu)\rvert < 2.5$	$\lvert\eta(\mu)\rvert < 2.1, 2.4$ $p_T(\mu) > 85, 45, 20$ GeV (depending on final state)

- Dominant systematic uncertainties:
  - Jet energy scale, t-tbar normalisation, parton shower and fragmentation, luminosity.

t-tbar resonances





Limits:

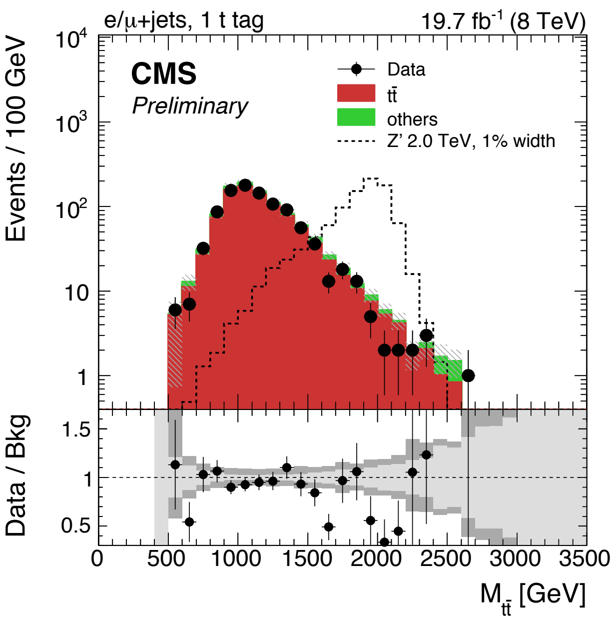
ATLAS

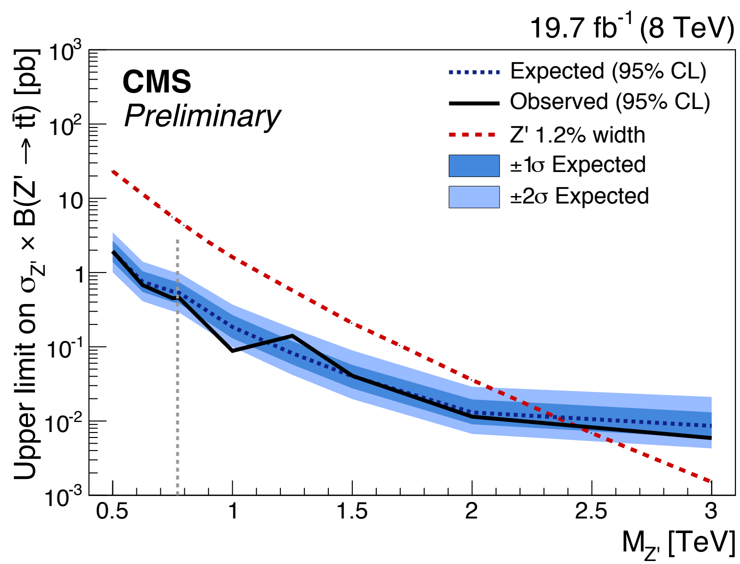
$m(Z') < 0.4$ TeV or

$m(Z') > 3.0$ TeV

CMS

$m(Z') > 2.4$ TeV



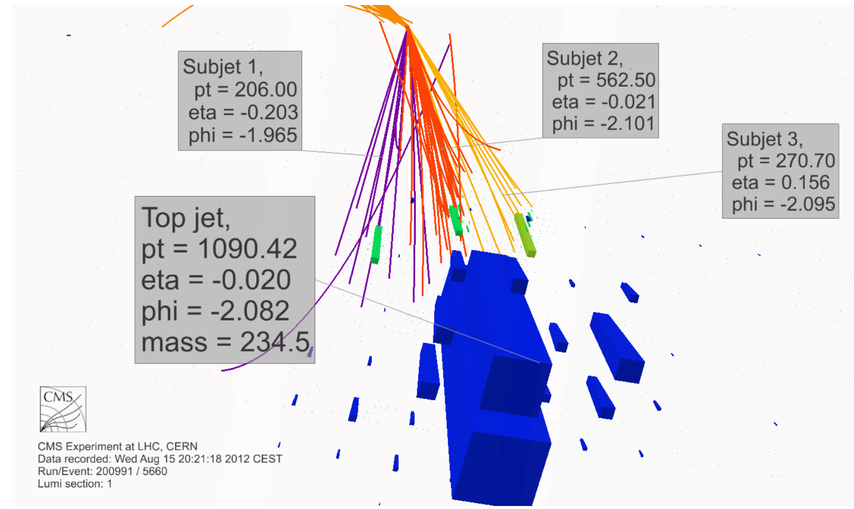


Top jet tagging

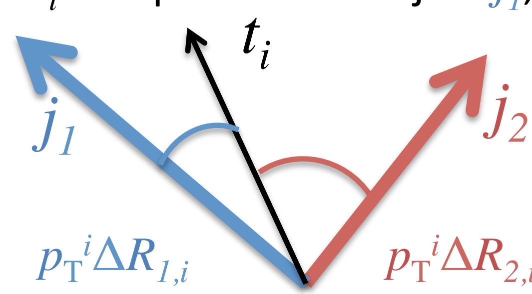
- Searches with boosted top quarks decaying hadronically can give rise to "top jets", with distinctive substructure.
- ATLAS and CMS have developed "top tagging" algorithms.
- Example from the CMS tagger:
  - $140 < m(j_t) < 250$ GeV
  - $N_{\text{sub-jets}} > 2$
  - Minimum pairwise mass, $m_{min} > 50$ GeV
- The "sub-jettiness" is defined as τ_N:

$$\tau_N = \sum_i p_T^i \min\{\Delta R_{1,i} \ldots \Delta R_{N,i}\} \Big/ \sum_i p_T^i R_0$$

  - R_0 is the characteristic jet radius.
  - τ_N measures consistency with a top decay.
  - τ_i/τ_j are discriminating variables, peaking near 1 for i sub-jets and 0 for j sub-jets.
- Further selections per analysis.
- Excellent discussion in the ATLAS paper: Eur. Phys. J. C (2015) 75:165



Track t_i compared to sub-jets j_1, j_2:



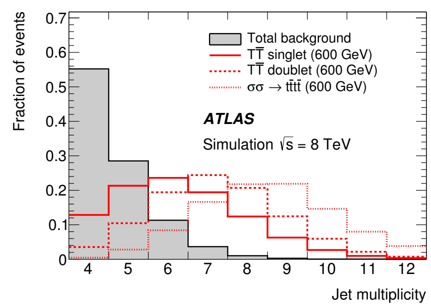
Latest results: $T \rightarrow tH$

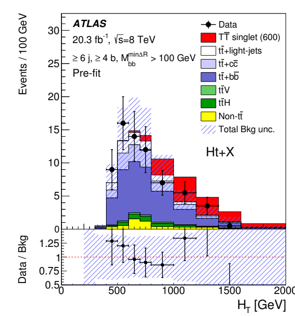
- ATLAS and CMS investigate vector like T quarks decaying to a tH.
- The CMS search makes use of boosted t-jet reconstruction:
  - At least one t-jet with $p_{\mathrm{T}} > 200$ GeV, that contains at least one b tagged jet.
  - At least one jet consistent with a scalar boson (two b tagged jets and $m(j_{\mathrm{CA}}) > 60$ GeV).
  - $H_{\mathrm{T}} > 720$ GeV

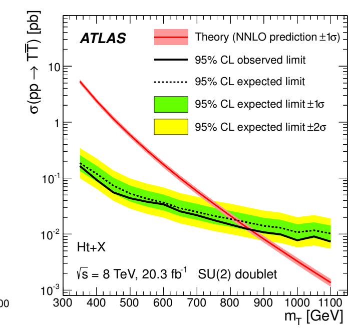
arXiV: 1505.04306

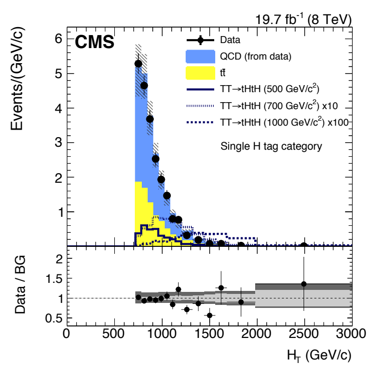
arXiV: 1503.01952

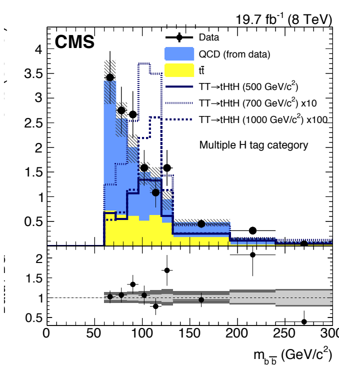
- For ATLAS there are non trivial kinematic selections and multiple final states.
- Dominant systematic uncertainties:
  - QCD estimate
  - Flavour tagging
  - Jet energy corrections
  - H-tagging

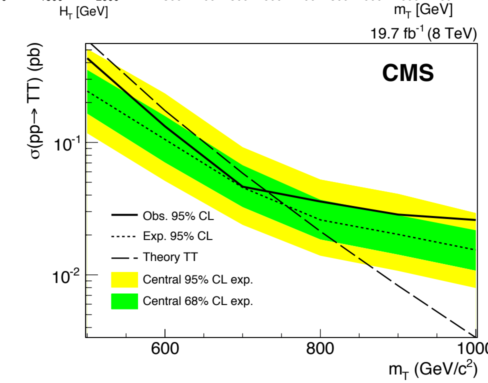








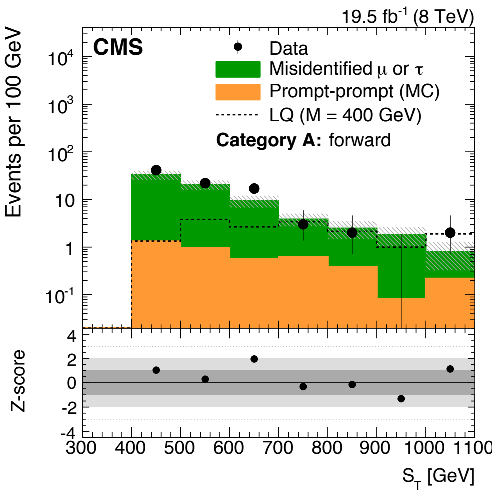


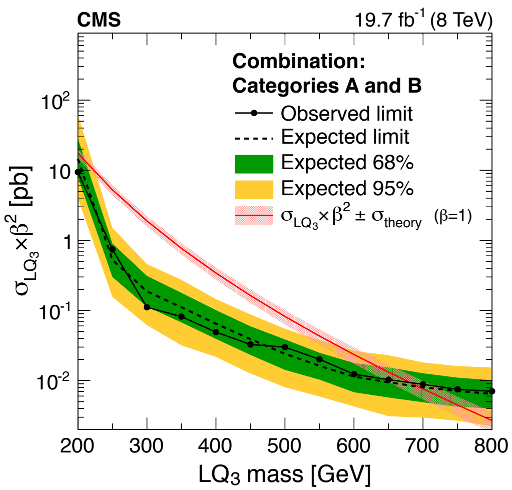


- Limits: ATLAS: $m(T \rightarrow tH) > 855$ GeV CMS: $m(T \rightarrow tH) > 745$ GeV

Latest results: $LQ \rightarrow t\tau$

- CMS investigate leptoquarks decaying to a $t\tau$ final state.
- Two categories A (B) on right:
- S_T is scalar sum of p_T in the event.





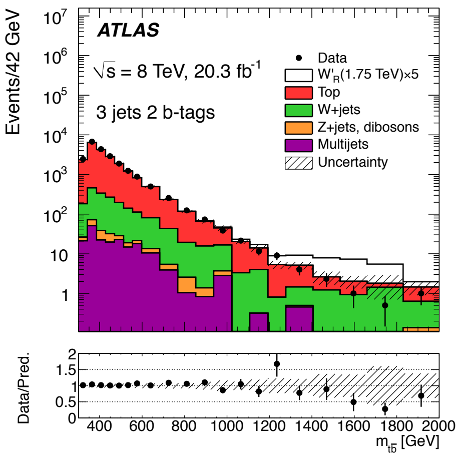
- Limits: $m(LQ \rightarrow t\tau) > 685$ GeV
- Dominant systematic uncertainties: t reconstruction, pileup, background estimation.

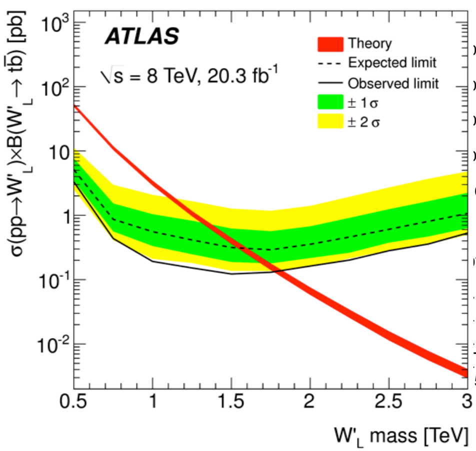
arXiV: 1503.09049	Category A (B)
τ_{had}	$p_T(\tau_{had}) > 20$ (35) GeV $\lvert\eta(\tau_{had})\rvert < 2.1$ (2.1)
e	$E_T(e) > 15$ (35) GeV $\lvert\eta(e)\rvert < 2.5$ (2.1)
μ	$p_T(\mu) > 25$ (30) GeV $\lvert\eta(\mu)\rvert < 2.1$ (2.1)
jet	$p_T(j) > 40$ (30) GeV $\lvert\eta(\mu)\rvert < 3.0$ (2.5)
E_T^{Miss}	No selection (>50 GeV)
S_T	Optimised by mass (S_T>1000 GeV)
$p_T(\tau_{had})$	Optimised by mass ($p_T(\tau_{had})$>20 GeV)
Leptons	Same sign $\mu\tau_{had}$ ($\mu\tau_{had}$ or $e\tau_{had}$)

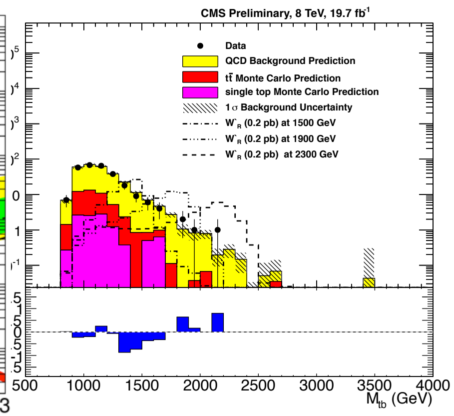
Latest results: $W' \rightarrow tb$

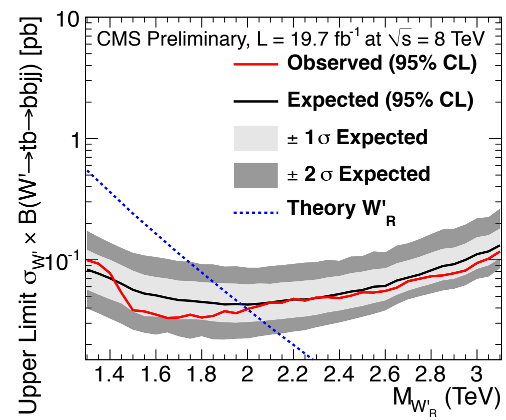
- ATLAS and CMS investigate W' boson decaying to tb final state.
- Dedicated algorithms for top-tagged jets and W' candidates.

Eur. Phys. J. C (2015) 75:165 | PLB 743 (2015) 235-255 | CMS-PAS-B2G-12009





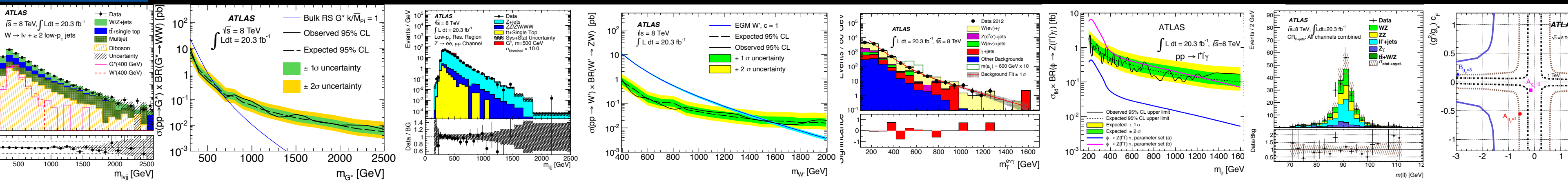




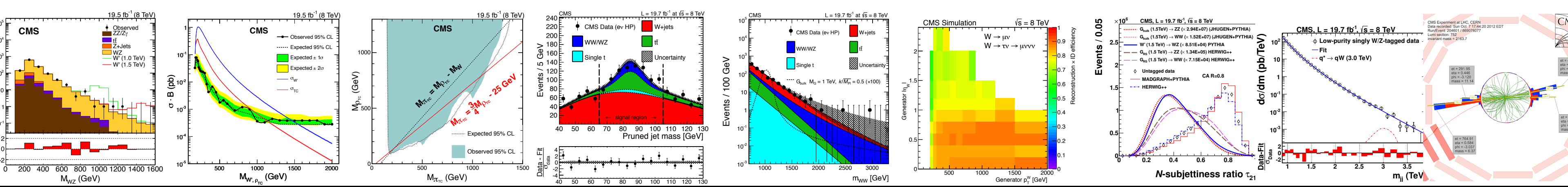
- Dominant systematic uncertainties: t-tbar production, top-tagging.
- Limits:

ATLAS: $m(W')_{\text{right handed}} > 1.92$ TeV CMS: $m(W')_{\text{right handed}} > 2.15$ TeV

Vector boson resonances



- Many final states (*lljj*, *llll*, *lllν*, *jjjj*, *lνjj*) to consider.
- Benchmark models include *W'*, Randall-Sundrum Graviton (G_{RS}), Techni-colour.
- Results are not necessarily easy to compare between experiments.
- Leading systematics are usually jet energy scale and jet energy resolution for hadronic final states, lepton scale factors and luminosity for purely leptonic states.
- I cannot cover everything, so I only show the limits!



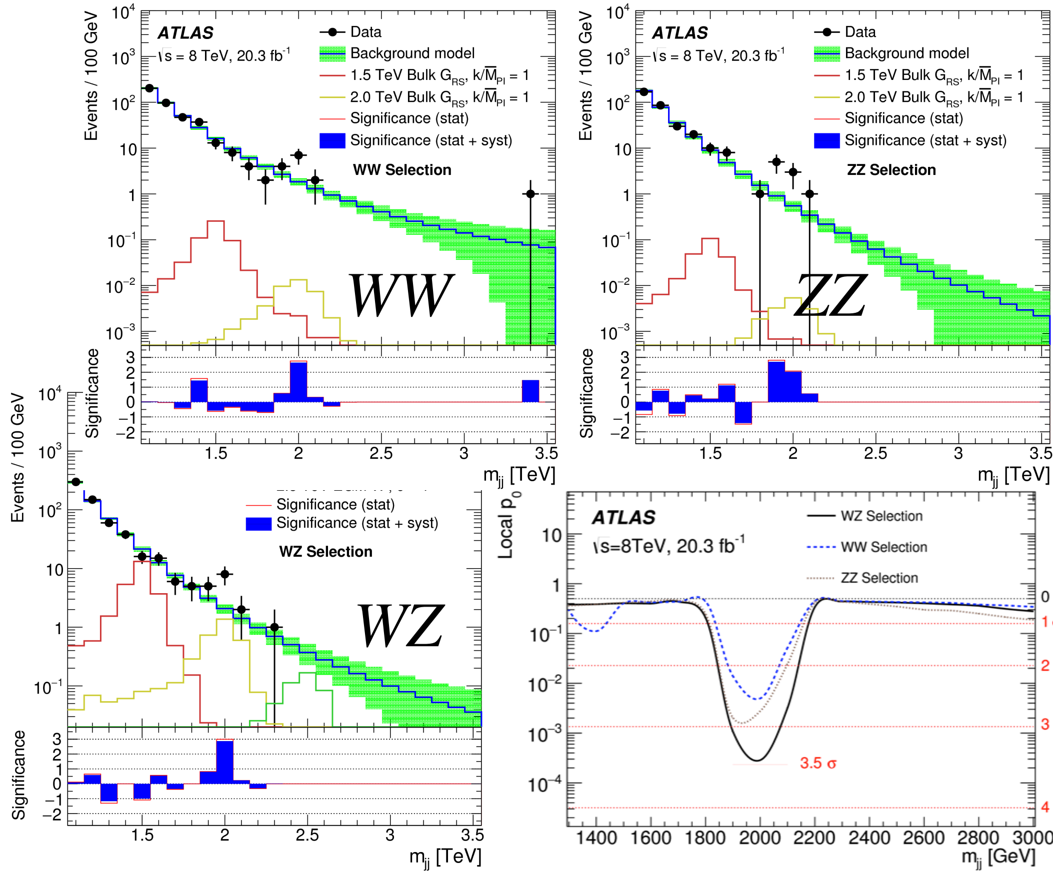
Vector boson resonances

Experiment	Search	Limits	arXiV
ATLAS	$G_{RS} \rightarrow l\nu jj$	$m(G_{RS}) > 700$ GeV	1503.04677
ATLAS	$W' \rightarrow l\nu jj$	$m(W') > 1490$ GeV	1503.04677
ATLAS	$W' \rightarrow WZ \rightarrow lljj$	$m(W') > 1590$ GeV	1409.6190
ATLAS	$G_{RS} \rightarrow WZ \rightarrow lljj$	$m(G_{RS}) > 740$ GeV @ k/MPl=1.0 $m(G_{RS}) > 540$ GeV @ k/MPl=0.5	1409.6190
ATLAS	$\alpha_T \rightarrow l\nu\gamma$	$m(\alpha_T) > 960$ GeV	1407.8150
ATLAS	$\alpha_T \rightarrow ll\gamma$	$m(\alpha_T) > 890$ GeV	1407.8150
ATLAS	$W' \rightarrow WZ \rightarrow lll\nu$	$m(W') > 1520$ GeV	1406.4456
CMS	$W' \rightarrow WZ \rightarrow lll\nu$	$m(W') > 1550$	1407.3476
CMS	$\varrho_{TC} \rightarrow WZ \rightarrow lll\nu$	$m(\varrho_{TC}) > 1140$ GeV	1407.3476
CMS	$WZ \rightarrow (l\nu/ll)+jj$ Graviton bulk	$\sigma(m(G_{RS}) = 600$ GeV$) < 700$ fb-1 $\sigma(m(G_{RS}) = 2500$ GeV$) < 10$ fb-1	1405.3447
CMS	$q^* \rightarrow qW \rightarrow jjjj$	$m(q^*) > 3200$ GeV	1405.1994
CMS	$q^* \rightarrow qZ \rightarrow jjjj$	$m(q^*) > 2900$ GeV	1405.1994
CMS	$W' \rightarrow WZ \rightarrow jjjj$	$m(W') > 1700$ GeV	1405.1994
CMS	$G_{RS} \rightarrow WW \rightarrow jjjj$	$m(G_{RS}) > 1200$ GeV	1405.1994

Exotica at 2 TeV

arXiV: 1506.00962

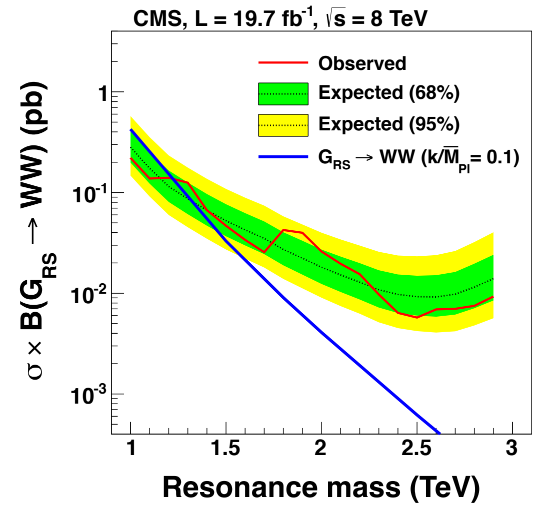
- Both ATLAS and CMS have recently show results for the *VV*→*jjjj* final state, where *V* is a *W* or *Z* boson
- Both experiments show an excess around $m(jjjj) = 2$ TeV!
- First, results from ATLAS:
- Most significant excess is $\sim 3.5\sigma$ at $m(VV) = 2$ TeV.
- Jets are "groomed" to reduce QCD backgrounds.

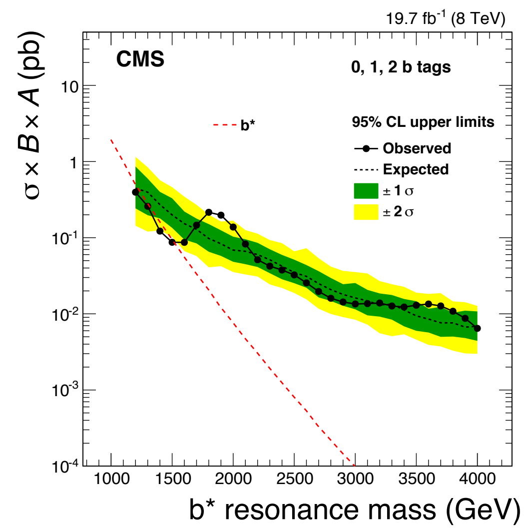


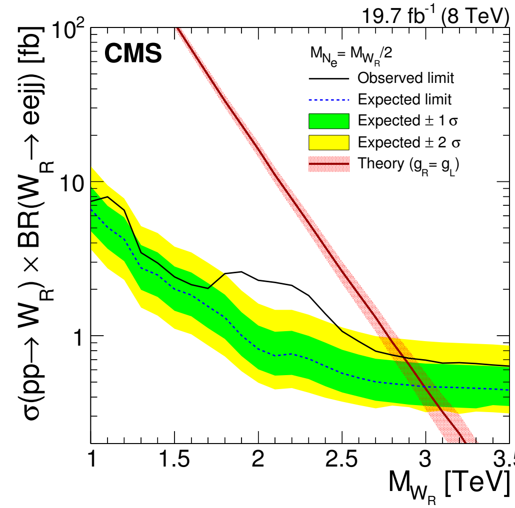
Exotica at 2 TeV

CMS-EXO-013-008
CMS-EXO-013-009
CMS-EXO-012-024

- Equivalent analysis for CMS shows an excess of ~2σ with an RS graviton model (right).
- There are also excesses around 2 TeV in the dijet spectrum for $b^* \rightarrow bg$ (below left) and right handed W' in the context of $W' \rightarrow eN_e$ (below right).
- Interesting hints of new physics around 2 TeV showing up in several final states!







ULB

Summary

- LHC Run 1 has seen many very active searches for new resonances.
- ATLAS and CMS have probed new parameter space, setting unprecedented limits, in the range of TeV.
- The experiments have rich programs of physics and diverse searches.
- Tantalising hints of something around $M \sim 2\ \mathrm{TeV}$

- Fingers crossed for LHC Run 2!

Backup

PDFs and background uncertainties

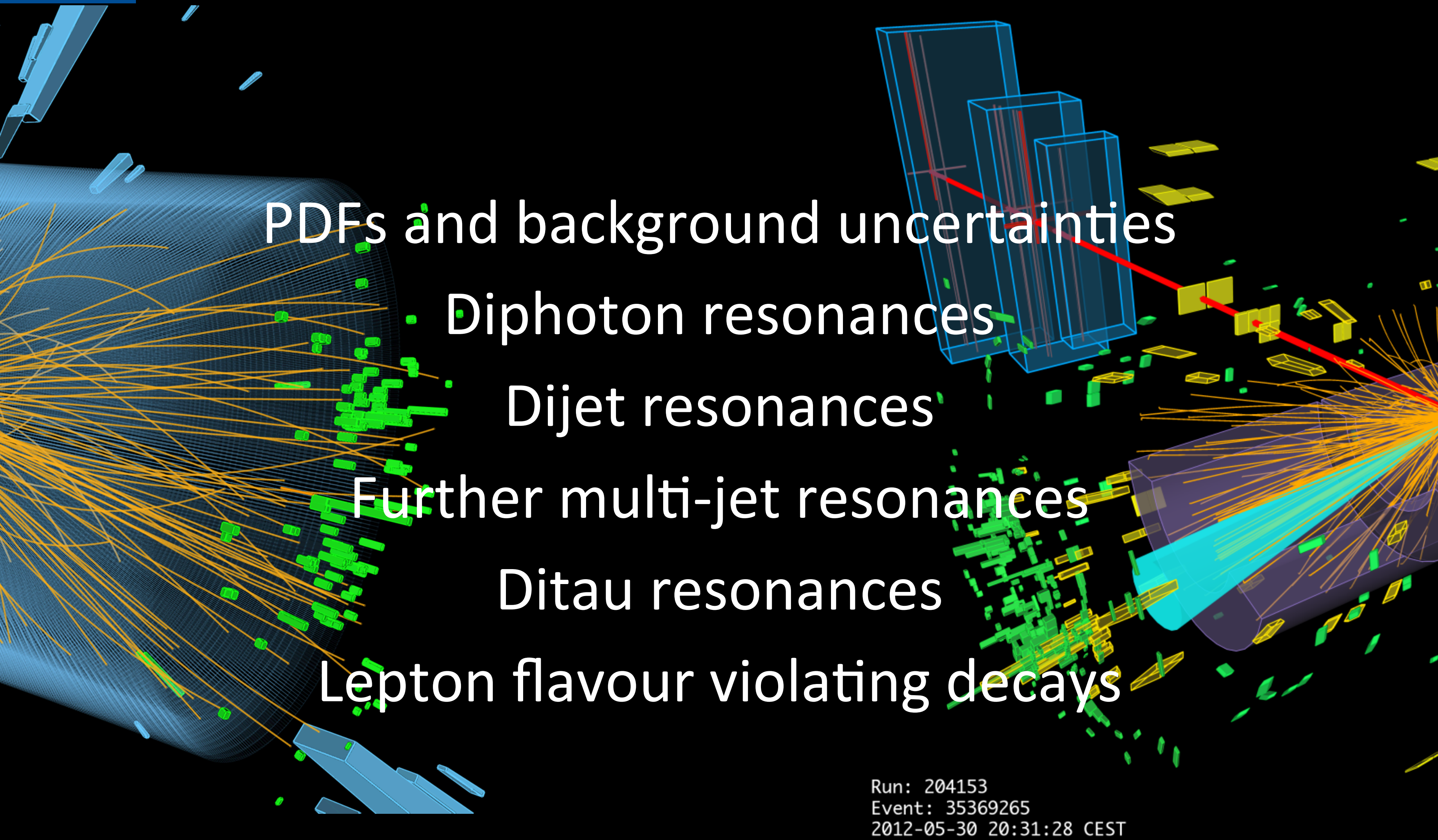
Diphoton resonances

Dijet resonances

Further multi-jet resonances

Ditau resonances

Lepton flavour violating decays



PDFs and background uncertainties

- For many searches (dilepton, ditau, diphoton) the dominant systematic uncertainties come from PDF uncertainties on the background
  - Often vary widely as a function of mass
  - Hard to quantify without giving benchmarks
  - Good example from ATLAS dilepton search (arXiV: 1405.4123):

2 TeV

TABLE III. Summary of systematic uncertainties on the expected numbers of events at a dilepton mass of $m_{\ell\ell} = 2$ TeV, where N/A indicates that the uncertainty is not applicable. Uncertainties $< 3\%$ for all values of m_{ee} or $m_{\mu\mu}$ are neglected in the respective statistical analysis.

Source ($m_{\ell\ell} = 2$ TeV)	Dielectrons		Dimuons	
	Signal	Backgr.	Signal	Backgr.
Normalization	4%	N/A	4%	N/A
PDF variation	N/A	11%	N/A	12%
PDF choice	N/A	7%	N/A	6%
α_s	N/A	3%	N/A	3%
Electroweak corr.	N/A	2%	N/A	3%
Photon-induced corr.	N/A	3%	N/A	3%
Beam energy	< 1%	3%	< 1%	3%
Resolution	< 3%	< 3%	< 3%	3%
Dijet and $W+$jets	N/A	5%	N/A	N/A
Total	4%	15%	4%	15%

3 TeV

TABLE IV. Summary of systematic uncertainties on the expected numbers of events at a dilepton mass of $m_{\ell\ell} = 3$ TeV, where N/A indicates that the uncertainty is not applicable. Uncertainties $< 3\%$ for all values of m_{ee} or $m_{\mu\mu}$ are neglected in the respective statistical analysis.

Source ($m_{\ell\ell} = 3$ TeV)	Dielectrons		Dimuons	
	Signal	Backgr.	Signal	Backgr.
Normalization	4%	N/A	4%	N/A
PDF variation	N/A	30%	N/A	17%
PDF choice	N/A	22%	N/A	12%
α_s	N/A	5%	N/A	4%
Electroweak corr.	N/A	4%	N/A	3%
Photon-induced corr.	N/A	6%	N/A	4%
Beam energy	< 1%	5%	< 1%	3%
Resolution	< 3%	< 3%	< 3%	8%
Dijet and $W+$jets	N/A	21%	N/A	N/A
Total	4%	44%	4%	23%

Diphoton resonances

- Both ATLAS and CMS investigate diphoton resonances.
- Simple final state.
- Kinematic selections:

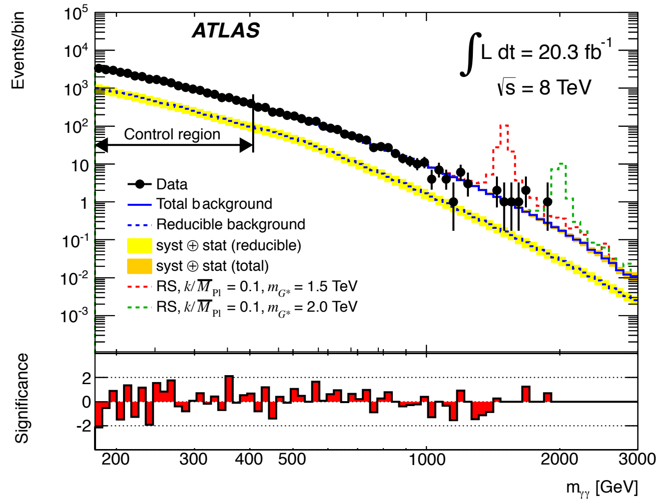
arXiV: 1505.04306

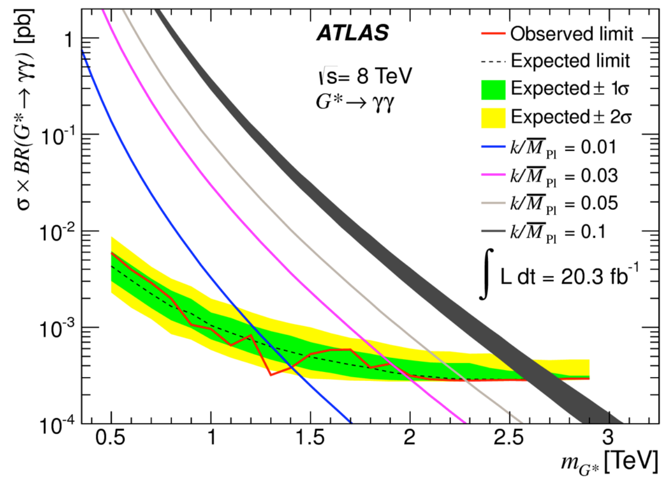
CMS-PAS-EXO-12-045

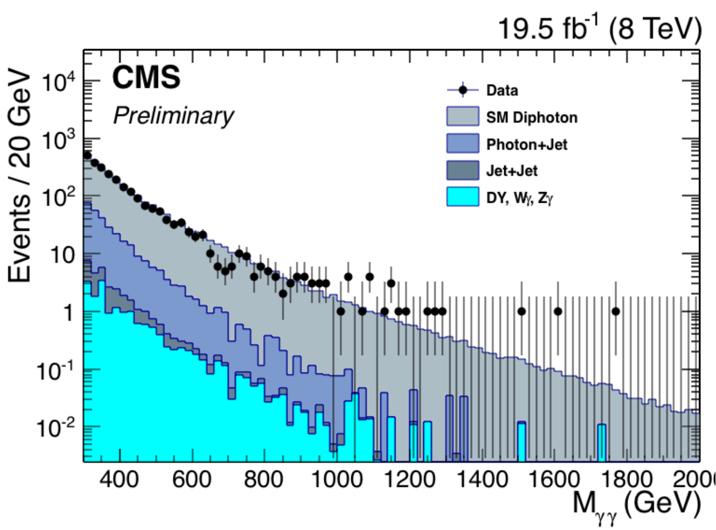
ATLAS	CMS
$p_T > 50$ GeV $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	$p_T > 80$ GeV $\lvert\eta\rvert < 1.4442$ $m(\gamma\gamma) > 300$ GeV

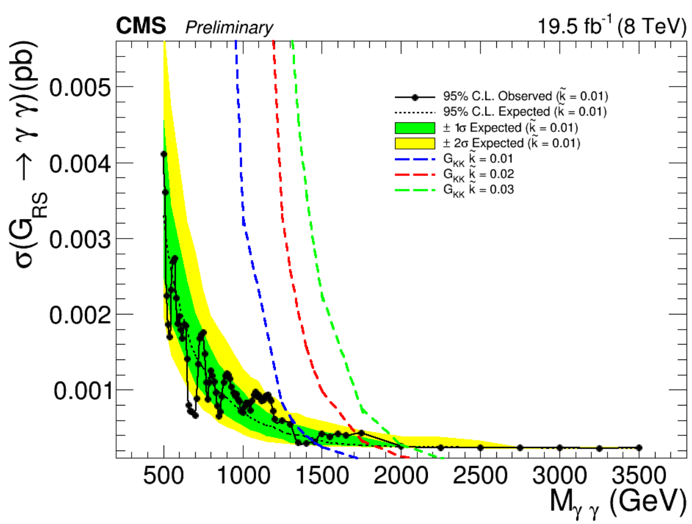
- Dominant systematic uncertainties: PDFs for background modeling, photon reconstruction efficiency, luminosity.

Diphoton resonances









Limits for $k/M_{Pl} = 0.1$: ATLAS: $m(G_{RS}) > 2.66$ TeV CMS: $m(G_{RS}) > 2.78$ TeV

Dijet resonances

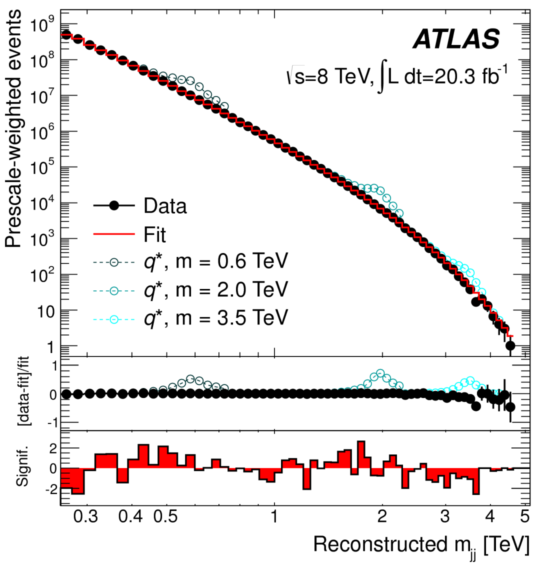
- Both ATLAS and CMS investigate dijet resonances.
- Many possible interpretations, including excited quarks, *W'* and *Z'* bosons, black holes etc.
- Kinematic selections:

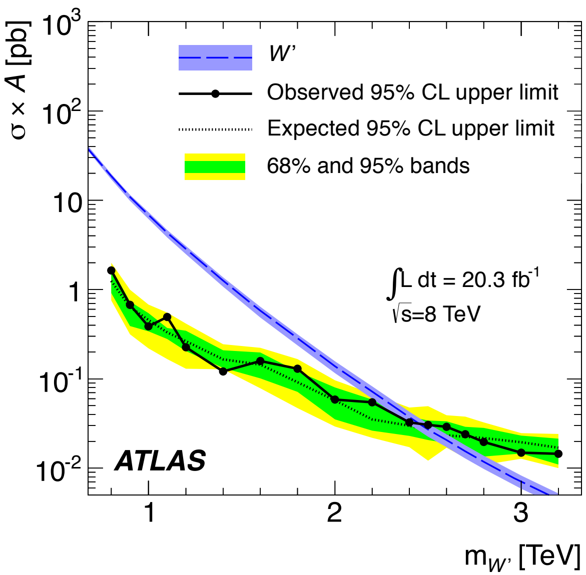
PRD 91, 052007 | PRD 91, 052009

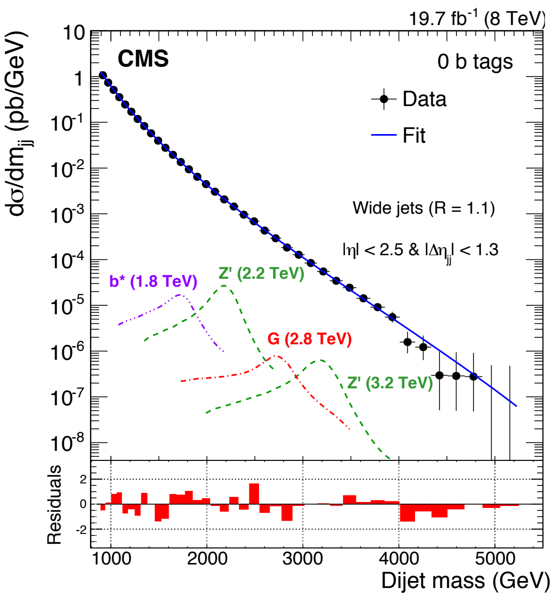
ATLAS	CMS
$p_T(\mathrm{j}) > 50$ GeV $\lvert\eta(j)\rvert < 2.8$ $\frac{1}{2}(\eta(j)_{leading} - \eta(j)_{subleading}) < 0.6$ and $m(jj) > 250$ GeV to remove p_T bias	$p_T(j) > 30$ GeV $\lvert\eta(j)\rvert < 2.5$ $m(jj) > 890$ GeV to remove trigger bias

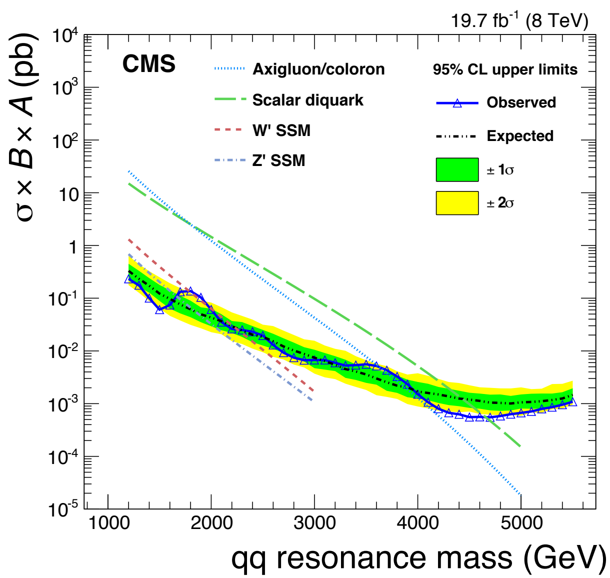
- Dominant systematic uncertainties: jet energy scale, jet energy resolution, luminosity.
- (More final states in backup slides.)

Dijet resonances









- Limits on W', qg searches:
- ATLAS
  - $m(W') > 2.45$ TeV
  - $m(qg) > 4.06$ TeV
- CMS
  - $m(W') > 2.2$ TeV
  - $m(qg) > 5.0$ TeV

Further multi-jet resonances

- CMS also investigate pair produced resonances decaying to jets, and three-jet final states:

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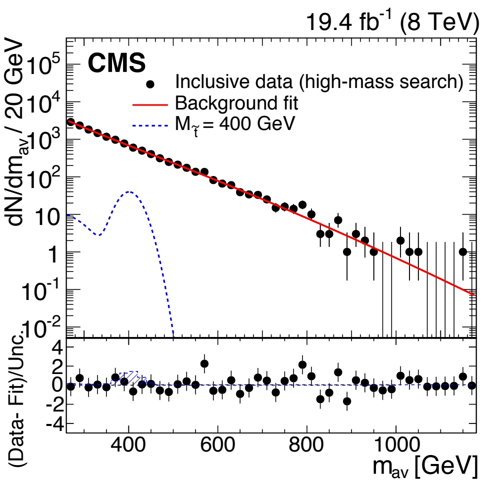
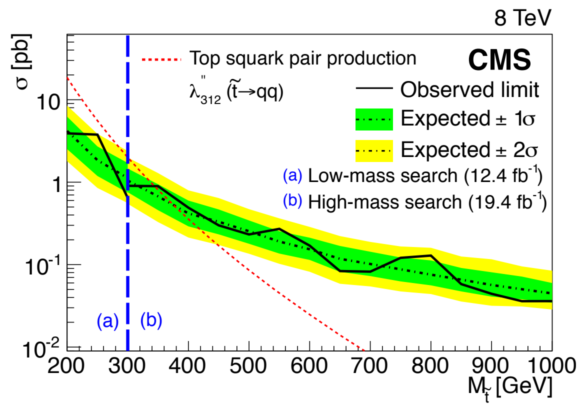
$X \rightarrow YY$, $Y \rightarrow jj$

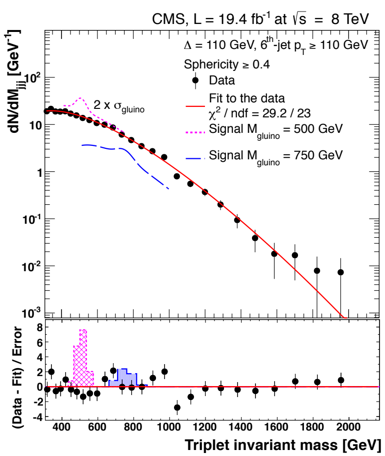


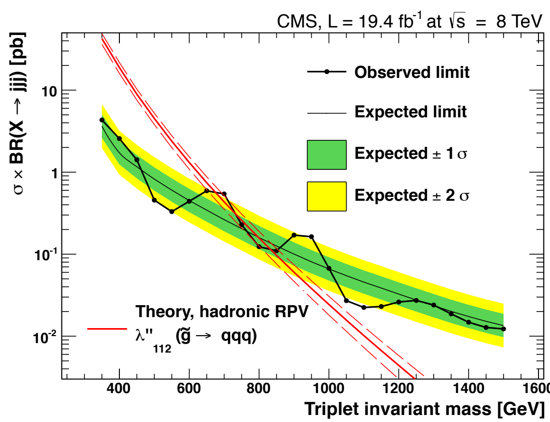


Exclude top squark masses for decays to light (heavy) jets in range: $200 < m(jj) < 350\ (385)$ GeV

Dominant uncertainties: Jet energy scale, resolution, initial and final state radiation, signal fits

$Z \rightarrow jjj$





Exclude gluino masses for decays to light (heavy) jets in range: $0\ (200) < m(jjj) < 350\ (835)$ GeV

arXiv:1412.7706

Ditau resonances

- Results from ATLAS and CMS
- ATLAS considers τ_{had}-τ_{had} and τ_{had}-τ_{lep} final states (τ_{had} is a τ jet)
- CMS consider τ_e-τ_μ final states
- Kinematic selections:

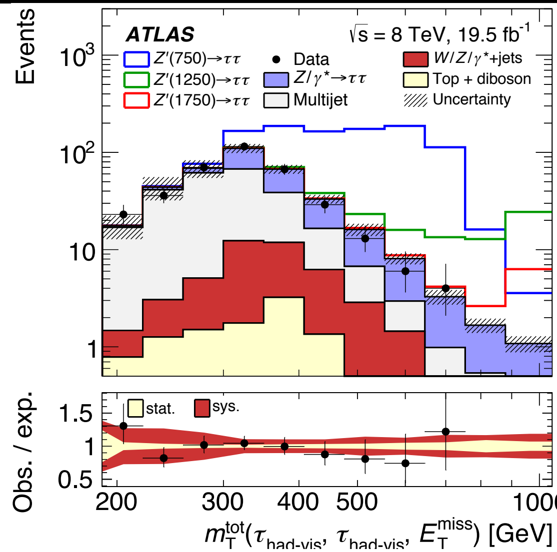
PRD 90, 052005

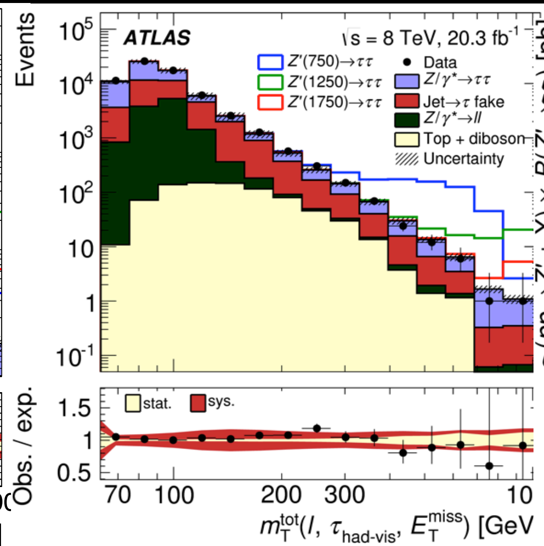
CMS-PAS-EXO-12-046

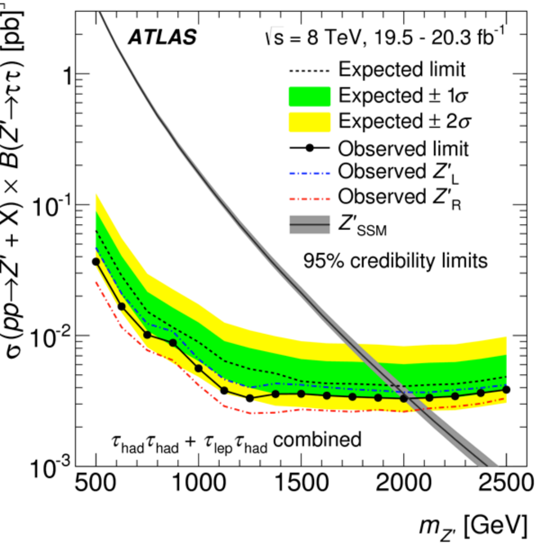
	ATLAS	CMS
τ_{had}	$p_T(\tau_{had}) > 30$ GeV $\lvert\eta(\tau_{had})\rvert < 1.37$ or $1.52 < \lvert\eta(\tau_{had})\rvert < 2.47$	
e	$E_T(e) > 15$ GeV $\lvert\eta(e)\rvert < 1.37$ or $1.52 < \lvert\eta(e)\rvert < 2.47$	$E_T(e) > 20$ GeV $\lvert\eta(e)\rvert < 1.442$ or $1.56 < \lvert\eta(e)\rvert < 2.5$
μ	$p_T(\mu) > 10$ GeV $\lvert\eta(\mu)\rvert < 2.5$	$p_T(\mu) > 20$ GeV $\lvert\eta(\mu)\rvert < 2.1$

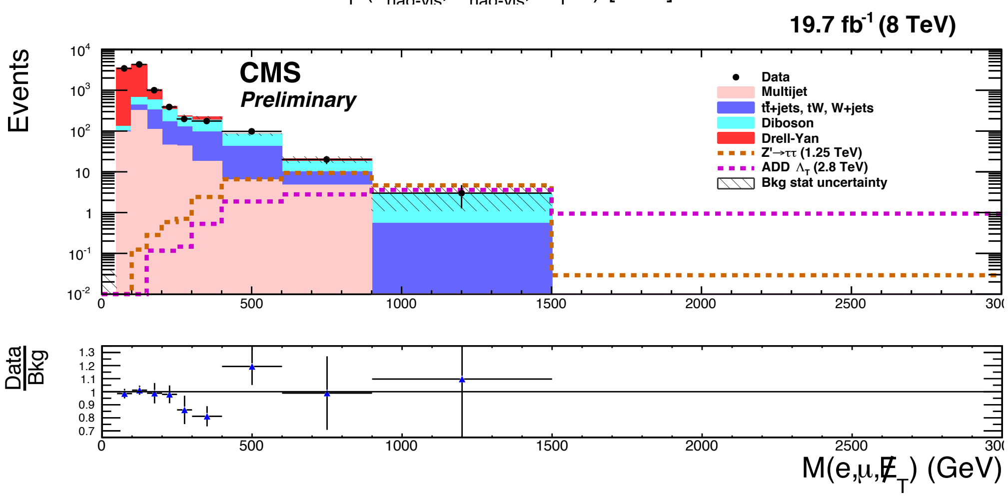
- Dominant systematic uncertainties: PDFs for background modeling, Signal efficiency for ATLAS, data driven background estimates for CMS.

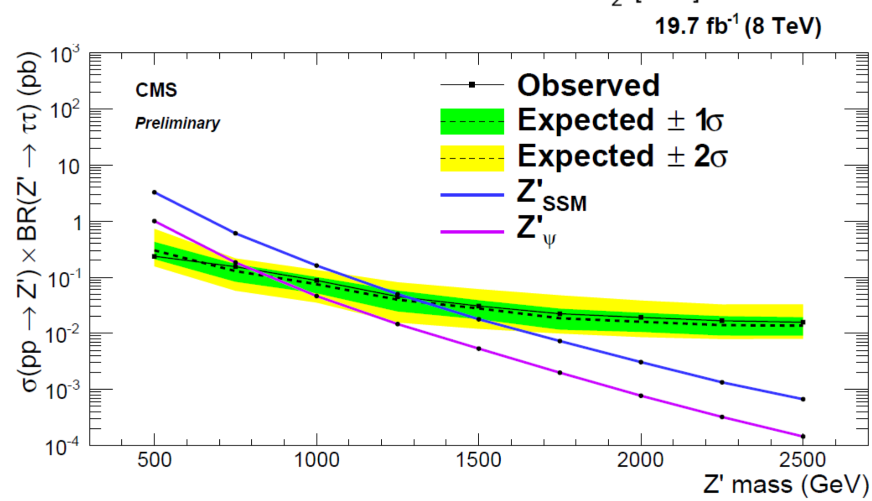
Ditau resonances











- Exclusion limits:

ATLAS: $m(Z'_{SSM}) > 2.02$ TeV CMS: $m(Z'_{SSM}) > 1.30$ TeV

Lepton flavour violating resonances

- Results from ATLAS and CMS
- ATLAS considers e-μ, e-τ, and μ-τ final states
- CMS consider e-μ final states
- Kinematic selections:

arXiv:1503.054420

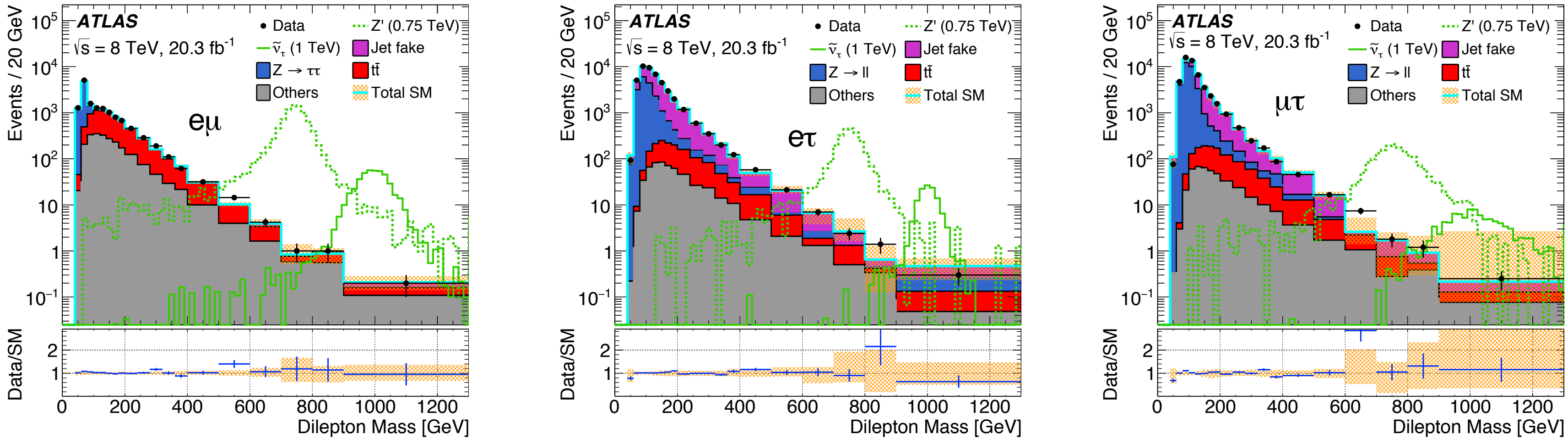
arXiv:1504.055115

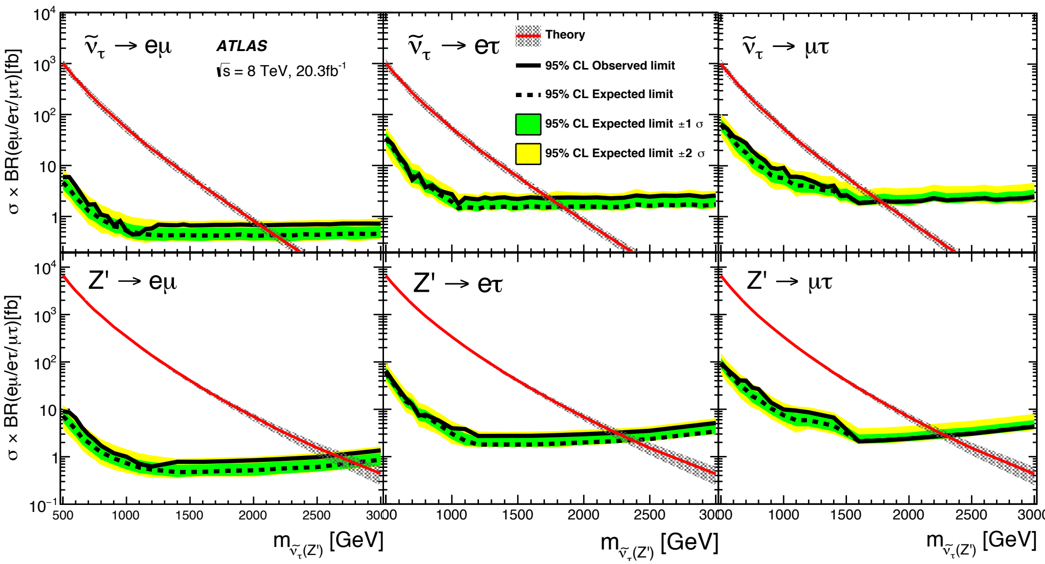
ATLAS	CMS
$p_T(\tau_{had}) > 25$ GeV $\lvert\eta(\tau_{had})\rvert < 2.47$ Single track	
$E_T(e) > 25$ GeV $\lvert\eta(e)\rvert < 1.37$ or $1.52 < \lvert\eta(e)\rvert < 2.47$	$E_T(e) > 35$ GeV $\lvert\eta(e)\rvert < 1.442$ or $1.56 < \lvert\eta(e)\rvert < 2.5$
$p_T(\mu) > 25$ GeV $\lvert\eta(\mu)\rvert < 2.4$	$p_T(\mu) > 45$ GeV $\lvert\eta(\mu)\rvert < 2.1$

- Dominant systematics: Acceptance and efficiency, 3-6% for ATLAS, ~5% for CMS.

Lepton flavour violating resonances

- ATLAS investigates $e\mu$, $e\tau$, $\mu\tau$ final states.



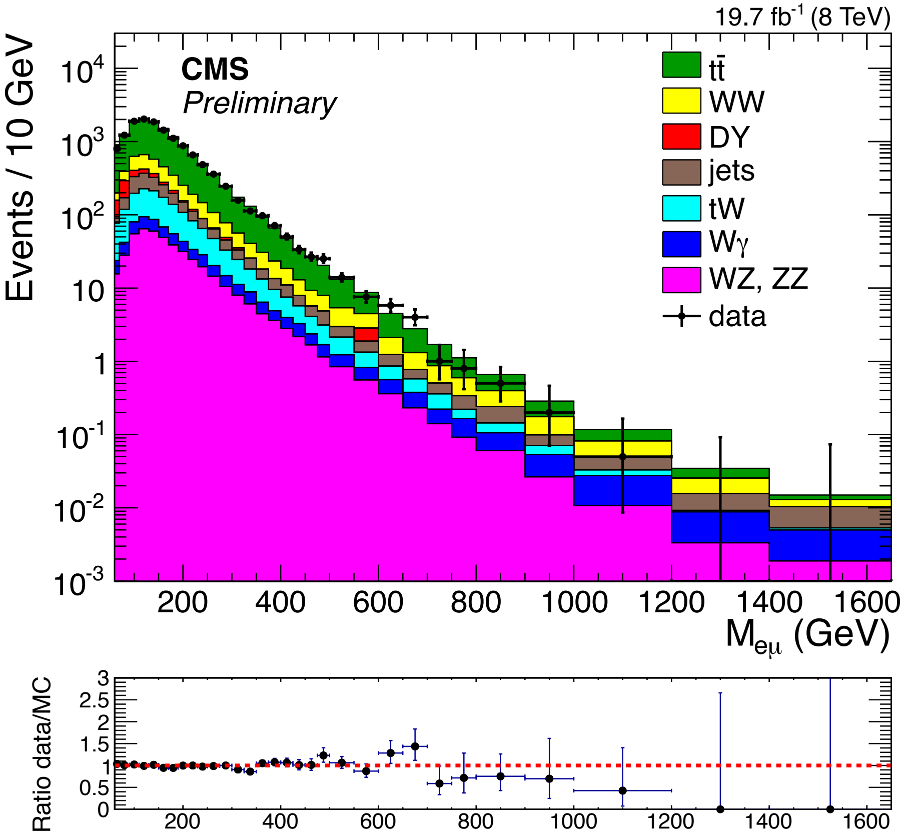


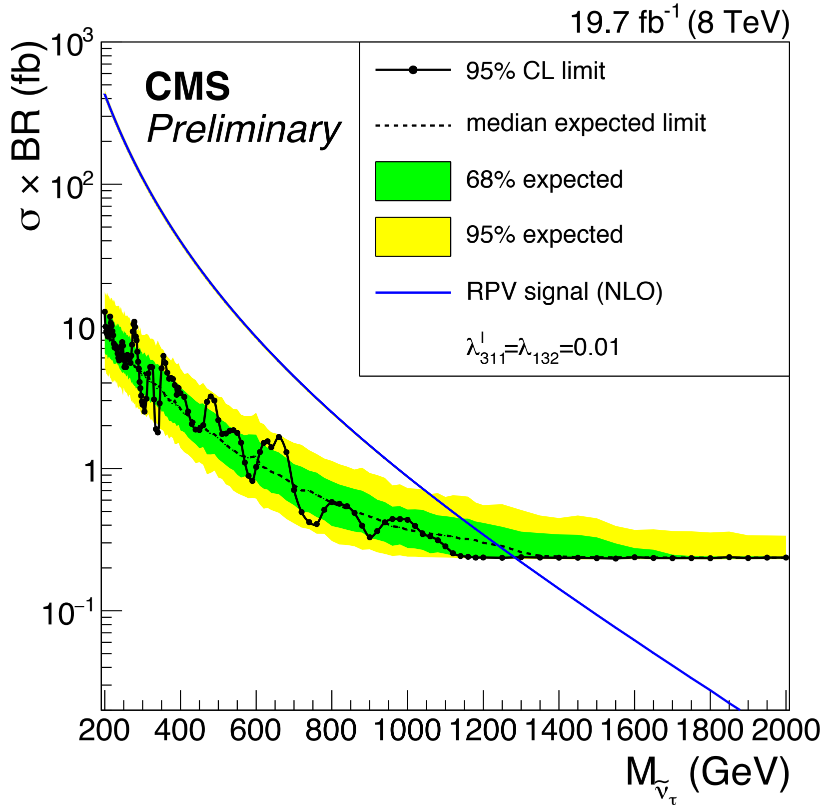
- Limits:
  - $e\mu$: $m(\tilde{\nu}_\tau) > 2.0$ TeV
  - $e\tau$: $m(\tilde{\nu}_\tau) > 1.7$ TeV
  - $\mu\tau$: $m(\tilde{\nu}_\tau) > 1.7$ TeV

Lepton flavour violating resonances

- CMS investigate $e\mu$ final state.

CMS-EXO-13-002





Limit: $m(\tilde{\nu}_\tau) > 2.1\ \text{TeV}$