Searches for heavy resonances at the LHC,

University of Liverpool

Aidan Randle-Conde

Université Libre de Bruxelles (ULB)

Overview

Introduction to the LHC, ATLAS and CMS

Resonance searches: Introduction and scope

Run 1 “fast” results

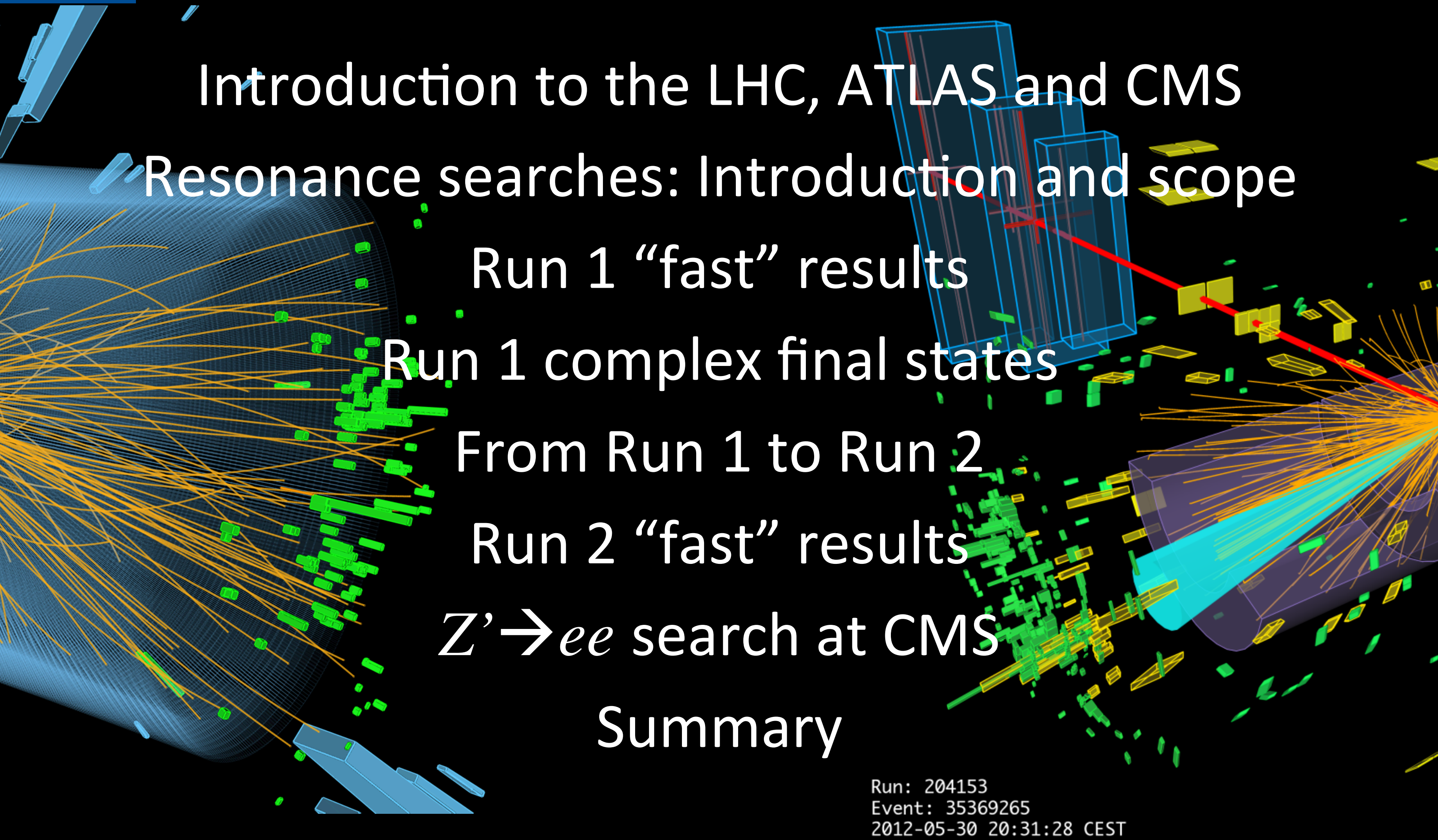
Run 1 complex final states

From Run 1 to Run 2

Run 2 “fast” results

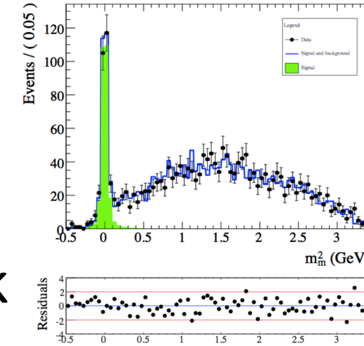
Z’→*ee* search at CMS

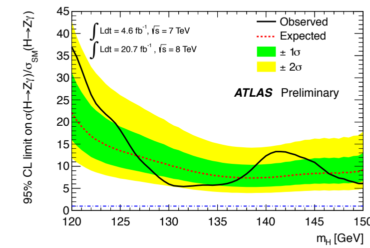
Summary

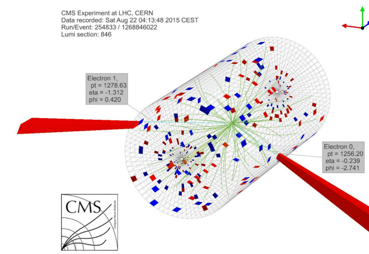


A personal history

- I studied at Oxford for undergraduate.
  - CDF: B_s mixing studies.
- Then Brunel for postgraduate.
  - BaBar: $D_s \to l\nu$ decays, a “hot topic” back in 2008.
- Then to SMU Dallas for my first postdoc.
  - ATLAS: Started the $H \to Z\gamma$ search.
- Currently at the ULB (Brussels).
  - CMS: $Z' \to ee$ search in Run 2.
- Also take part in a lot of outreach (blogs, vlogs, comedy, writing apps, interactive public talks)
- It’s a ULB thing:
  - `sed “/s/scalar/Higgs/”`

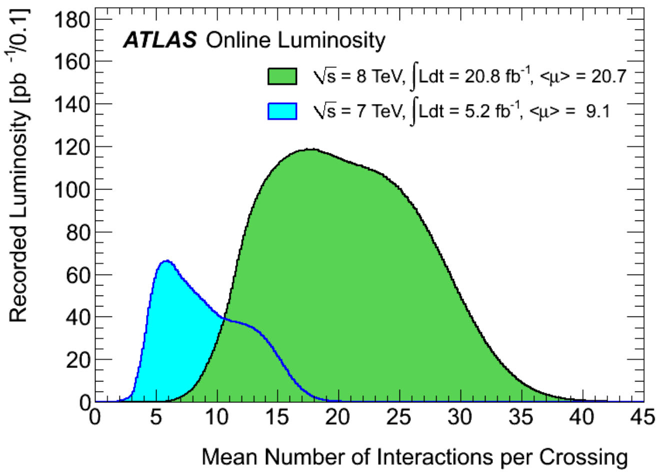


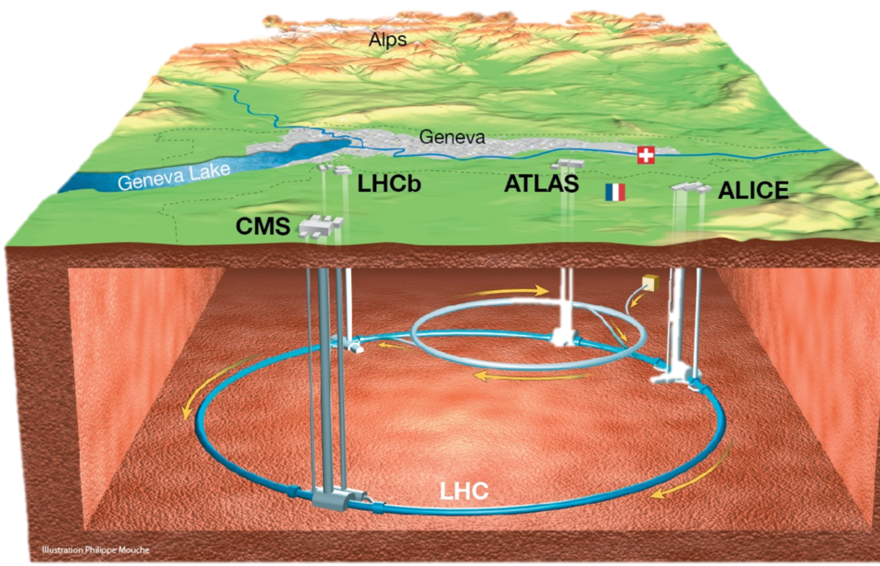




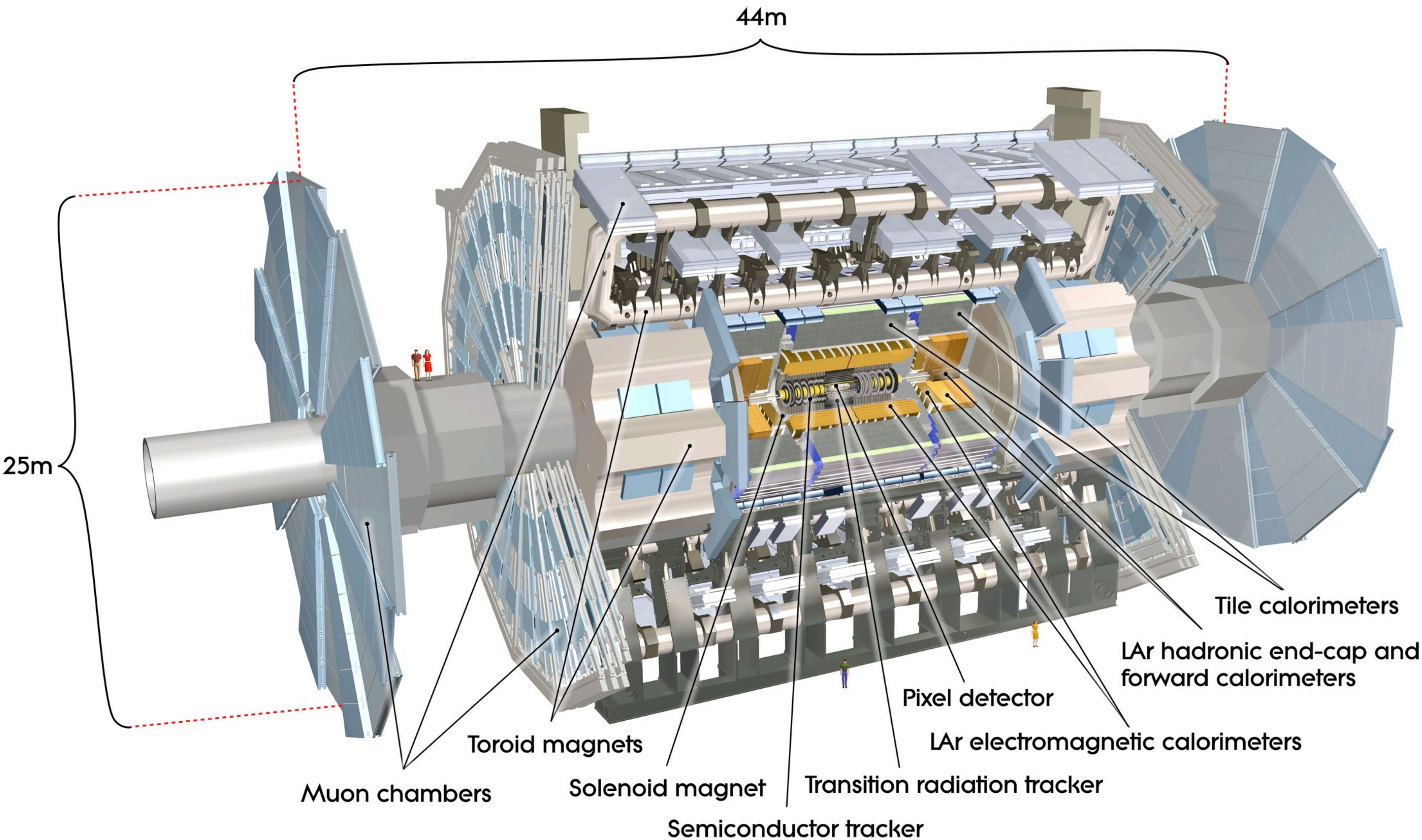
The LHC

- The LHC is a 27 km long ring located at CERN on the French-Swiss border
- Capable of accelerating and colliding protons:
  - Run 1:
    - $\sqrt{s} = 7$ TeV at 50 ns
    - $\sqrt{s} = 8$ TeV at 50 ns
  - Run 2: $\sqrt{s} = 13$ TeV at 50, 25 ns
  - Also lead ions in Pb-Pb and Pb-p collisions
- Typical luminosities of $1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

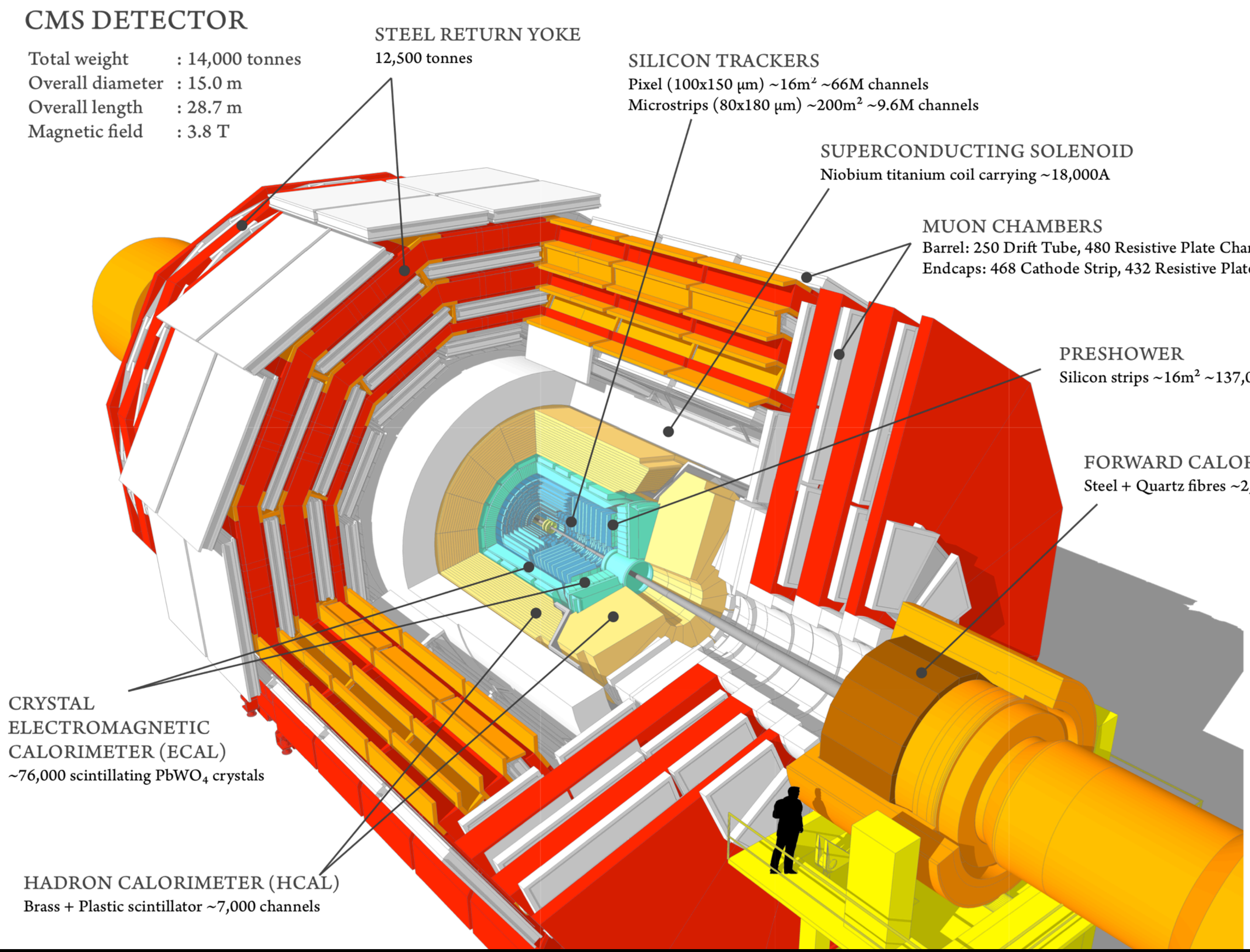




The ATLAS detector

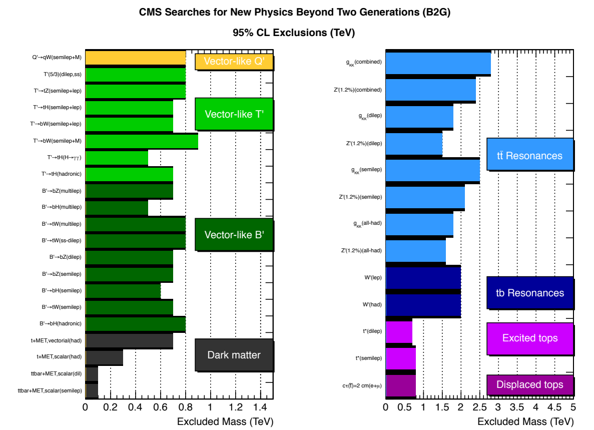


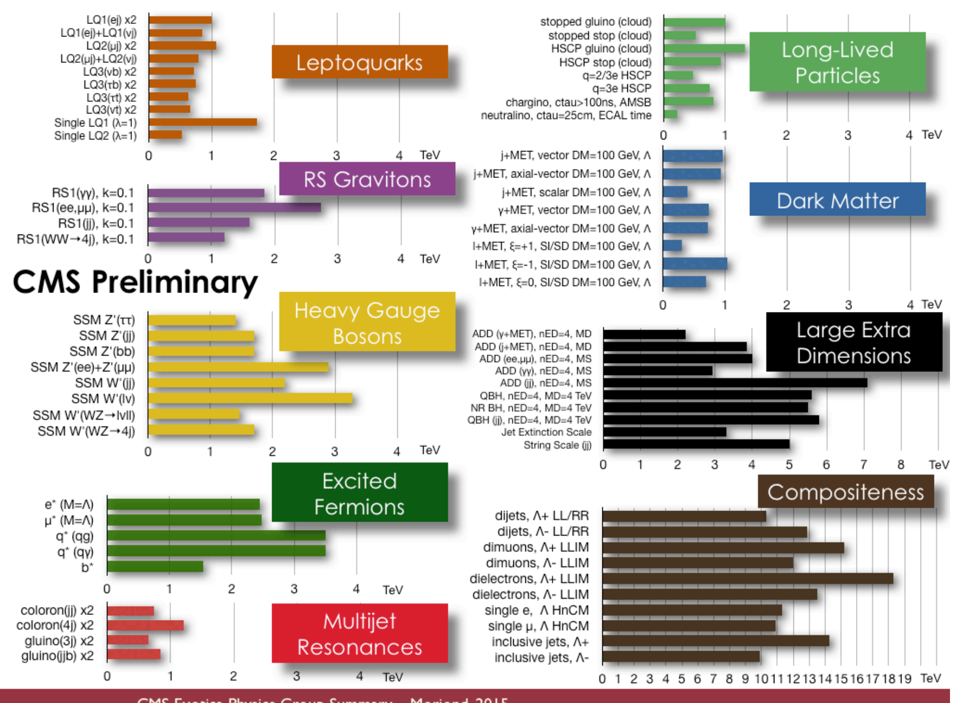
The CMS detector

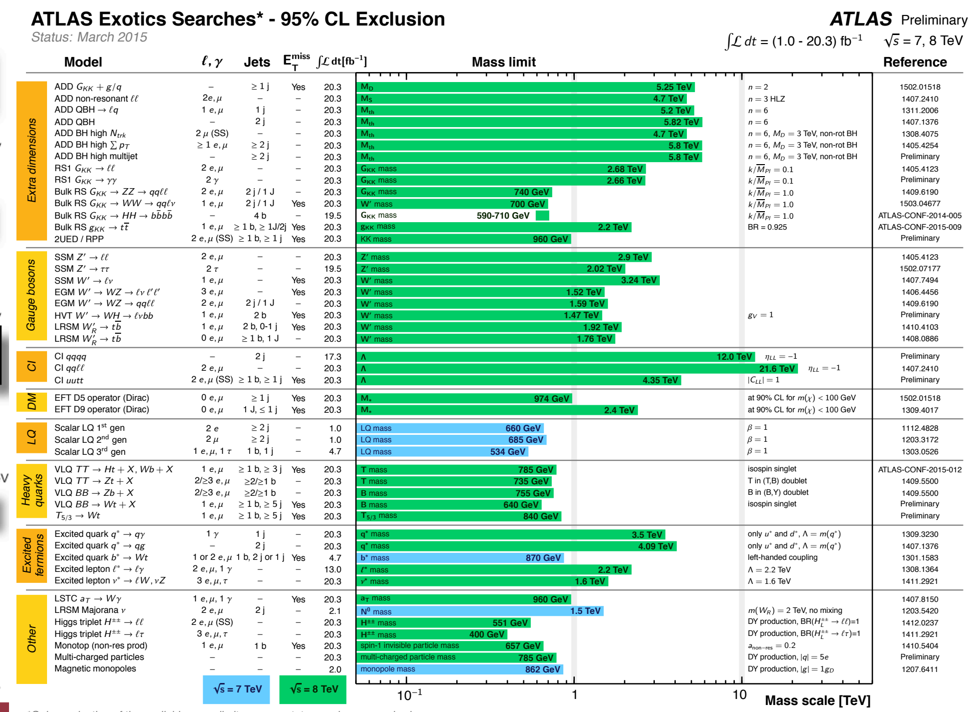


Resonances: scope

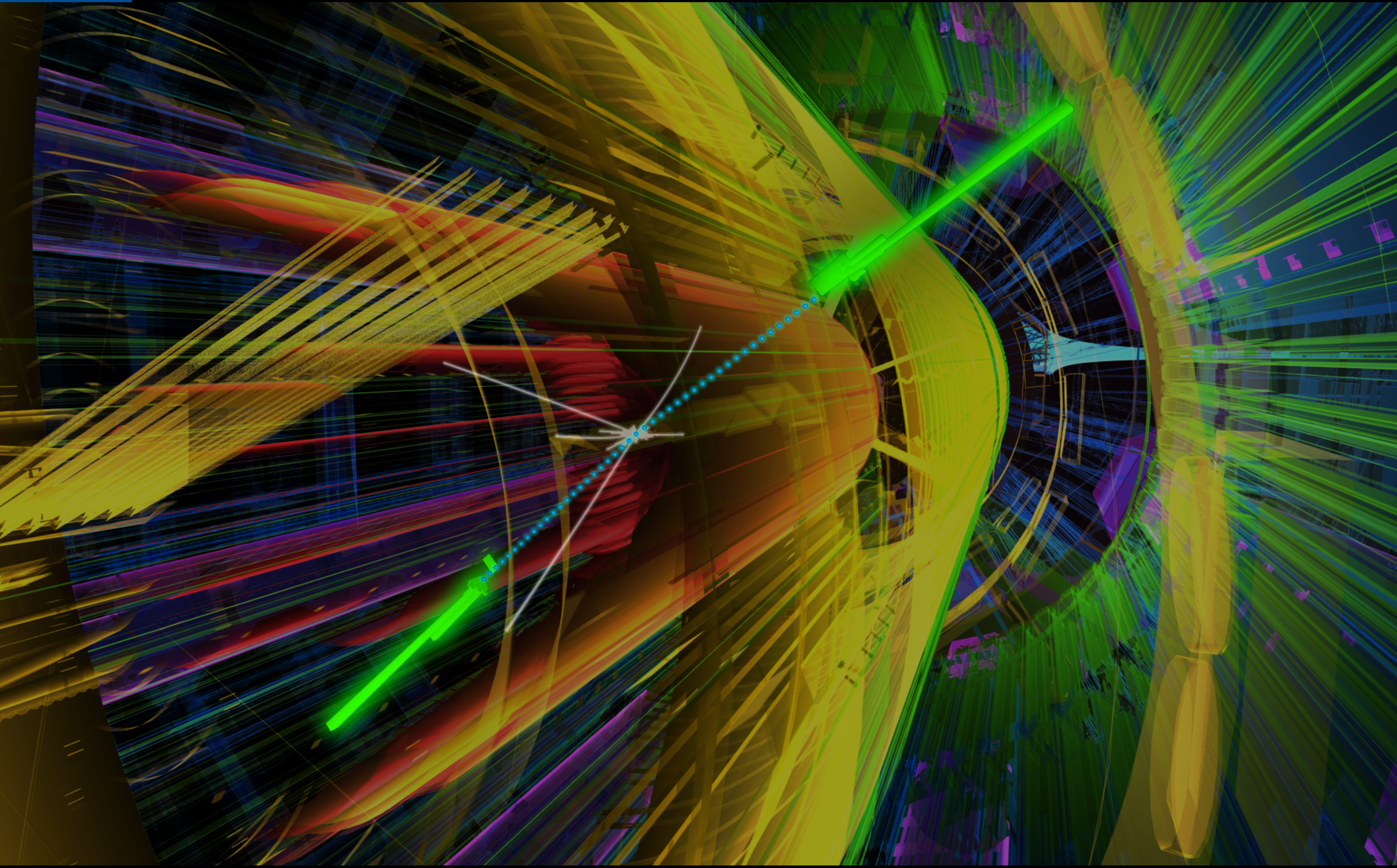
- A huge number of analyses fit into the topic “resonances”
- I can only cover a fraction of these!
- Mostly di-something searches





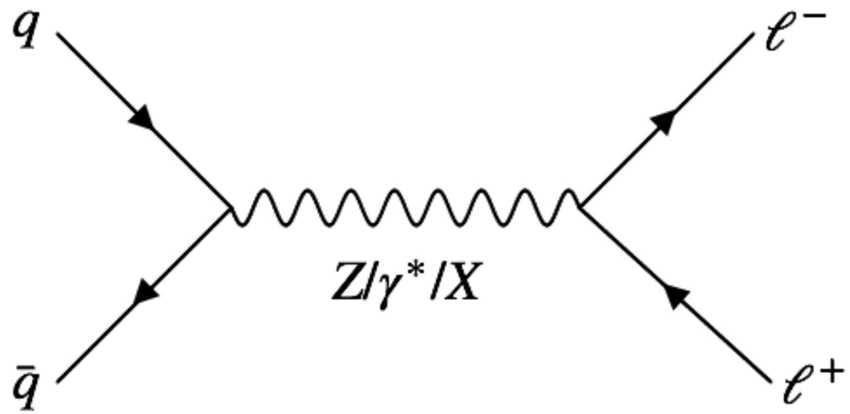


Run 1 "fast" results



Dilepton resonances

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



- Many Z' models available
  - Sequential SM, extra dimensions, extended electroweak sectors

Dilepton resonances

- Main selections:

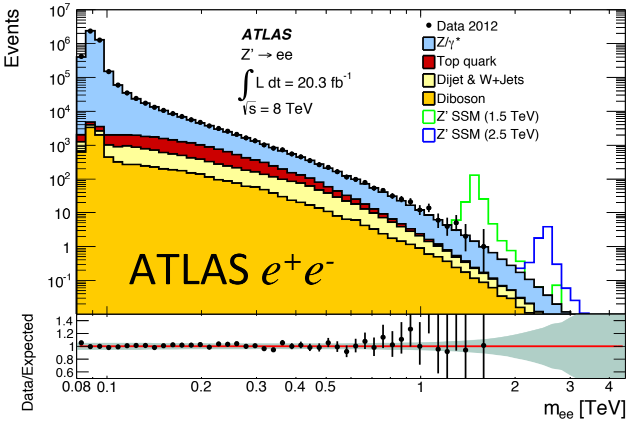
PRD 90, 052005 | JHEP04(2015)025

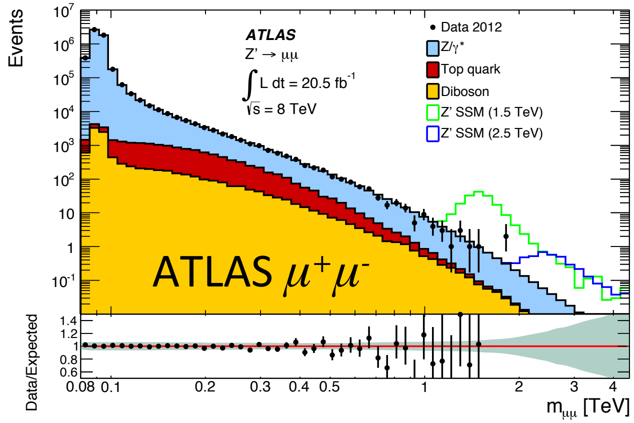
	ATLAS	CMS
ee	$E_T > 40, 30$ GeV $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	$E_T > 35, 35$ GeV $\|\eta\| < 1.442$ or $1.56 < \|\eta\| < 2.5$
$\mu\mu$	$p_T > 25, 25$ GeV $\|\eta\| < 1.05$	$p_T > 45, 45$ GeV $\|\eta\| < 2.4$ ($\|\eta\| < 2.1$ for triggering muon)

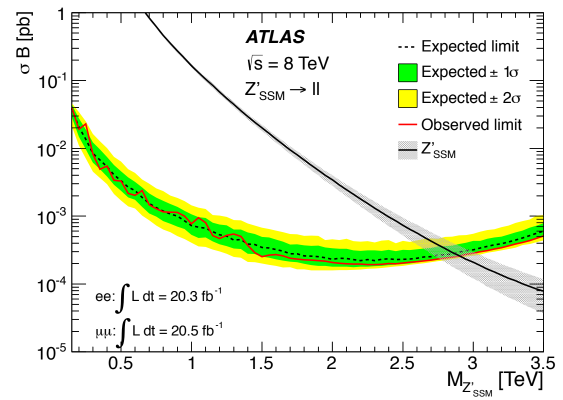
- Leading systematic uncertainties come from the PDFs for background modeling (more information in backup slides), and lepton scale factors (statistically limited at high transverse momentum.)
  - ATLAS: 4% for all channels.
  - CMS: 3% for dimuon, $4(6)\%$ for dielectron barrel-barrel (barrel-endcap)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

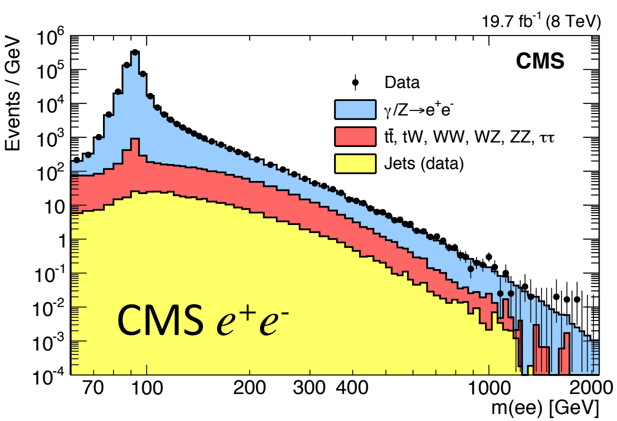
Dilepton resonances

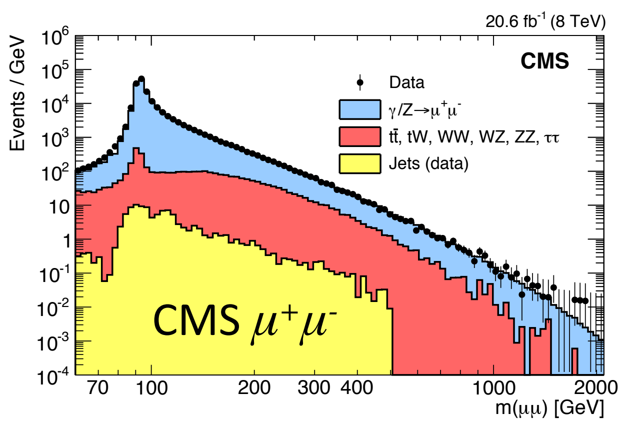
- Results from ATLAS and CMS:

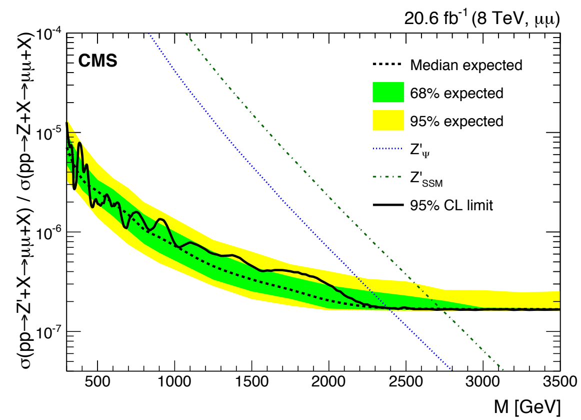










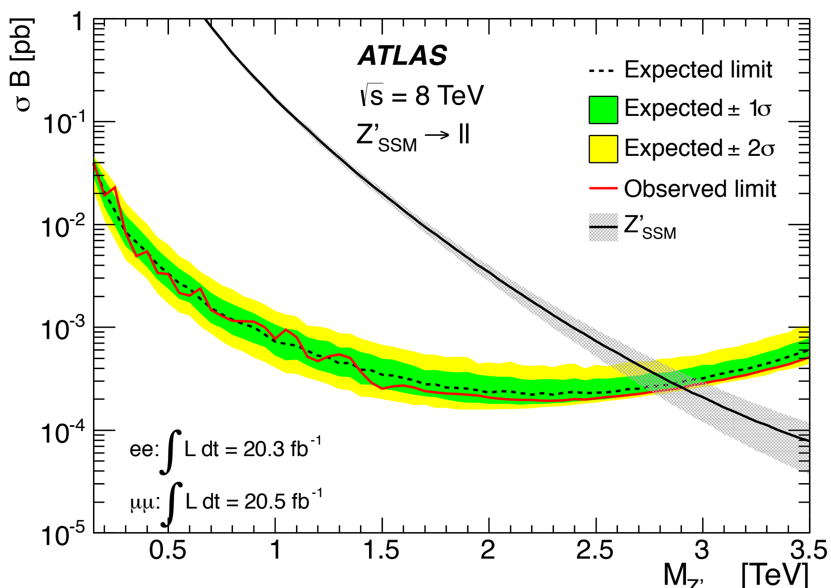


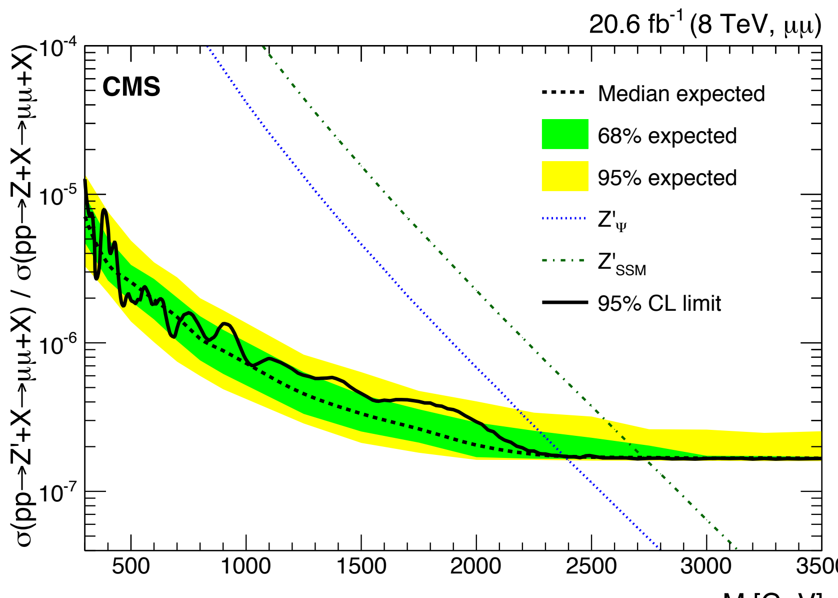
- Exclusion limits:

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

Dilepton resonances

- Models and interpretations are not trivial:
  - Should we pick a width and make ourselves model dependent?
    - ATLAS: Yes! And include a relevant choice of interference terms.
    - CMS: No! We should assume zero width and be agnostic about structure.
  - Should we quote a cross section or a ratio?
    - ATLAS: A cross section (assuming 100% BF) so it's easier to interpret.
    - CMS: A ratio, to cancel out systematic uncertainties.





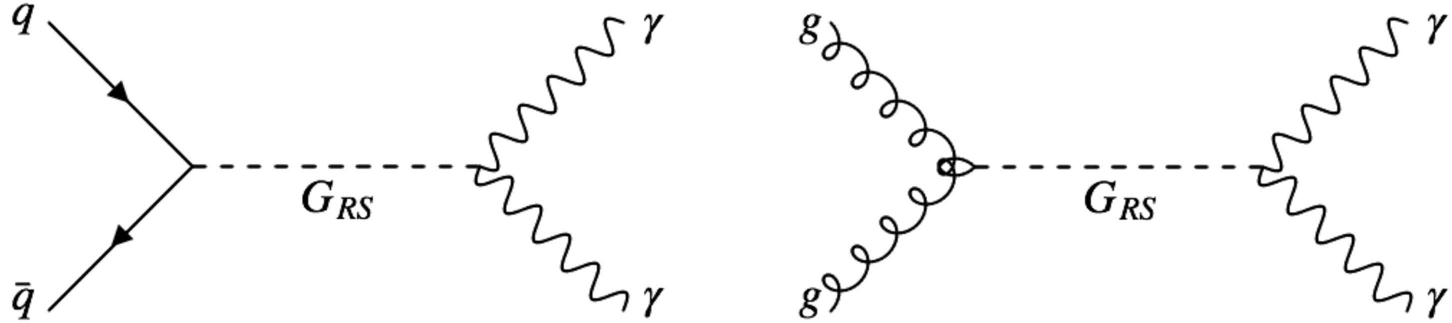
Diphoton resonances

- Both ATLAS and CMS investigate diphoton resonances.

arXiV: 1505.04306

CMS-PAS-EXO-12-045

- There are many models, with popular benchmarks including Randall-Sundrum graviton models.



- Generally slightly higher cross section due to presence of gluon-gluon fusion.
- Sensitive to spin-0 and spin-2 resonances.

Diphoton resonances

- Kinematic selections:

PRD 92, 032994 (2015)

CMS-PAS-EXO-12-045

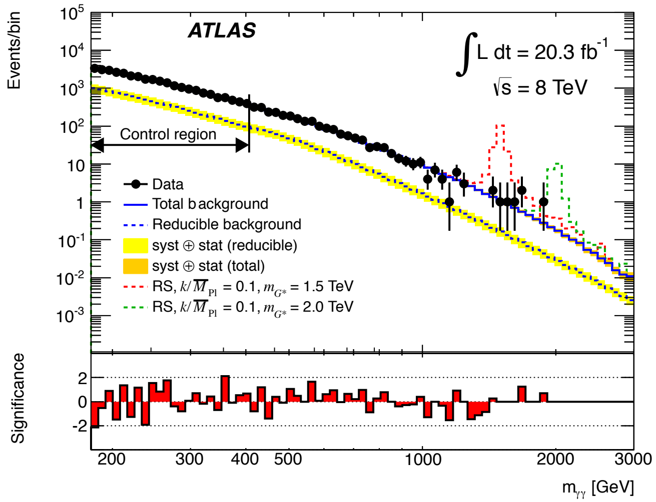
ATLAS	CMS
$p_T > 50$ GeV $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	$p_T > 80$ GeV $\lvert\eta\rvert < 1.4442$ $m(\gamma\gamma) > 300$ GeV

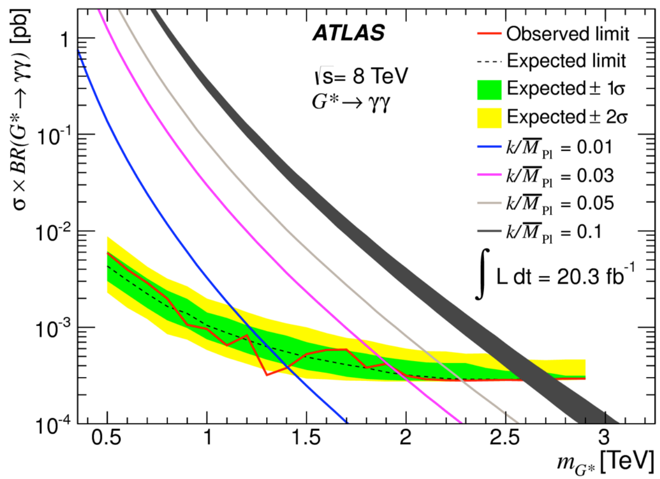
- Isolation selections:

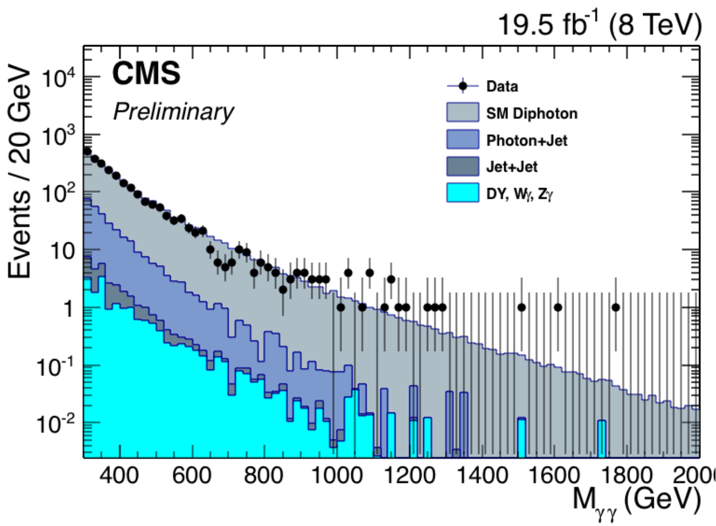
ATLAS	CMS
ECAL $E_T^{iso}(\Delta R<0.4) < 8$ GeV	HCAL $\gamma_{iso}(\Delta R<0.3)/E_T(\gamma) < 0.05$

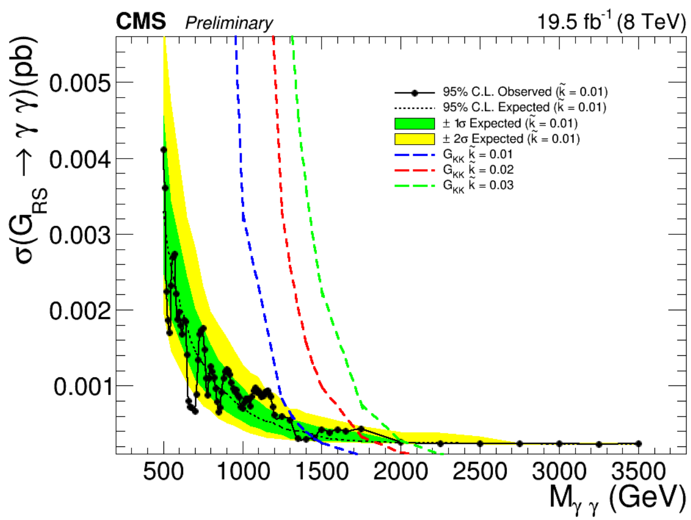
- Dominant systematic uncertainties: PDFs for background modeling, photon reconstruction efficiency, luminosity.

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

- Dijet resonances tend to have very high mass reaches:
  - Coupling to hadronic initial and final states lead to high cross sections.
  - But also suffer from large backgrounds.
  - And have poor mass resolution due to jet energy scales.
  - Mass reach depends very much on the choice of model.

Dijet resonances

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

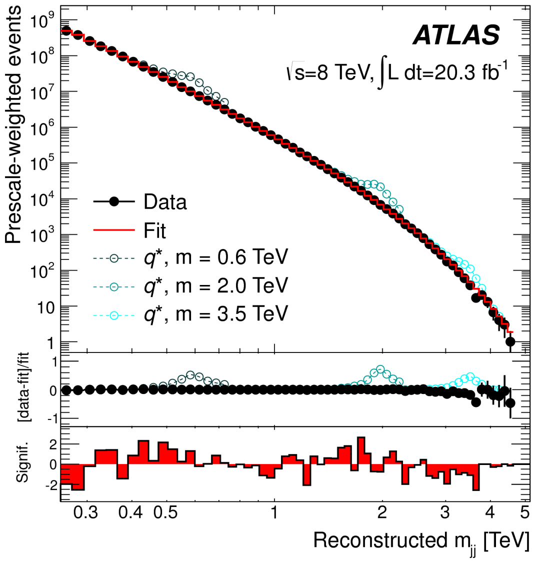
PRD 91, 052007 | PRD 91, 052009

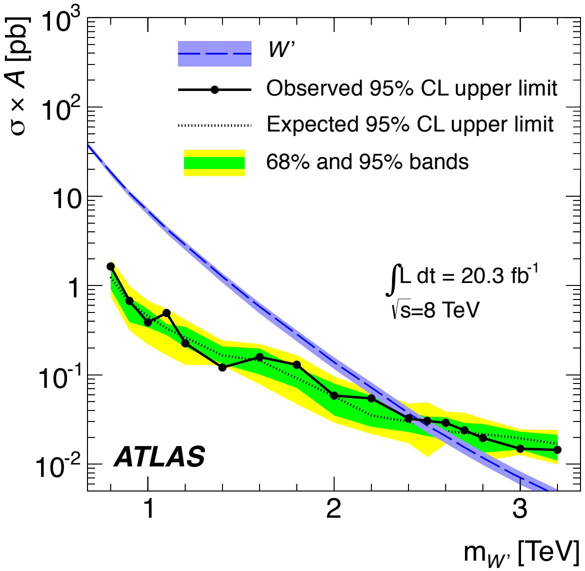
ATLAS	CMS
$p_T(j) > 50$ GeV $\lvert\eta(j)\rvert < 2.8$ $\frac{1}{2}(\eta(j)_{leading} - \eta(j)_{subleading}) < 0.6$ and $m(jj) > 250$ GeV to remove p_T bias	$p_T(j) > 30$ GeV $\lvert\eta(j)\rvert < 2.5$ $m(jj) > 890$ GeV to remove trigger bias

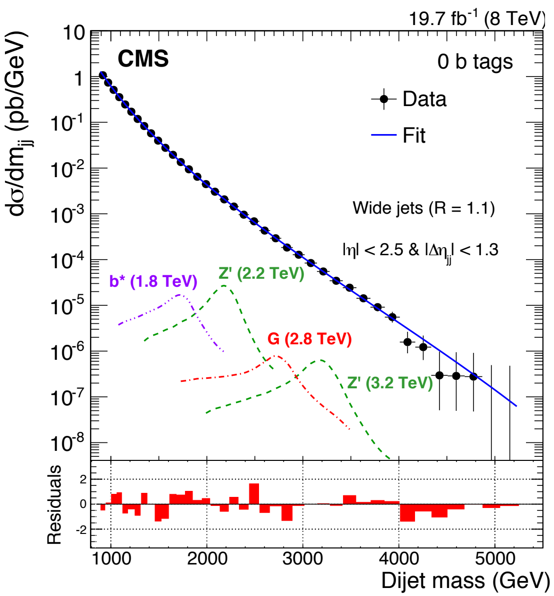
- Dominant systematic uncertainties: jet energy scale, jet energy resolution, luminosity.
- (More final states in backup slides.)

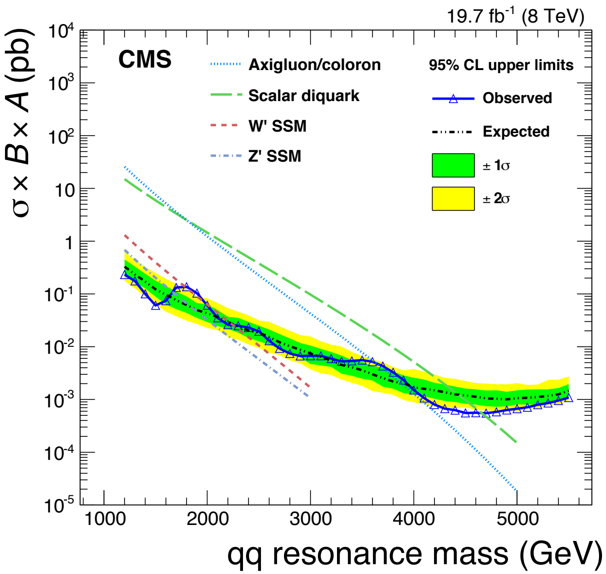
ULB

Dijet resonances







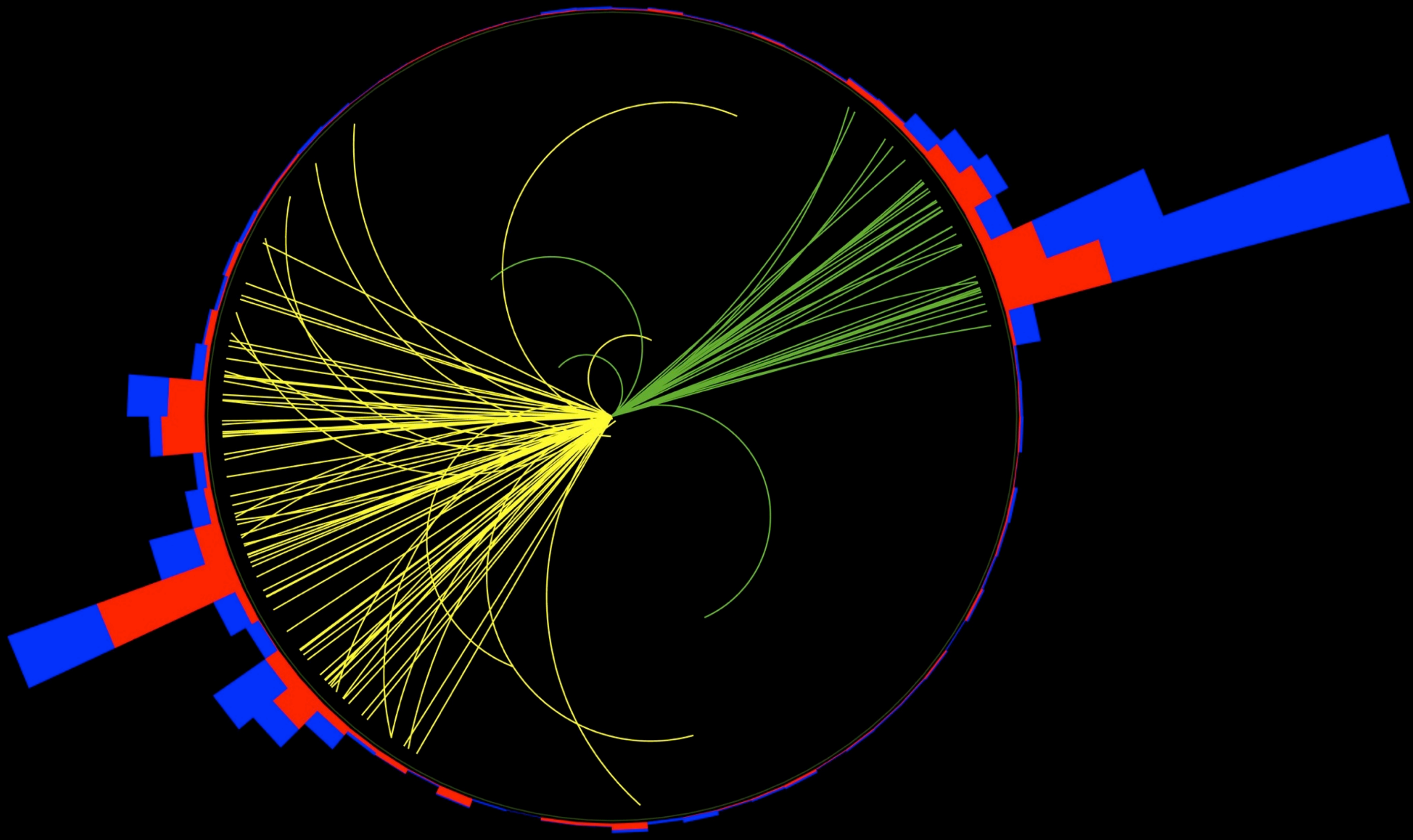


- Limits on W', qg searches:
- ATLAS
  - $m(W') > 2.45$ TeV
  - $m(qg) > 4.06$ TeV
- CMS
  - $m(W') > 2.2$ TeV
  - $m(qg) > 5.0$ TeV

Run 1 “fast” searches summary

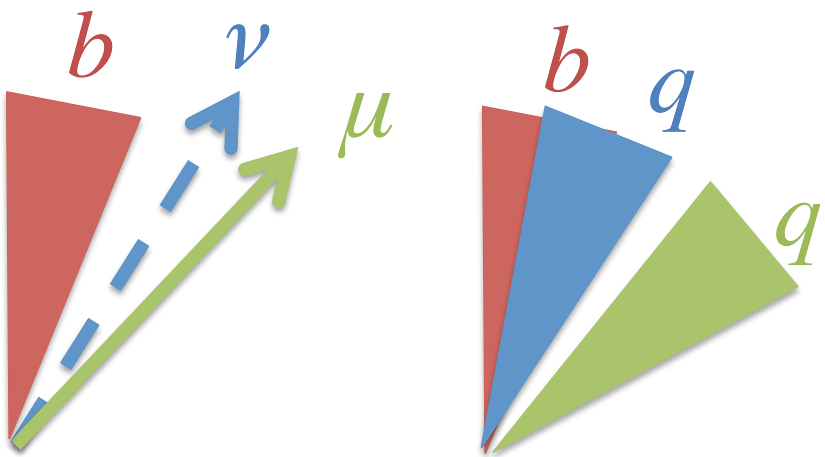
- The “fast” searches give unprecendeted mass reaches.
- Typically in the range of a few TeV.
- Results generally comparable between ATLAS and CMS
- Most sensitivity comes early on
  - We are limited by the energy of the collisions.
- Classic bump searches with high discovery potential.
- Let’s look at something more fun!

Run 1 complex final states



Fat jet tagging

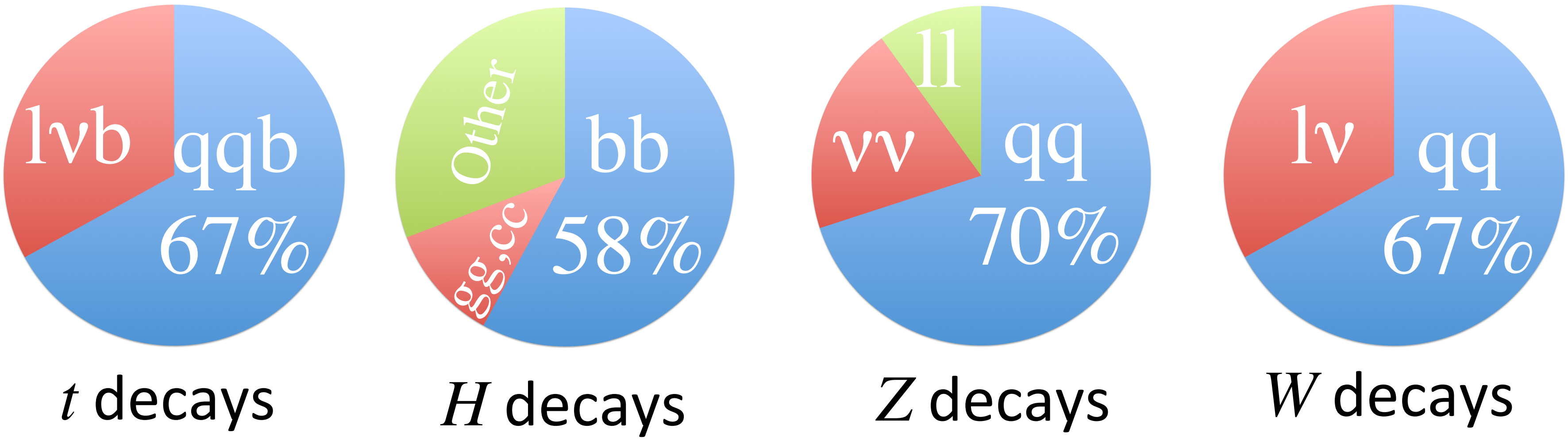
- At the LHC with centre of mass energy of 7-13 TeV
  - $m_t = 175\ \text{GeV}, m_H = 125\ \text{GeV}, m_Z = 91\ \text{GeV}, m_W = 80\ \text{GeV}$
  - We can expect boosted bosons and top quarks at the LHC!
- How does a boosted object decay?
- A top quark decays a bit like this:



- For all hadronic decays the jets tend to overlap with each other.
- Overlapping jets are hard to work with.

Fat jet tagging

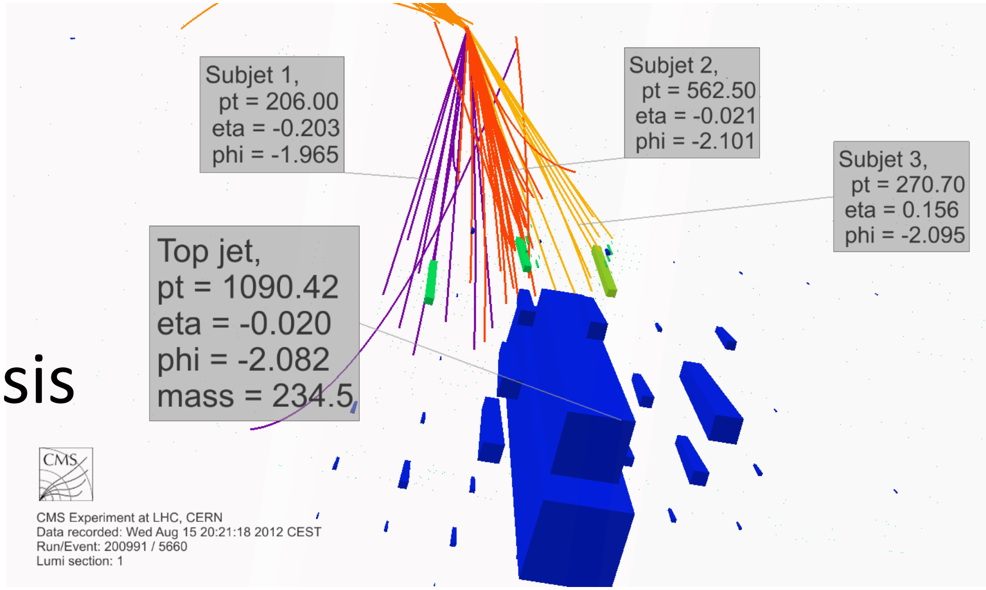
- Should we care about the hadronic decays?
- Yes! They make up > 50% of decays:



- What we need is “fat” jet reconstruction.
- With that we can search for resonances involving top quarks and massive bosons in the final state.

Top jet tagging

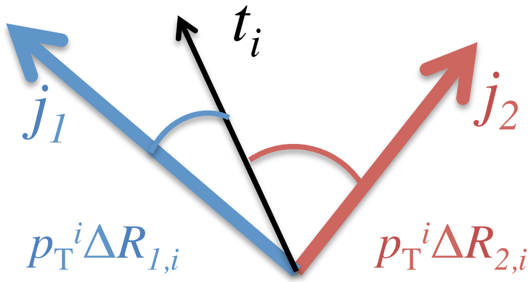
- "Top jets" have a distinctive substructure.
- ATLAS and CMS have developed "top tagging" algorithms.
- Example from the CMS tagger:
  - $140 < m(j_t) < 250$ GeV
  - $N_{\text{sub-jets}} > 2$
  - Minimum pairwise mass, $m_{min} > 50$ GeV
- Further selections per analysis
- Excellent discussion in the ATLAS paper: Eur. Phys. J. C (2015) 75:165



Top jet tagging

- The "sub-jettiness" variable is defined as τ_N:

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



Track t_i compared to sub-jets j_1, j_2:

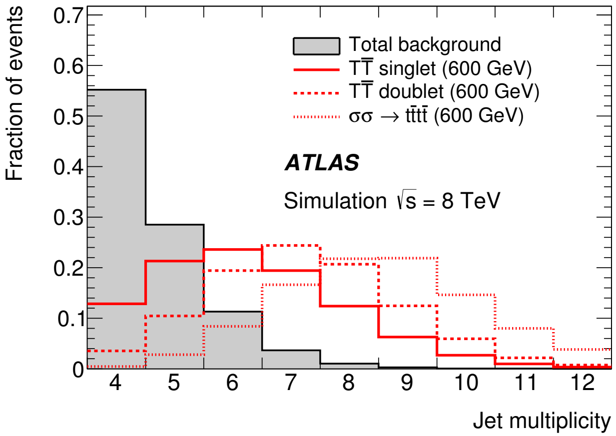
  - R_0 is the characteristic jet radius.
  - τ_N measures consistency with a top decay.
  - τ_i/τ_j are discriminating variables, peaking near 1 for i sub-jets and 0 for j sub-jets.
- Similar algorithms exist for W, Z, H bosons

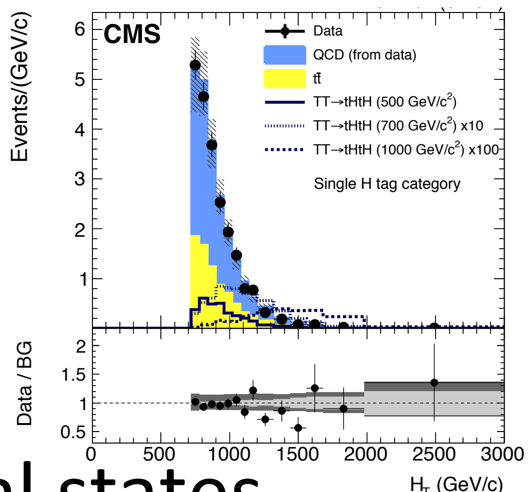
Latest results: $T \rightarrow tH$

arXiV: 1505.04306

arXiV: 1503.01952

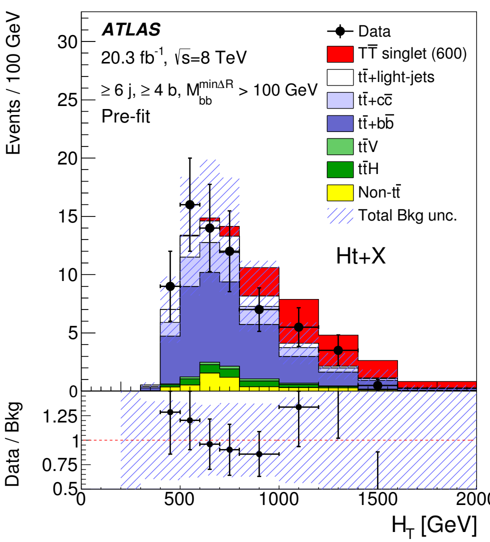
- ATLAS and CMS investigate vector like T quarks decaying to a tH.
- The CMS search makes use of boosted t-jet reconstruction:
  - At least one t-jet with $p_T > 200$ GeV, that contains at least one b tagged jet.
  - At least one jet consistent with a scalar boson (two b tagged jets and $m(j_{CA}) > 60$ GeV).
  - $H_T > 720$ GeV
- For ATLAS there are non trivial kinematic selections and multiple final states.

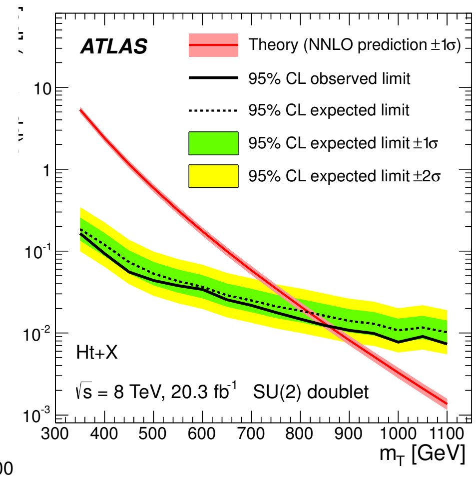


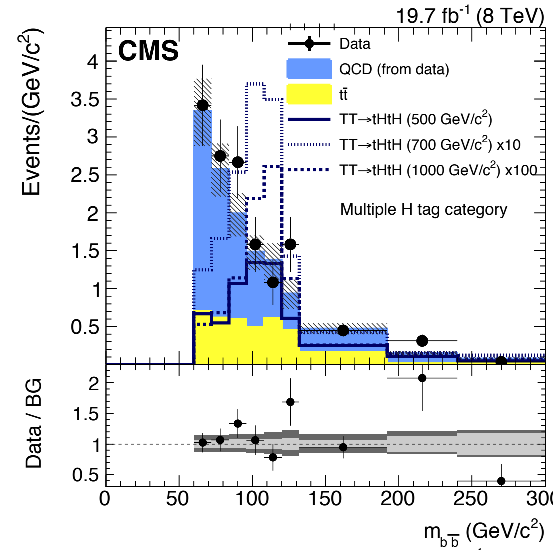


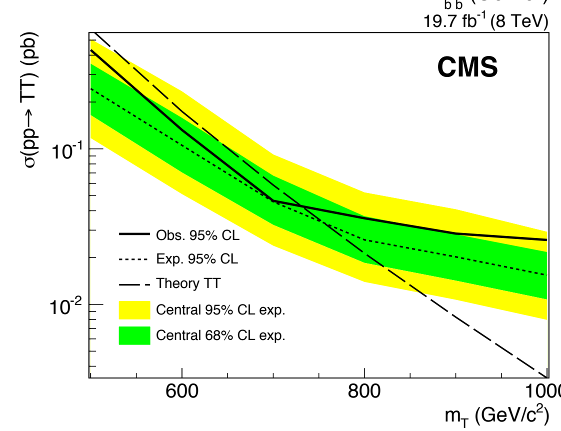
Latest results: $T \rightarrow tH$

- Dominant systematic uncertainties:
  - QCD estimate, Flavour tagging, Jet energy corrections, H-tagging
- Need more than just mass variables to gain sensitivity.







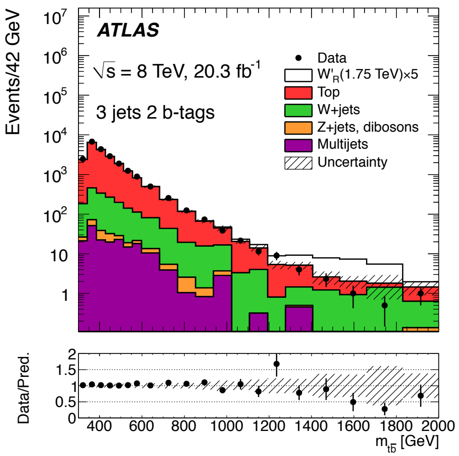


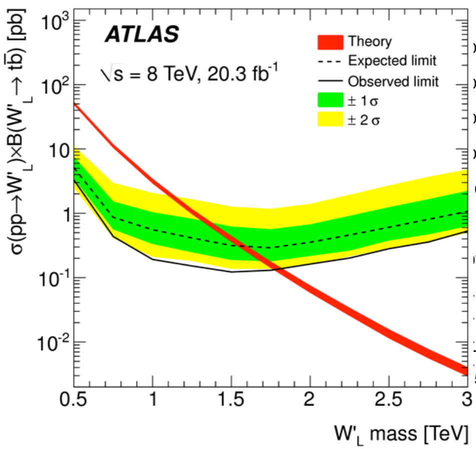
- Limits: ATLAS: $m(T \rightarrow tH) > 855$ GeV
  CMS: $m(T \rightarrow tH) > 745$ GeV

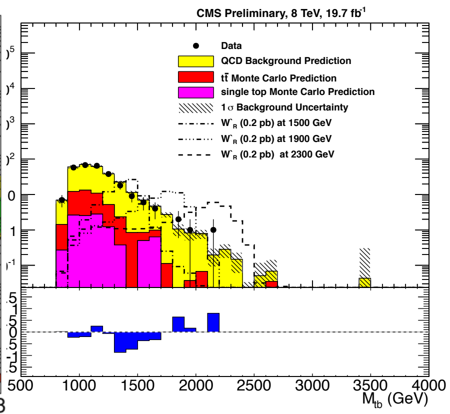
Latest results: $W' \rightarrow tb$

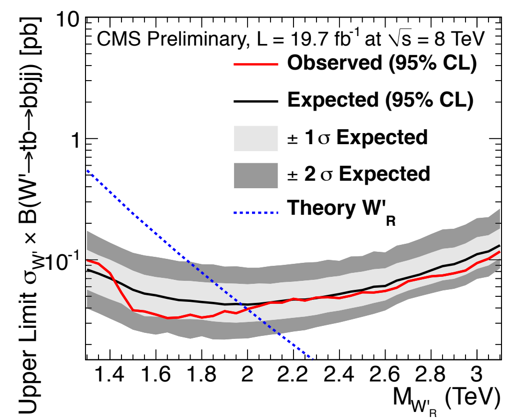
- ATLAS and CMS investigate W' boson decaying to tb final state.
- Dedicated algorithms for top-tagged jets and W' candidates.

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

t-tbar resonances

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

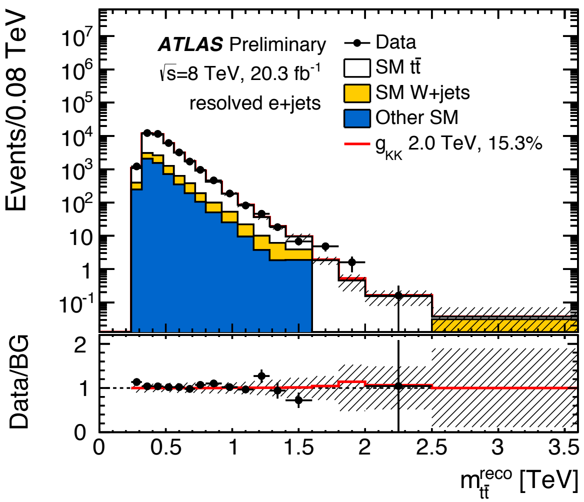
CMS-B2G-13-008

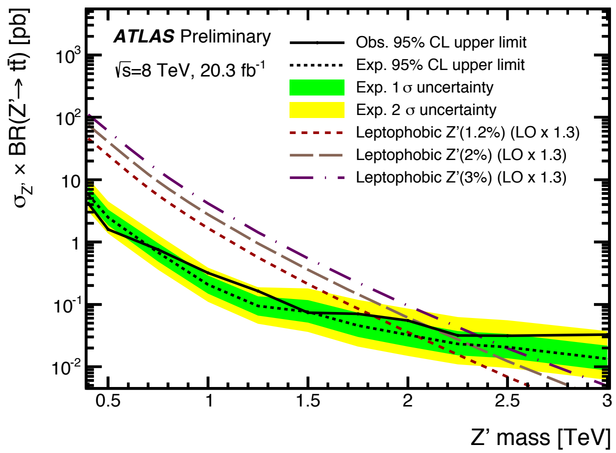
CERN-PH-EP-2015-090

	ATLAS	CMS
jets	anti-kT ΔR = 0.4: $p_T(j)$> 25 GeV, $\lvert\eta(j)\rvert < 2.5$ anti-kT ΔR = 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:

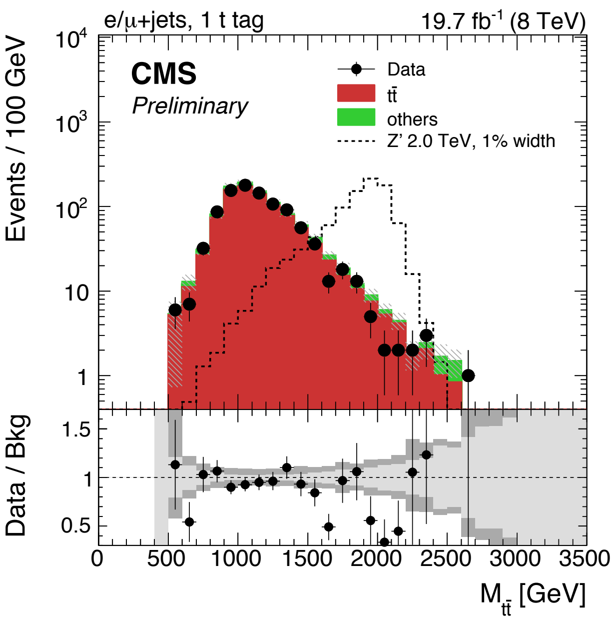
ATLAS

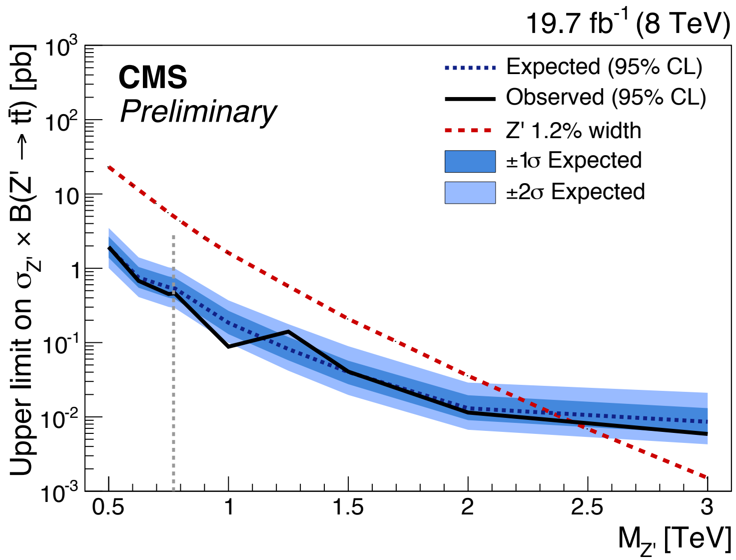
$m(Z') < 0.4$ TeV or

$m(Z') > 3.0$ TeV

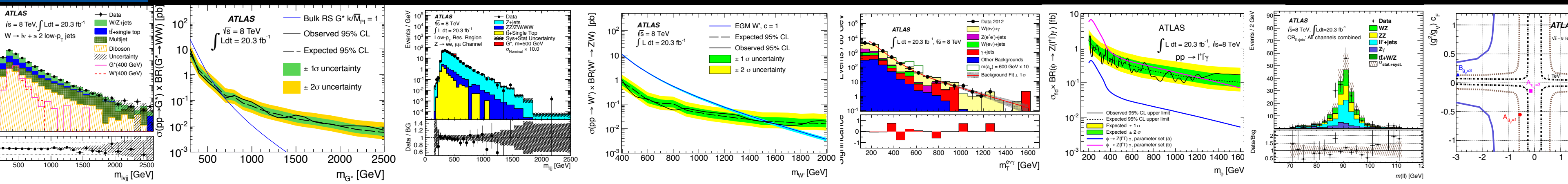
CMS

$m(Z') > 2.4$ TeV

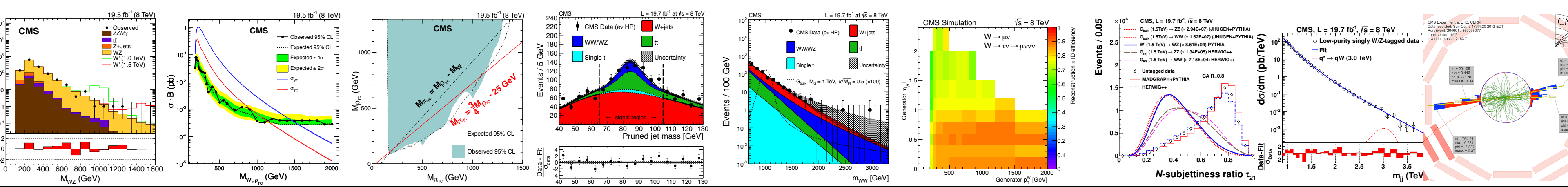




Vector boson resonances



- Many final states ($lljj$, $llll$, $ll l\nu$, $jjjj$, $l\nu jj$) 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

$W' \rightarrow WZ \rightarrow lll\nu$

- Benchmark model of $W' \rightarrow WZ$.
- Clean final states.
- Kinematic selections:

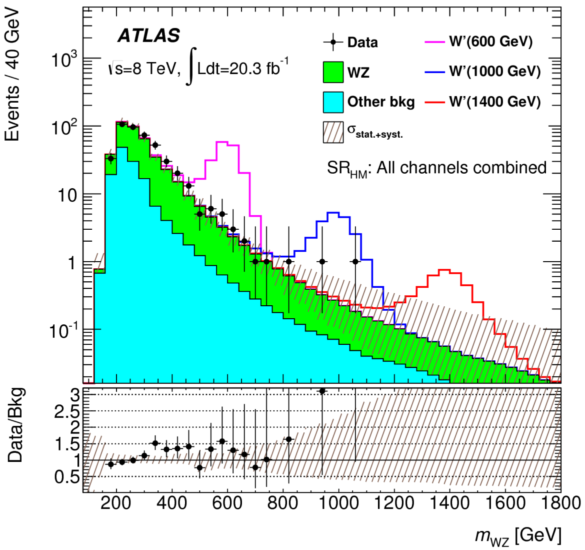
PLB 737, 223 (2014)

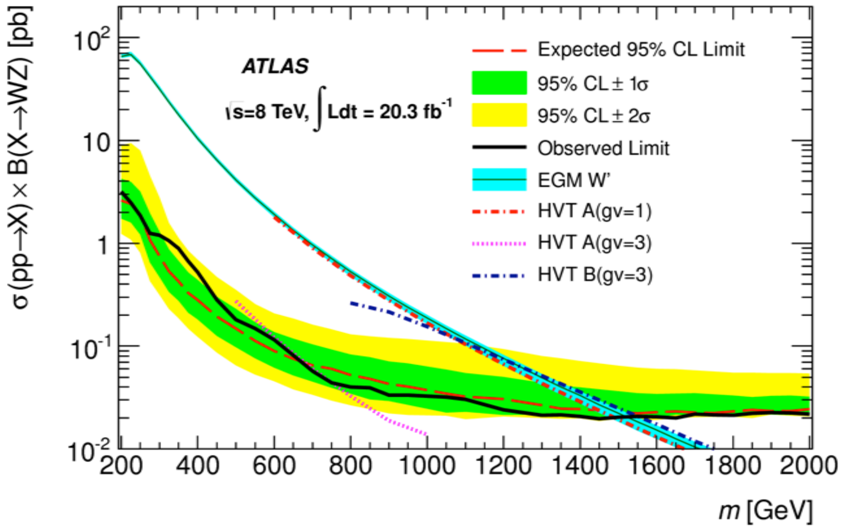
PLB 2014.11.026

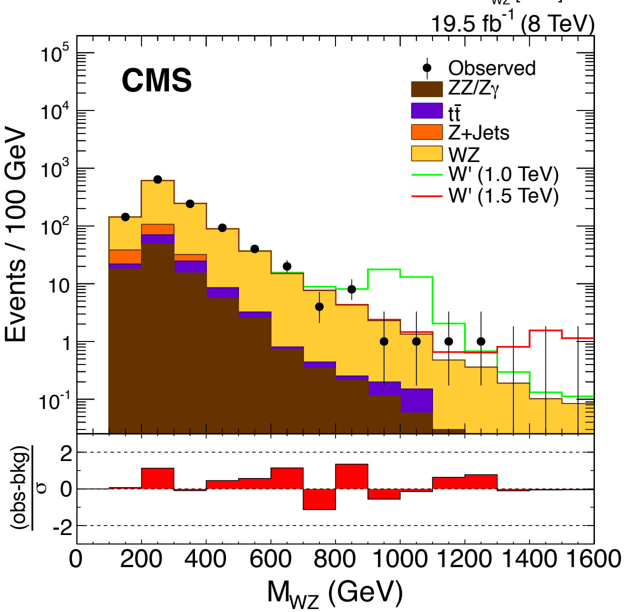
	ATLAS	CMS
e	$E_T > 40, 30$ GeV $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	$E_T > 35$ (20) GeV for Z (W) boson $\lvert\eta\rvert < 1.442$ or $1.56 < \lvert\eta\rvert < 2.5$
μ	$p_T > 25, 25$ GeV $\lvert\eta\rvert < 1.05$	$p_T > 25, 10$ GeV for Z boson $p_T > 20$ GeV for W boson $\lvert\eta\rvert < 2.4$

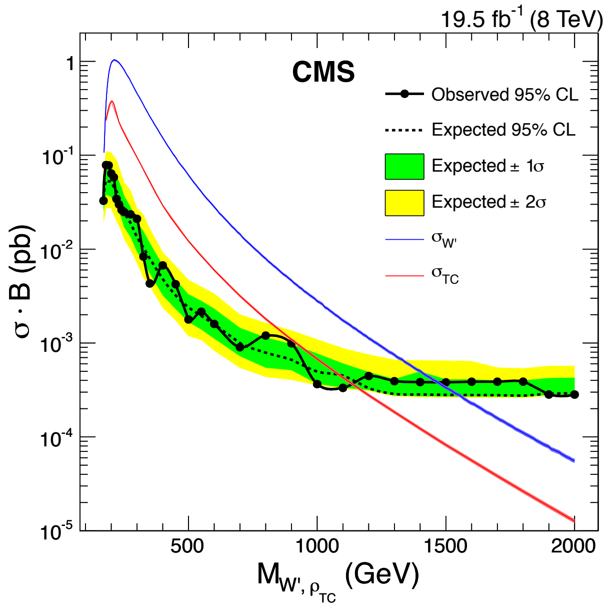
- Dominant systematic uncertainties:
  - ATLAS: Lepton scale factors, simulation statistics, luminosity.
  - CMS: Trigger efficiency, missing energy resolution, luminosity.

$W' \rightarrow WZ \rightarrow lll\nu$









- Limits:
  - ATLAS $m(W') >$ 1520 GeV
  - CMS $m(W') >$ 1550 GeV

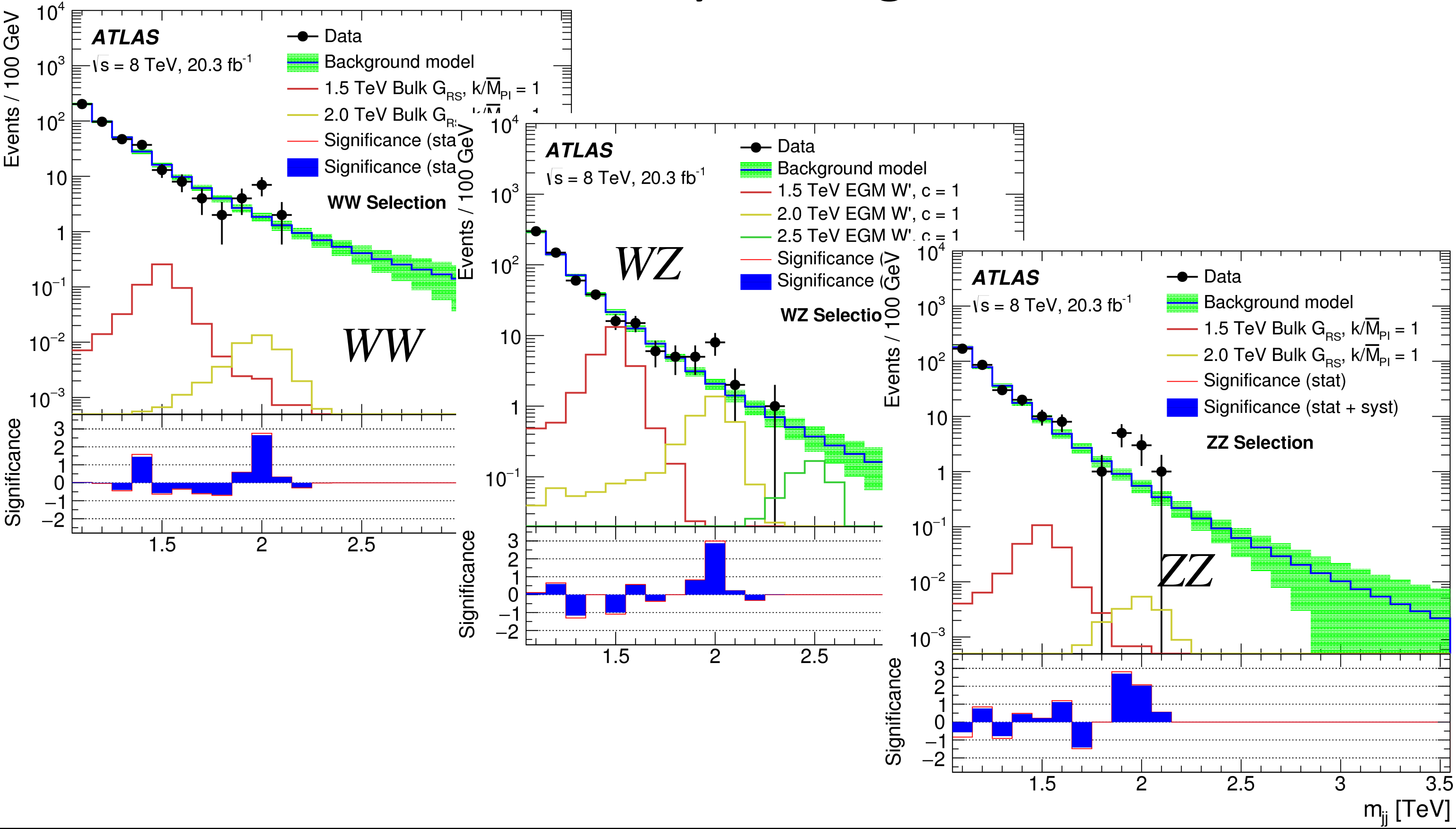
The diboson bump

- Everything seemed fairly boring, and then...

ULB

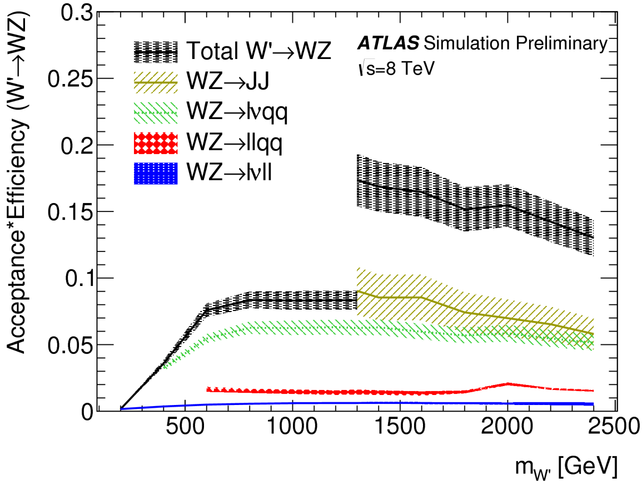
The diboson bump

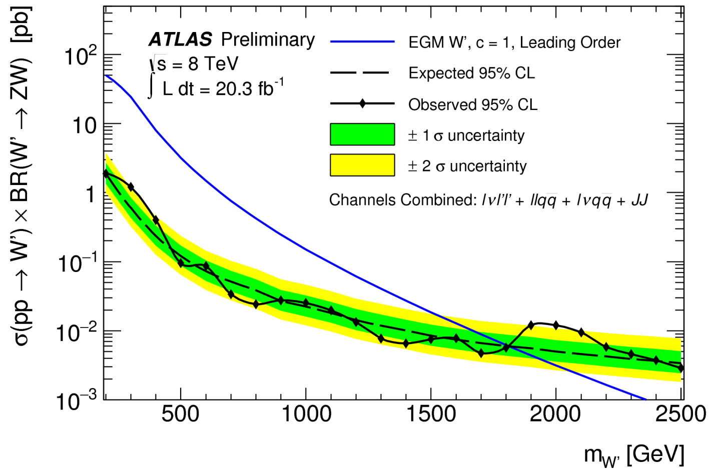
- Everything seemed fairly boring, and then...



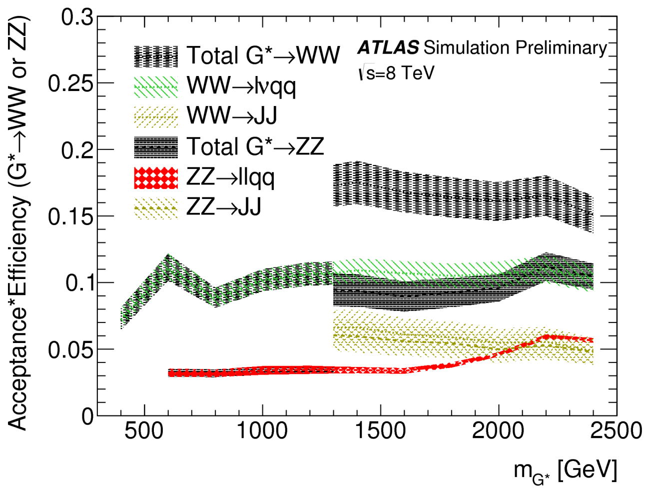
The diboson bump

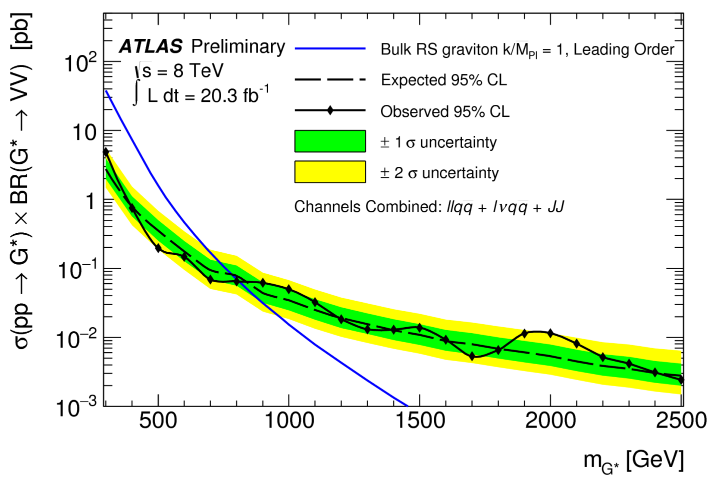
- ATLAS saw some bumps in the diboson mass spectra around $2\ \mathrm{TeV}$!
- More detailed study with multiple final states:





$W' \to WZ$

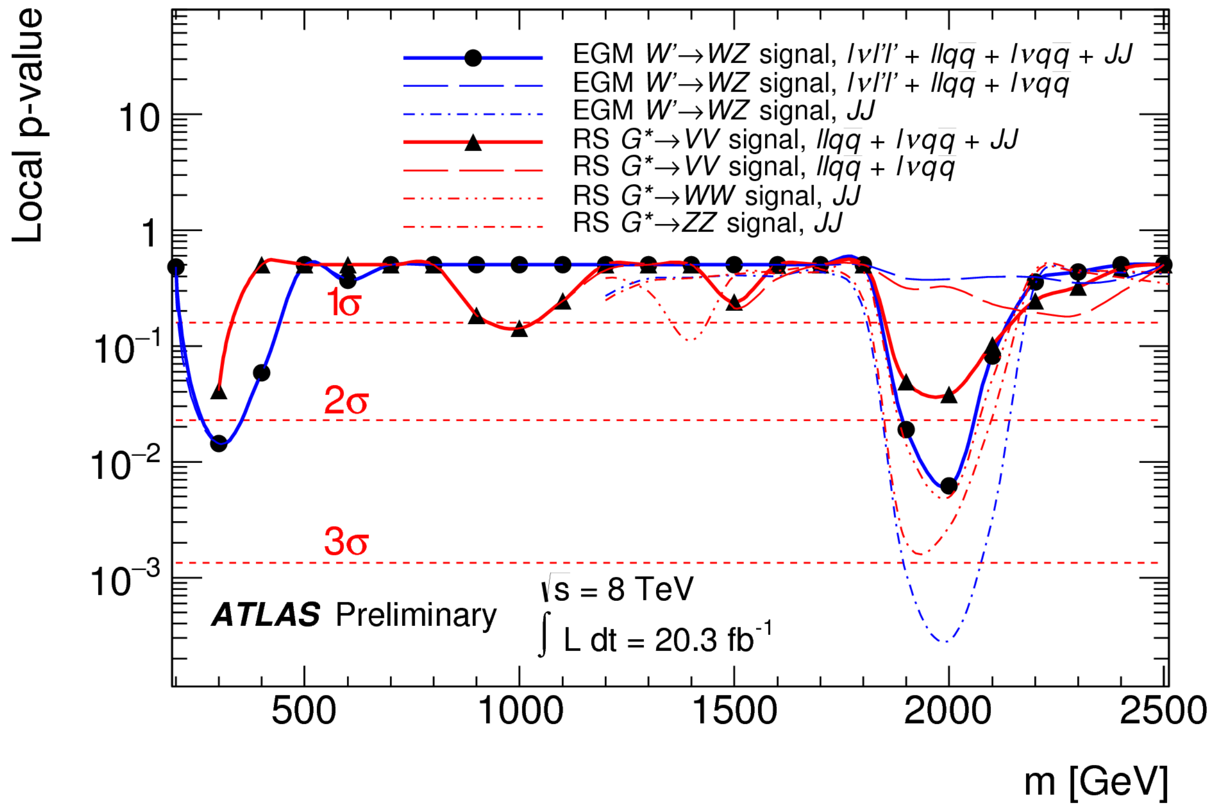




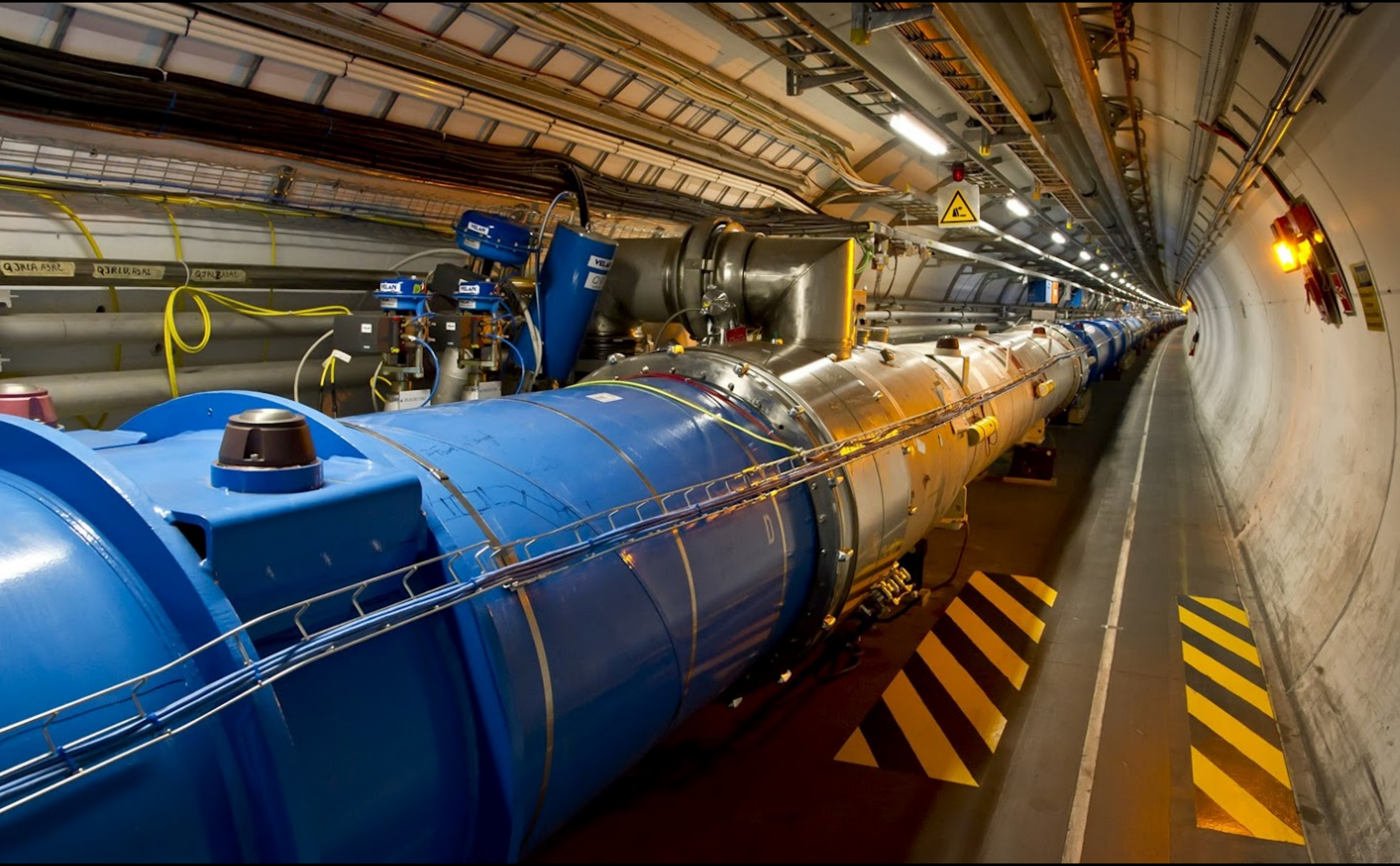
$G_{RS} \to VV$

The diboson bump

- Can't be a single new particle!
- Could it be a multiplet of charged and neutral states?
- As usual, the answer will come with more data
- 3.5σ local significance in $W' \rightarrow WZ \rightarrow JJ$



From Run 1 to Run 2

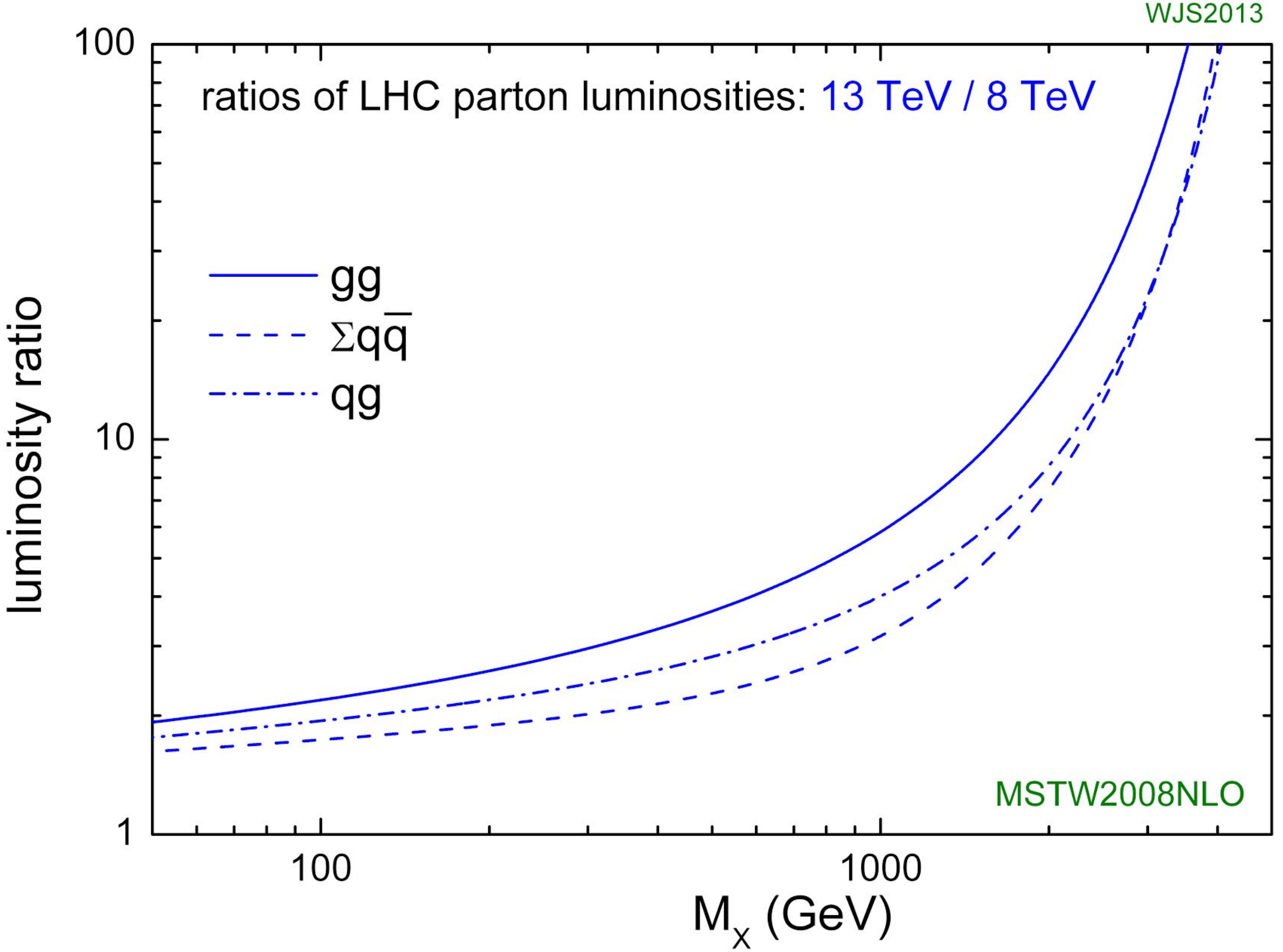


From Run 1 to Run 2

- With LHC Run 1 we had 5 fb^{-1} at 7 TeV and 20 fb^{-1} at 8 TeV
- What can Run 2 offer us?
- Naïvely, more of the same...
- ...except at 13 TeV

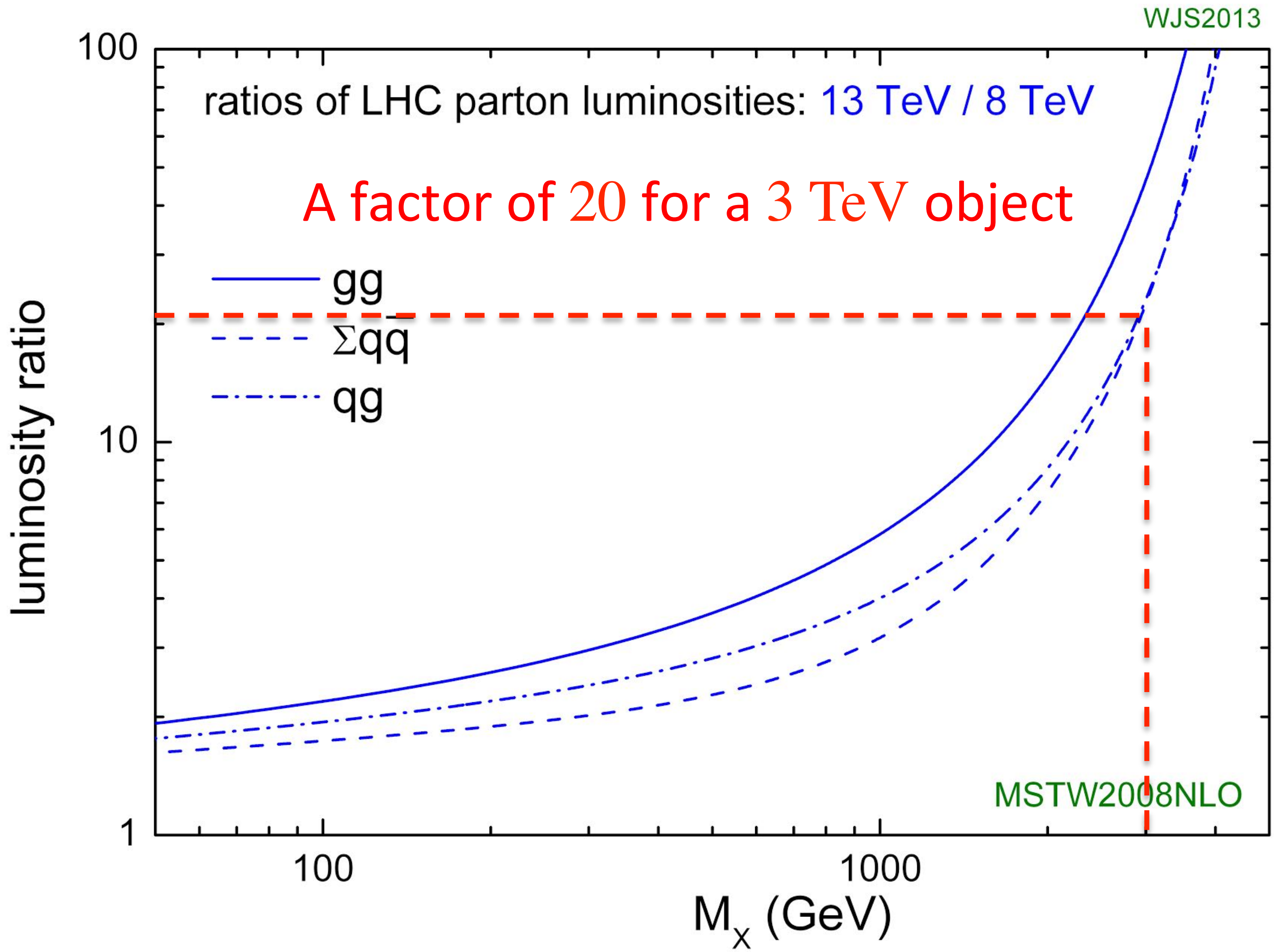
From Run 1 to Run 2

- In fact effective luminosity increases substantially!



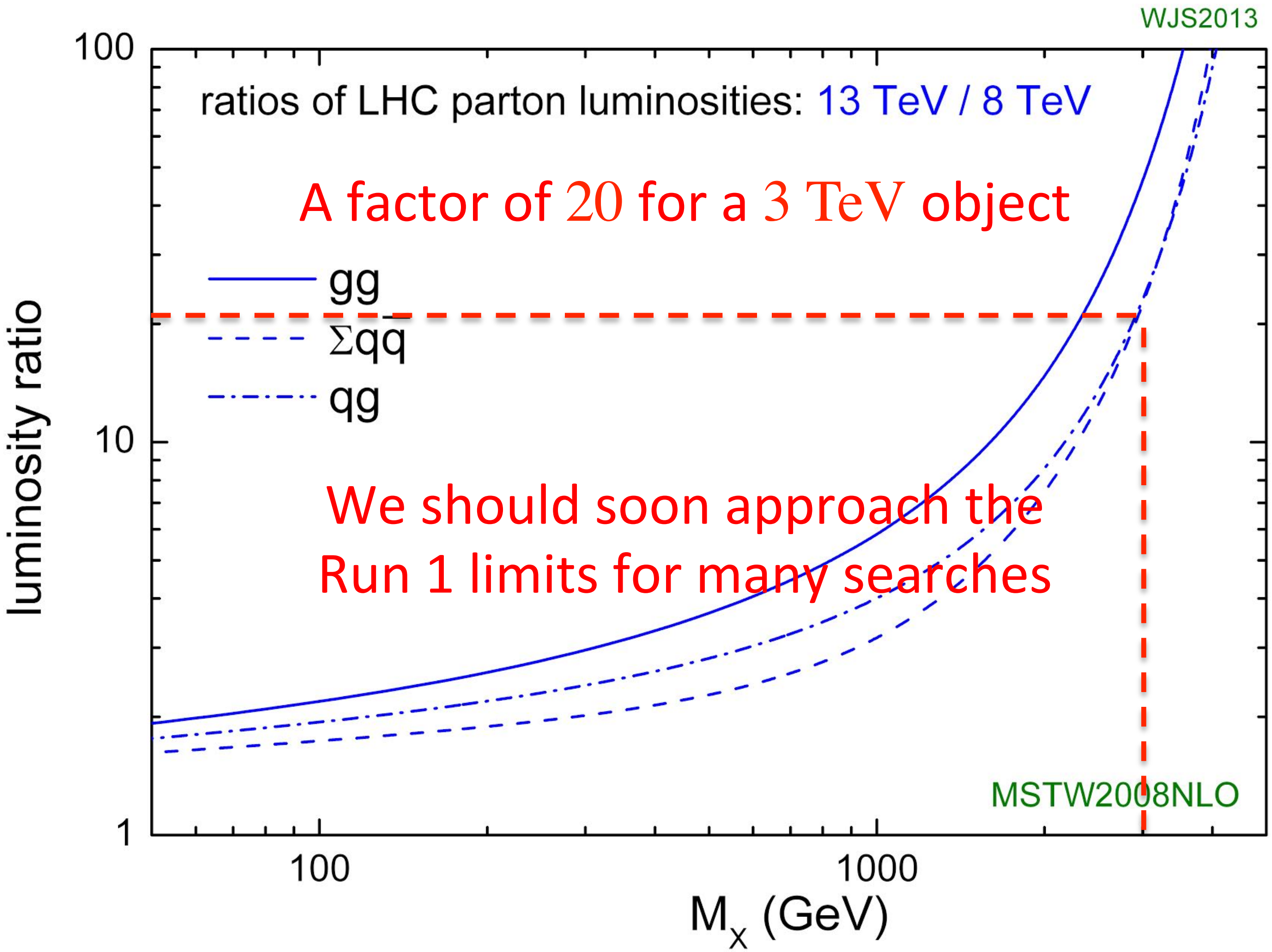
From Run 1 to Run 2

- In fact effective luminosity increases substantially!



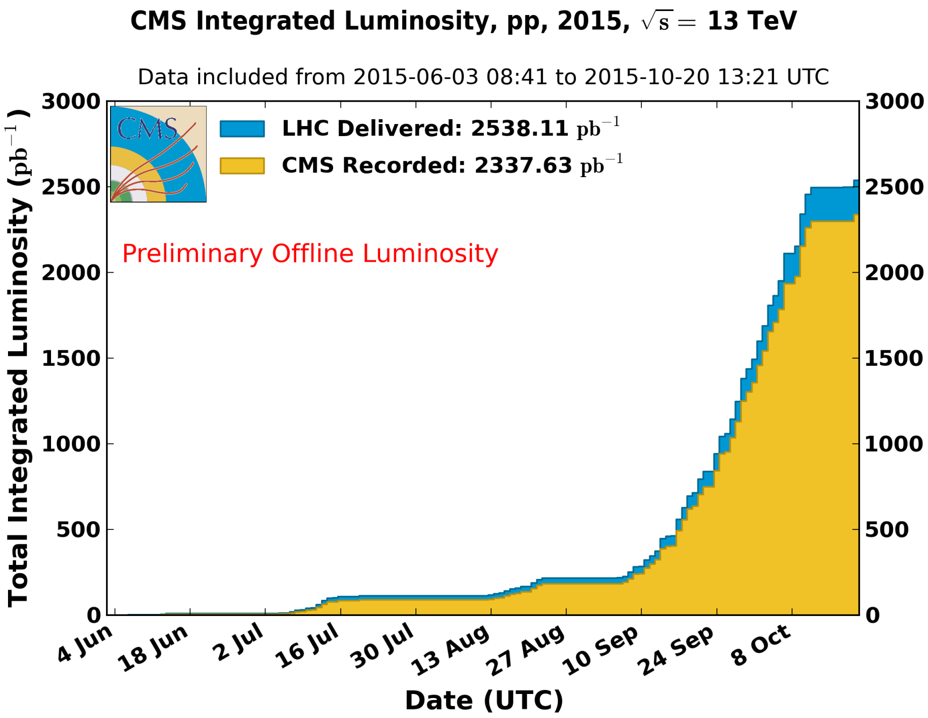
From Run 1 to Run 2

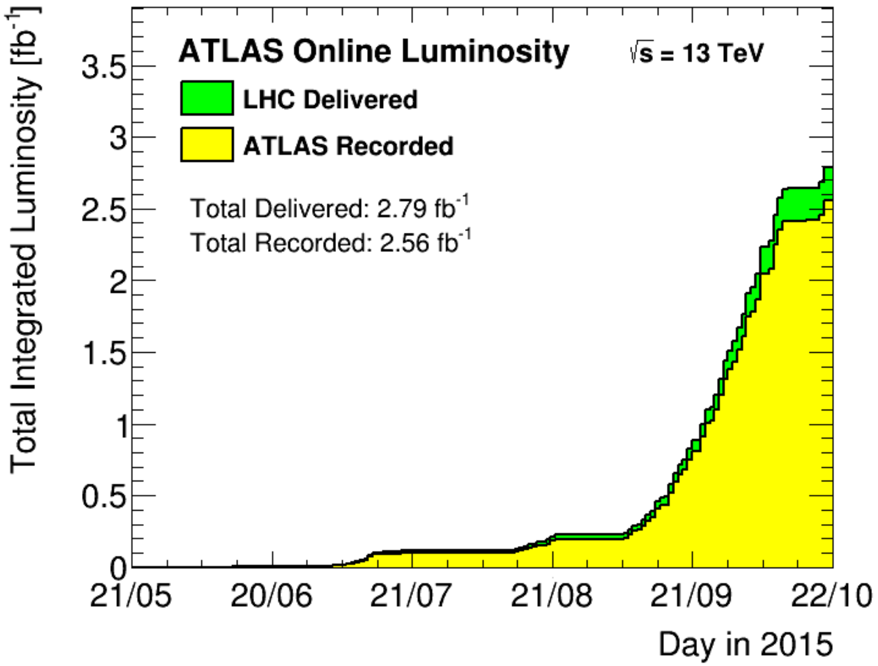
- In fact effective luminosity increases substantially!



From Run 1 to Run 2

- Luminosity of Run 2:

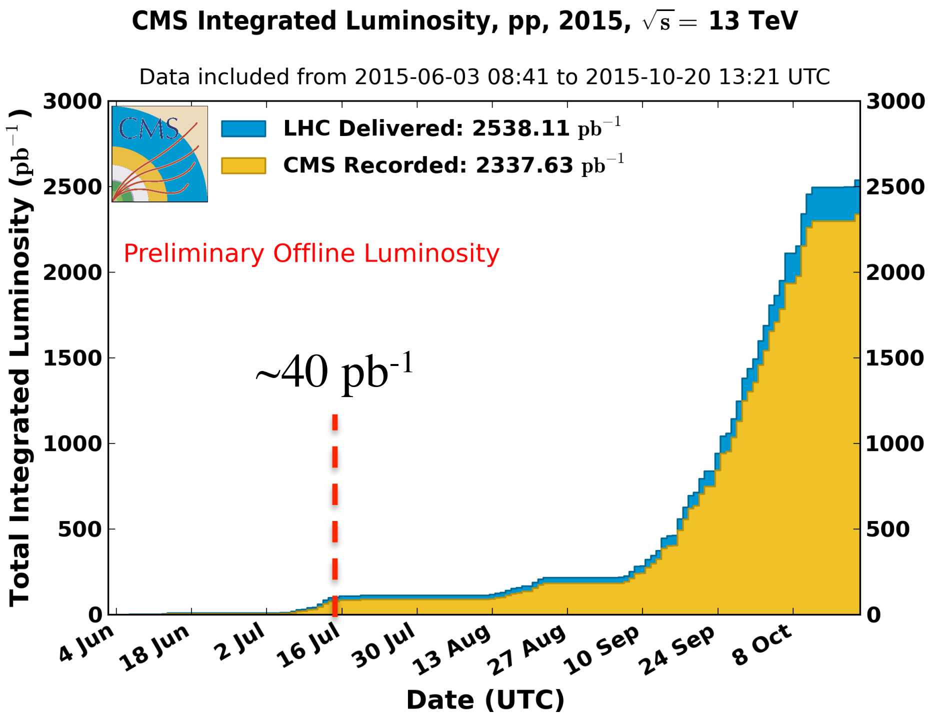


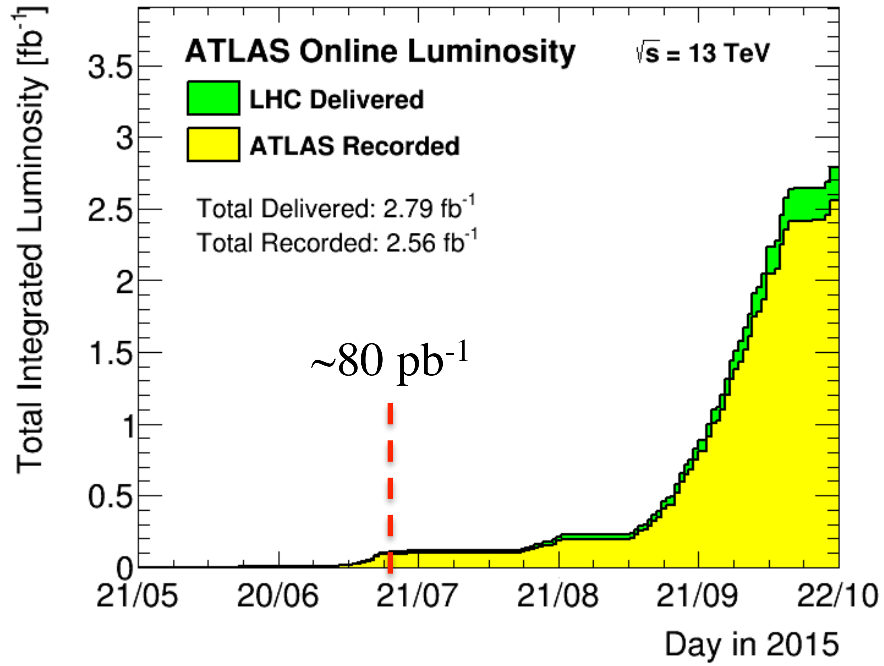


- About 2.5 fb^{-1} so far

From Run 1 to Run 2

- Luminosity of Run 2:

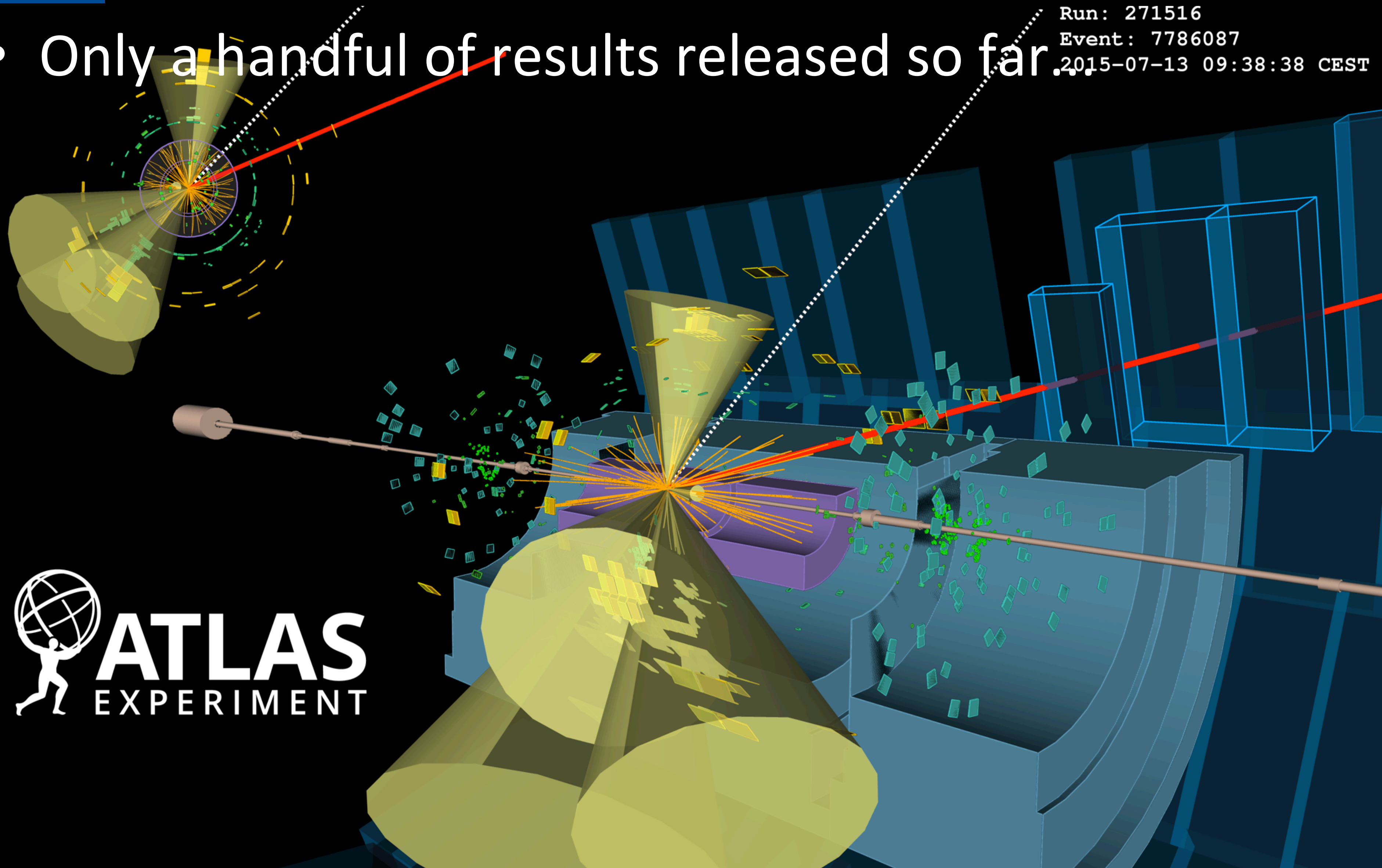




- About 2.5 fb^{-1} so far

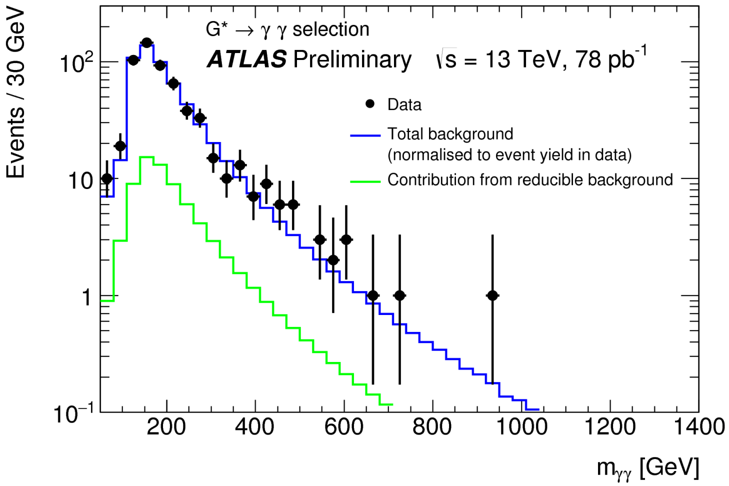
Some Run 2 results

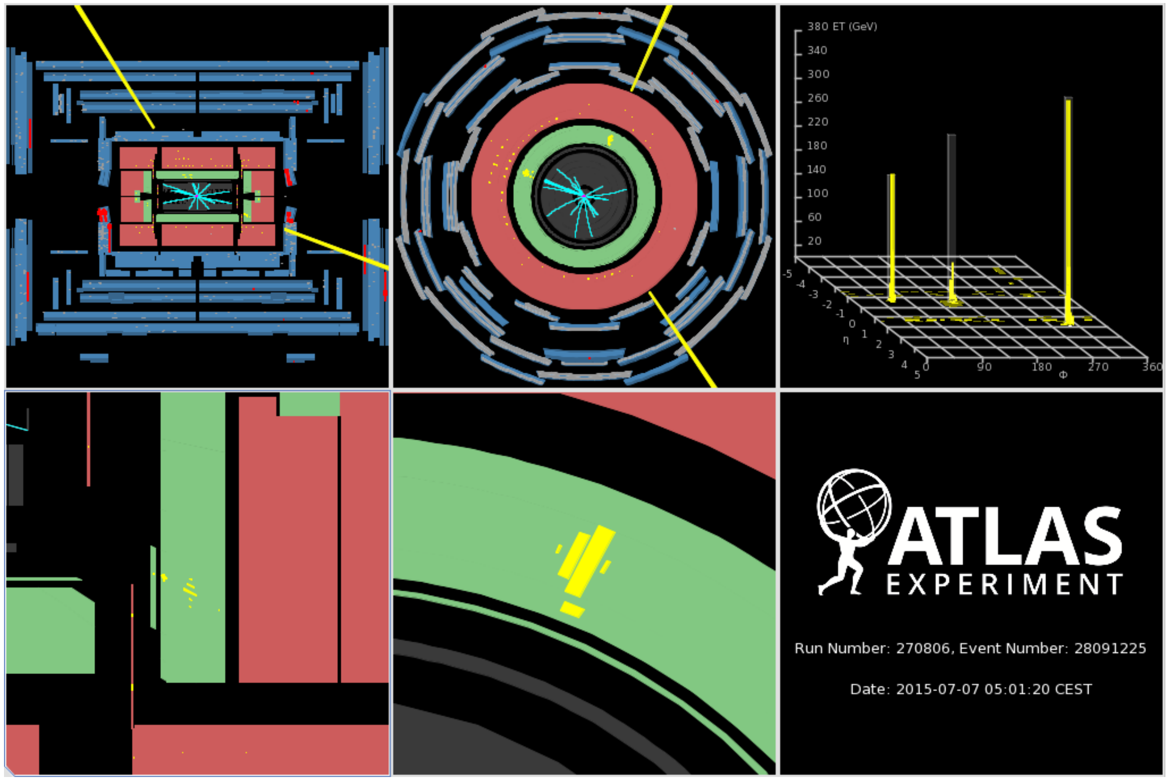
- Only a handful of results released so far…



ATLAS diphoton search

- Latest ATLAS results for the diphoton search:



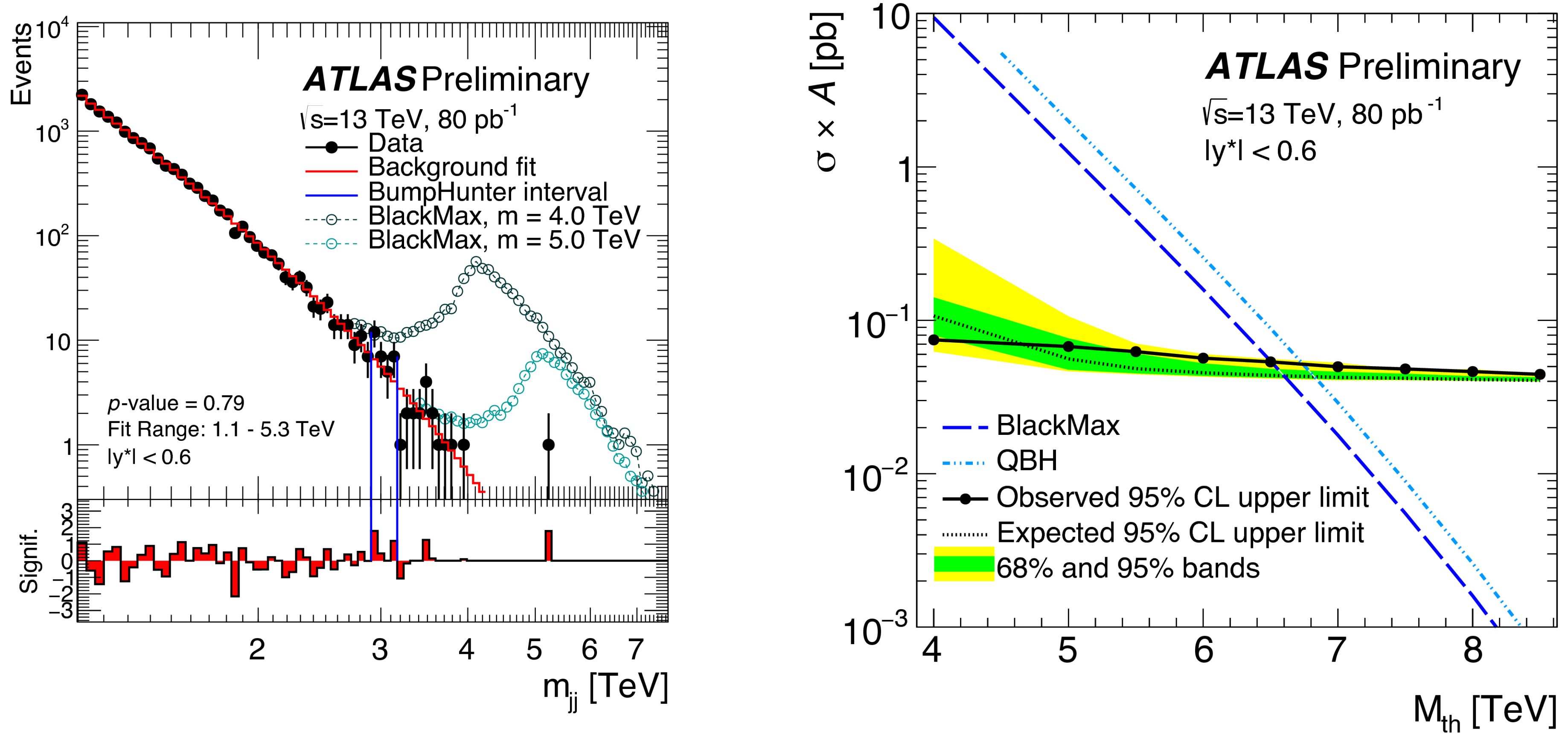


- No bump with 78 pb^{-1}

$m(\gamma\gamma) = 940$ GeV

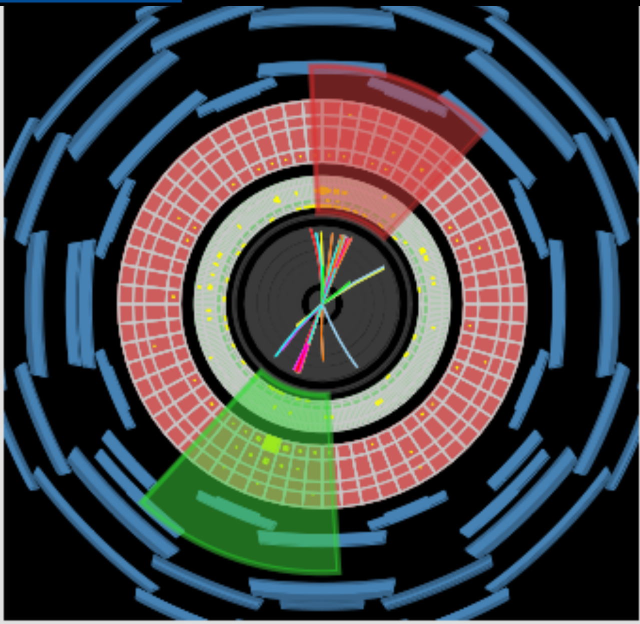
ATLAS dijet search

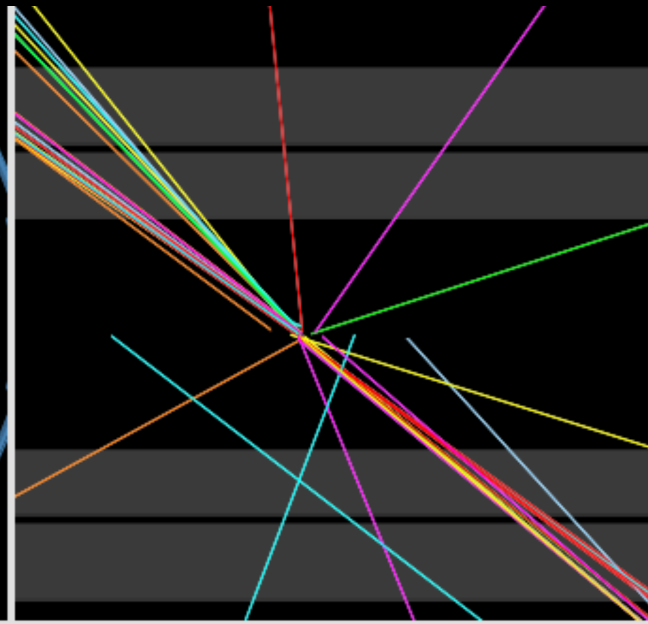
- The dijet searches benefit form the new mass reach



ATLAS dijet search

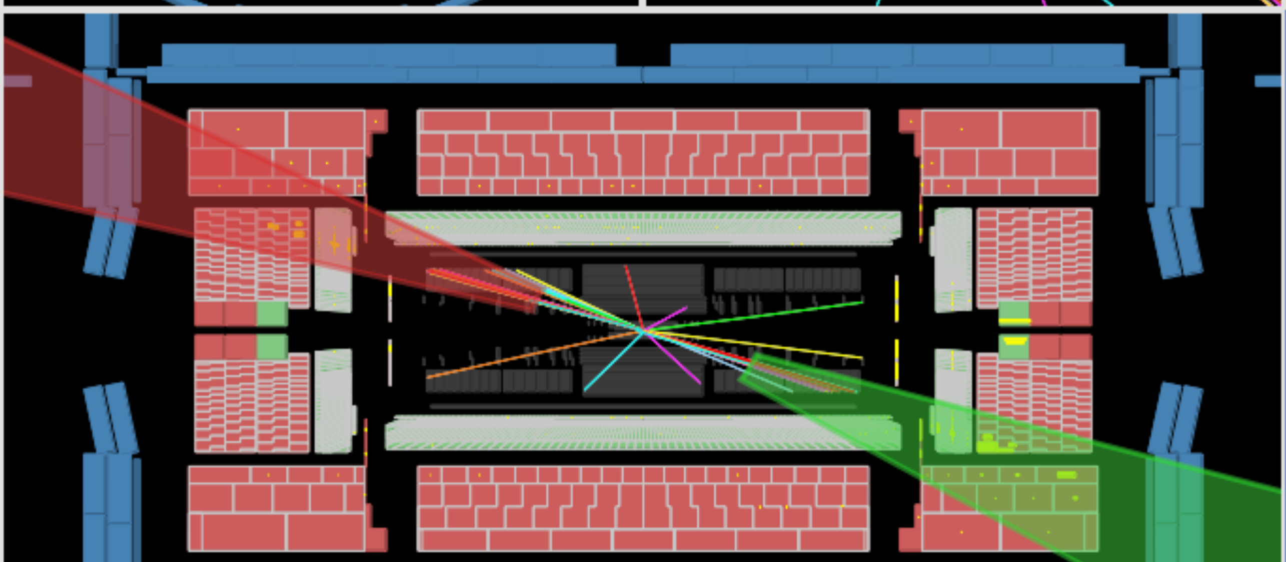
$m(jj) = 6.9\ \mathrm{TeV}$

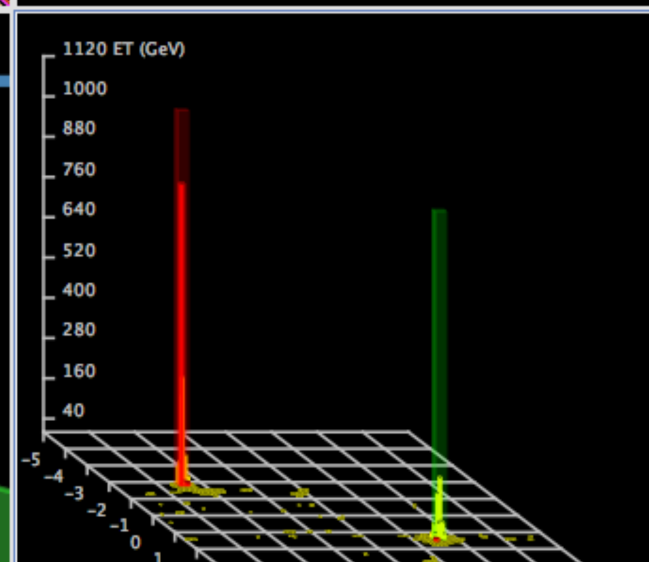




Run Number: 276731, Event Number: 876578955

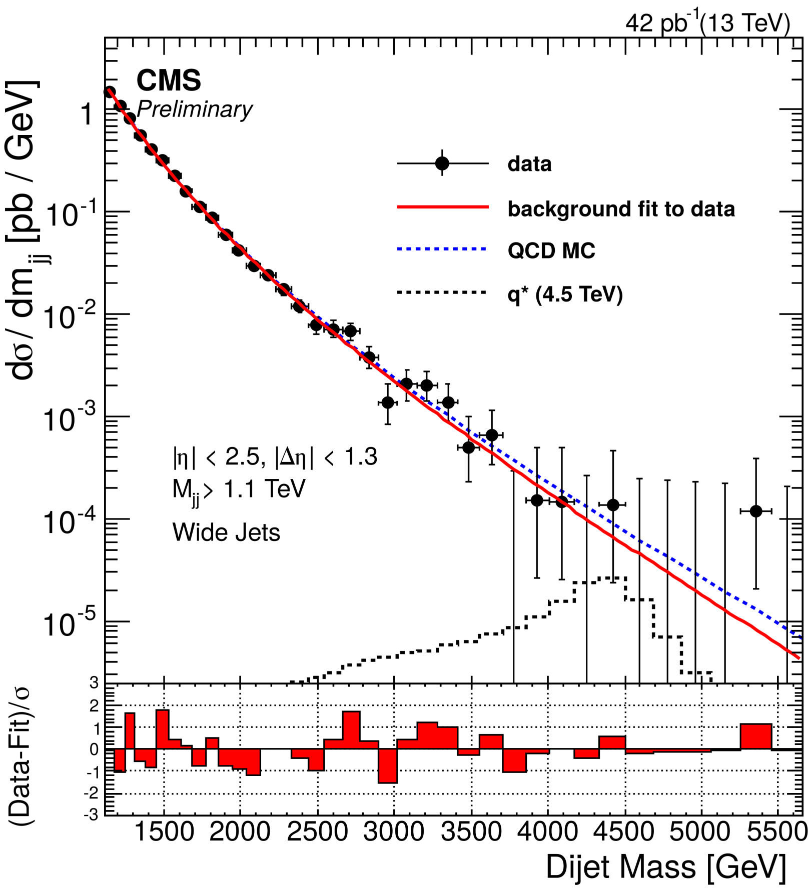
Date: 2015-08-22 07:43:18 CEST

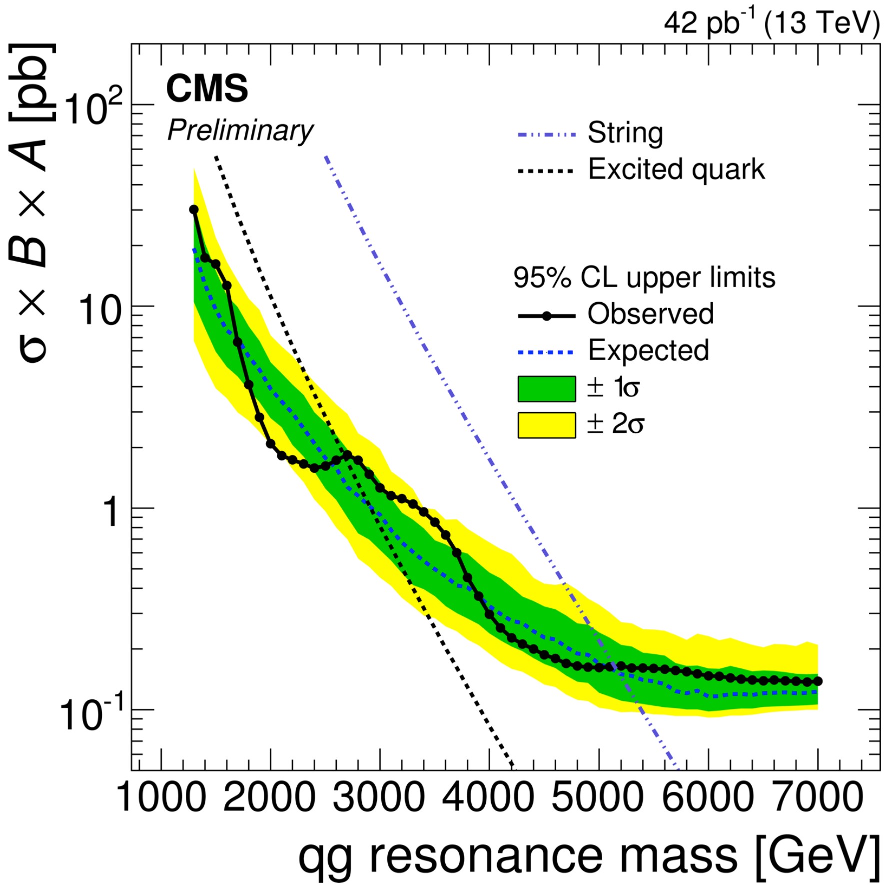




CMS dijet search

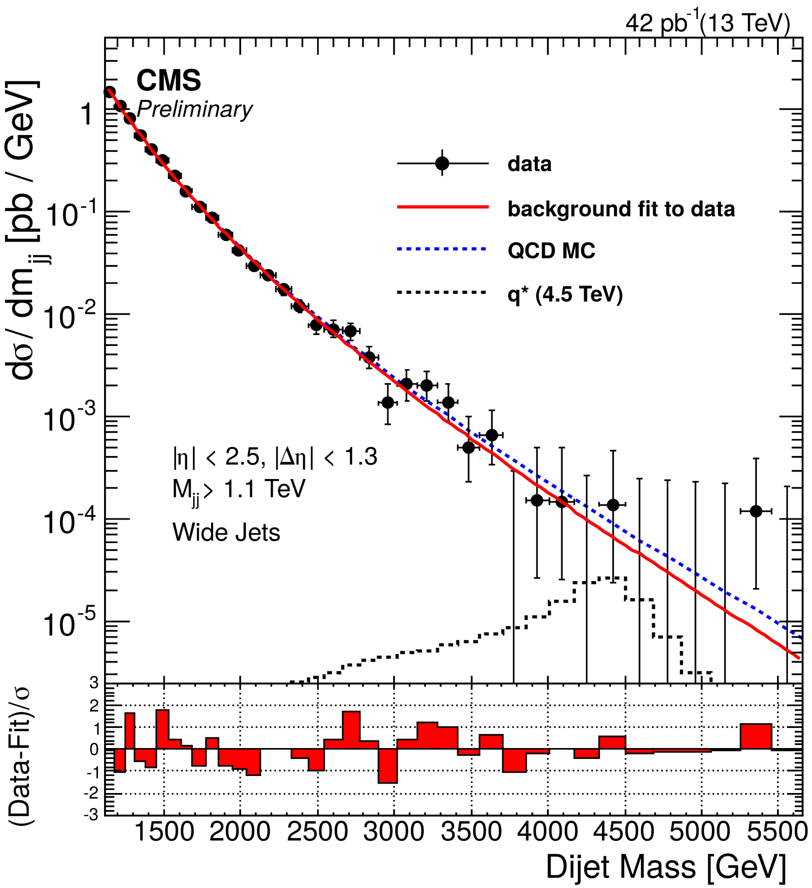
- The dijet searches benefit form the new mass reach

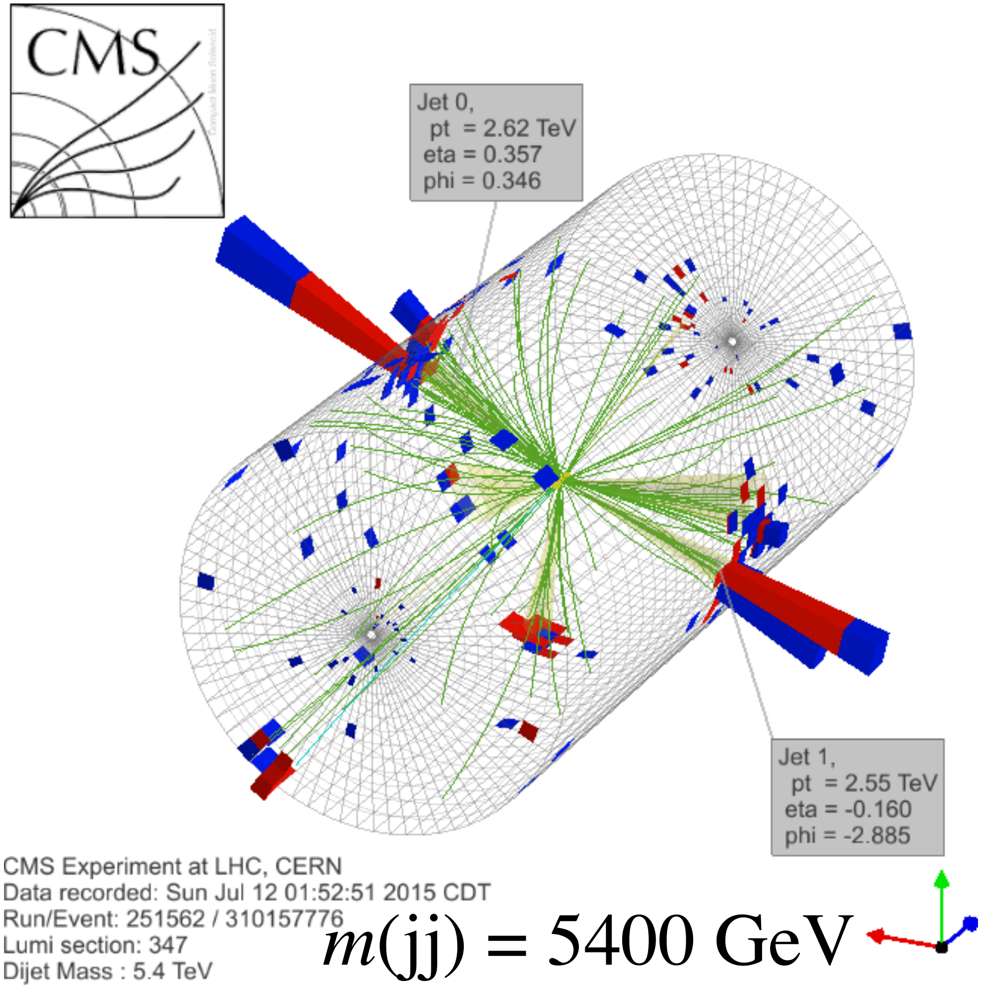




CMS dijet search

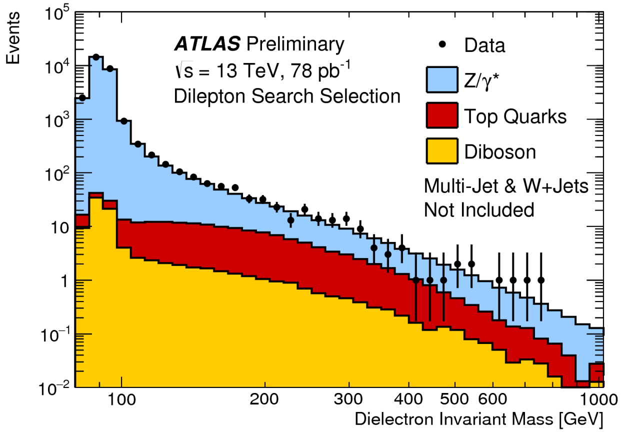
- Also no bump seen here

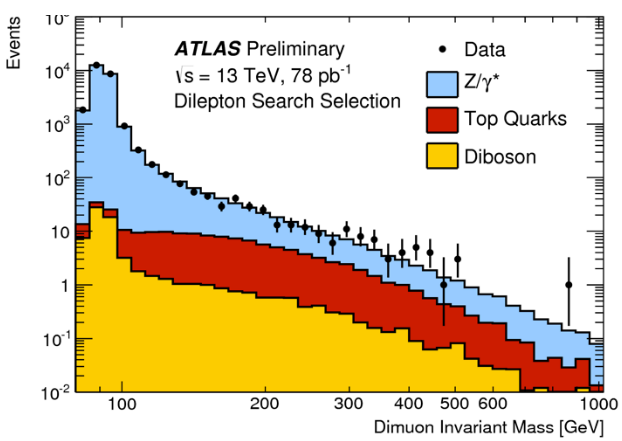


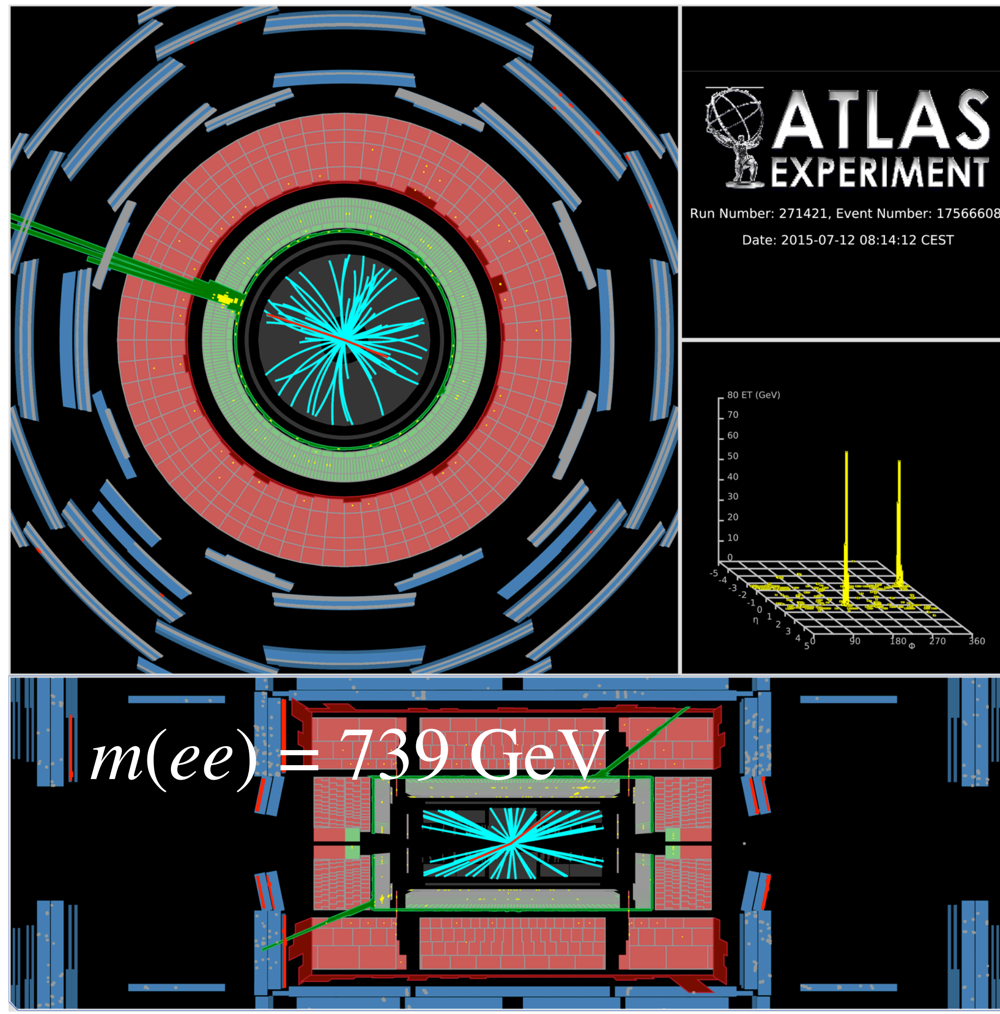


ATLAS dilepton search

- Latest ATLAS results for the dilepton searches:



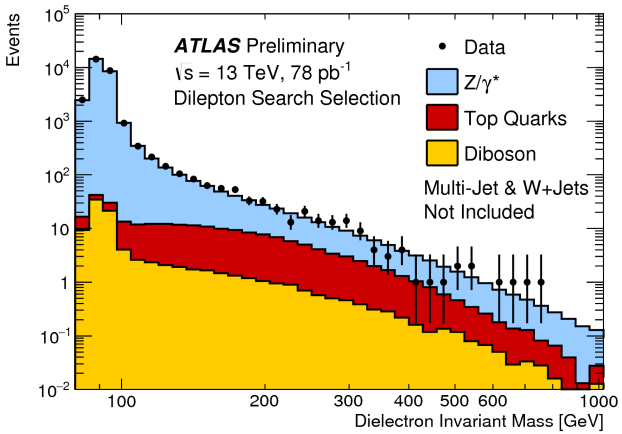


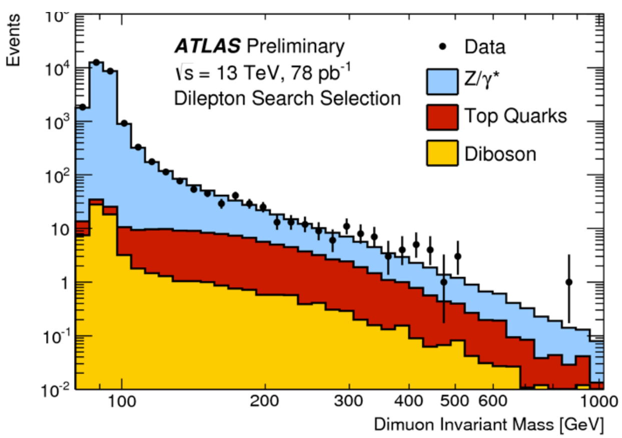


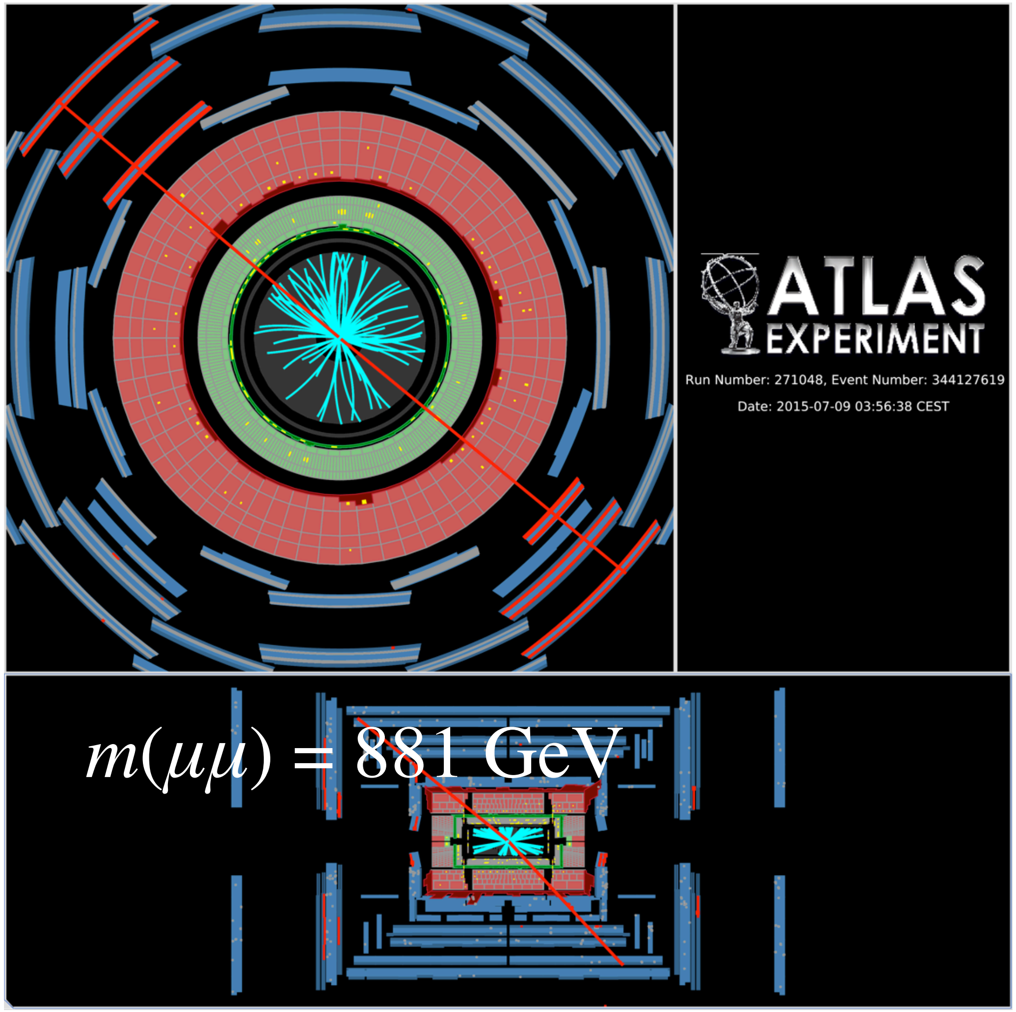
- No bump with 78 pb^{-1}

ATLAS dilepton search

- Latest ATLAS results for the dilepton searches:



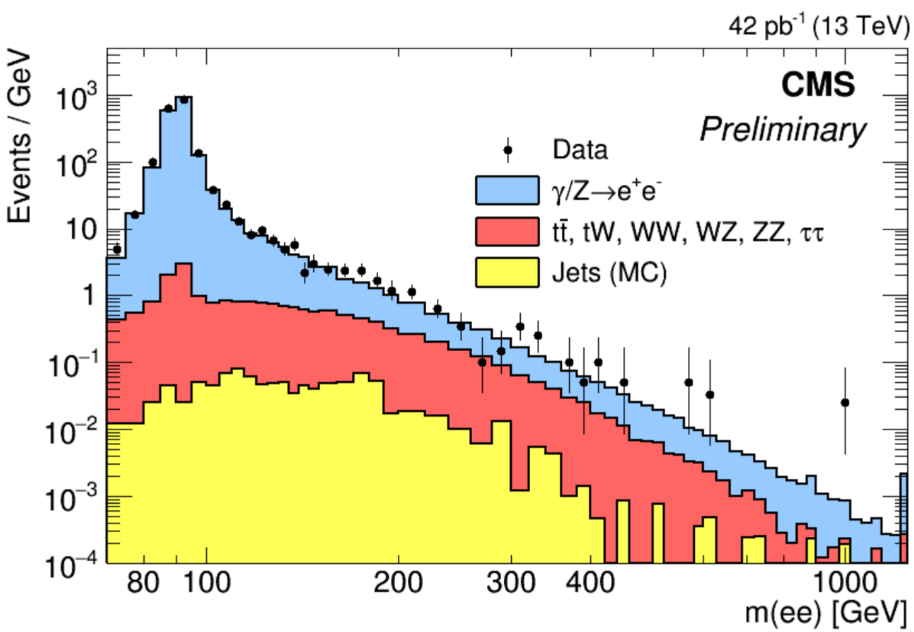


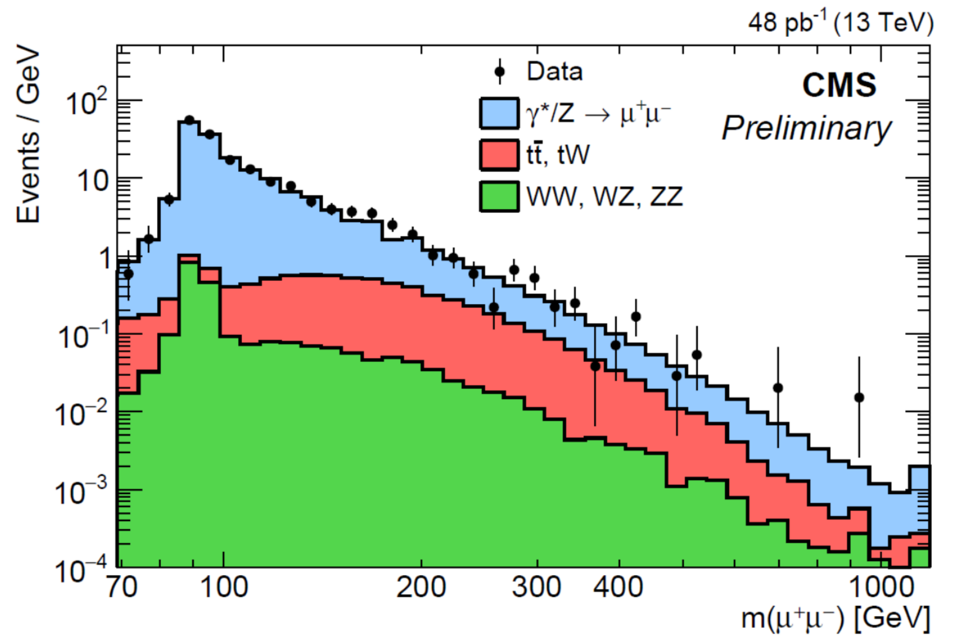


- No bump with 78 pb^{-1}

CMS dilepton search

- Latest CMS results for the dilepton searches:

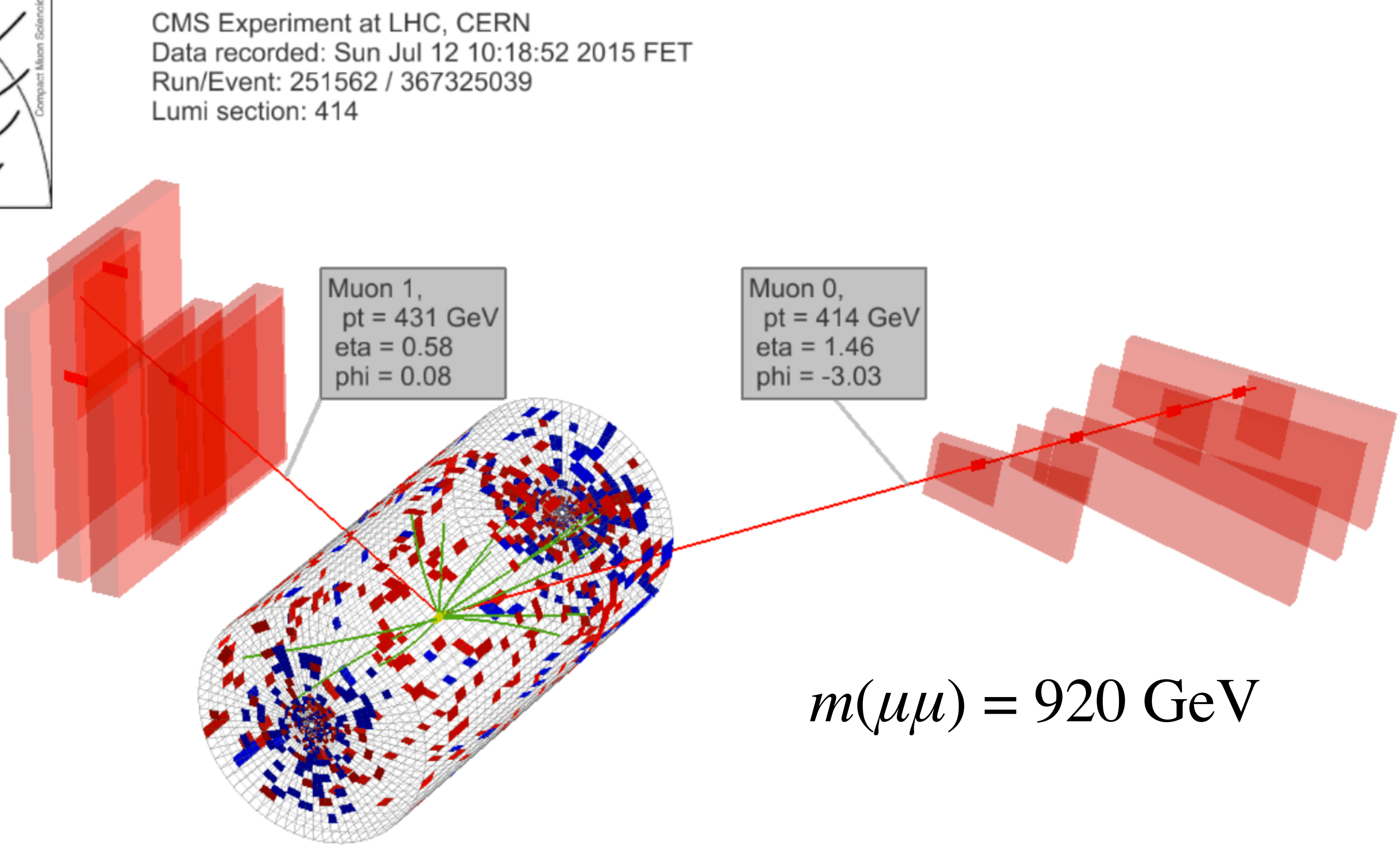




- No bump with 42-48 pb^{-1}

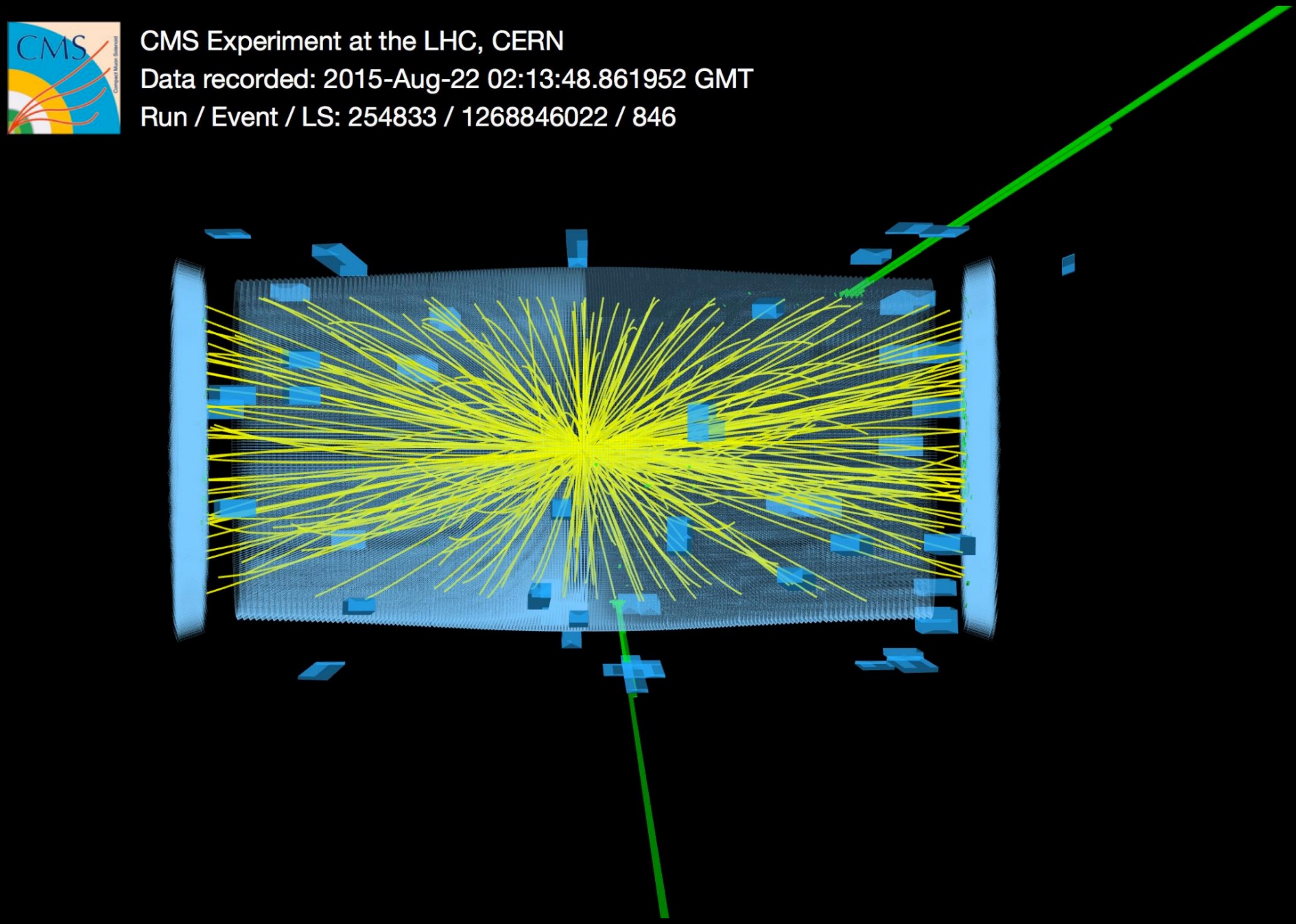
CMS dilepton search

- Highest mass dimuon event

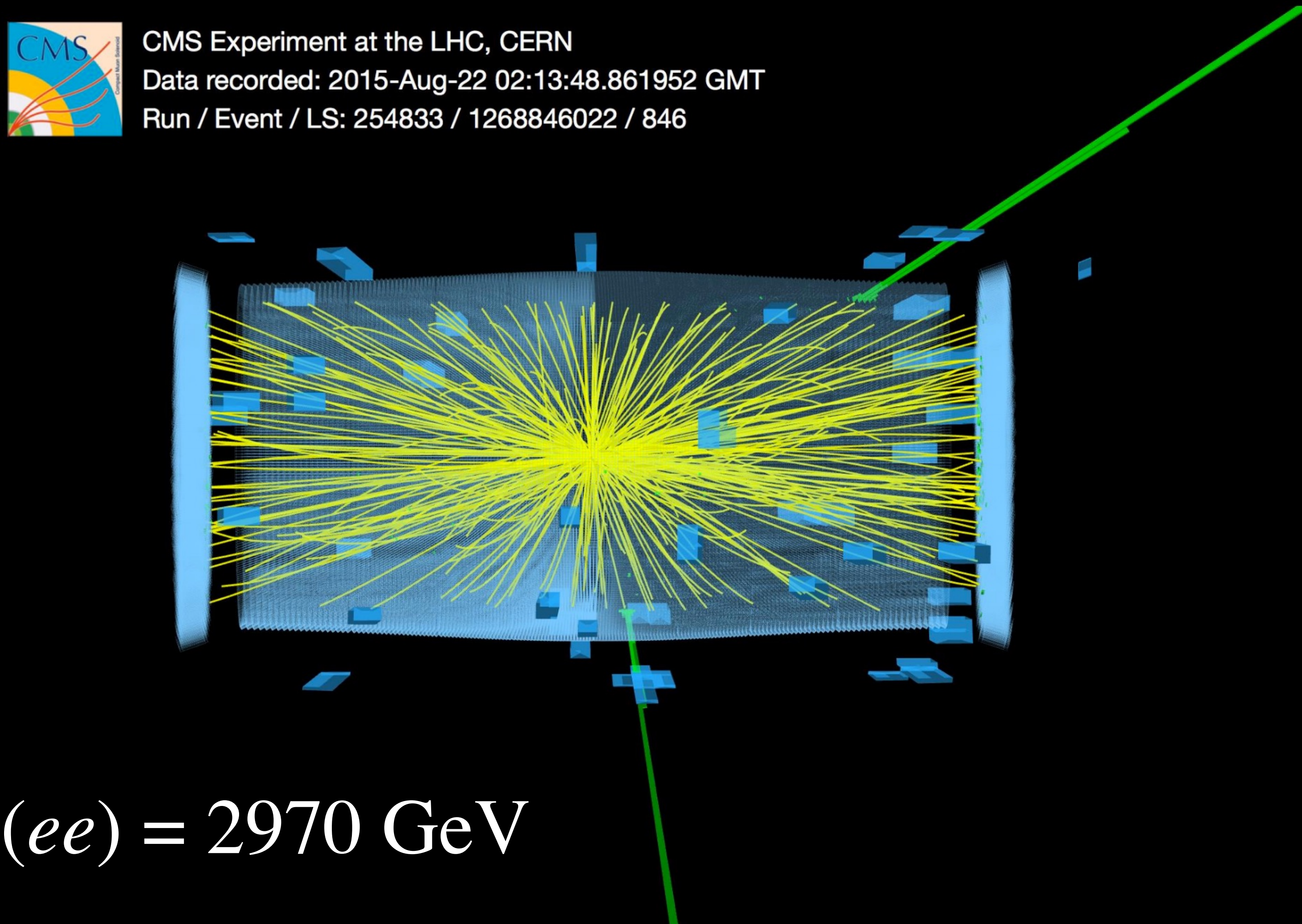


$$m(\mu\mu) = 920\ \text{GeV}$$

CMS dilepton search



CMS dilepton search



$$m(ee) = 2970 \text{ GeV}$$

CMS 3 TeV $m(ee)$ event

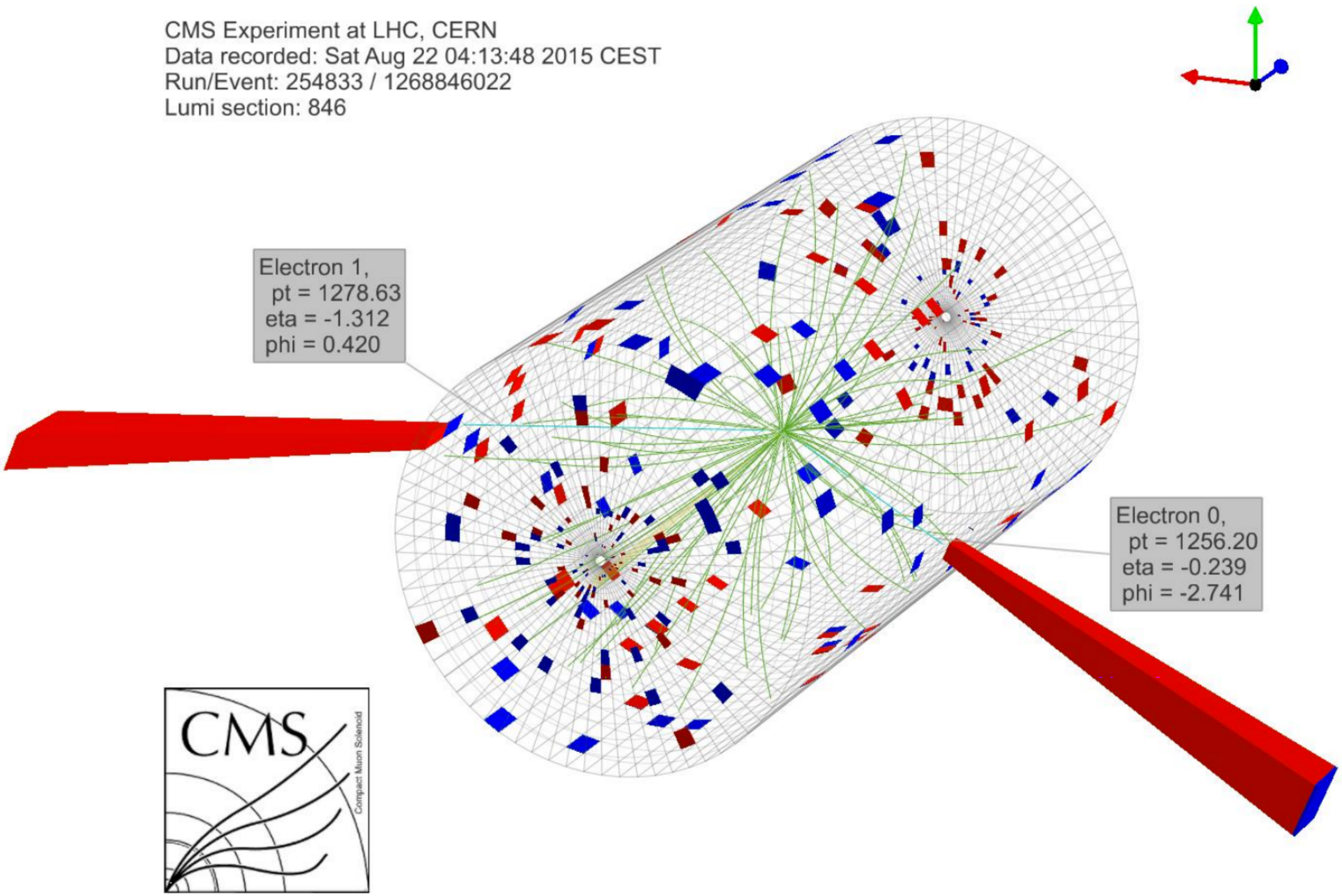
- What is this 3 TeV event?
  - Hard to tell for a single event
  - Expectation of SM events:

Mass range	SM expectation
$m(ee) > 1$ TeV	0.21
$m(ee) > 2$ TeV	0.007
$m(ee) > 2.5$ TeV	0.002

- Are they real electrons?
  - Yes, we find no issues with the objects or event.
- The positron is more boosted than the electron
  - $\cos\theta_{CS} = -0.49$ (DY favours positive values.)
- ATLAS and CMS have not seen similar events in other channels.

CMS 3 TeV $m(ee)$ event

- Event display with kinematic variables:



Dielectron strategy

- The dielectron search is relatively simple:
  - A dedicated high energy electron pair (HEEP) ID has been developed:
    - Cut based by design to keep it simple and credible.
    - Some tweaks to handle high energy (eg isolation.)
    - Largely unchanged since 2012, except for $E(\mathrm{HCAL})/E(\mathrm{ECAL})$.
  - Normalise cross sections to the Z peak
    - Cancel out most systematic uncertainties.
    - Enable a very rapid analysis, no need to wait for luminosity measurements.
  - Many fail safes built in from an early stage:
    - Redundant triggers, $B=0$ T strategy, supercluster only studies.

Dielectron strategy

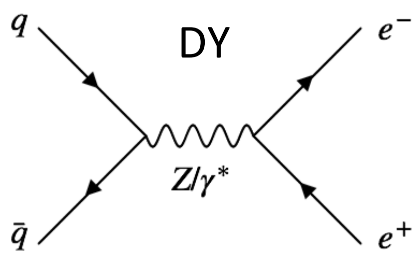
- ID is very simple:
- $E_{\mathrm{T}} > 35\ \mathrm{GeV}$ ("low" enough to get a good Z peak)
- $|\eta|<2.5$, excluding transition the regions.
- Various shower shape and track matching variables.
- $E(\mathrm{HCAL})/E(\mathrm{ECAL}) < 0.05$ + energy dependent term
- Calorimeter isolation is relative with a constant term
  - A purely relative term is not acceptable, as 10% of $1\ \mathrm{TeV}$ is $100\ \mathrm{GeV}$!

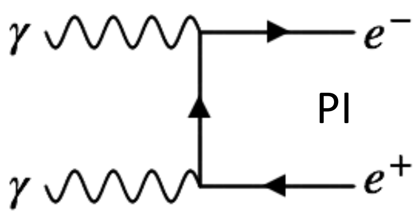
Dielectron challenges at 13 TeV

- Working at 13 TeV brings new problems...
  - A 2.5 TeV electron can reach the limits of the CMS ECAL.
  - This is known as saturation.
  - Must be taken into account if we are to see 5 TeV objects.
  - Studies ongoing.
  - Use of multivariate techniques and detailed understanding of ECAL geometry to recover saturated crystals.

Dielectron challenges at 13 TeV

- Working at 13 TeV brings new problems...
  - A new SM process comes into play.
  - Protons can exchange photons to give us photon induced (PI) backgrounds:

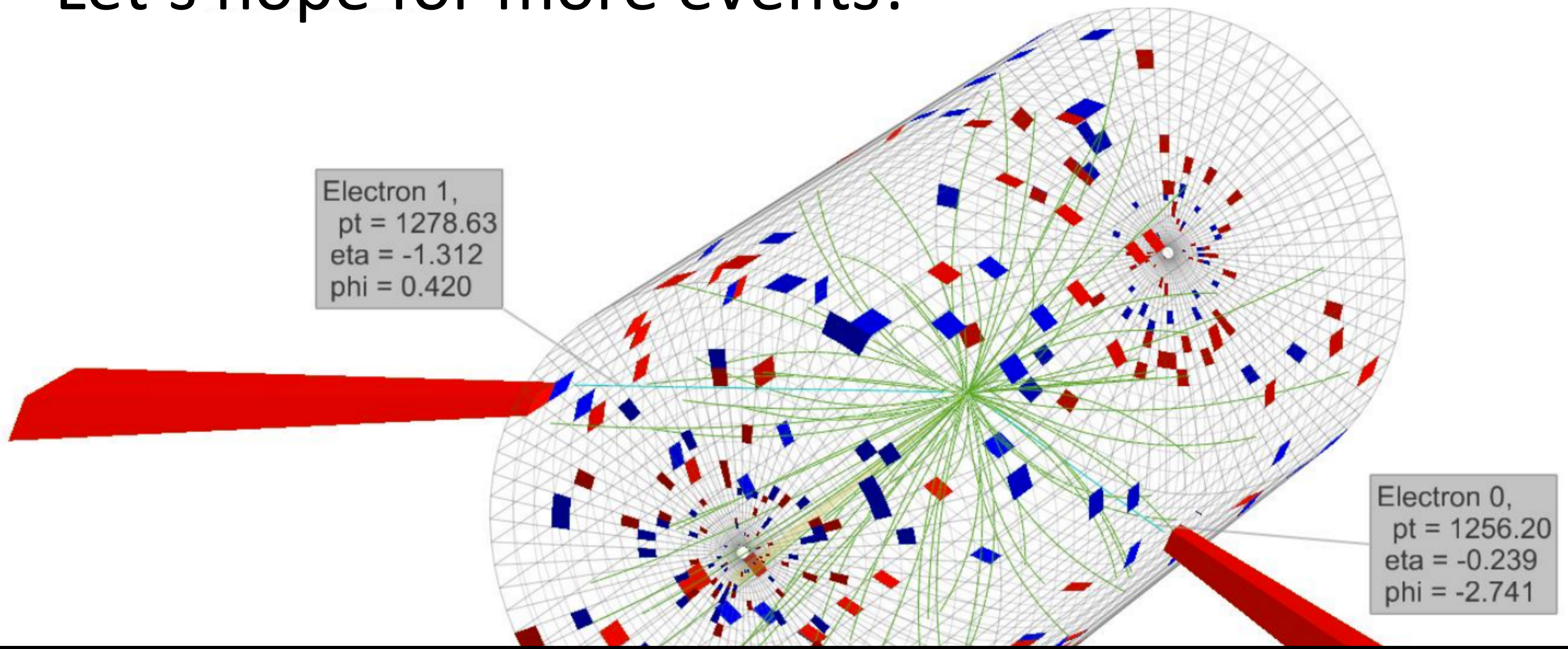




  - Irreducible background.
  - PDFs not well known.
  - Some studies suggest primary vertex track multiplicities might be lower for PI backgrounds.

CMS dielectron summary

- The punch line is, as usual, to "wait and see".
- We may see more $3\ \mathrm{TeV}$ events rain down in 2016.
- Or we may just be extremely (un)lucky.
- Let's hope for more events!

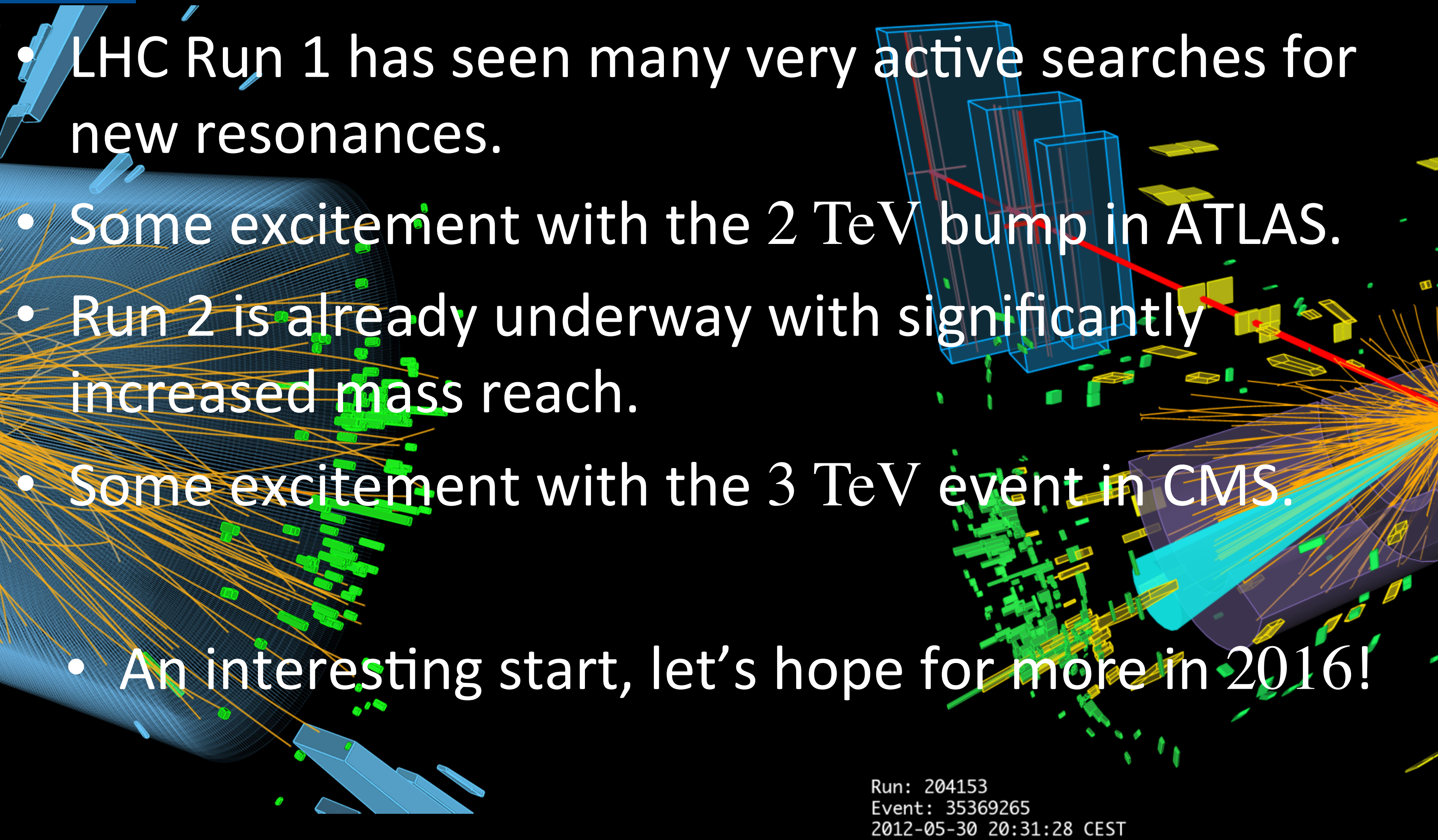


ULB

Summary

- LHC Run 1 has seen many very active searches for new resonances.
- Some excitement with the 2 TeV bump in ATLAS.
- Run 2 is already underway with significantly increased mass reach.
- Some excitement with the 3 TeV event in CMS.

  - An interesting start, let's hope for more in 2016!

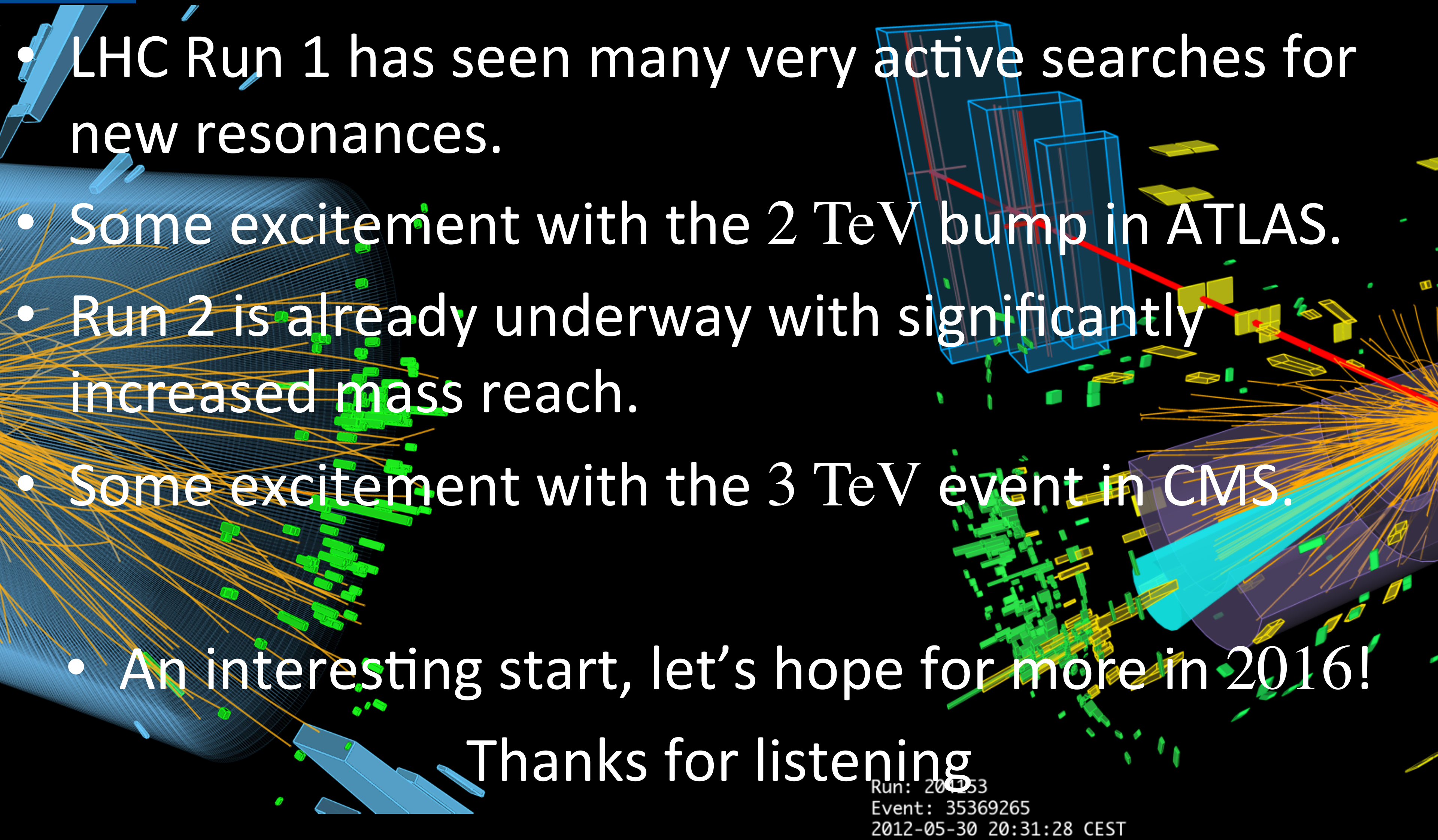


Summary

- LHC Run 1 has seen many very active searches for new resonances.
- Some excitement with the 2 TeV bump in ATLAS.
- Run 2 is already underway with significantly increased mass reach.
- Some excitement with the 3 TeV event in CMS.

  - An interesting start, let's hope for more in 2016!

Thanks for listening



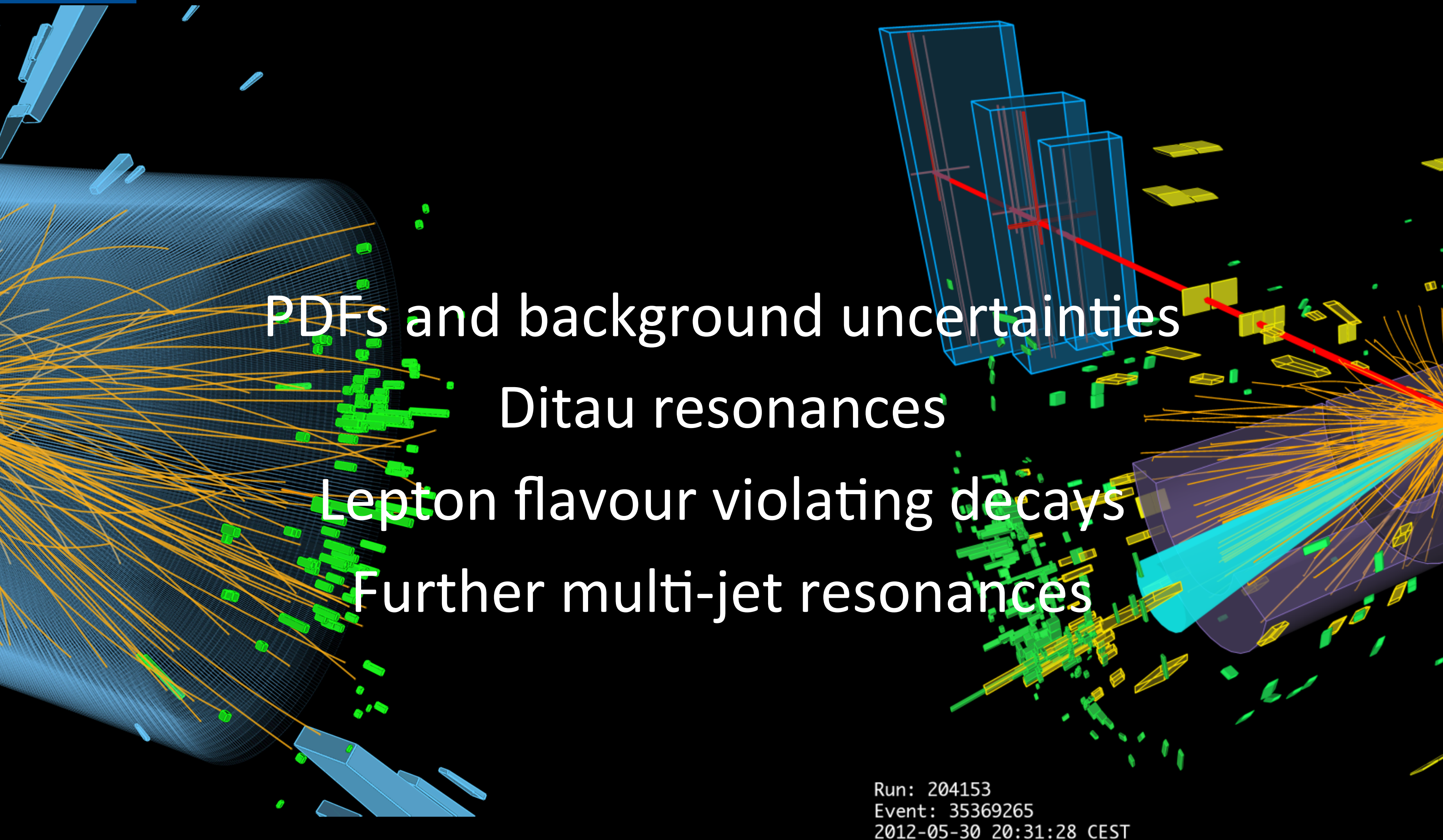
Backup

PDFs and background uncertainties

Ditau resonances

Lepton flavour violating decays

Further multi-jet resonances



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%

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:

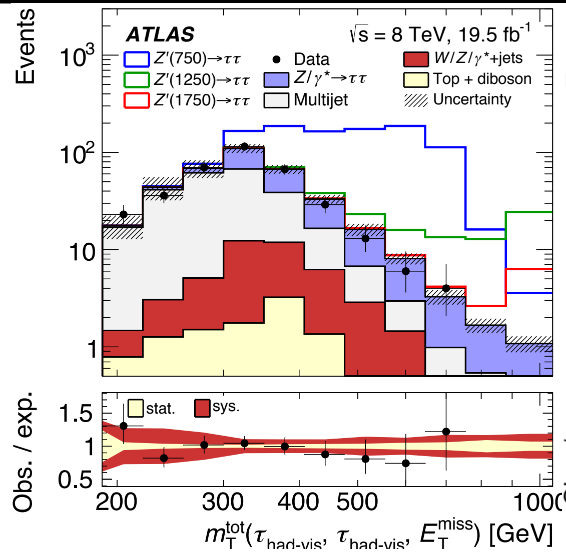
PRD 90, 052005

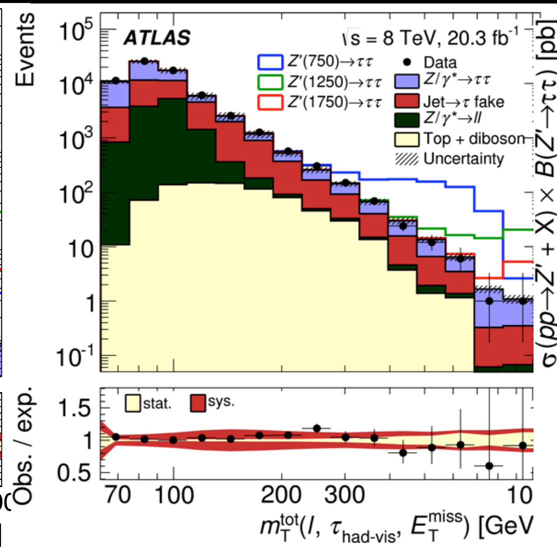
CMS-PAS-EXO-12-046

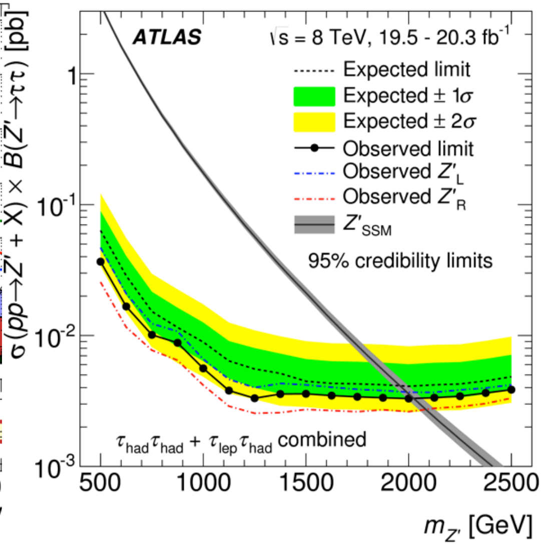
	ATLAS	CMS
τ_{had}	$p_T(\tau_{had}) > 30$ GeV $\lvert\eta(\tau_{had})\rvert < 1.37$ or $1.52 < \lvert\eta(\tau_{had})\rvert < 2.47$	
e	E_T (e) > 15 GeV $\lvert\eta(e)\rvert < 1.37$ or $1.52 < \lvert\eta(e)\rvert < 2.47$	$E_T(e) > 20$ GeV $\lvert\eta(e)\rvert < 1.442$ or $1.56 < \lvert\eta(e)\rvert < 2.5$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

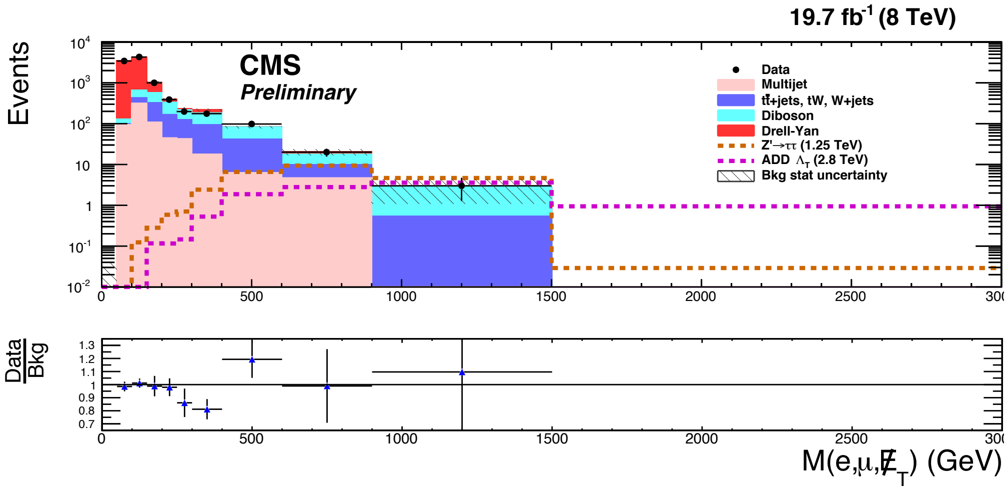
- Dominant systematic uncertainties: PDFs for background modeling, Signal efficiency for ATLAS, data driven background estimates for CMS.

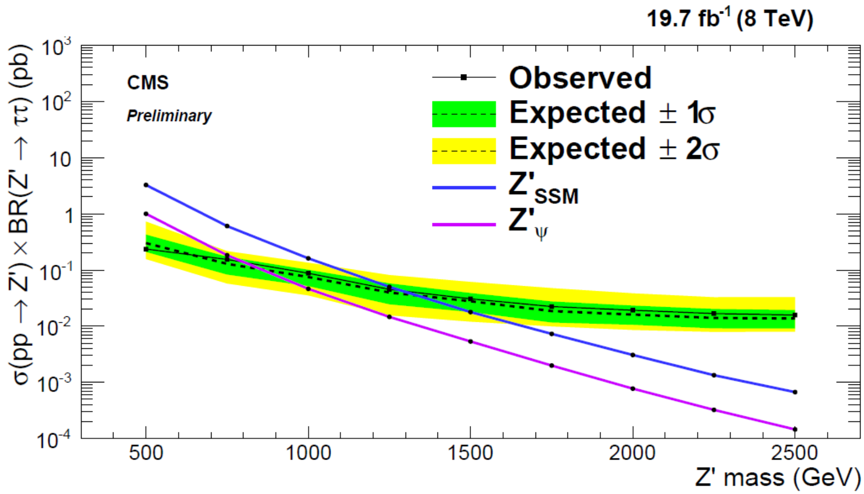
Ditau resonances











- 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

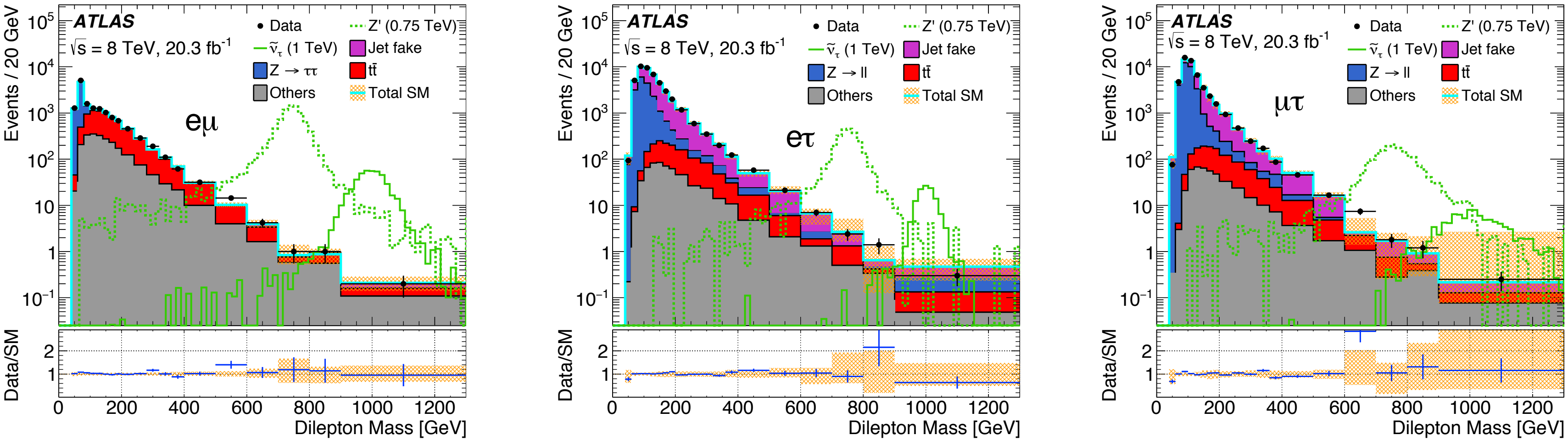
arXiv:1504.055115

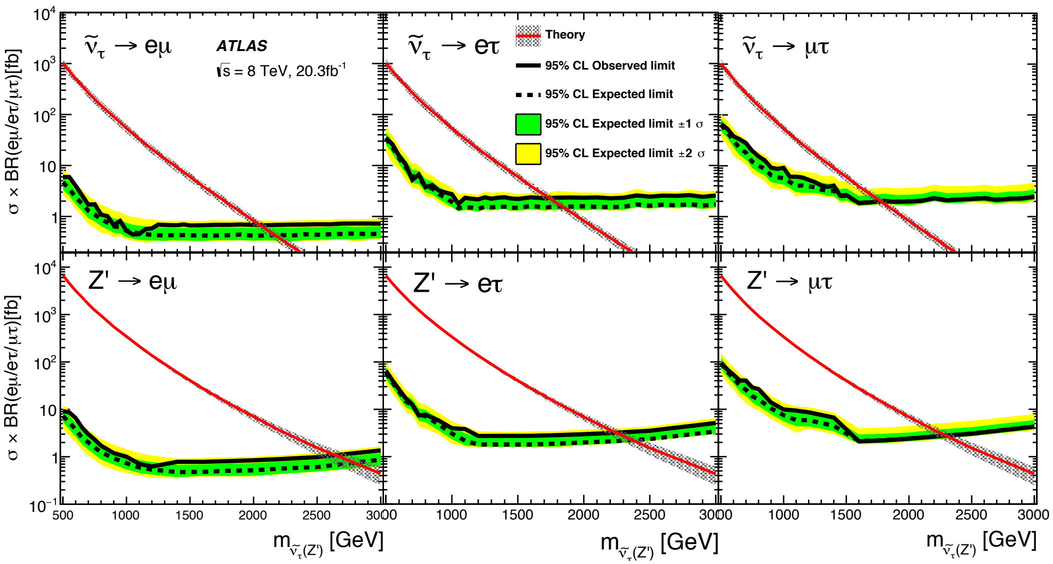
ATLAS	CMS
$p_T(\tau_{had}) > 25$ GeV $\lvert\eta(\tau_{had})\rvert < 2.47$ Single track	
E_T(e) > 25 GeV $\lvert\eta(e)\rvert < 1.37$ or $1.52 < \lvert\eta(e)\rvert < 2.47$	$E_T(e) > 35$ GeV $\lvert\eta(e)\rvert < 1.442$ or $1.56 < \lvert\eta(e)\rvert < 2.5$
$p_T(\mu) > 25$ GeV $\lvert\eta(\mu)\rvert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



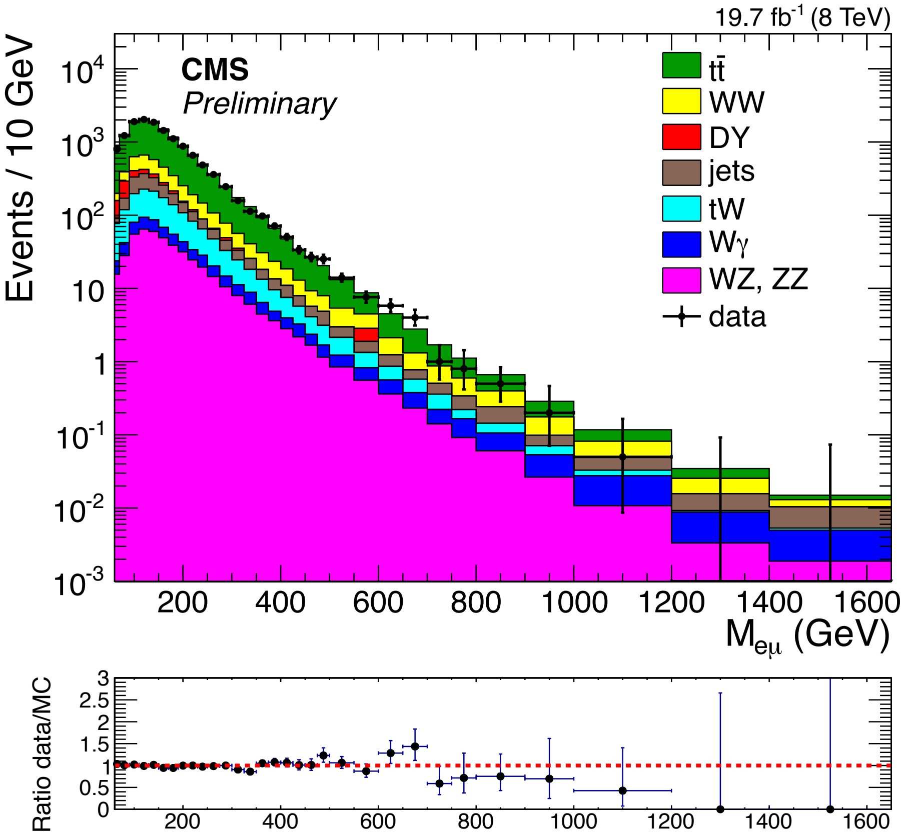


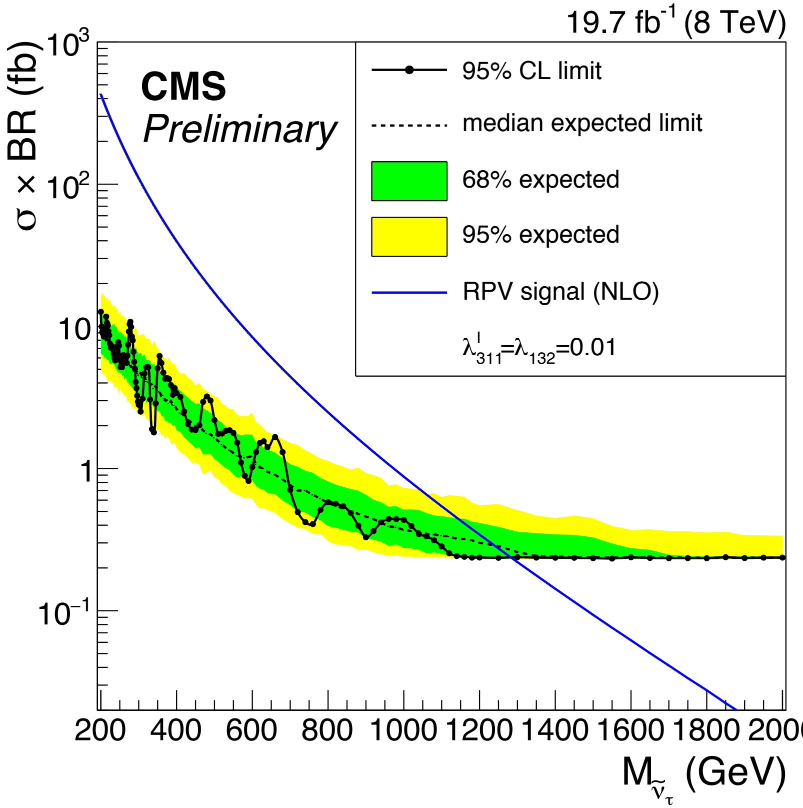
- Limits:
  - $e\mu$: $m(\tilde{\nu}_\tau) > 2.0$ TeV
  - $e\tau$: $m(\tilde{\nu}_\tau) > 1.7$ TeV
  - $\mu\tau$: $m(\tilde{\nu}_\tau) > 1.7$ TeV

Lepton flavour violating resonances

- CMS investigate $e\mu$ final state.

CMS-EXO-13-002



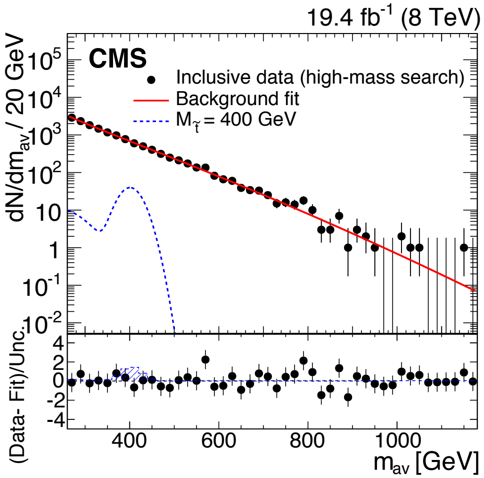


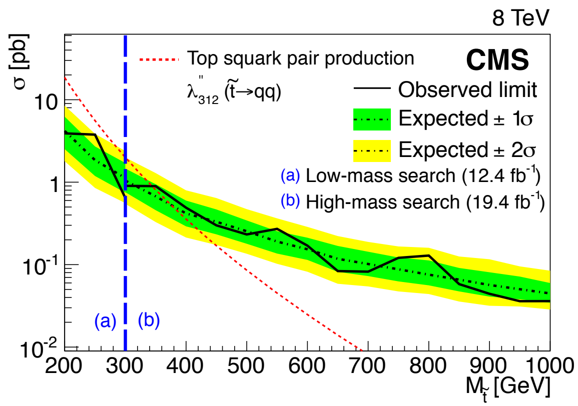
Limit: $m(\tilde{\nu}_\tau) > 2.1\ \mathrm{TeV}$

Further multi-jet resonances

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

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



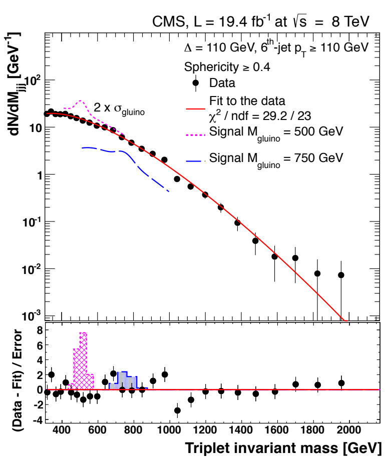


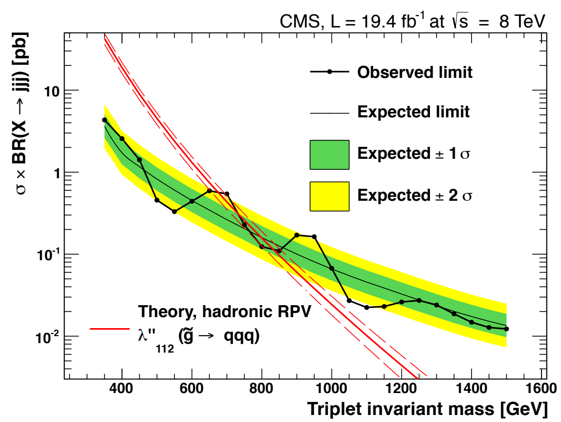
Phys. Lett. B 730 (2014) 193

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

HEEP ID V6.0	Barrel	Endcap
E_T	< 35 GeV	
η	$\lvert\eta_{SC}\rvert < 1.4442$	$1.566 < \lvert\eta_{SC}\rvert < 2.5$
`isEcalDriven`	=1	
$\lvert\Delta\eta_{in}^{seed}\rvert$	< 0.004	< 0.006
$\lvert\Delta\phi_{in}\rvert$	< 0.06	
H/E	$< 1/E + 0.05$	$< 5/E + 0.05$
full 5x5 $\sigma_{i\eta i\eta}$	-	< 0.03
full 5×5 $E_{1\times5}/E_{5\times5}$	> 0.83	-
full 5x5 $E_{2\times5}/E_{5\times5}$	> 0.94	-
Inner layer lost hits	< 2	
d_{xy}*(first PV)*	< 0.02	< 0.05
EM+had depth1 iso	$< 2 + 0.03$ ET $+ 0.28\varrho$	$E_T < 50$: $< 2.5 + 0.28\varrho$ $E_T > 50$: $< 2.5 + 0.03(E_T\text{-}50) + 0.28\varrho$
Track pt iso	< 5 GeV	< 5 GeV