

Searches for heavy resonances at the LHC, University of Liverpool

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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

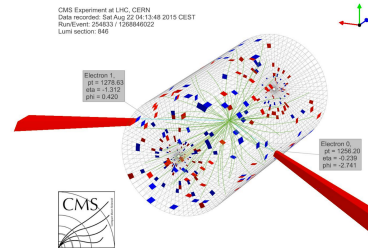
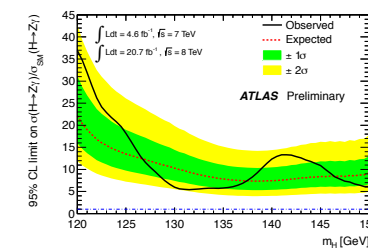
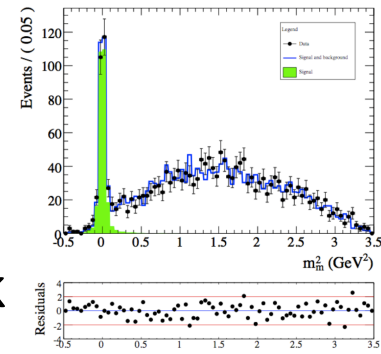
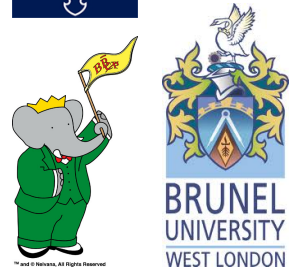
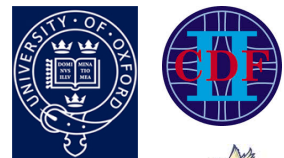
$Z' \rightarrow ee$ search at CMS

Summary

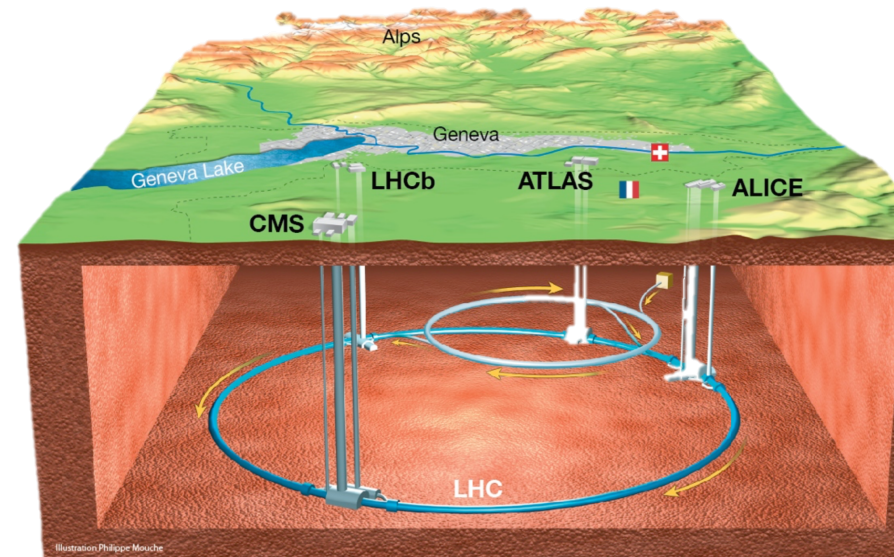
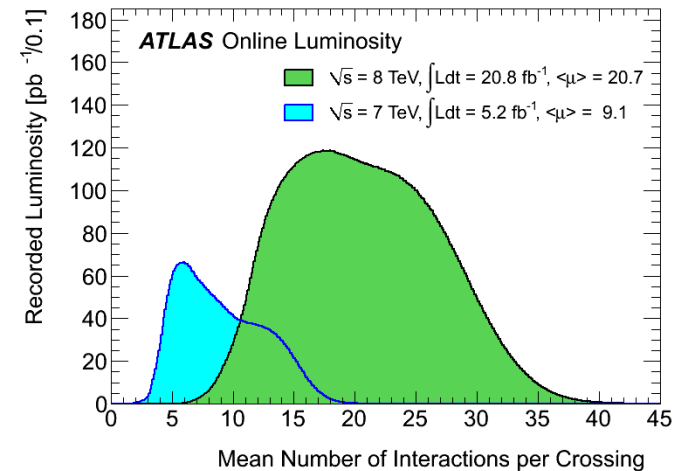
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2012-05-30 20:31:28 CEST

A personal history

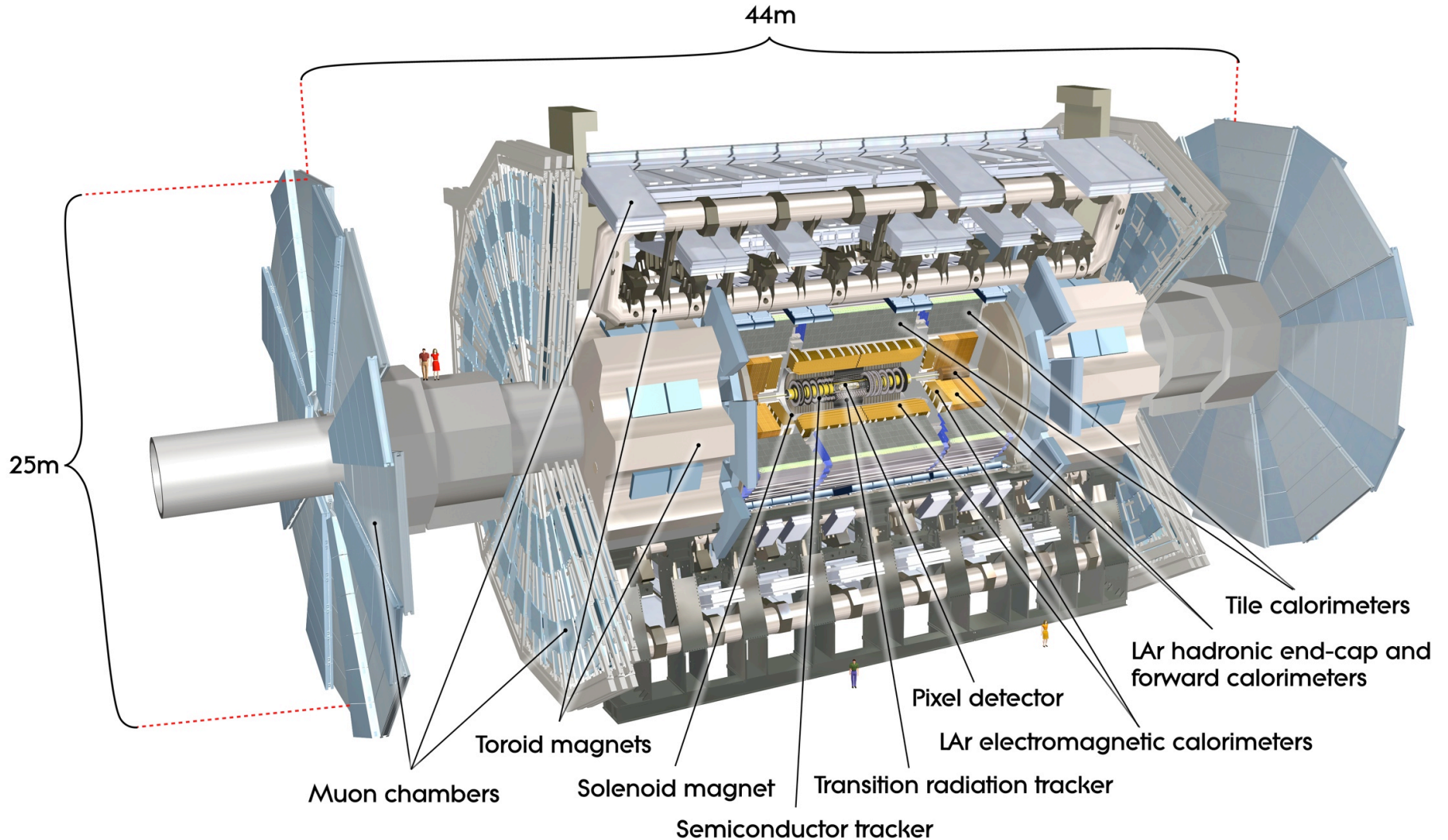
- I studied at Oxford for undergraduate.
 - CDF: B_s mixing studies.
- Then Brunel for postgraduate.
 - BaBar: $D_s \rightarrow l\nu$ decays, a “hot topic” back in 2008.
- Then to SMU Dallas for my first postdoc.
 - ATLAS: Started the $H \rightarrow Z\gamma$ search.
- Currently at the ULB (Brussels).
 - CMS: $Z' \rightarrow ee$ 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 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 $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$



The ATLAS detector



The CMS detector

CMS DETECTOR

Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T

STEEL RETURN YOKE
 12,500 tonnes

SILICON TRACKERS
 Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
 Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
 Niobium titanium coil carrying $\sim 18,000\text{A}$

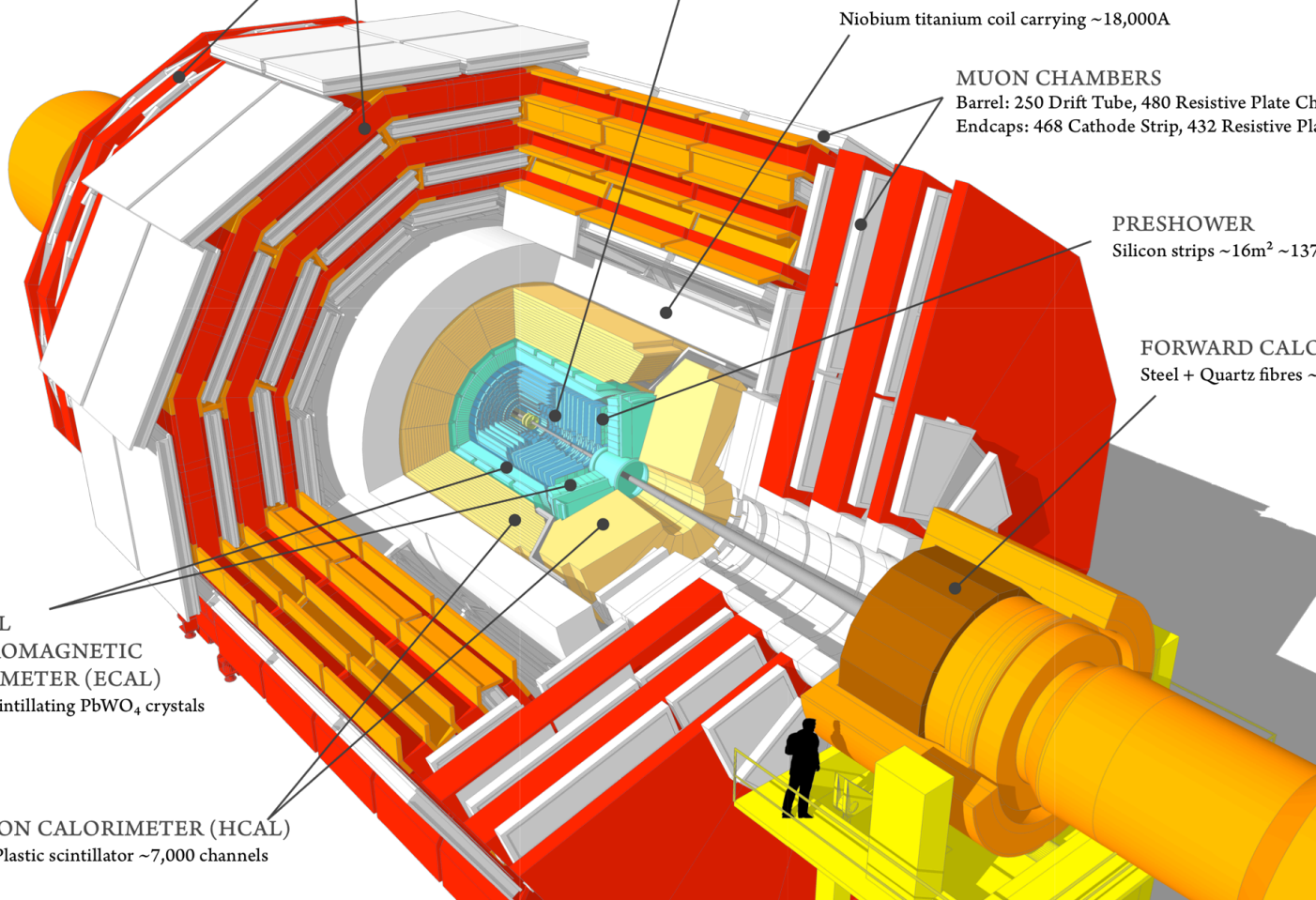
MUON CHAMBERS
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
 Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
 Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
 Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
 ELECTROMAGNETIC
 CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

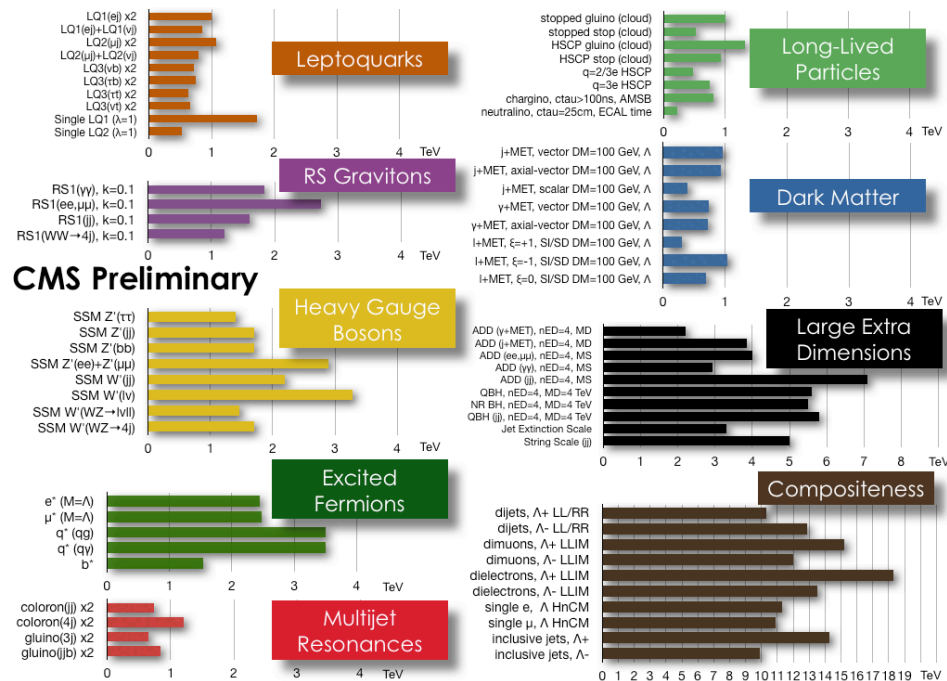
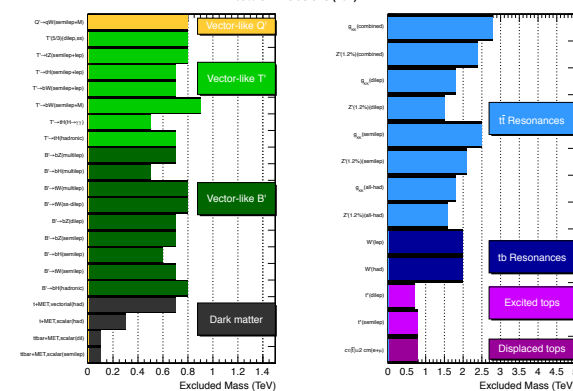
HADRON CALORIMETER (HCAL)
 Brass + Plastic scintillator $\sim 7,000$ channels



Resonances: scope

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

CMS Searches for New Physics Beyond Two Generations (B2G)
95% CL Exclusions (TeV)

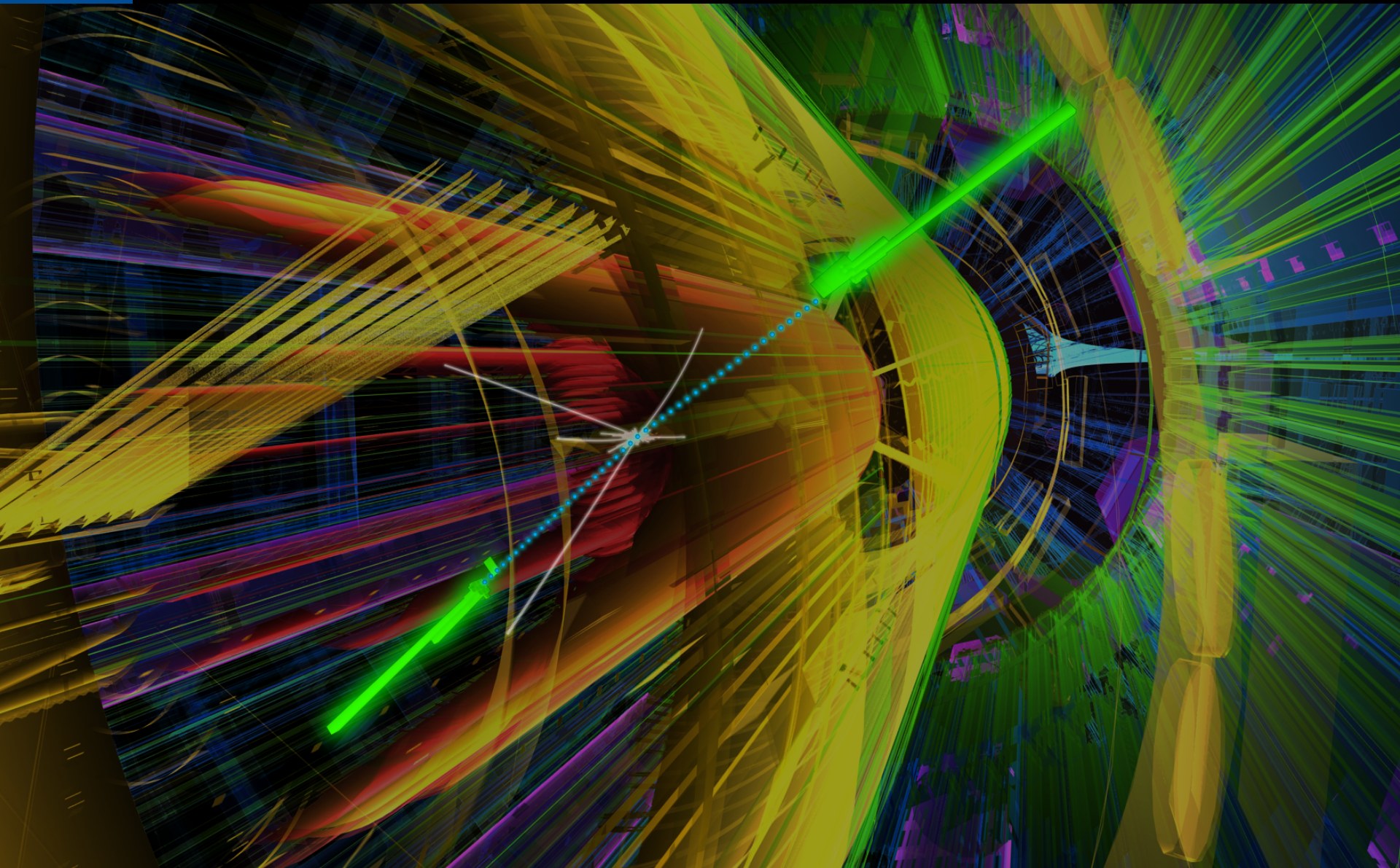


ATLAS Exotics Searches* - 95% CL Exclusion
Status: March 2015

Model	ℓ, γ	Jets	E_{miss}	$[\mathcal{L} dt(\text{fb}^{-1})]$	Mass limit	Reference
Extra dimensions	ADD $G_{\mu\nu} + g/\ell$	≥ 1	Yes	20.3	M_{pl} 5.25 TeV	$n=2$ 1502.01518
	ADD non-resonant $\ell\ell$	-	-	20.3	M_{pl} 4.7 TeV	$n=3$ HLZ 1407.2410
	ADD OBH $\rightarrow f\bar{g}$	$1 e, \mu$	1	20.3	M_{pl} 5.2 TeV	$n=6$ 1311.2006
	ADD OBH	-	2	20.3	M_{pl} 5.82 TeV	1407.1376
	ADD BH high N_{ch}	2μ (SS)	-	20.3	M_{pl} 4.7 TeV	1308.4075
	ADD BH high $\geq 2 \mu$	$\geq 1 e, \mu$	≥ 2	20.3	M_{pl} 5.8 TeV	$n=6, M_{\text{pl}}=3$ TeV, non-rot BH 1405.4254
	ADD BH high multijet	-	≥ 2	20.3	M_{pl} 5.8 TeV	$n=6, M_{\text{pl}}=3$ TeV, non-rot BH 1308.4075
	RS1 $G_{\mu\nu} + \ell\ell$	$2 e, \mu$	-	20.3	$G_{\text{cut}} \text{ mass}$ 2.88 TeV	$k/\overline{M}_{\text{pl}}=0.1$ 1405.4123
	RS1 $G_{\mu\nu} + \gamma\gamma$	2γ	-	20.3	$G_{\text{cut}} \text{ mass}$ 2.86 TeV	$k/\overline{M}_{\text{pl}}=0.1$ Preliminary
	Buk RS $G_{\mu\nu} + ZZ \rightarrow qq\ell\ell$	2μ	2 (1,1)	20.3	$G_{\text{cut}} \text{ mass}$ 740 GeV	$k/\overline{M}_{\text{pl}}=1.0$ 1405.6190
	Buk RS $G_{\mu\nu} + WW \rightarrow qq\ell\ell$	$1 e, \mu$	2 (1,1)	Yes 20.3	$G_{\text{cut}} \text{ mass}$ 700 GeV	$k/\overline{M}_{\text{pl}}=1.0$ 1503.04677
	Buk RS $G_{\mu\nu} + HH \rightarrow b\bar{b}b\bar{b}$	-	4 b	19.5	$G_{\text{cut}} \text{ mass}$ 590-710 GeV	$k/\overline{M}_{\text{pl}}=1.0$ ATLAS-COIN-2014-005
	Buk RS $G_{\mu\nu} + \ell\ell$	$1 e, \mu$	$\geq 1 b, \geq 14\ell$	Yes 20.3	$G_{\text{cut}} \text{ mass}$ 2.2 TeV	BR = 0.925 ATLAS-COIN-2015-009
	ZUED / RRP	$2 e, \mu$ (SS)	$\geq 1 b, \geq 1$	Yes 20.3	$G_{\text{cut}} \text{ mass}$ 900 GeV	Preliminary
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	20.3	Z' mass 2.9 TeV	1405.4123
	SSM $Z' \rightarrow \tau\tau$	2τ	-	19.5	Z' mass 2.02 TeV	1502.07177
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes 20.3	W' mass 3.24 TeV	1407.7484
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$	$3 e, \mu$	-	Yes 20.3	W' mass 1.52 TeV	1406.4456
	EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$	$2 e, \mu$	2 (1,1)	20.3	W' mass 1.89 TeV	1405.6190
	HVT $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$	$1 e, \mu$	2 b	Yes 20.3	W' mass 1.47 TeV	Preliminary
	LRSM $W'_2 \rightarrow \ell\bar{\nu}$	$1 e, \mu$	$2 b, 0-1$	Yes 20.3	W' mass 1.82 TeV	1410.4103
	LRSM $W'_2 \rightarrow \ell\nu$	$0 e, \mu$	$\geq 1 b, 1-1$	Yes 20.3	W' mass 1.76 TeV	1408.0886
CI	CI $qqqq$	-	2	17.3	A mass 12.0 TeV	$\beta_{\text{CI}} = -1$ Preliminary
	CI $qq\ell\ell$	$2 e, \mu$	-	20.3	A mass 4.35 TeV	$ \zeta_{\text{CI}} = 1$ 1407.2410
	CI $uvtt$	$2 e, \mu$ (SS)	$\geq 1 b, \geq 1$	Yes 20.3	A mass 3.74 TeV	1502.01518
DM	EFT D operator (Dirac)	$0 e, \mu$	≥ 1	Yes 20.3	M_{pl} 2.4 TeV	1309.4017
	EFT D operator (Dirac)	$0 e, \mu$	$1 \ell, \leq 1$	Yes 20.3	M_{pl} 974 GeV	at 90% CL for $m(\chi) < 100$ GeV
LQ	Scalar LQ 1 st gen	$2 e$	≥ 2	-	LQ mass 660 GeV	$\beta = 1$ 1112.4828
	Scalar LQ 2 nd gen	2μ	≥ 2	-	LQ mass 685 GeV	$\beta = 1$ 1203.3172
	Scalar LQ 3 rd gen	$1 e, \mu, 1 \tau$	$1 b, 1$	-	LQ mass 534 GeV	$\beta = 1$ 1303.0526
Heavy quarks	VLO $TT \rightarrow H\bar{t} + X, W\bar{b} + X$	$1 e, \mu$	$\geq 1 b, \geq 1$	Yes 20.3	T mass 785 GeV	isospin singlet ATLAS-COIN-2015-012
	VLO $TT \rightarrow Z\bar{t} + X$	$2 \geq 3 e, \mu$	$\geq 0-1 b$	20.3	T mass 735 GeV	T in (T) doublet
	VLO $BB \rightarrow Z\bar{b} + X$	$2 \geq 3 e, \mu$	$\geq 0-1 b$	20.3	B mass 795 GeV	B in (B,V) doublet
	VLO $BB \rightarrow W\bar{t} + X$	$1 e, \mu$	$\geq 1 b, \geq 1$	Yes 20.3	B mass 840 GeV	isospin singlet
	$T_{3/3} \rightarrow Wt$	$1 e, \mu, 1 \tau$	$\geq 1 b, \geq 1$	Yes 20.3	$T_{3/3}$ mass 840 GeV	isospin singlet
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1γ	1	-	q^* mass 3.5 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1309.3290
	Excited quark $q^* \rightarrow g\gamma$	2μ (SS)	2	-	q^* mass 4.09 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1401.13176
	Excited quark $b^* \rightarrow W\gamma$	1 or $2 e, \mu$	1 b, 2 (or 1)	Yes 4.7	b^* mass 870 GeV	left-handed coupling 1301.1583
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$2 e, \mu, 1 \gamma$	-	-	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV 1308.1364
	Excited lepton $\nu^* \rightarrow \ell W, \nu Z$	$3 e, \mu, 1 \tau$	-	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV 1411.2921
Other	LSTC $\nu\bar{\nu} \rightarrow W\gamma$	$1 e, \mu, 1 \gamma$	-	Yes 20.3	ν mass 850 GeV	$m(W_{\text{eff}}) = 3$ TeV, no mixing 1407.8150
	LRSM Majorana ν	$2 e, \mu$ (SS)	2	-	ν mass 551 GeV	1203.3420
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2 e, \mu$ (SS)	-	20.3	$H^{\pm\pm}$ mass 400 GeV	1412.0207
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\nu$	$3 e, \mu, 1 \tau$	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DV production, BR($H^{\pm\pm} \rightarrow \ell\nu$)=1 1411.2921
	Monotop (non-res prod)	$1 e, \mu$	1 b	Yes 20.3	sum 1 monoton particle mass 657 GeV	$\beta_{\text{mono}} = 0.2$ 1410.5404
	Multi-charged particles	-	-	20.3	ν mass 785 GeV	DV production, $ \zeta = 5\epsilon$ Preliminary
	Magnetic monopoles	-	-	2.0	monopole mass 882 GeV	DV production, $ \zeta = 1\epsilon_0$ 1207.6411

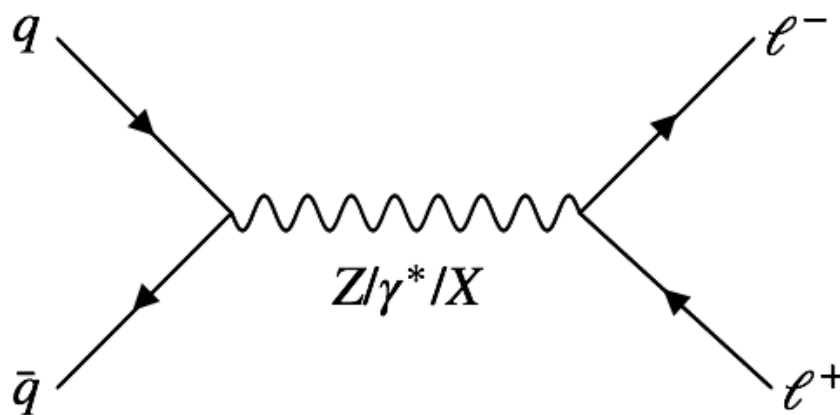
*Only a selection of the available mass limits on new states or phenomena is shown.

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

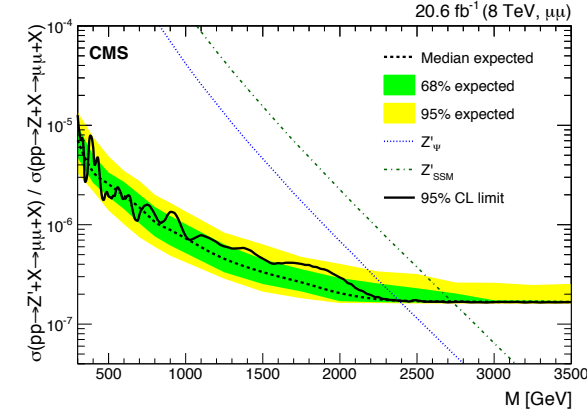
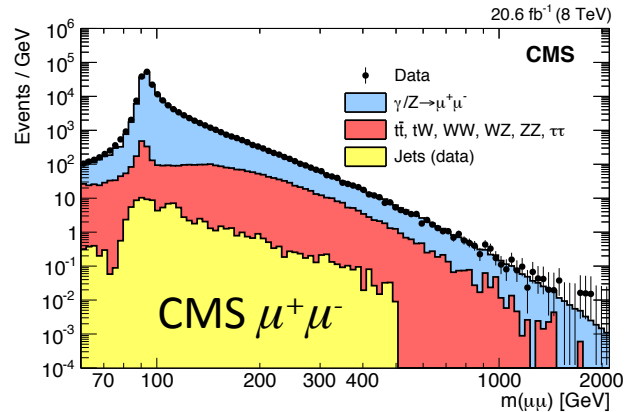
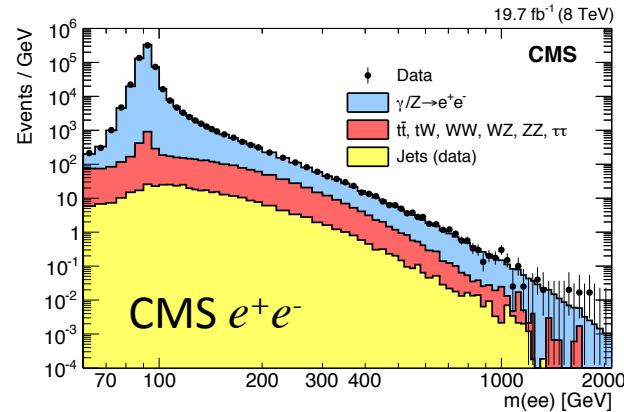
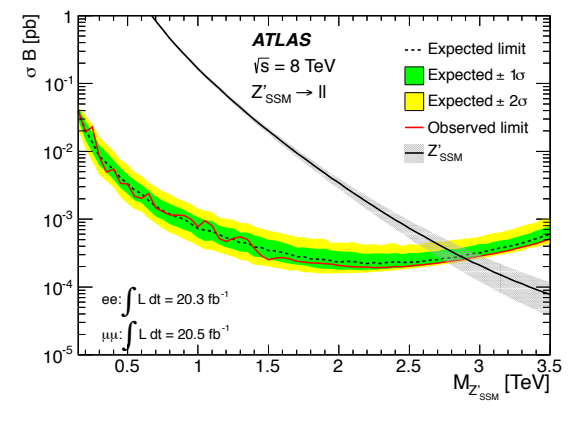
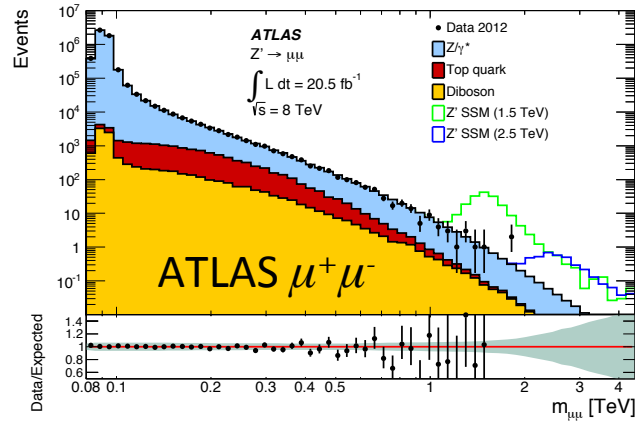
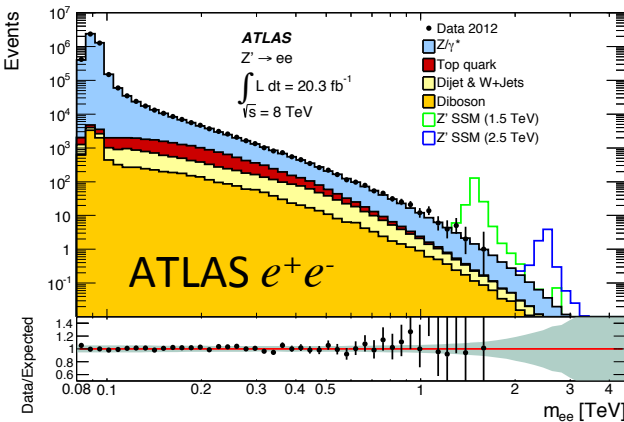
JHEP04(2015)025

	ATLAS	CMS
ee	$E_T > 40, 30 \text{ GeV}$ $ \eta < 1.37$ or $1.52 < \eta < 2.47$	$E_T > 35, 35 \text{ GeV}$ $ \eta < 1.442$ or $1.56 < \eta < 2.5$
$\mu\mu$	$p_T > 25, 25 \text{ GeV}$ $ \eta < 1.05$	$p_T > 45, 45 \text{ GeV}$ $ \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:



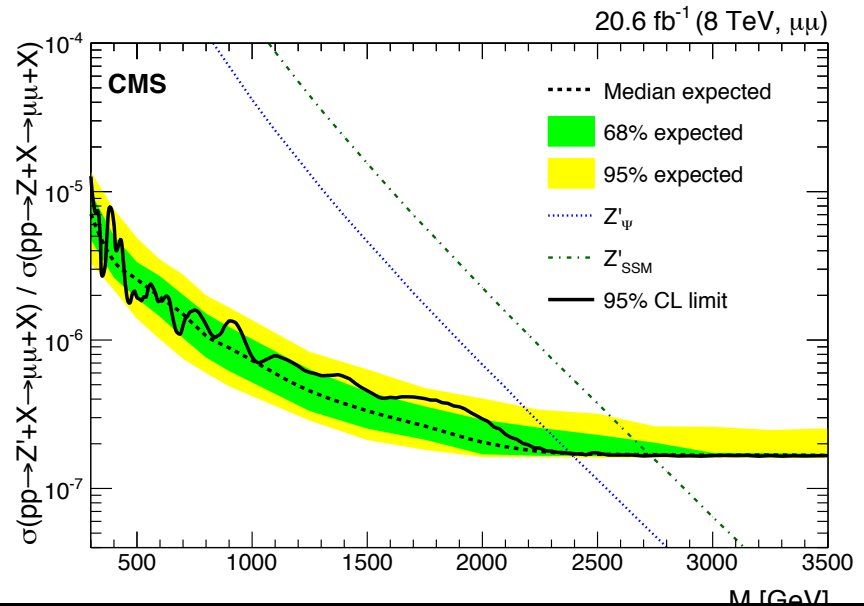
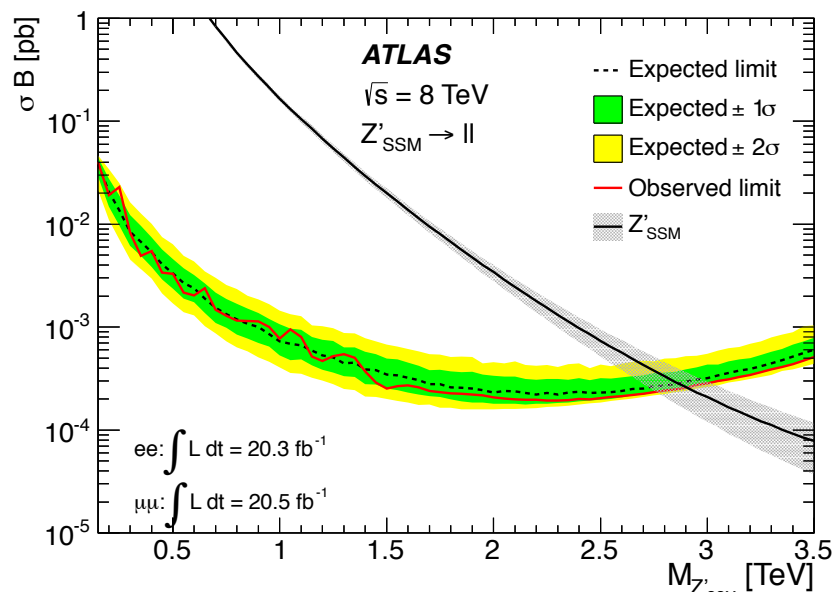
- Exclusion limits:

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

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

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.



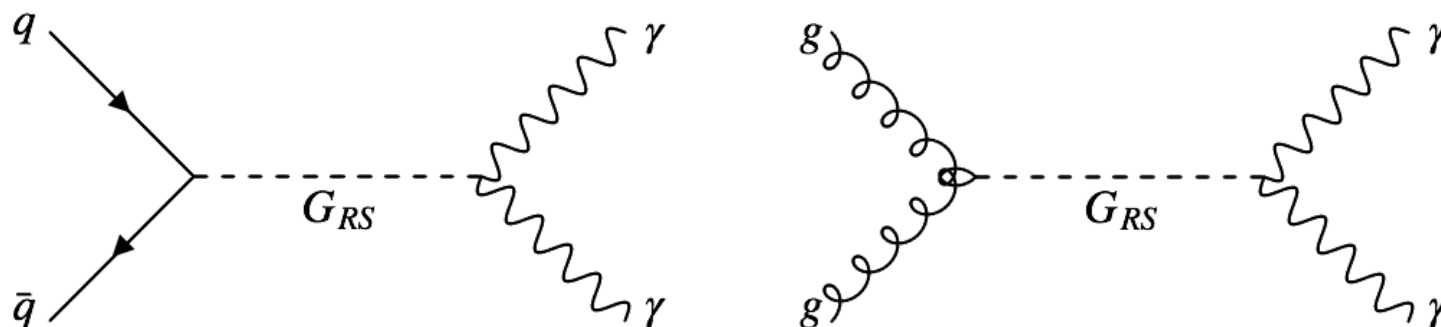
Diphoton resonances

- 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

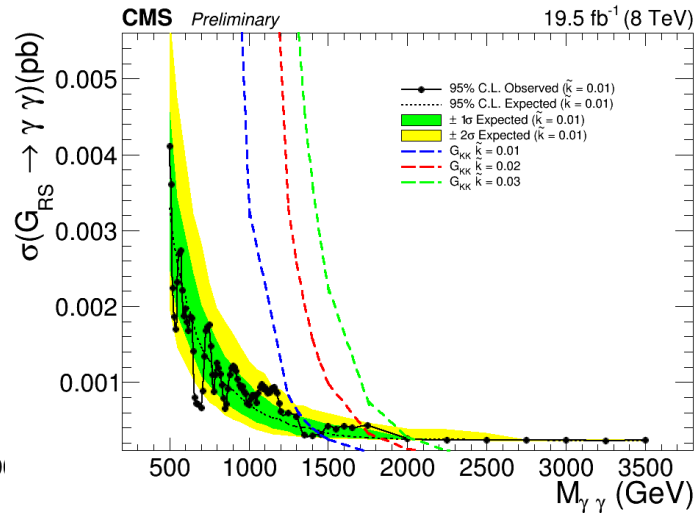
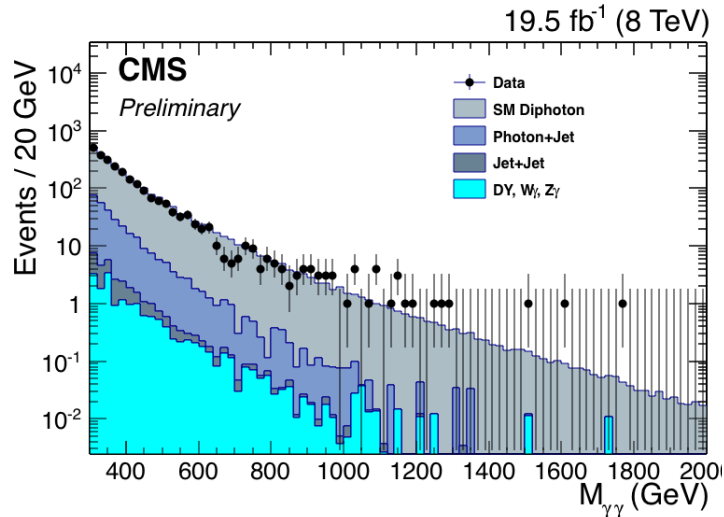
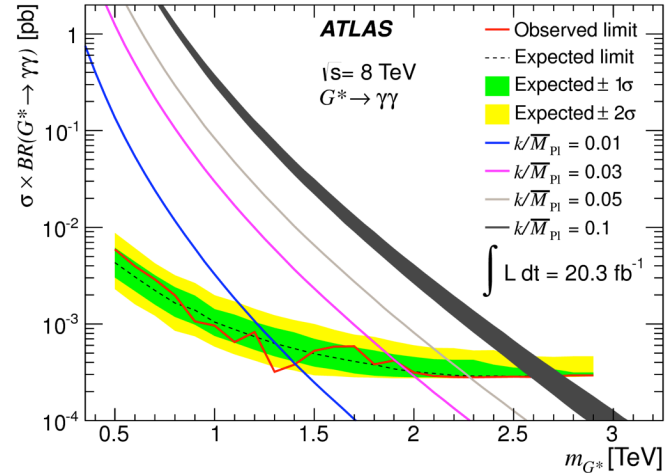
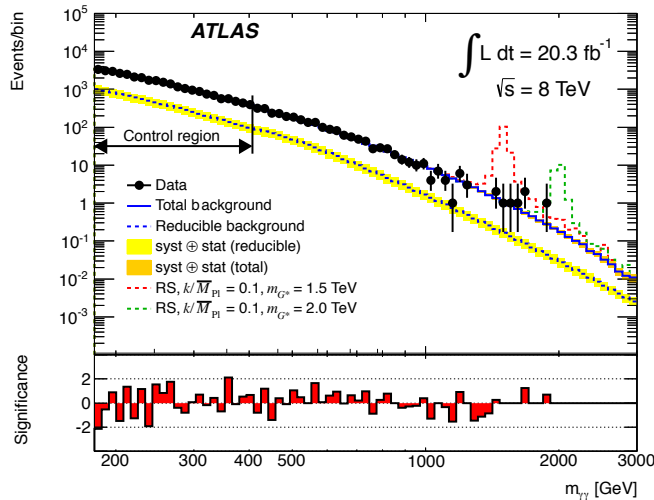
ATLAS	CMS
$p_T > 50 \text{ GeV}$ $ \eta < 1.37 \text{ or } 1.52 < \eta < 2.47$	$p_T > 80 \text{ GeV}$ $ \eta < 1.4442$ $m(\gamma\gamma) > 300 \text{ GeV}$

- Isolation selections:

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

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

Diphoton resonances



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

- 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.

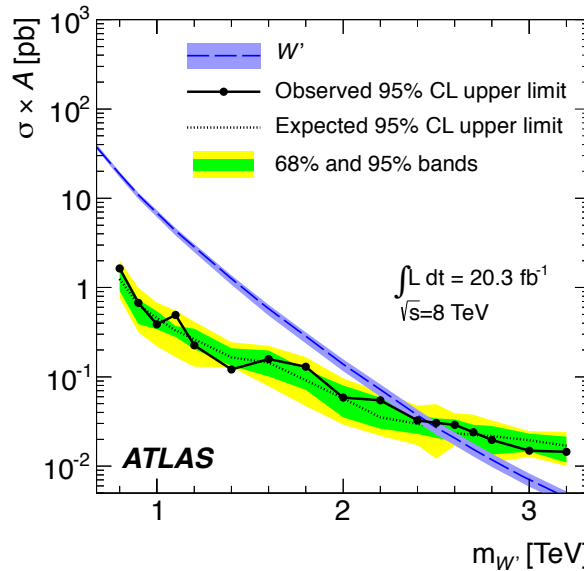
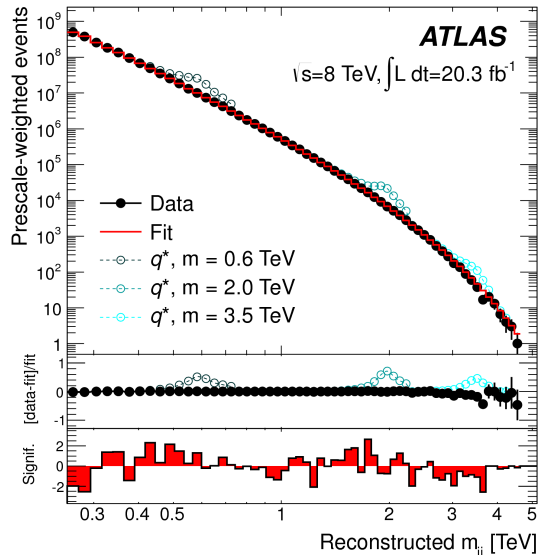
Dijet resonances

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

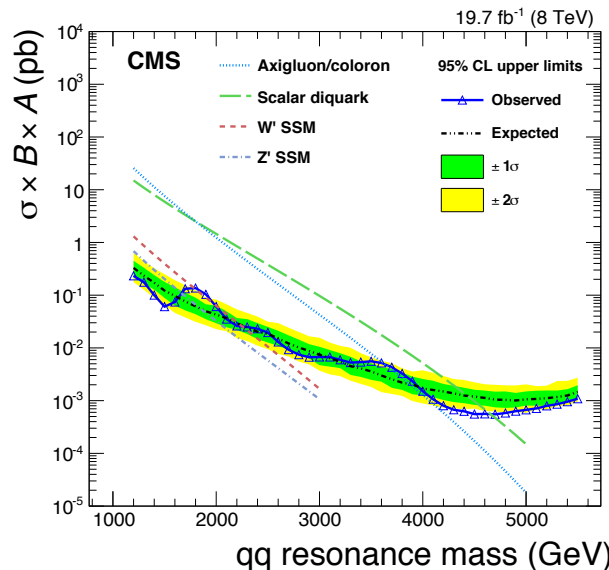
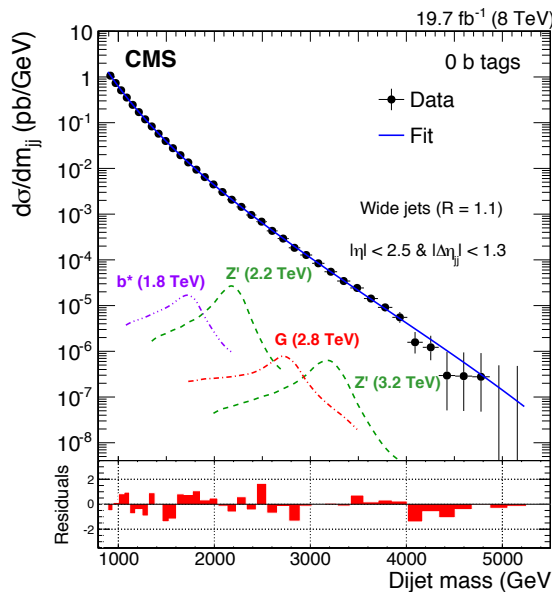
$$m(W') > 2.45 \text{ TeV}$$

$$m(qg) > 4.06 \text{ TeV}$$

- CMS

$$m(W') > 2.2 \text{ TeV}$$

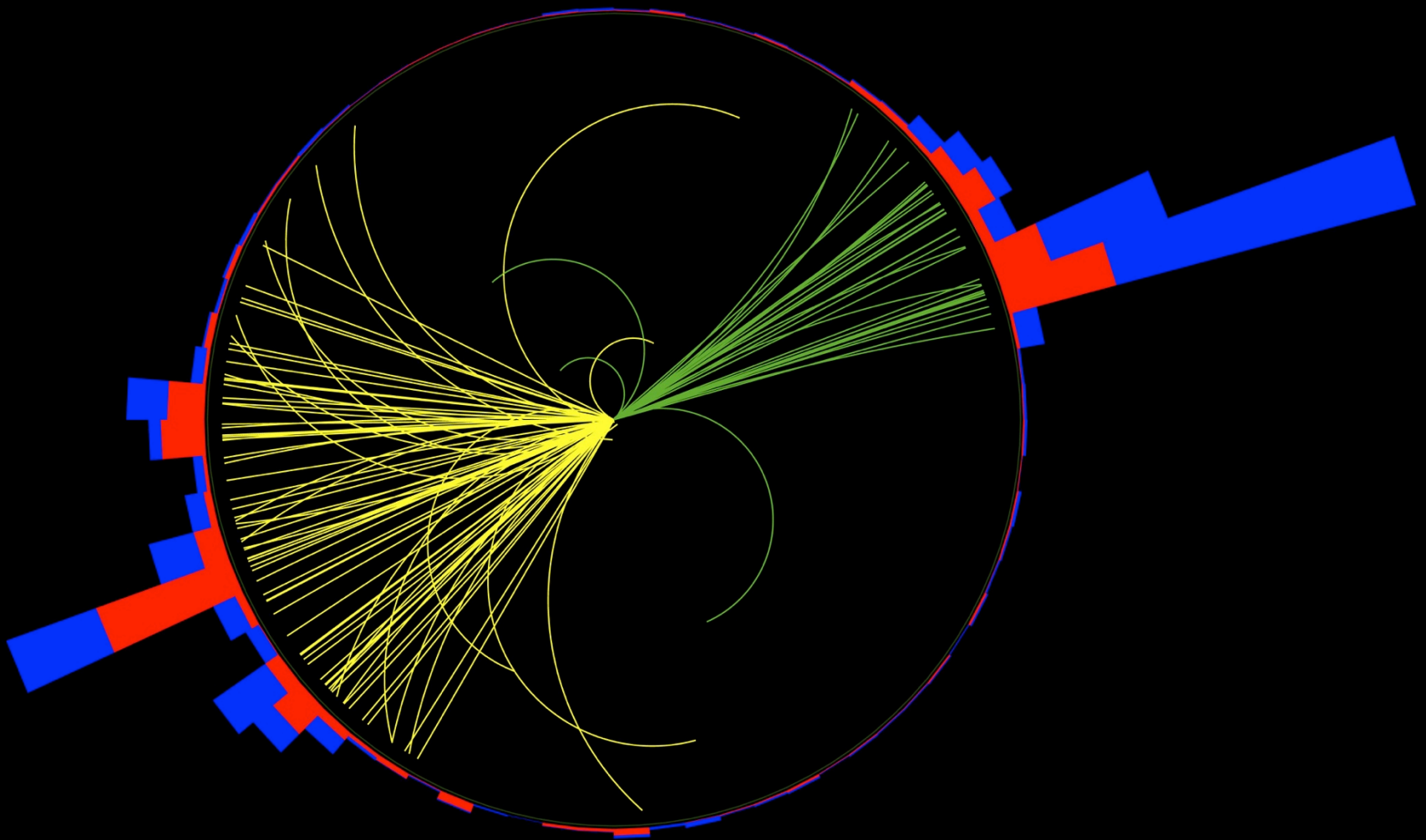
$$m(qg) > 5.0 \text{ TeV}$$



ULB Run 1 “fast” searches summary

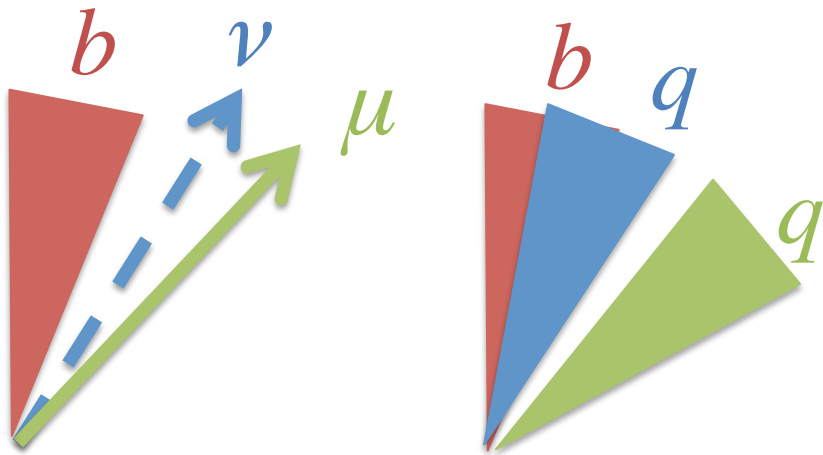
- The “fast” searches give unprecedented mass reaches.
- Typically in the range of a few TeV.
- Results generally comparable between ATLAS and CMS
- Most sensitivity comes early on
 - We are limited by the energy of the collisions.
- Classic bump searches with high discovery potential.
- Let’s look at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

Run 1 complex final states



Fat jet tagging

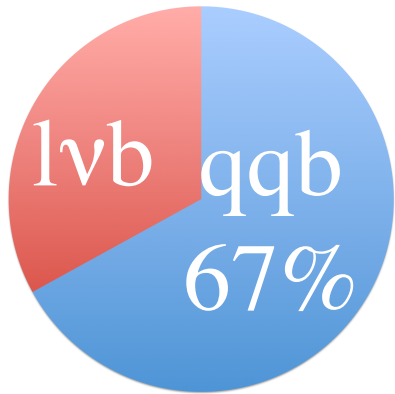
- At the LHC with centre of mass energy of 7-13 TeV
 - $m_t = 175$ GeV, $m_H = 125$ GeV, $m_Z = 91$ GeV, $m_W = 80$ GeV
 - We can expect boosted bosons and top quarks at the LHC!
- How does a boosted object decay?
- A top quark decays a bit like this:



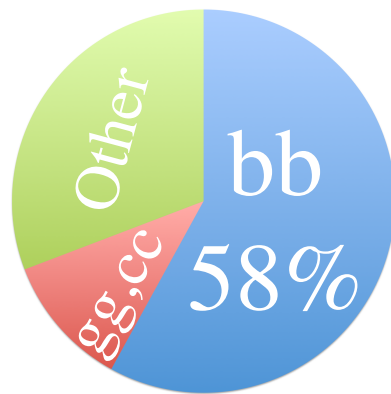
- For all hadronic decays the jets tend to overlap with each other.
- Overlapping jets are hard to work with.

Fat jet tagging

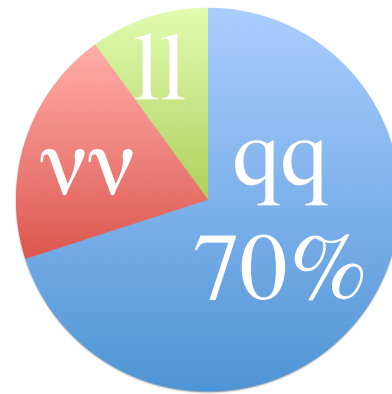
- Should we care about the hadronic decays?
- Yes! They make up $> 50\%$ of decays:



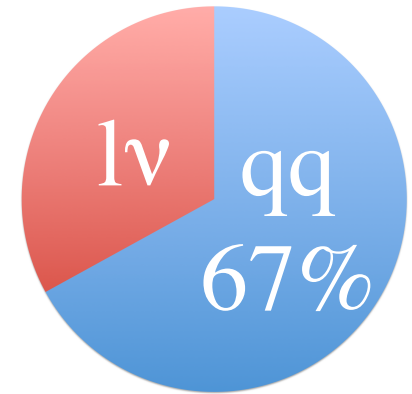
t decays



H decays



Z decays

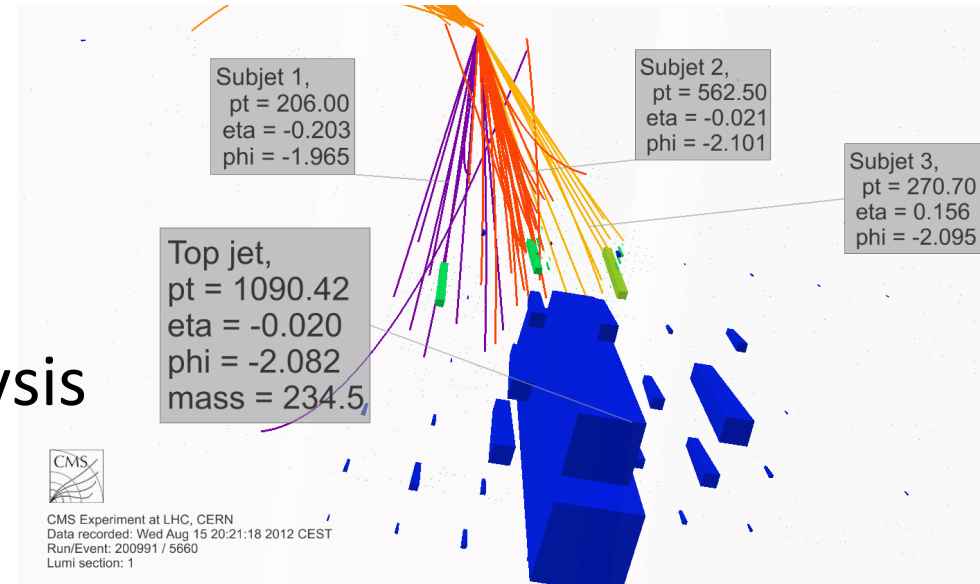


W decays

- 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

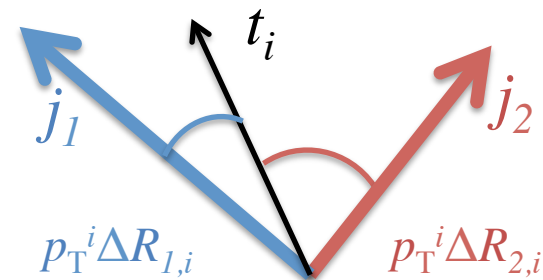
- “Top jets” have a distinctive substructure.
- ATLAS and CMS have developed “top tagging” algorithms.
- Example from the CMS tagger:
 - $140 < m(j_t) < 250 \text{ GeV}$
 - $N_{\text{sub-jets}} > 2$
 - Minimum pairwise mass, $m_{\text{min}} > 50 \text{ GeV}$
- Further selections per analysis
- Excellent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



- The “sub-jettiness” variable is defined as τ_N :

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

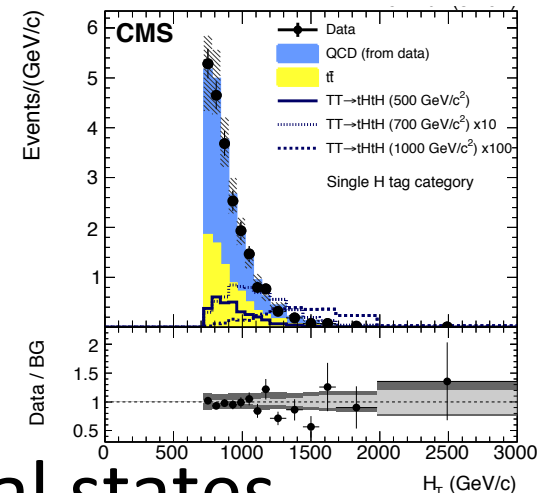
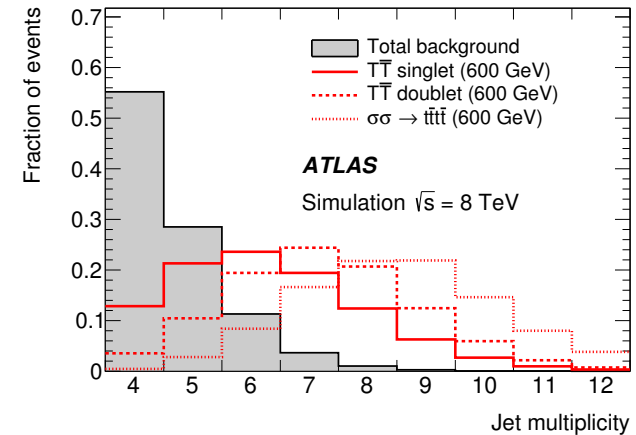
- R_0 is the characteristic jet radius.
- τ_N measures consistency with a top decay.
- τ_i/τ_j are discriminating variables, peaking near 1 for i sub-jets and 0 for j sub-jets.



Track t_i compared to sub-jets j_1, j_2 :

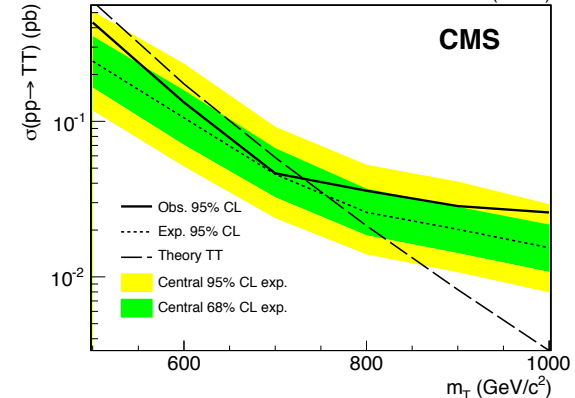
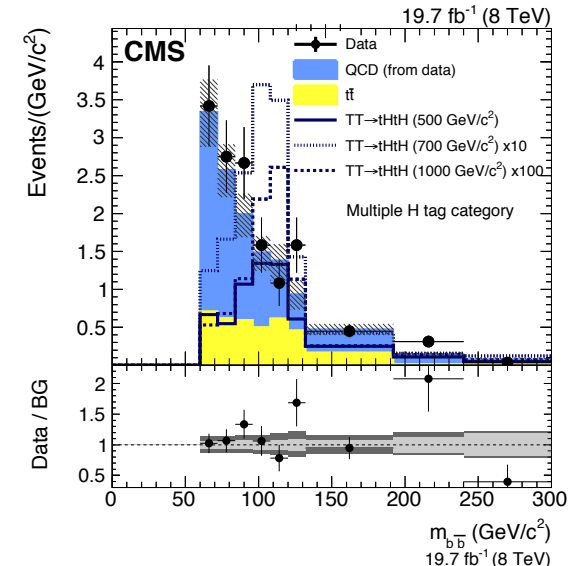
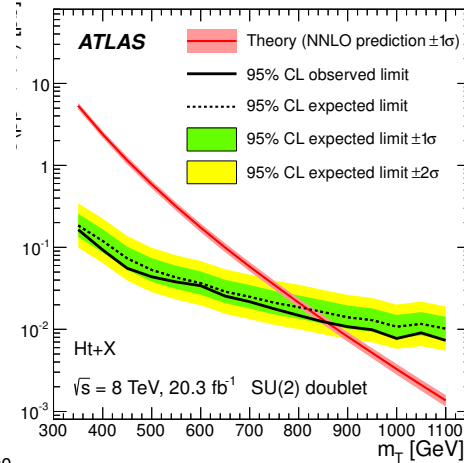
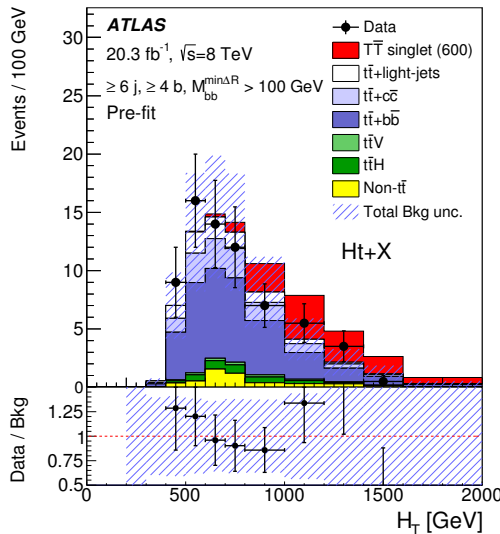
- Similar algorithms exist for W, Z, H bosons

- 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: $m(T \rightarrow tH) > 855 \text{ GeV}$
 CMS: $m(T \rightarrow tH) > 745 \text{ GeV}$

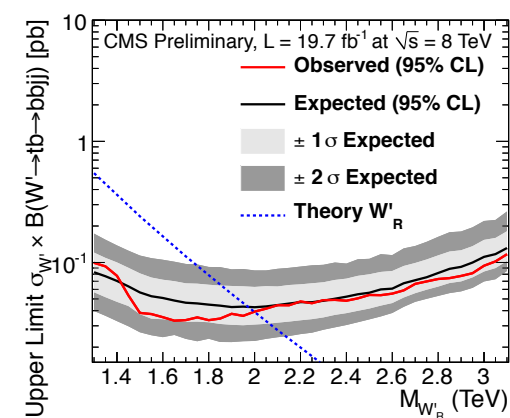
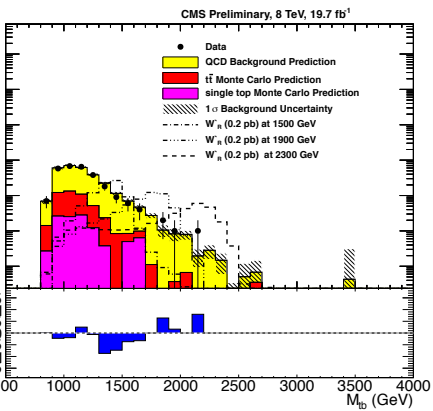
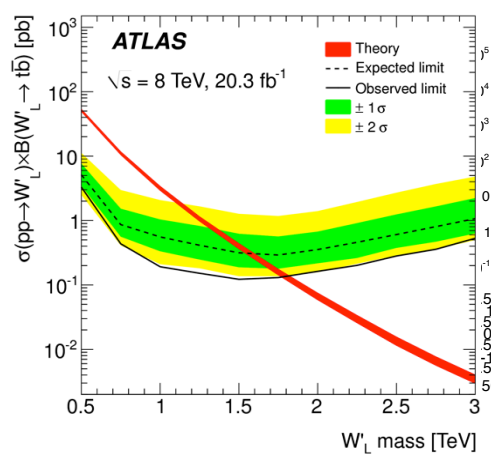
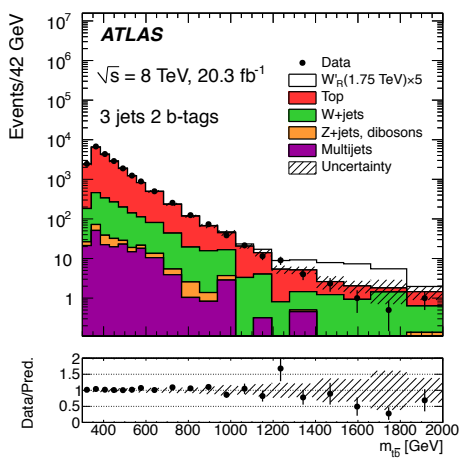
Latest results: $W' \rightarrow tb$

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

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

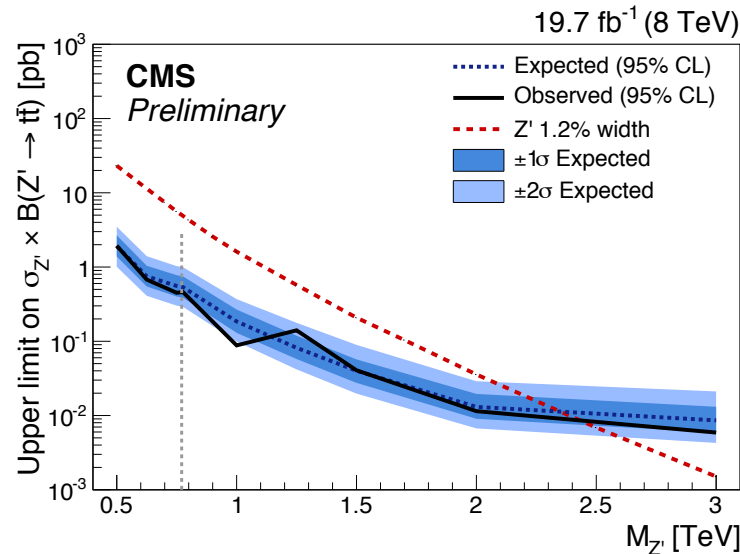
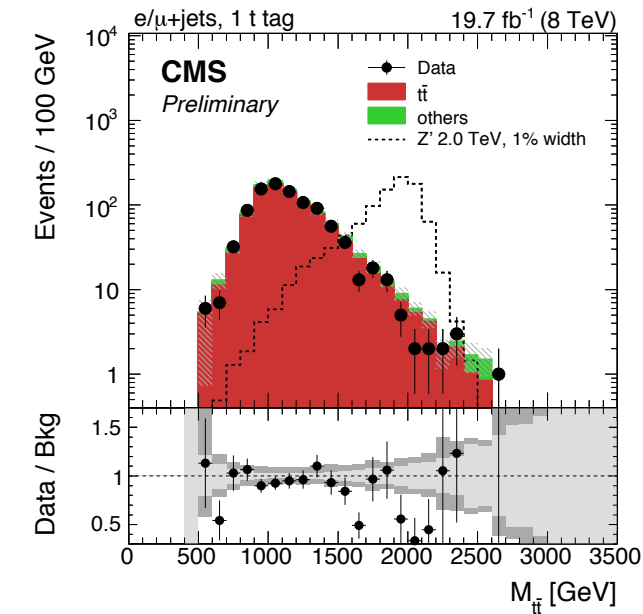
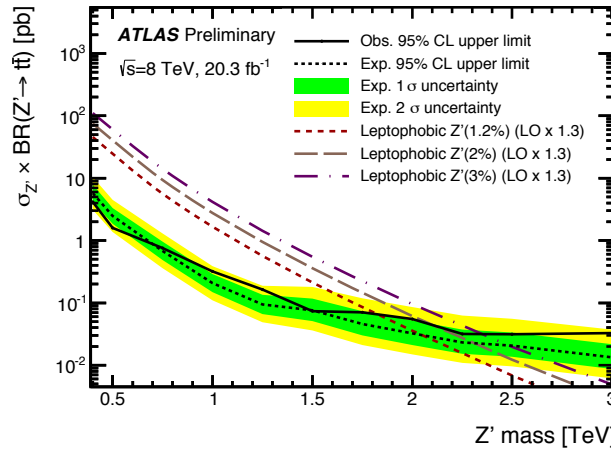
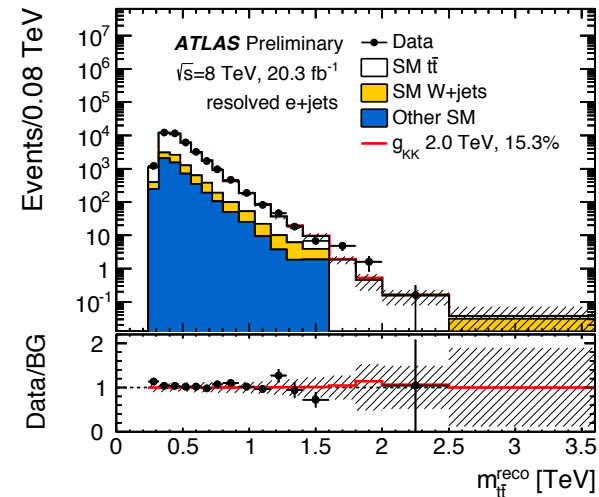
Limits:

ATLAS

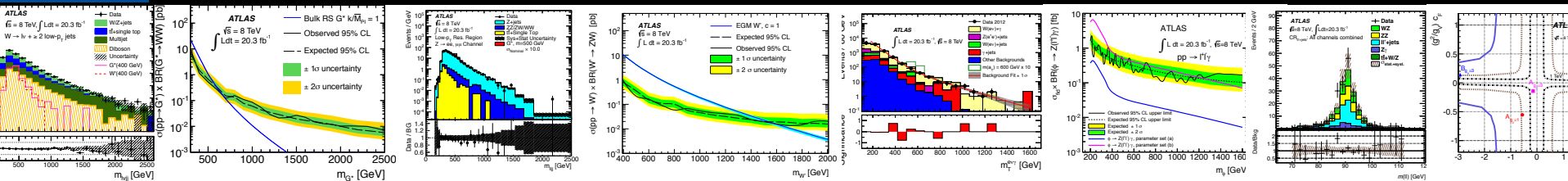
$$m(Z') < 0.4 \text{ TeV or } m(Z') > 3.0 \text{ TeV}$$

CMS

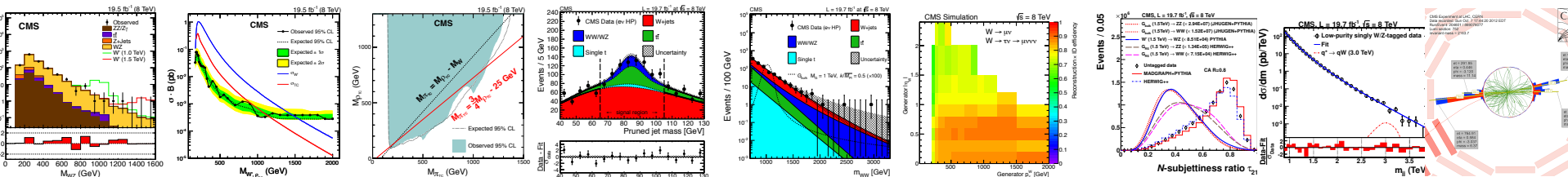
$$m(Z') > 2.4 \text{ TeV}$$



Vector boson resonances



- Many final states ($lljj, llll, ll\nu, jjjj, lvjj$) 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	$G_{RS} \rightarrow lvjj$	$m(G_{RS}) > 700 \text{ GeV}$	1503.04677
ATLAS	$W' \rightarrow lvjj$	$m(W') > 1490 \text{ GeV}$	1503.04677
ATLAS	$W' \rightarrow WZ \rightarrow lljj$	$m(W') > 1590 \text{ GeV}$	1409.6190
ATLAS	$G_{RS} \rightarrow WZ \rightarrow lljj$	$m(G_{RS}) > 740 \text{ GeV @ k/MPI}=1.0$ $m(G_{RS}) > 540 \text{ GeV @ k/MPI}=0.5$	1409.6190
ATLAS	$\alpha_T \rightarrow lv\gamma$	$m(\alpha_T) > 960 \text{ GeV}$	1407.8150
ATLAS	$\alpha_T \rightarrow ll\gamma$	$m(\alpha_T) > 890 \text{ GeV}$	1407.8150
ATLAS	$W' \rightarrow WZ \rightarrow ll\nu$	$m(W') > 1520 \text{ GeV}$	1406.4456
CMS	$W' \rightarrow WZ \rightarrow ll\nu$	$m(W') > 1550$	1407.3476
CMS	$Q_{TC} \rightarrow WZ \rightarrow ll\nu$	$m(Q_{TC}) > 1140 \text{ GeV}$	1407.3476
CMS	$WZ \rightarrow (lv/ll)+jj$ Graviton bulk	$\sigma(m(G_{RS}) = 600 \text{ GeV}) < 700 \text{ fb}^{-1}$ $\sigma(m(G_{RS}) = 2500 \text{ GeV}) < 10 \text{ fb}^{-1}$	1405.3447
CMS	$q^* \rightarrow qW \rightarrow jjjj$	$m(q^*) > 3200 \text{ GeV}$	1405.1994
CMS	$q^* \rightarrow qZ \rightarrow jjjj$	$m(q^*) > 2900 \text{ GeV}$	1405.1994
CMS	$W' \rightarrow WZ \rightarrow jjjj$	$m(W') > 1700 \text{ GeV}$	1405.1994
CMS	$G_{RS} \rightarrow WW \rightarrow jjjj$	$m(G_{RS}) > 1200 \text{ GeV}$	1405.1994

$$W' \rightarrow WZ \rightarrow ll\nu$$

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

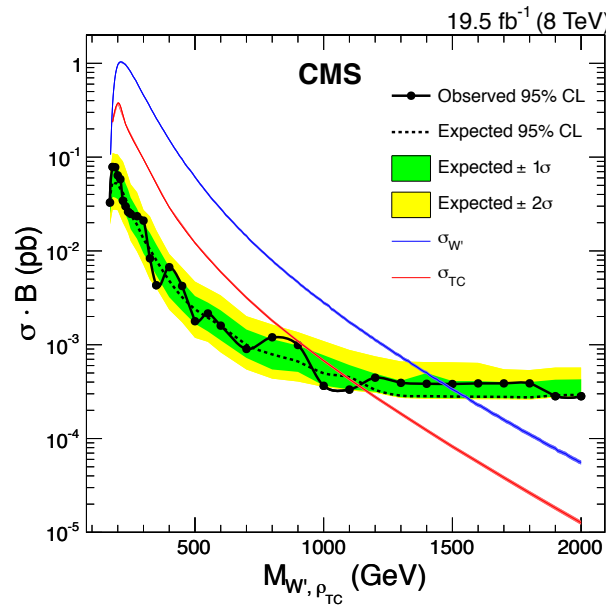
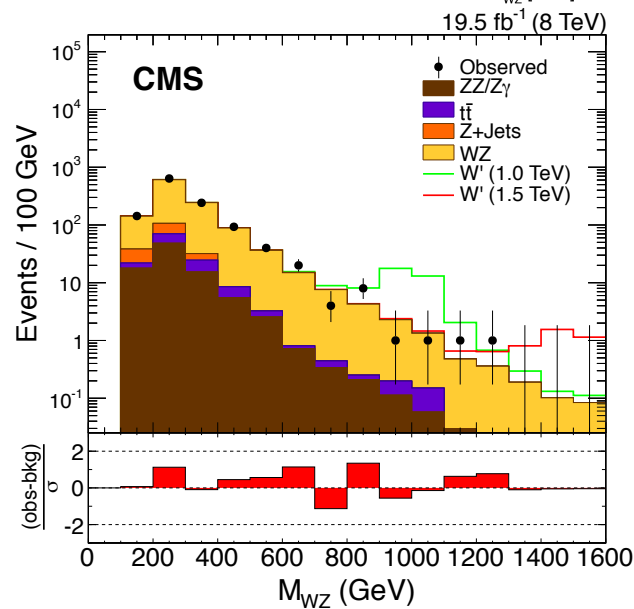
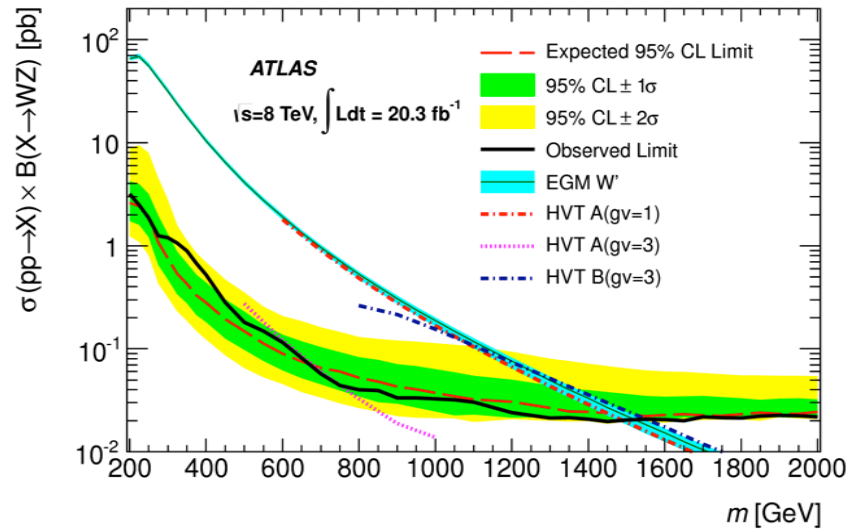
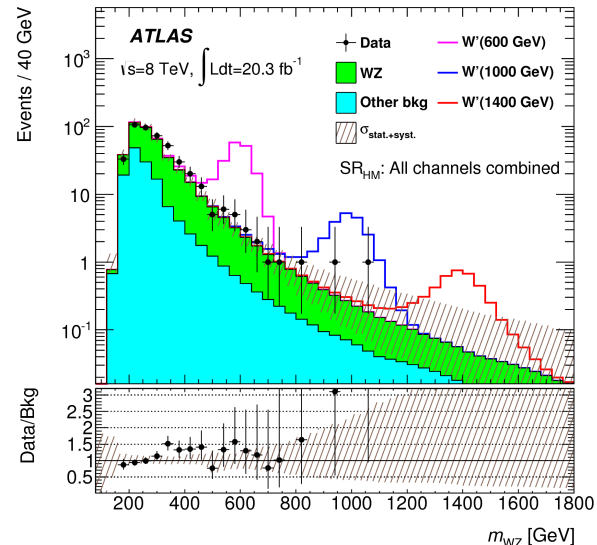
PLB 737, 223 (2014)

PLB 2014.11.026

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

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

$W' \rightarrow WZ \rightarrow ll\nu$



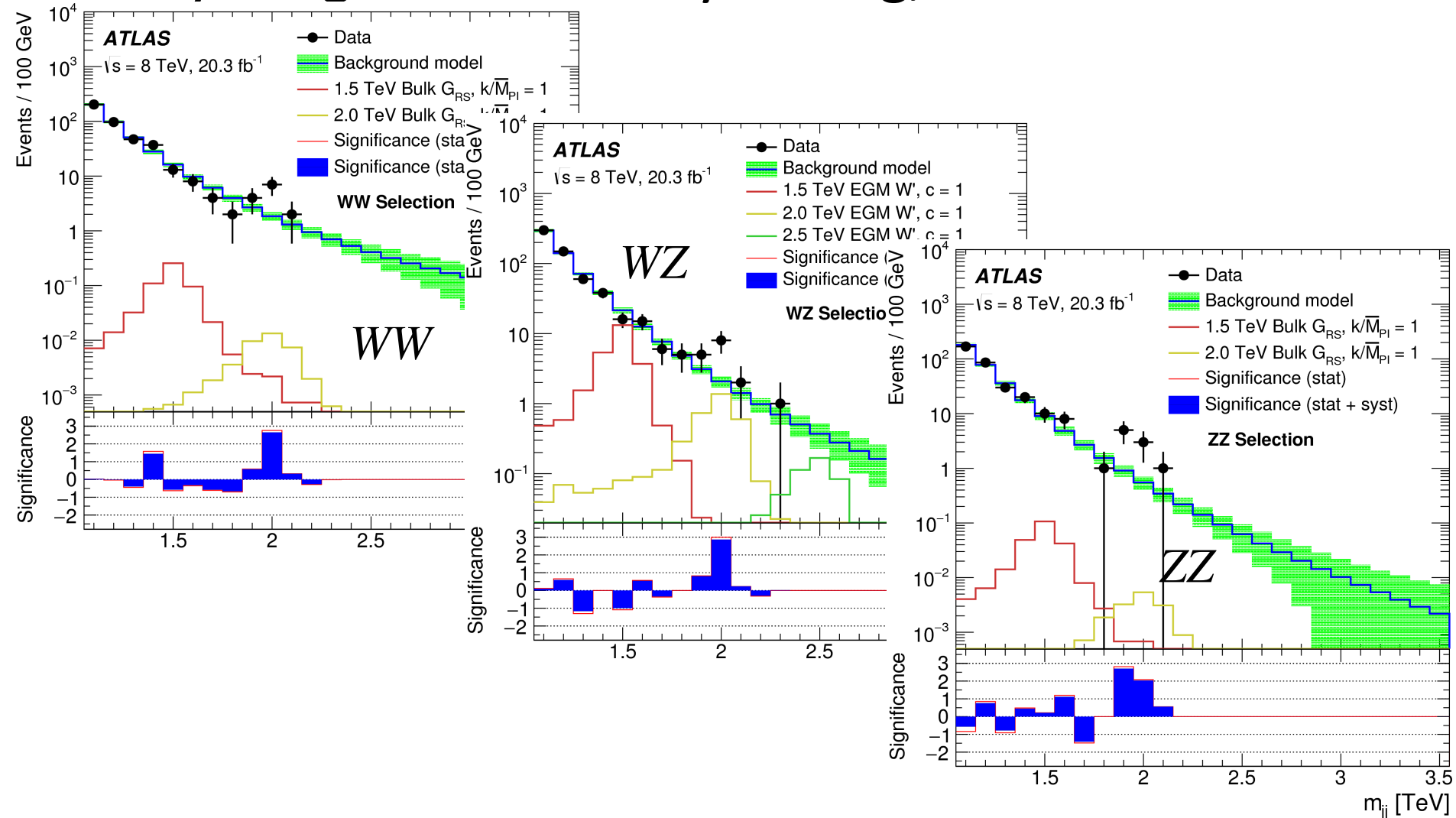
- Limits:
 - ATLAS $m(W') > 1520$ GeV
 - CMS $m(W') > 1550$ GeV

The diboson bump

- Everything seemed fairly boring, and then...

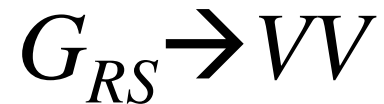
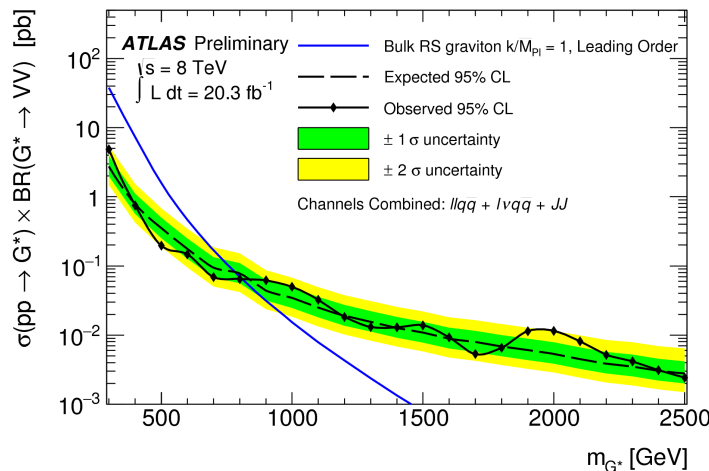
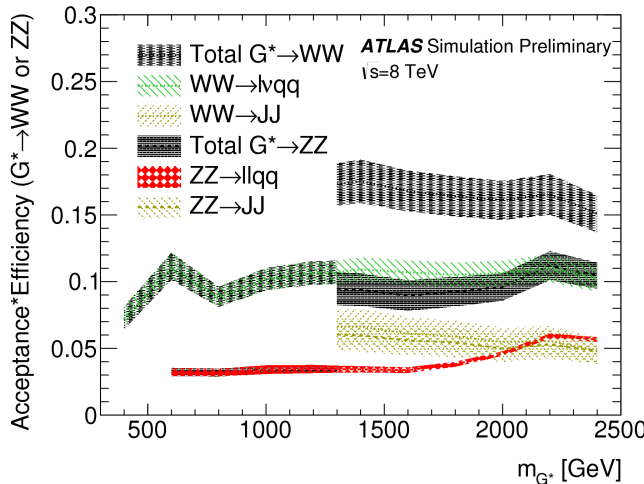
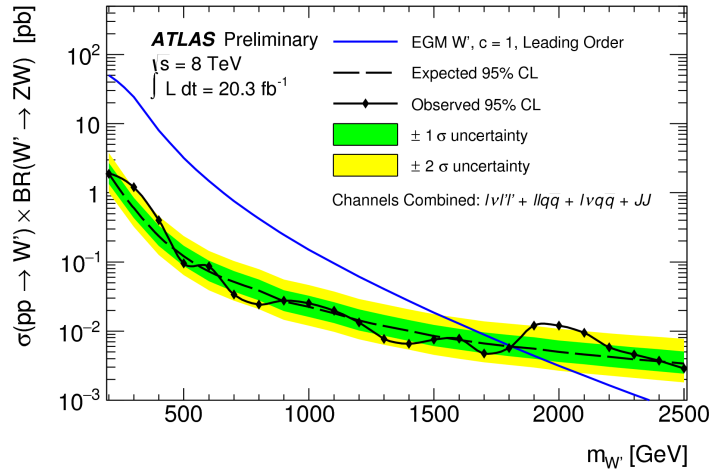
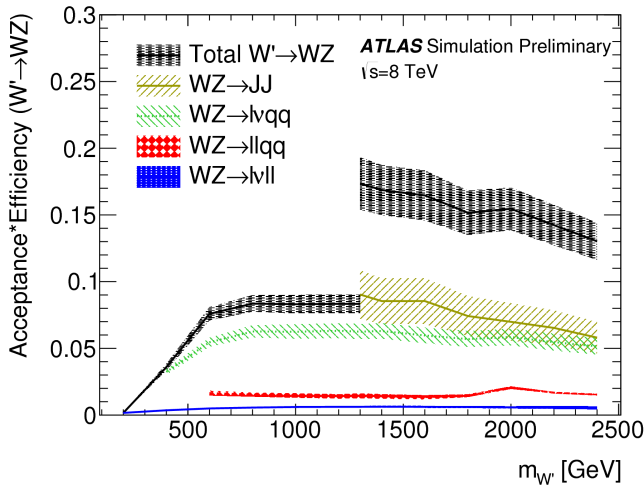
The diboson bump

- Everything seemed fairly boring, and then...



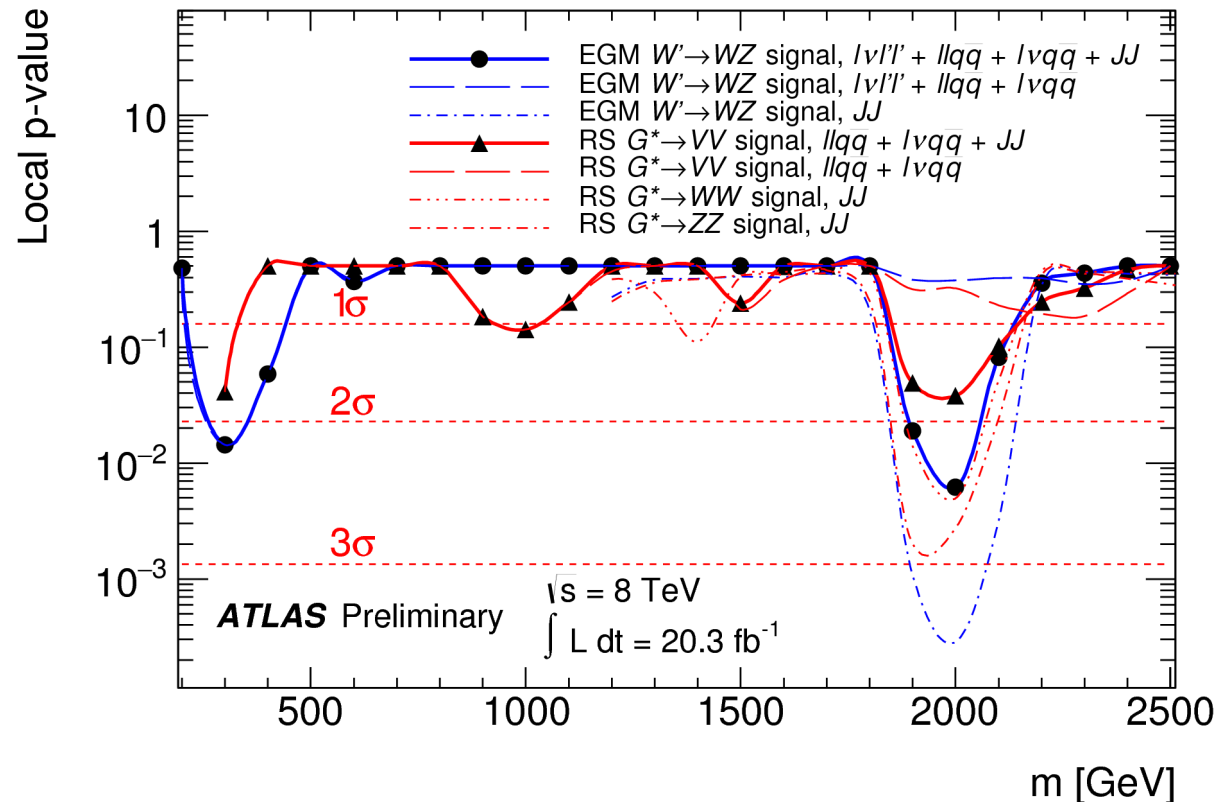
The diboson bump

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

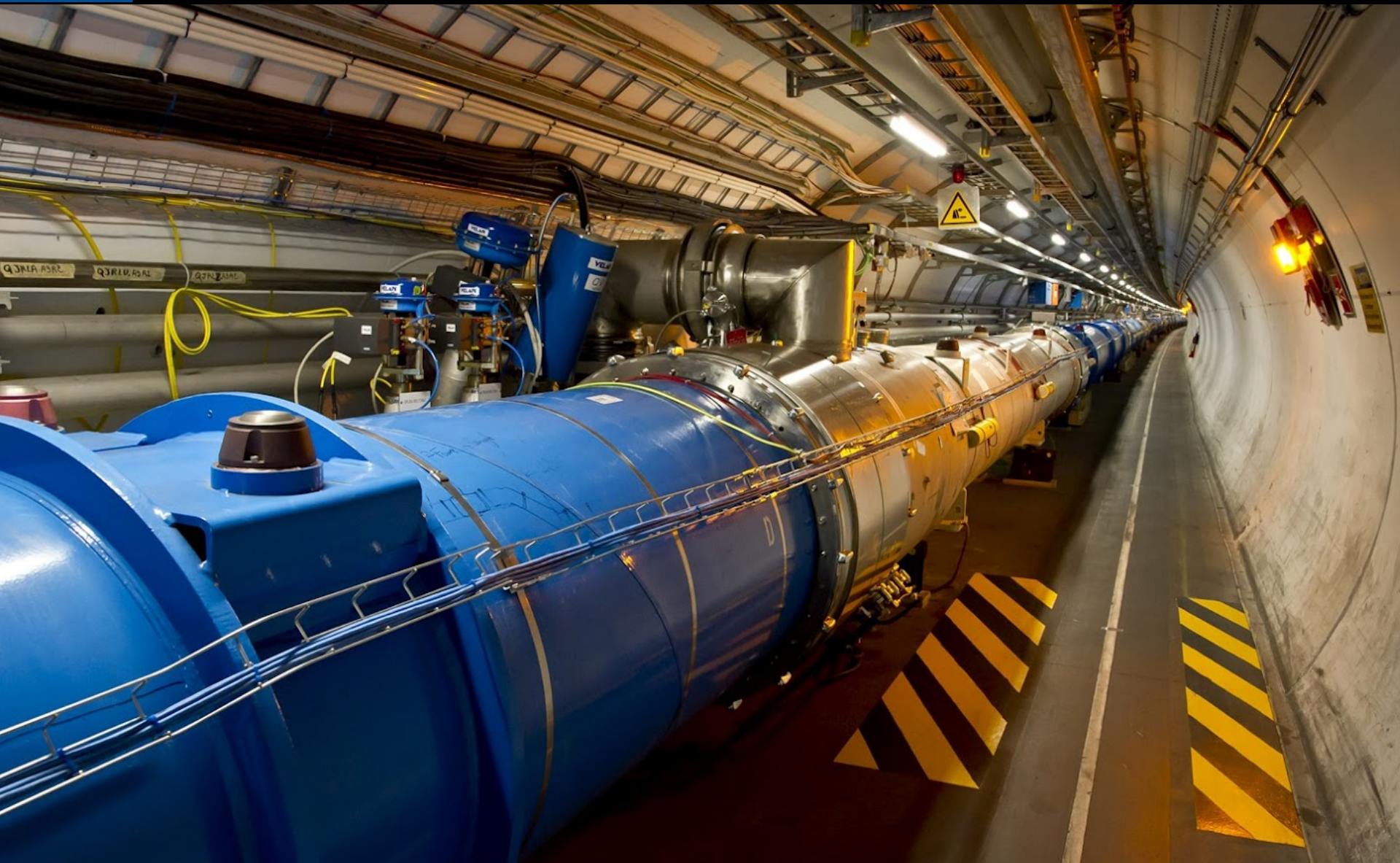


The diboson bump

- 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

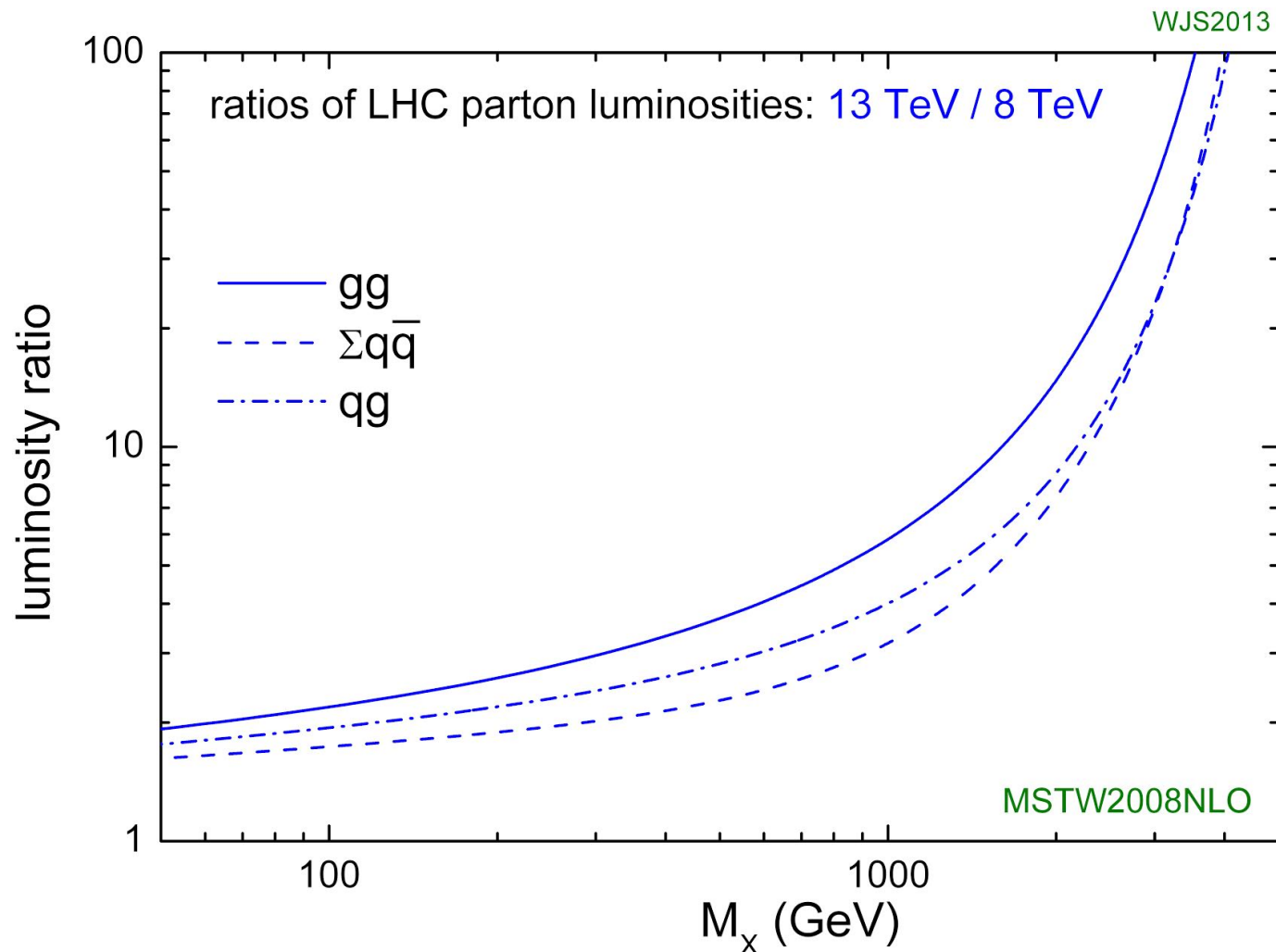


From Run 1 to Run 2

- 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

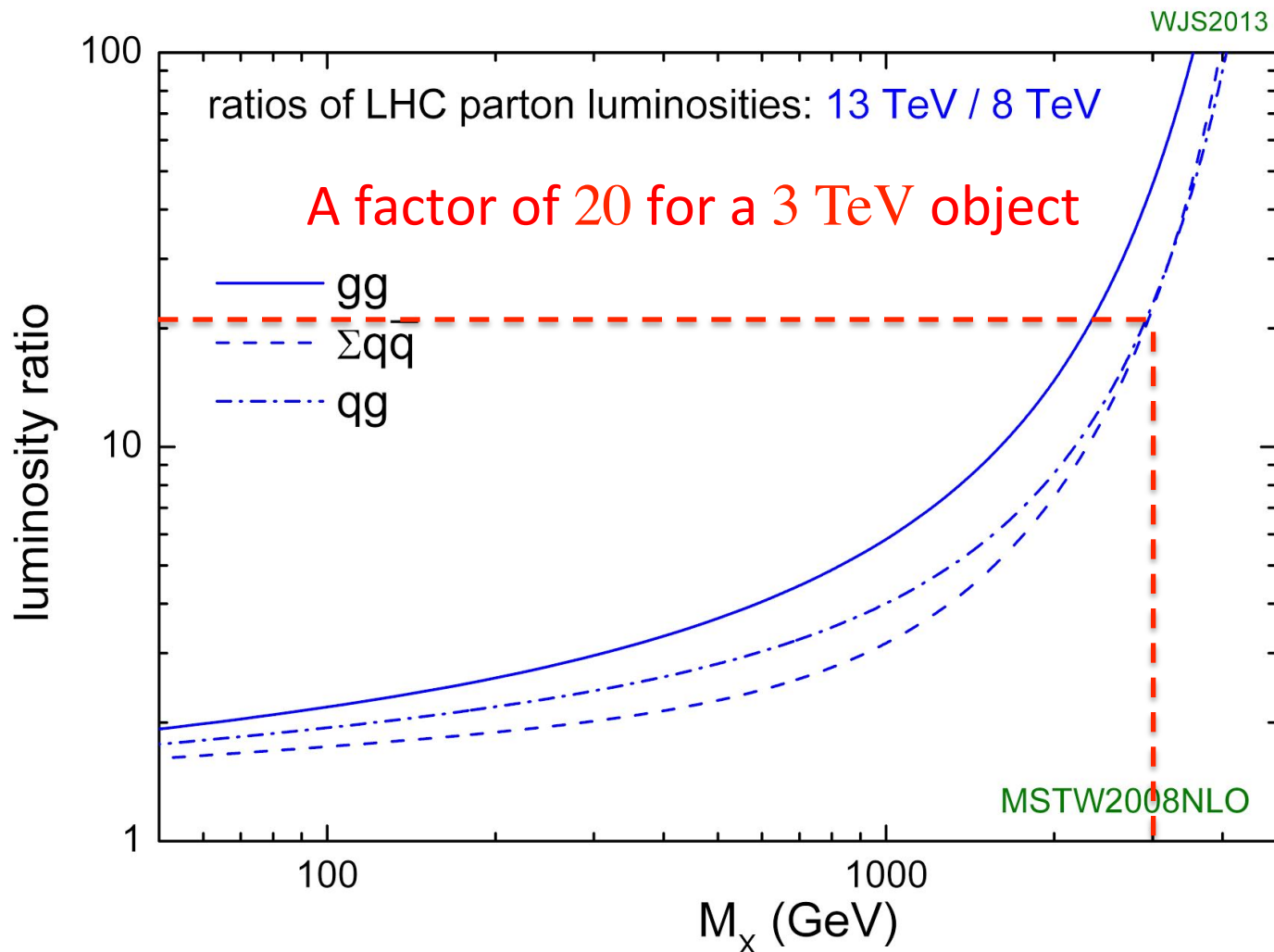
From Run 1 to Run 2

- In fact effective luminosity increases substantially!



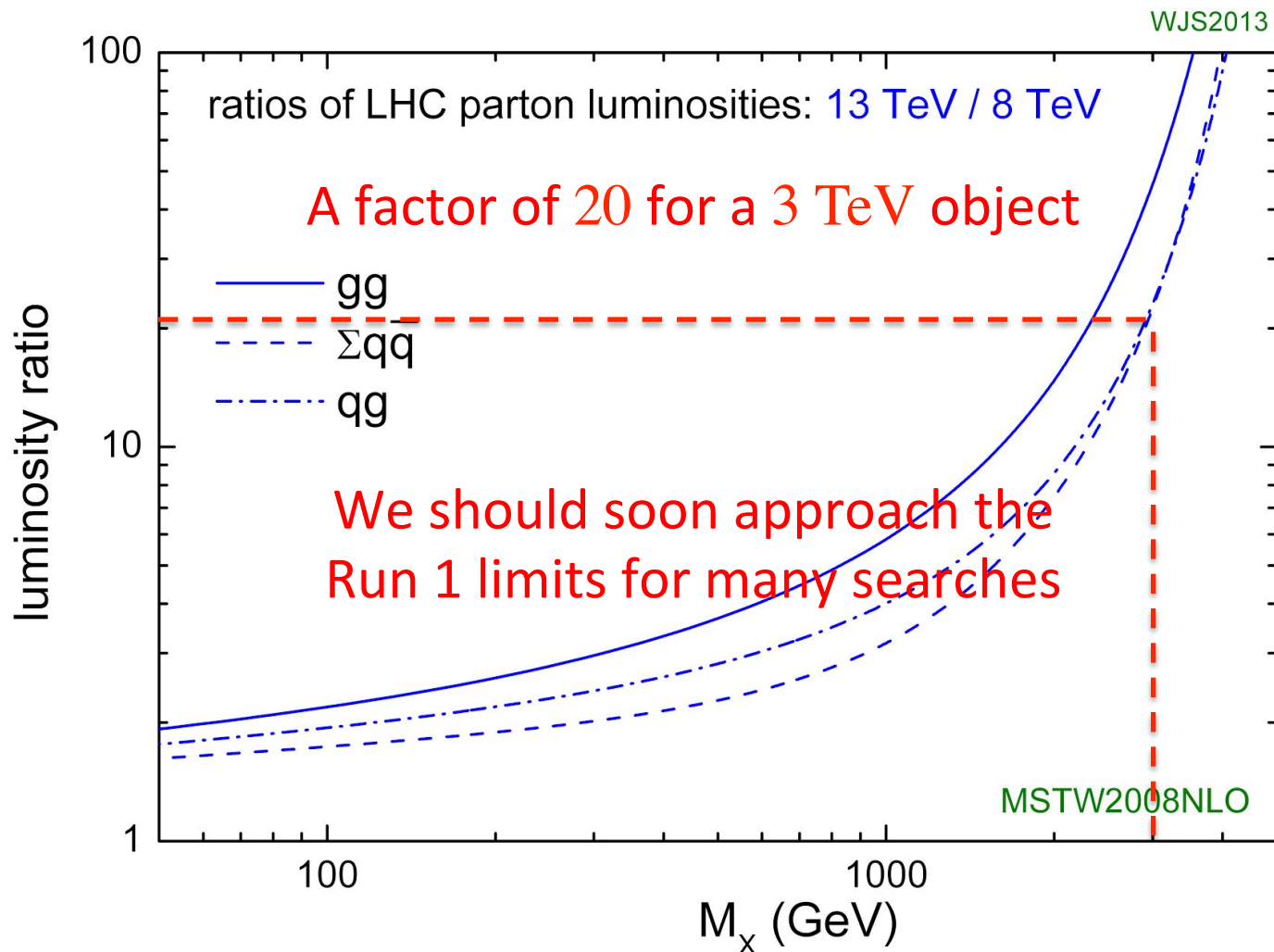
From Run 1 to Run 2

- In fact effective luminosity increases substantially!



From Run 1 to Run 2

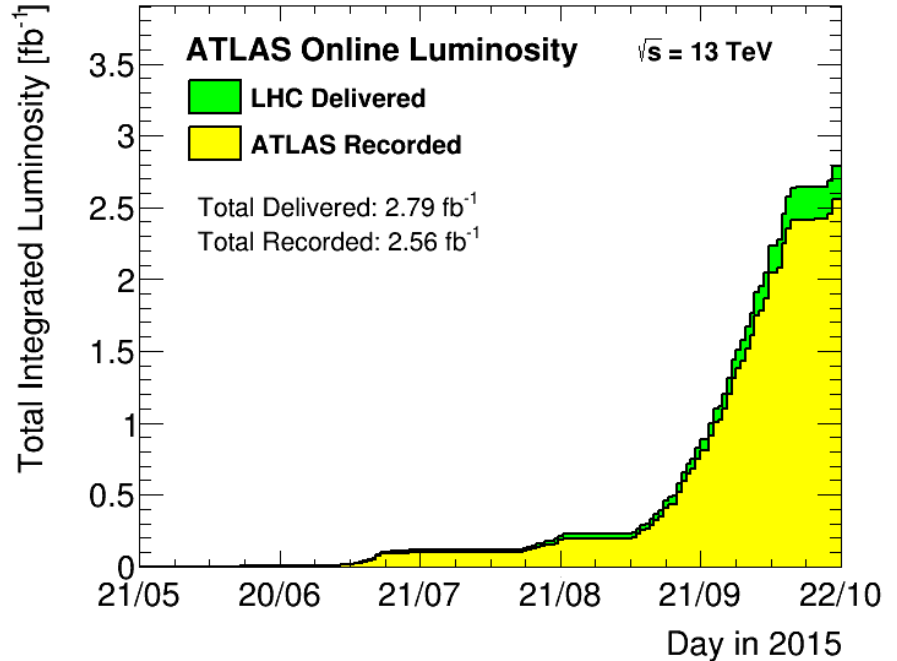
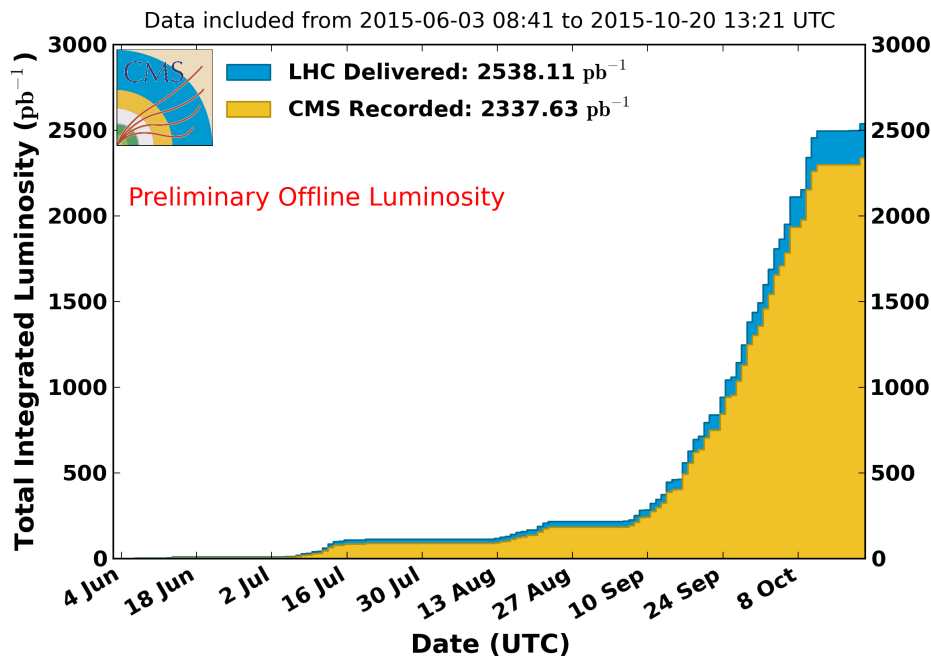
- In fact effective luminosity increases substantially!



From Run 1 to Run 2

- Luminosity of Run 2:

CMS Integrated Luminosity, pp, 2015, $\sqrt{s} = 13$ TeV

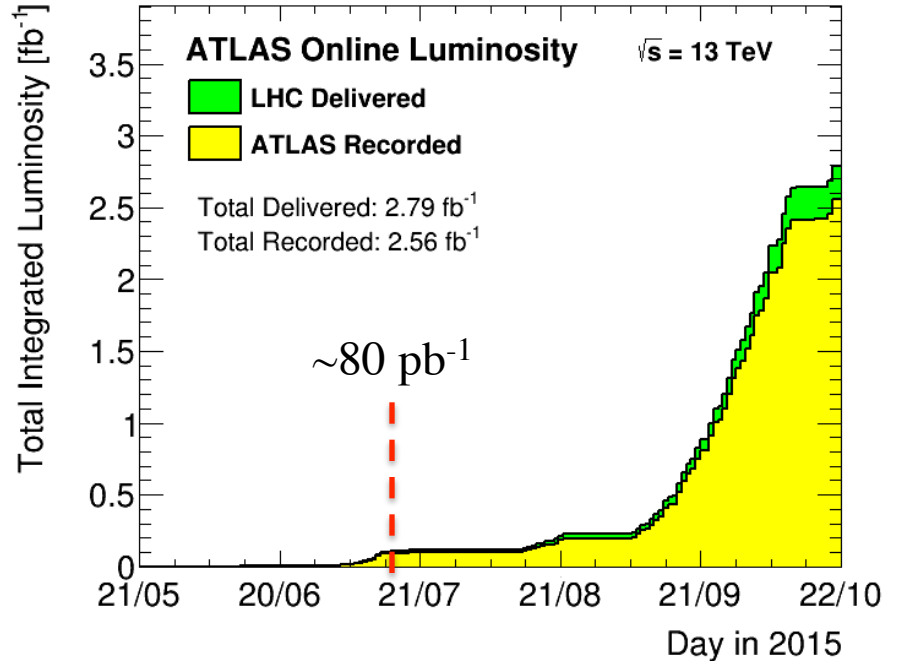
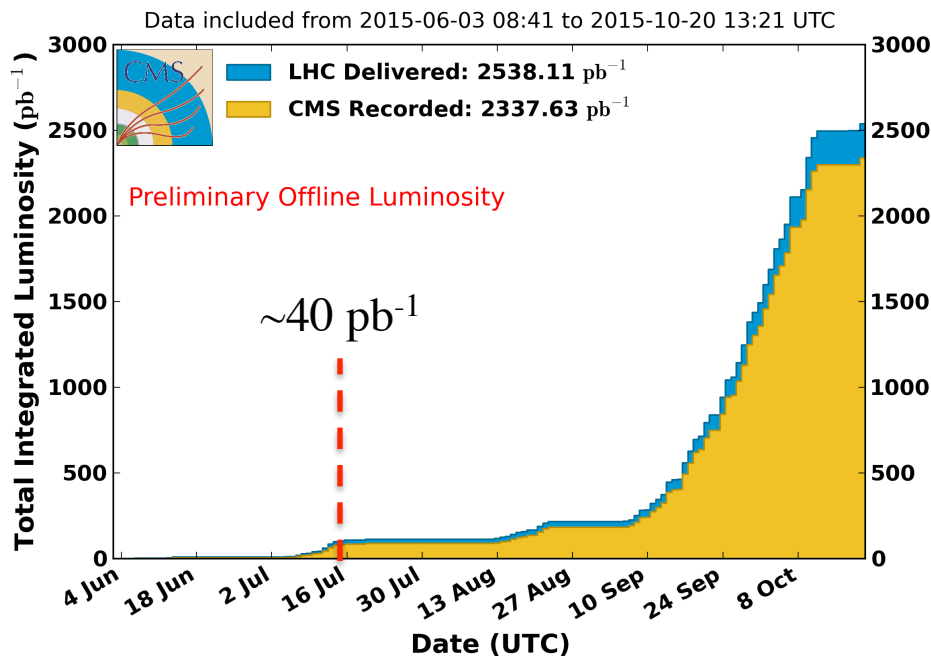


- About 2.5 fb^{-1} so far

From Run 1 to Run 2

- Luminosity of Run 2:

CMS Integrated Luminosity, pp, 2015, $\sqrt{s} = 13$ TeV

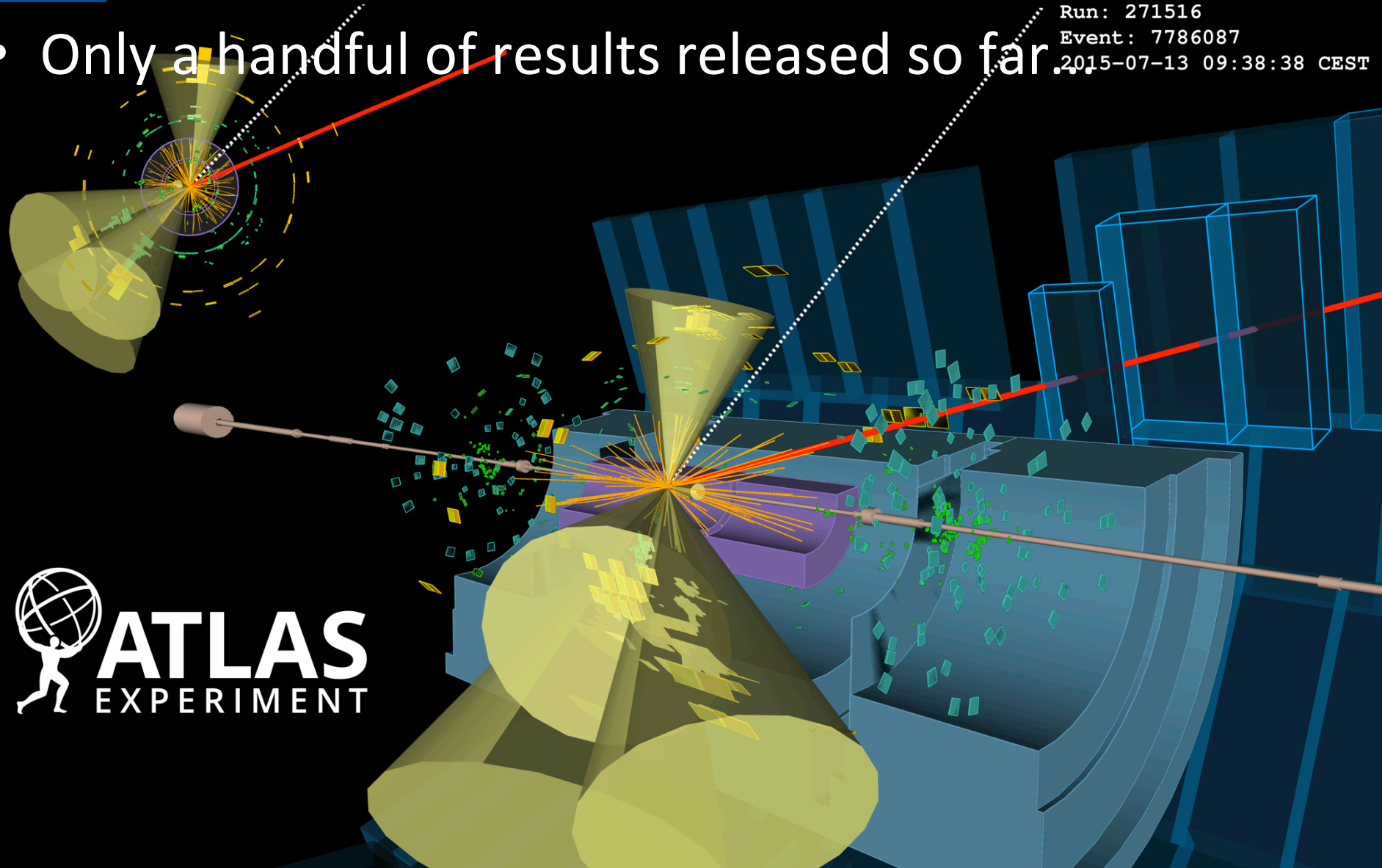


- About 2.5 fb⁻¹ so far

Some Run 2 results

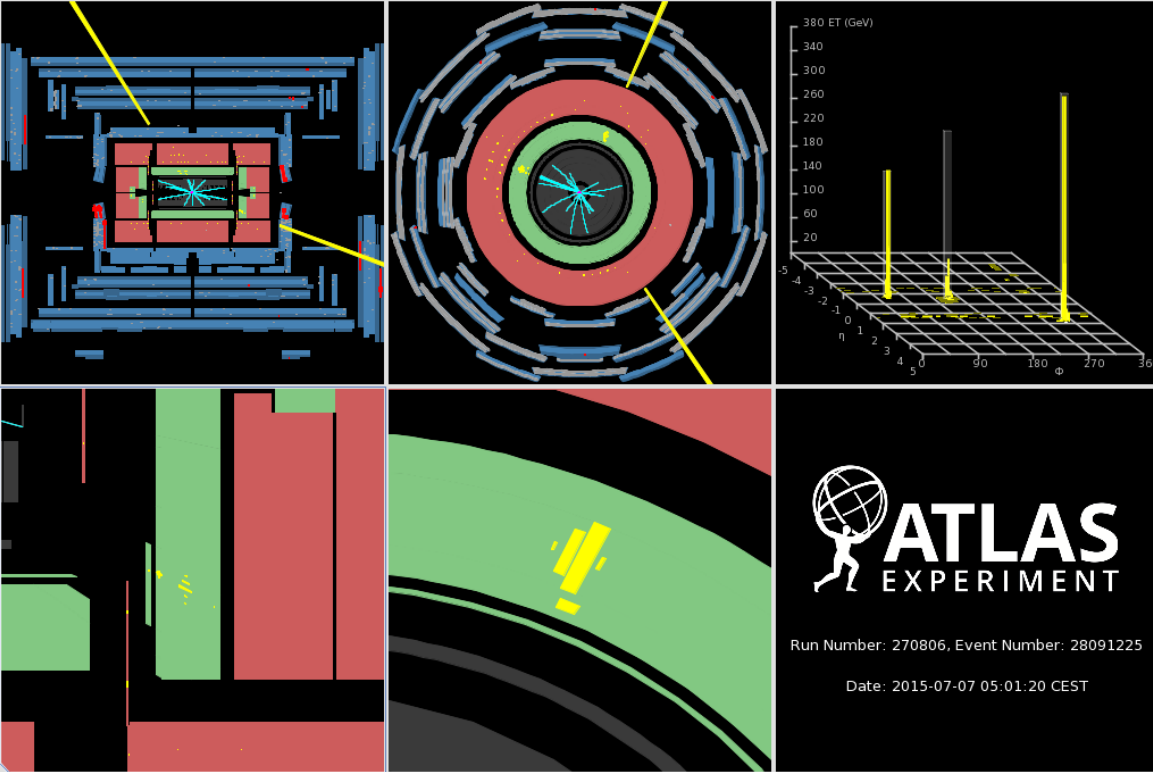
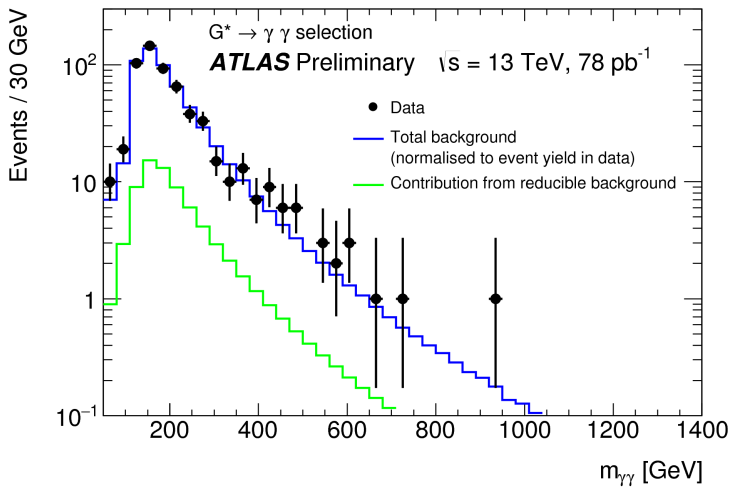
- Only a handful of results released so far.

Run: 271516
Event: 7786087
2015-07-13 09:38:38 CEST



ATLAS diphoton search

- Latest ATLAS results for the diphoton search:

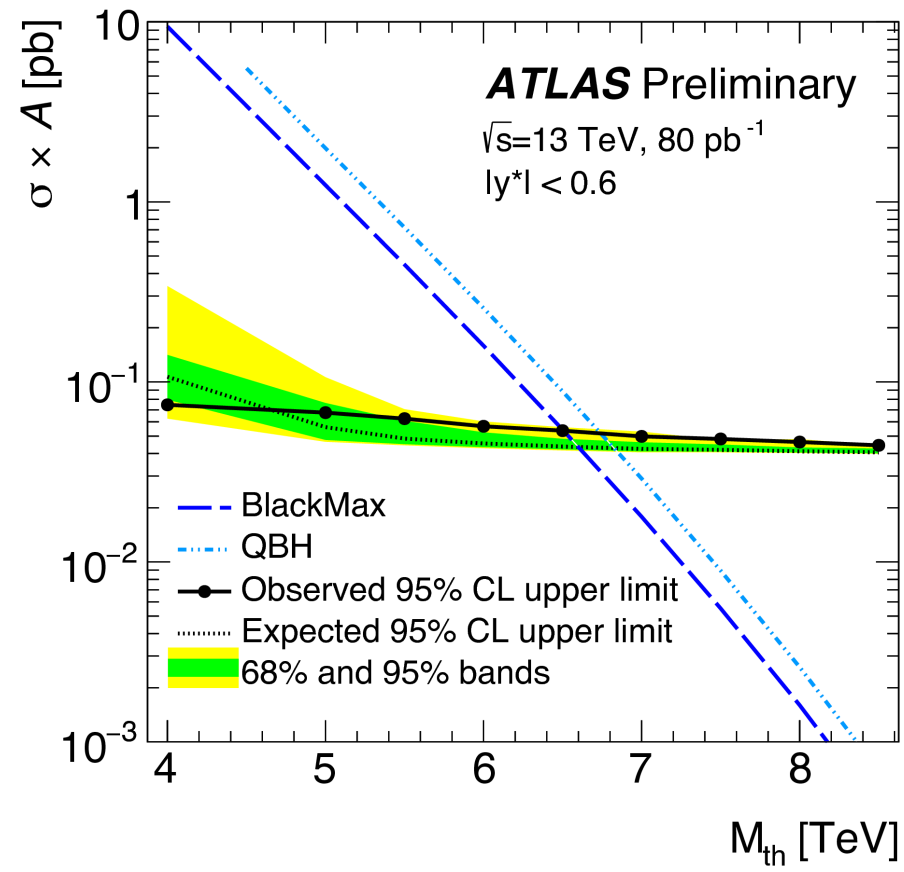
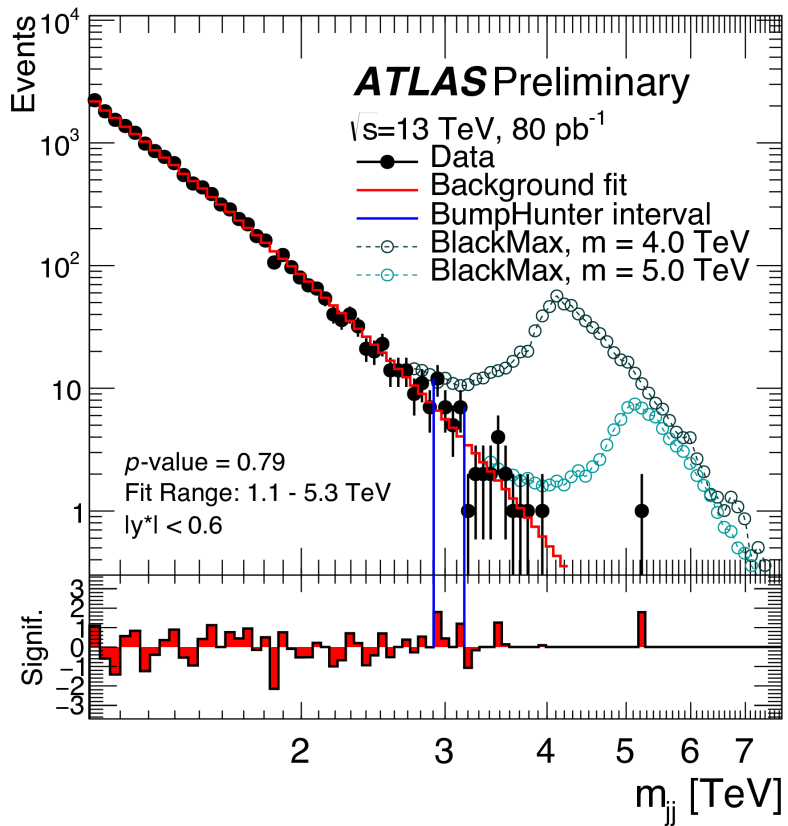


- No bump with 78 pb⁻¹

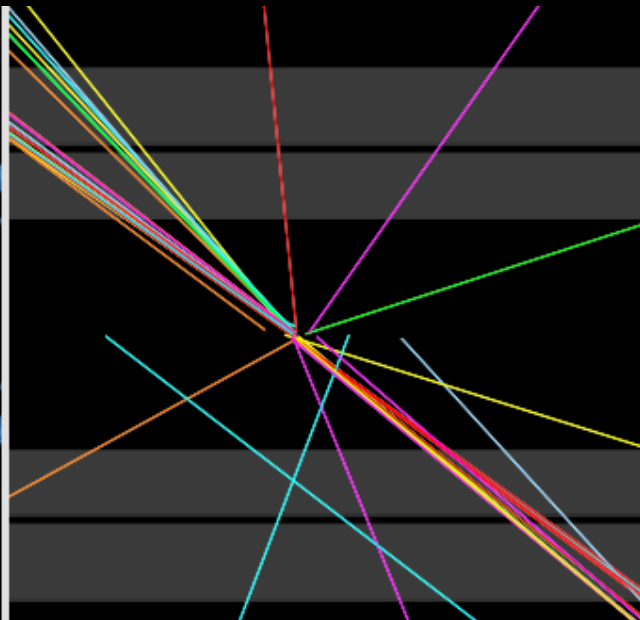
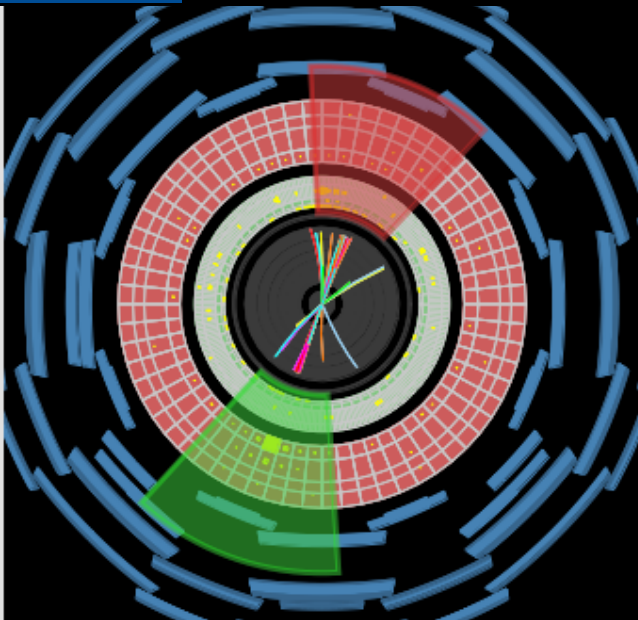
$$m(\gamma\gamma) = 940 \text{ GeV}$$

ATLAS dijet search

- The dijet searches benefit from the new mass reach



ATLAS dijet search

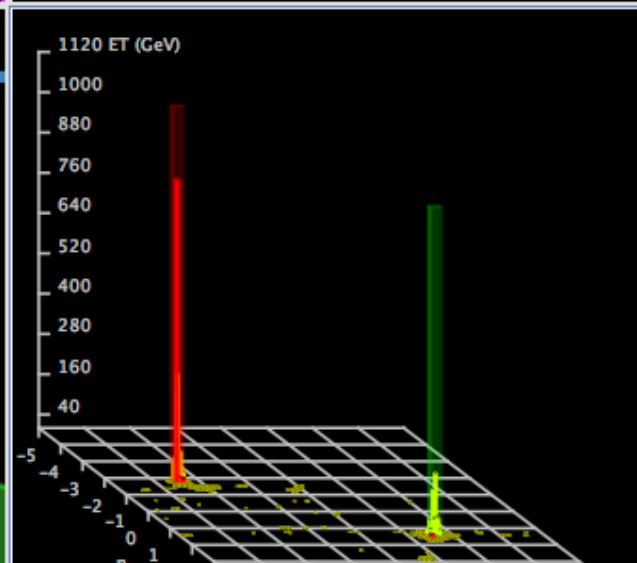
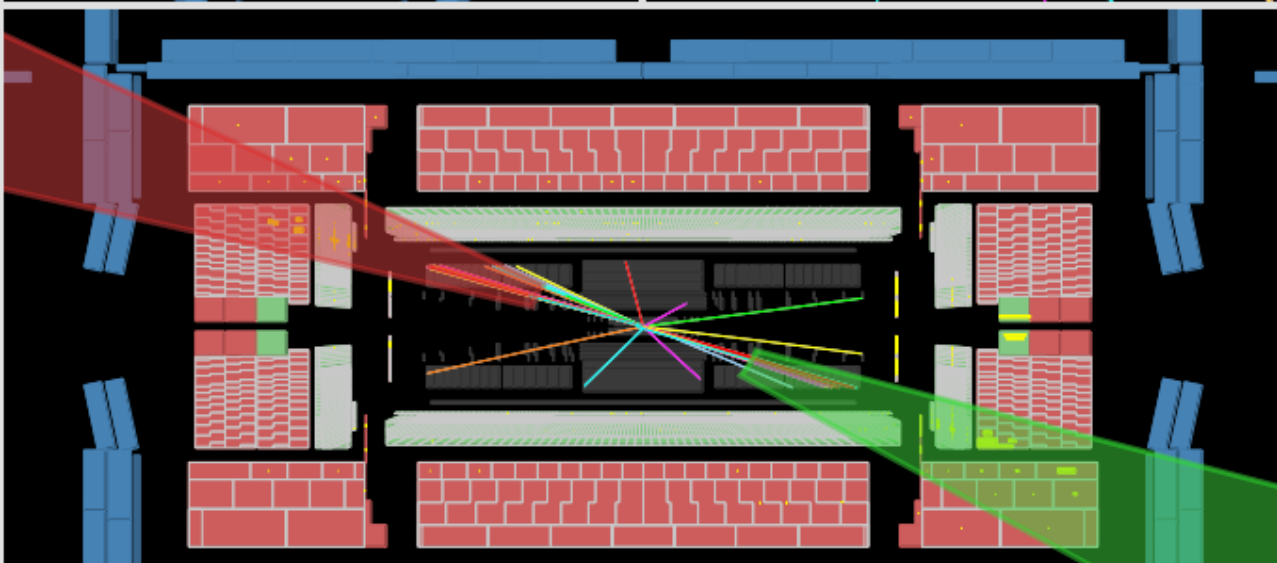


$$m(jj) = 6.9 \text{ TeV}$$



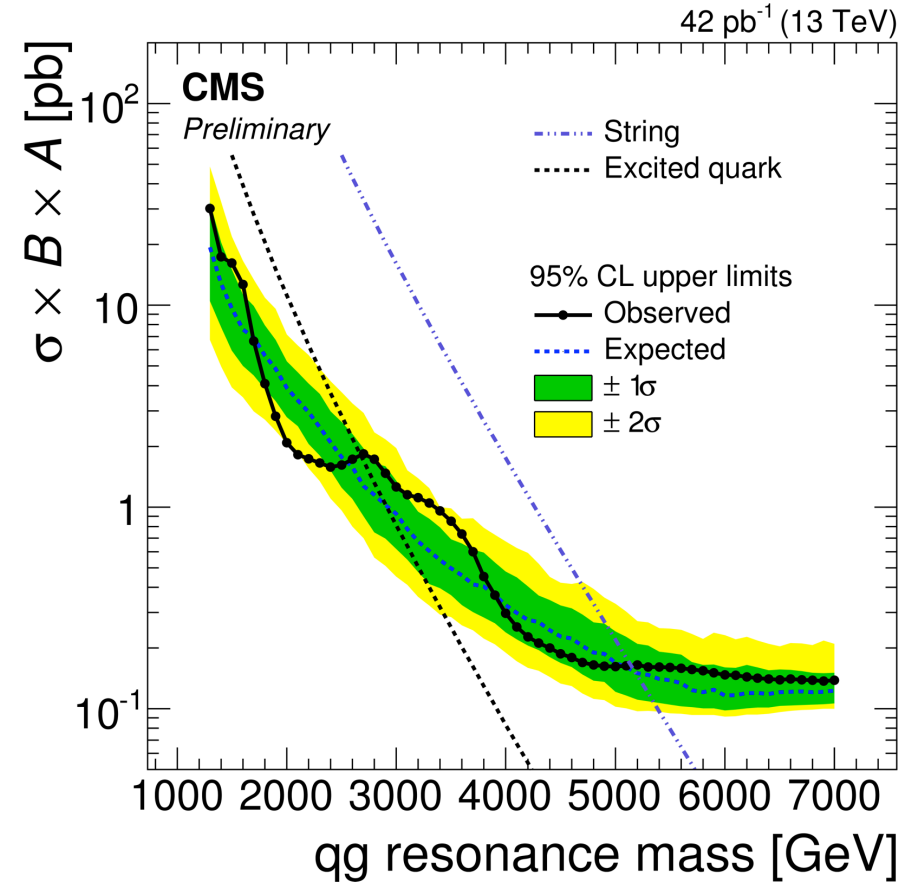
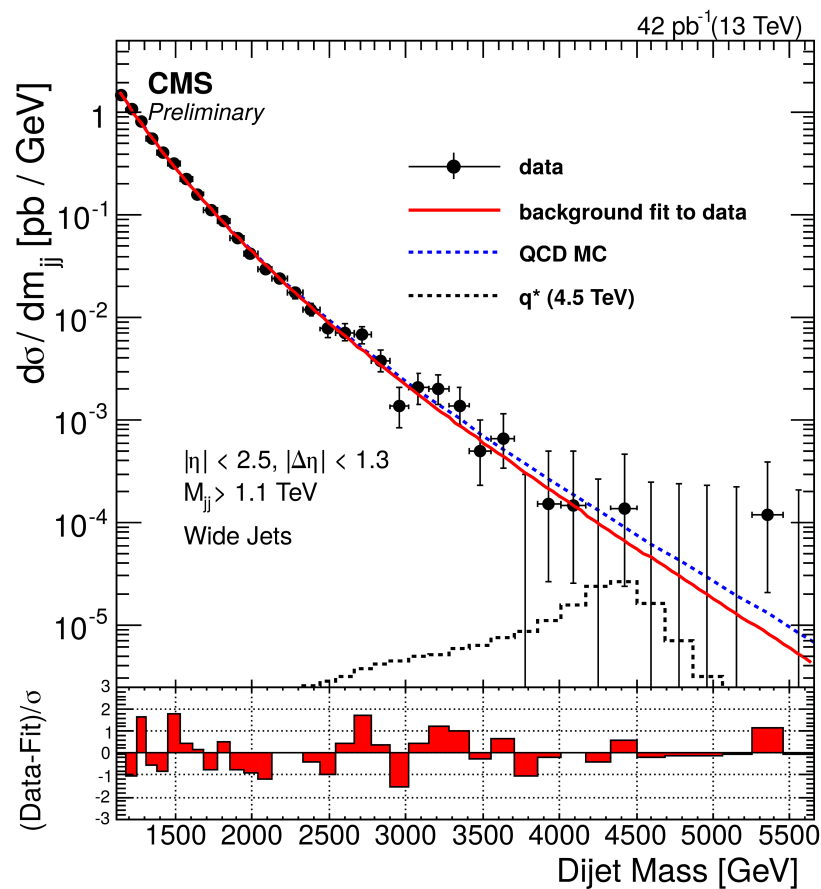
Run Number: 276731, Event Number: 876578955

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



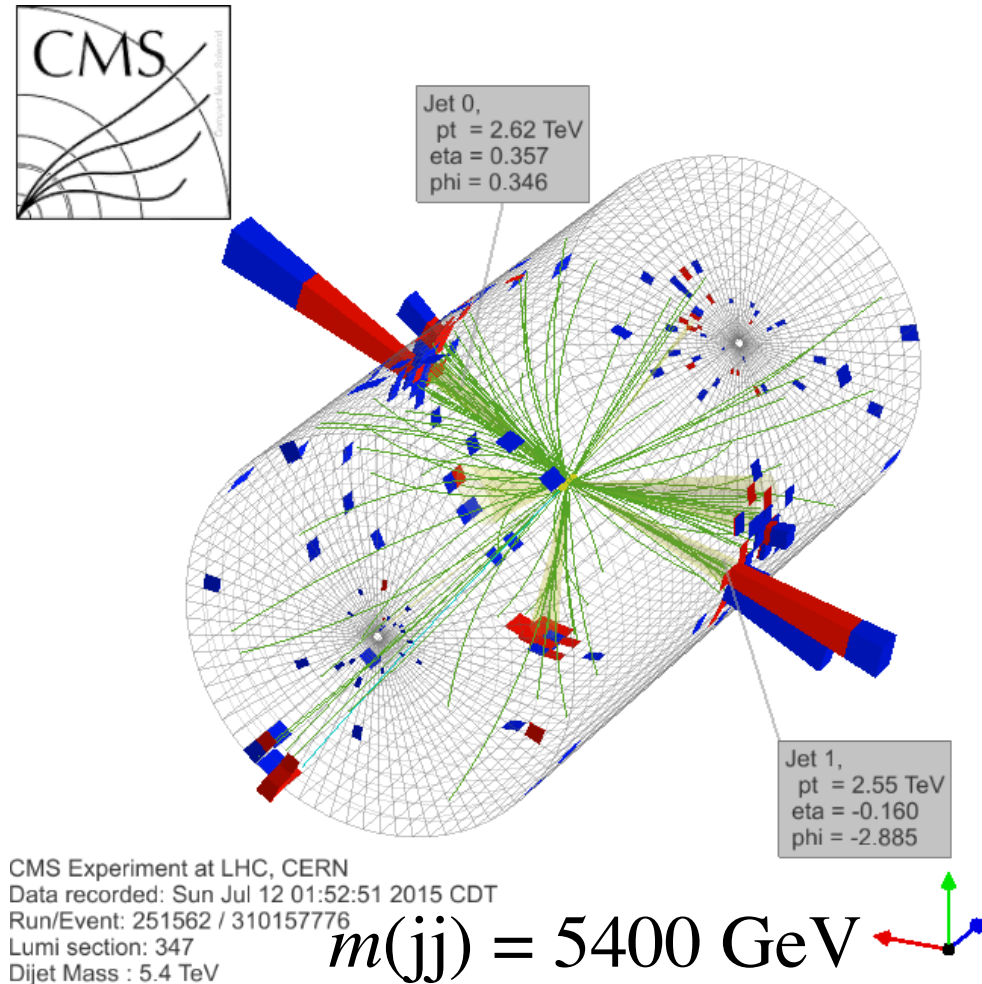
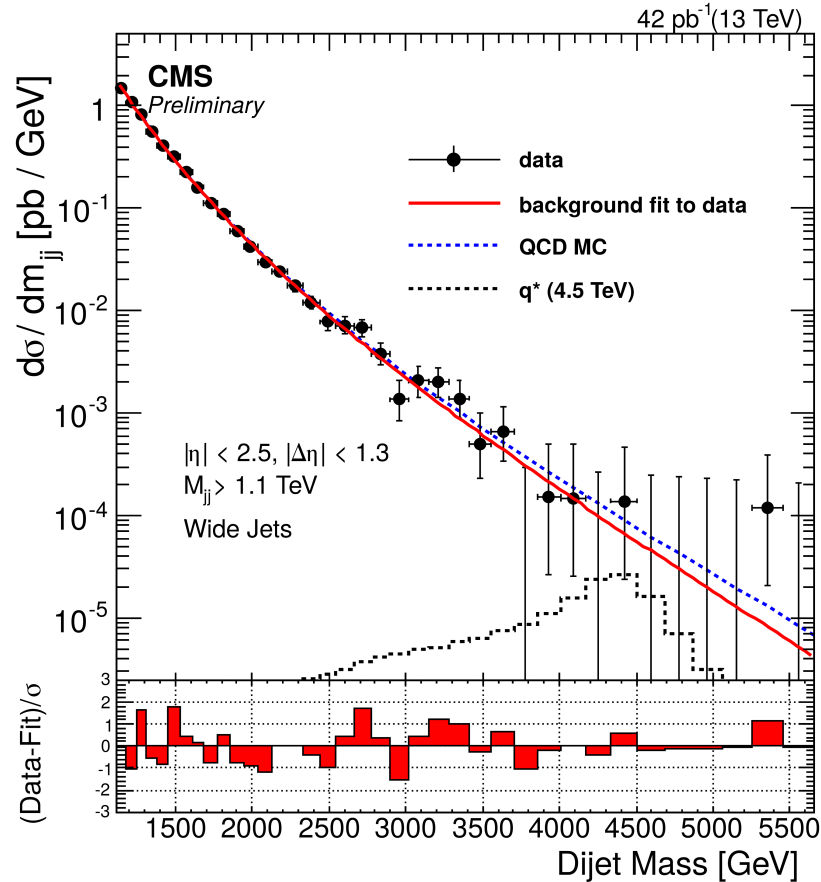
CMS dijet search

- The dijet searches benefit from the new mass reach



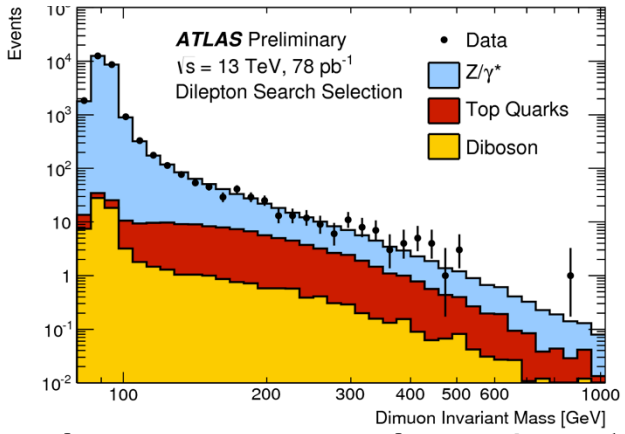
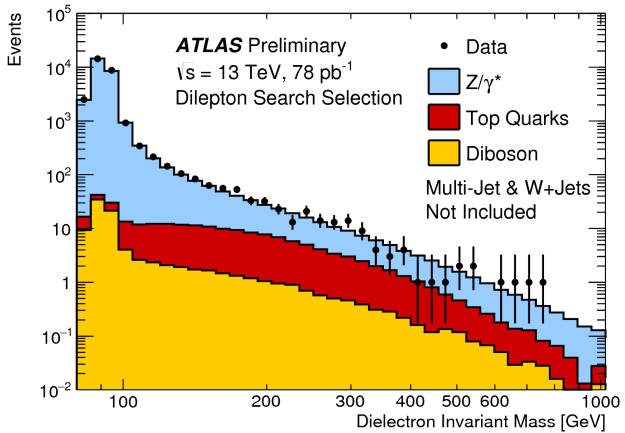
CMS dijet search

- Also no bump seen here



ATLAS dilepton search

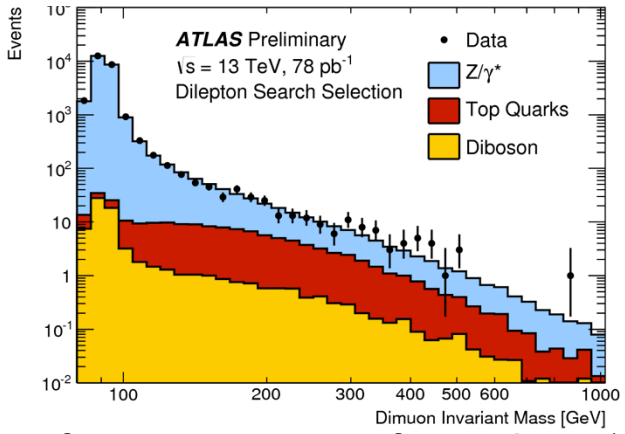
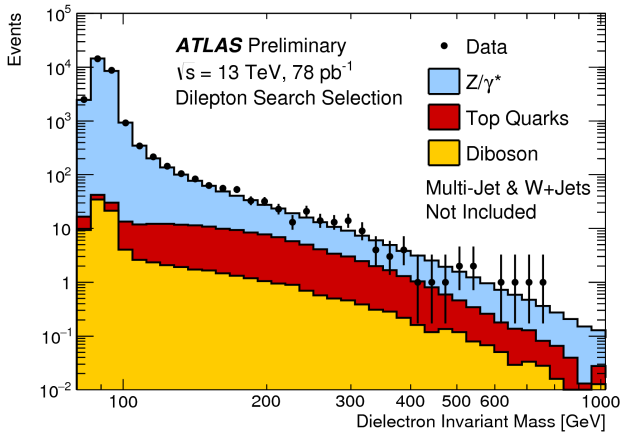
- Latest ATLAS results for the dilepton searches:



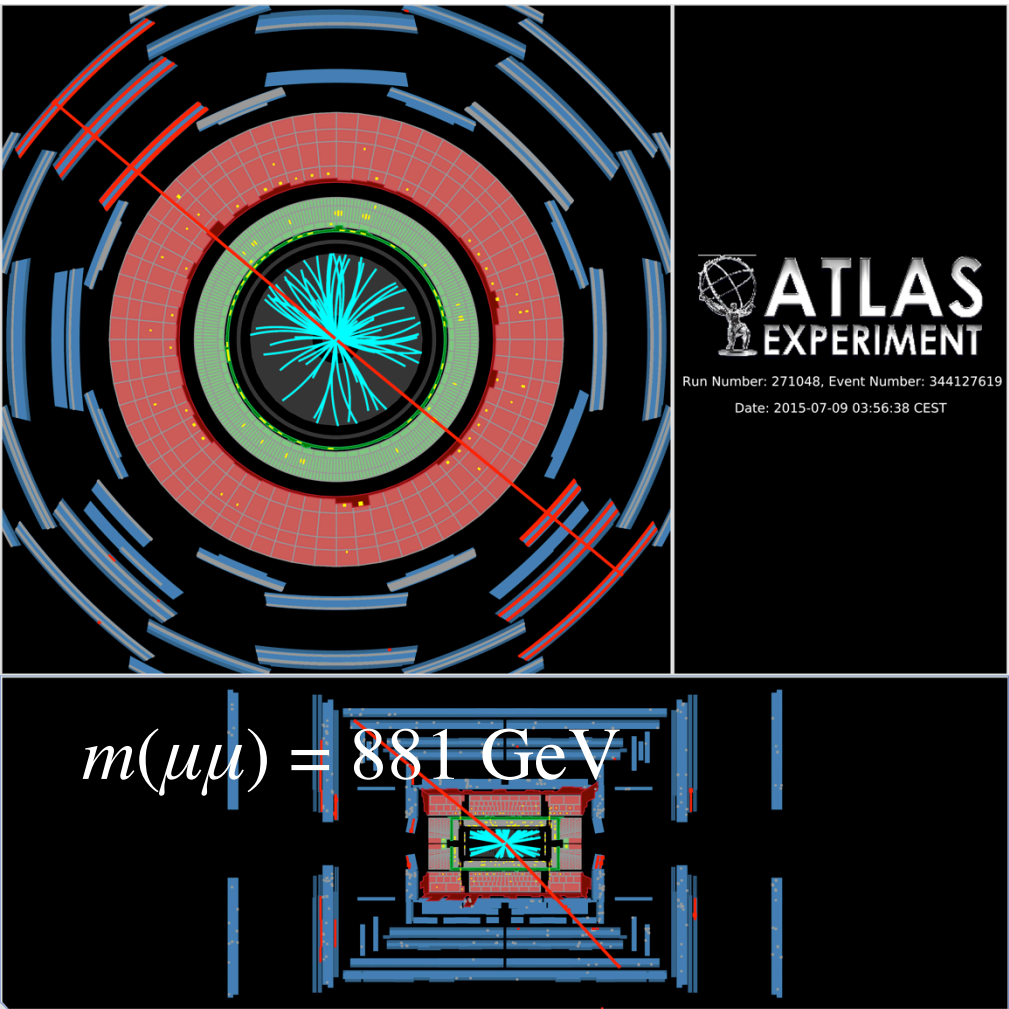
- No bump with 78 pb⁻¹

ATLAS dilepton search

- Latest ATLAS results for the dilepton searches:

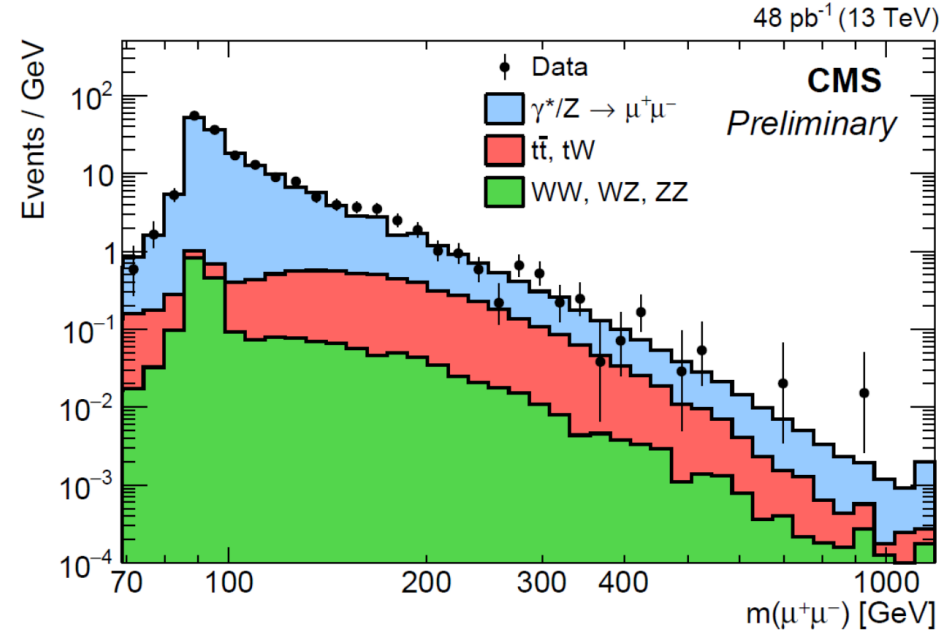
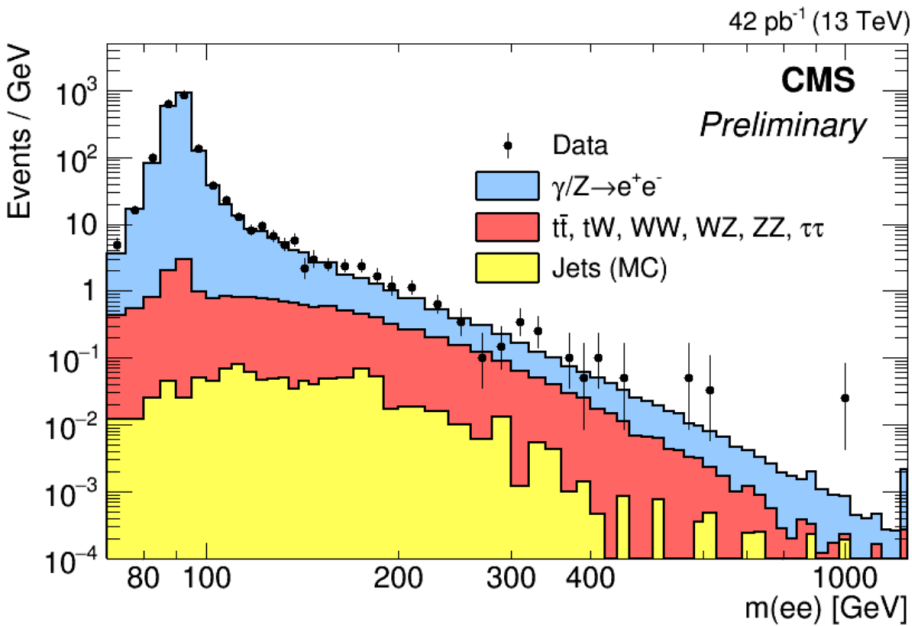


- No bump with 78 pb^{-1}



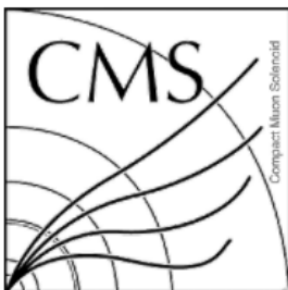
CMS dilepton search

- Latest CMS results for the dilepton searches:

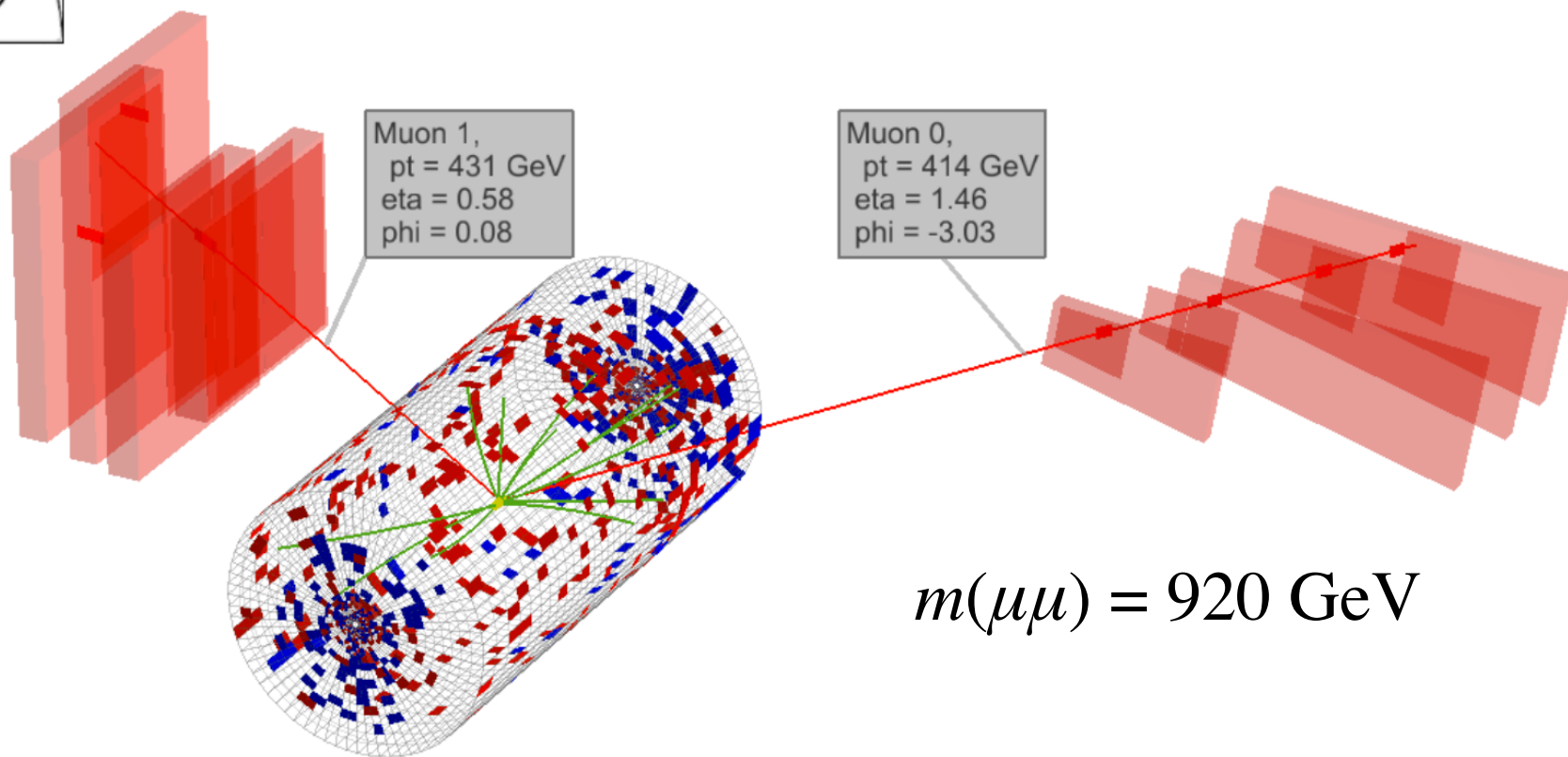


- No bump with 42-48 pb⁻¹

- Highest mass dimuon event



CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 10:18:52 2015 FET
Run/Event: 251562 / 367325039
Lumi section: 414



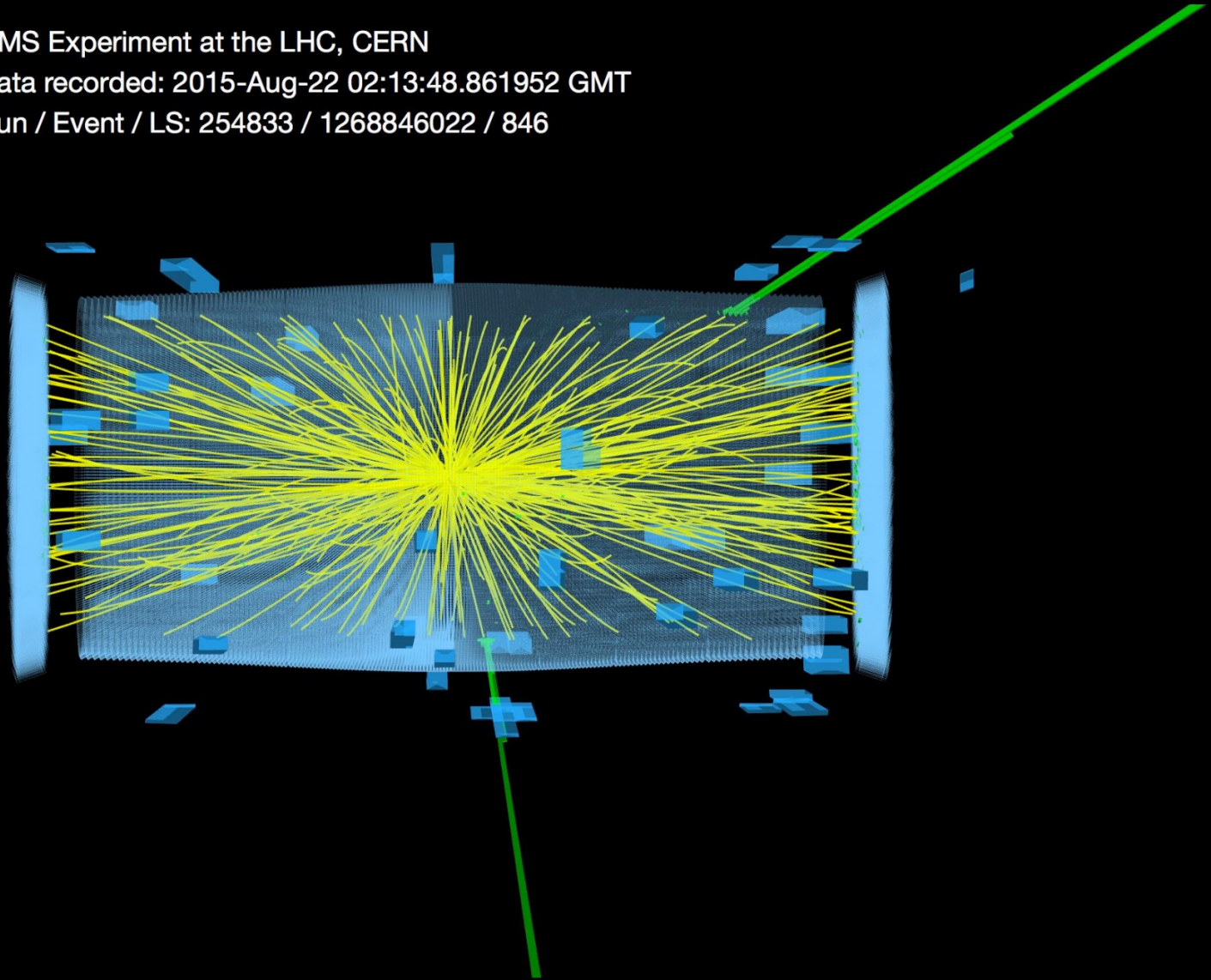
CMS dilepton search



CMS Experiment at the LHC, CERN

Data recorded: 2015-Aug-22 02:13:48.861952 GMT

Run / Event / LS: 254833 / 1268846022 / 846



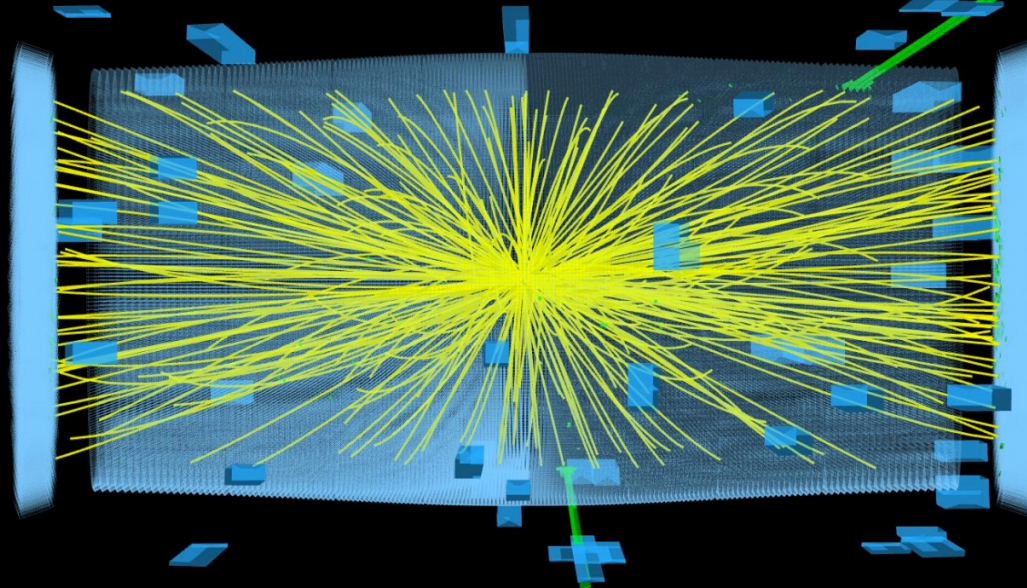
CMS dilepton search



CMS Experiment at the LHC, CERN

Data recorded: 2015-Aug-22 02:13:48.861952 GMT

Run / Event / LS: 254833 / 1268846022 / 846



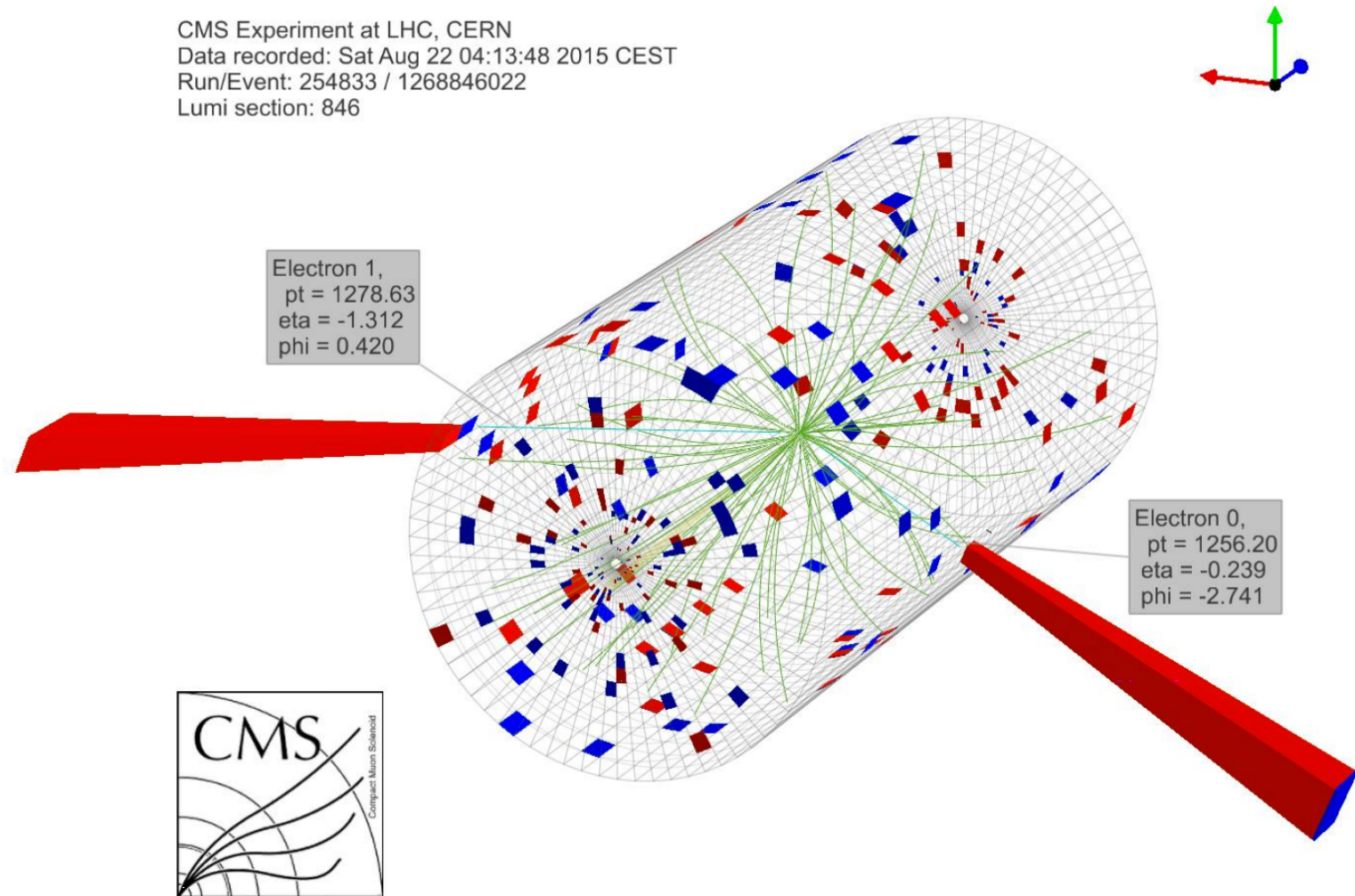
$$m(ee) = 2970 \text{ GeV}$$

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

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

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 $E(\text{HCAL})/E(\text{ECAL})$.
 - 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

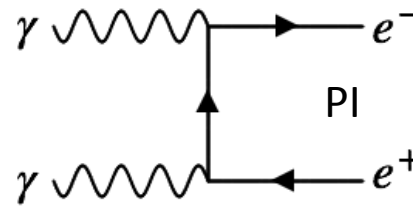
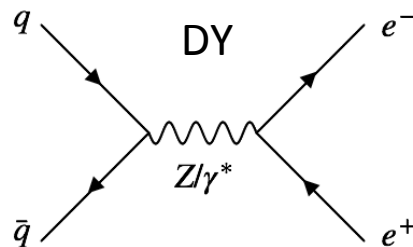
- ID is very simple:
- $E_T > 35$ GeV (“low” enough to get a good Z peak)
- $|\eta| < 2.5$, excluding transition the regions.
- Various shower shape and track matching variables.
- $E(\text{HCAL})/E(\text{ECAL}) < 0.05$ + energy dependent term
- Calorimeter isolation is relative with a constant term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

ULB 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.

ULB Dielectron challenges at 13 TeV

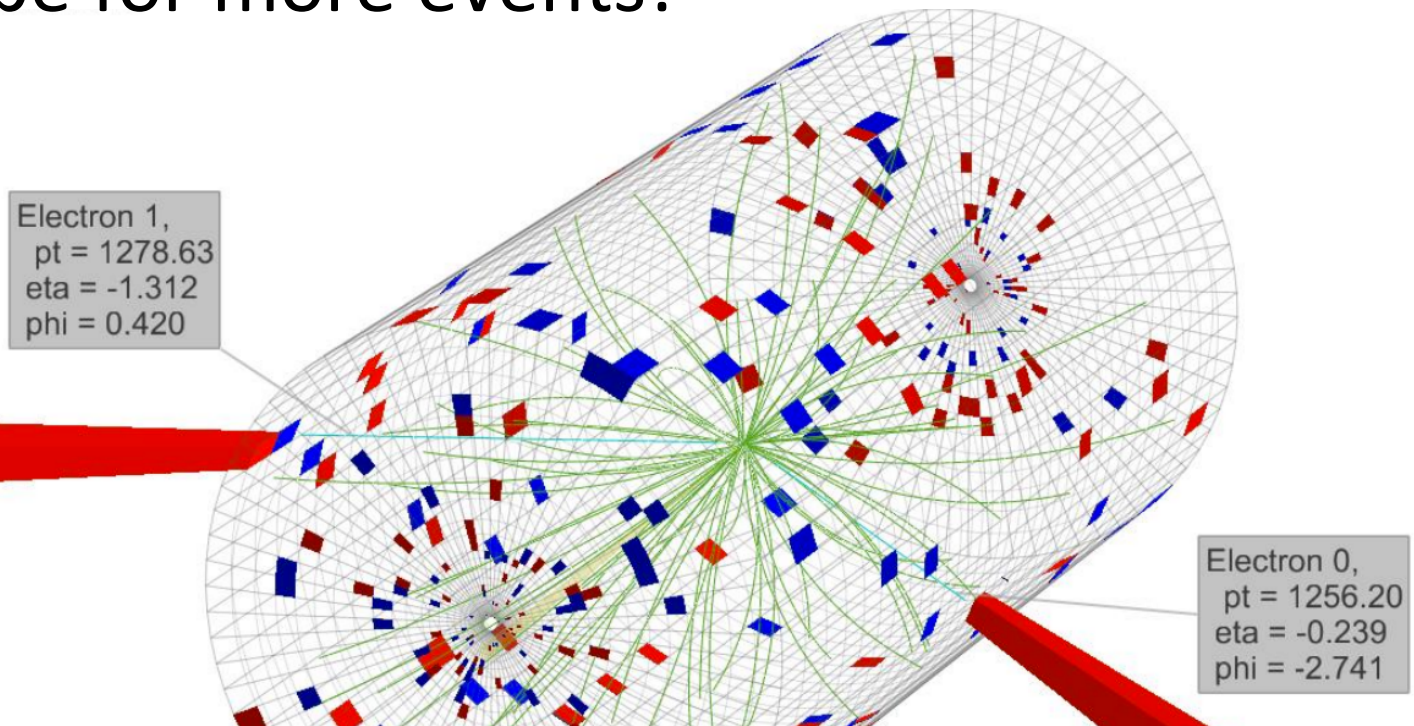
- Working at 13 TeV brings new problems...
 - A new SM process comes into play.
 - Protons can exchange photons to give us photon induced (PI) backgrounds:



- 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 TeV events rain down in 2016.
- Or we may just be extremely (un)lucky.
- Let’s hope for more events!



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!

Run: 204153
Event: 35369265
2012-05-30 20:31:28 CEST

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

Run: 201253
Event: 35369265
2012-05-30 20:31:28 CEST

A 3D visualization of particle tracks and detector components. The image shows a complex network of orange and yellow lines representing particle paths, originating from a central point and spreading outwards. The tracks are overlaid on a blue cylindrical structure, likely representing a detector component. A red line is also visible, extending from the center towards the right. The background is dark, with various colored elements (blue, green, yellow) representing different parts of the detector or simulation.

PDFs and background uncertainties

Ditau resonances

Lepton flavour violating decays

Further multi-jet resonances

Run: 204153
Event: 35369265
2012-05-30 20:31:28 CEST

ULB 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):

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%

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%

2 TeV

3 TeV

- Results from ATLAS and CMS
- ATLAS considers $\tau_{had}^- \tau_{had}^-$ and $\tau_{had}^- \tau_{lep}$ final states (τ_{had} is a τ jet)
- CMS consider $\tau_e^- \tau_\mu^-$ final states
- Kinematic selections:

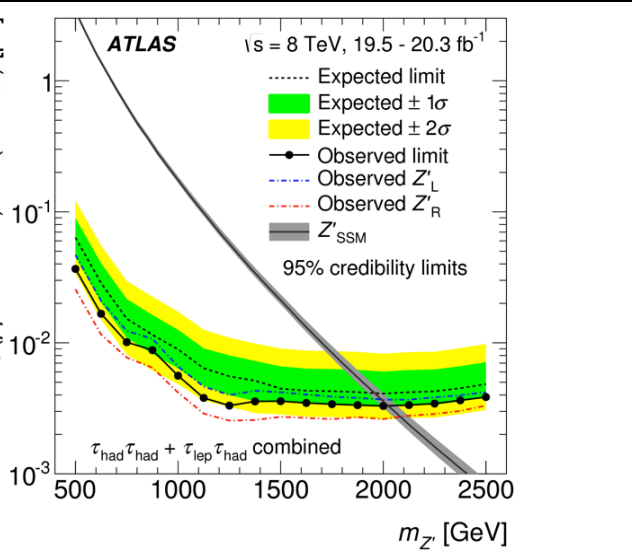
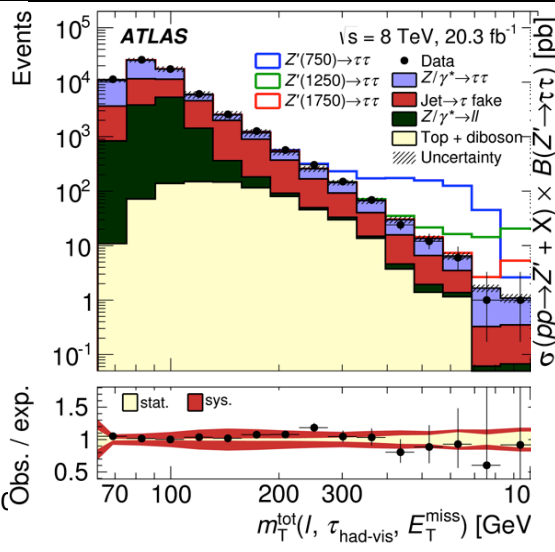
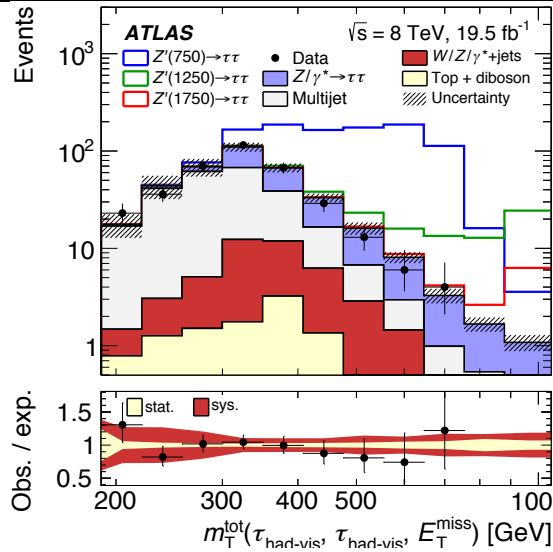
PRD 90, 052005

CMS-PAS-EXO-12-046

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

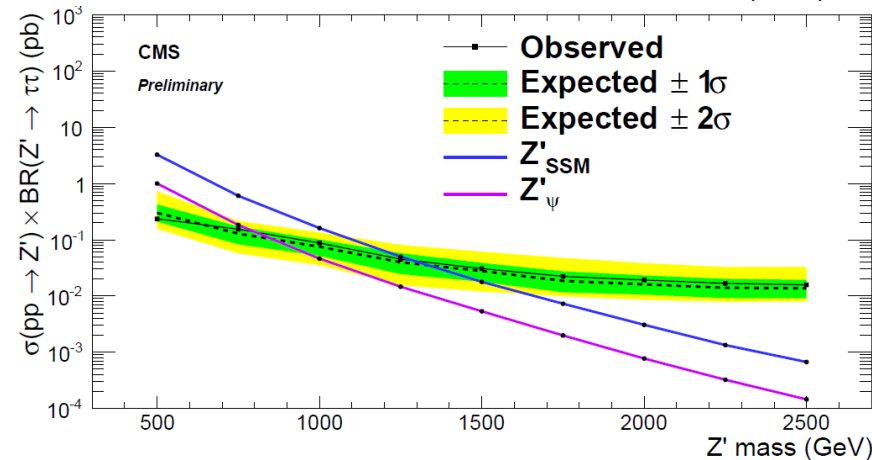
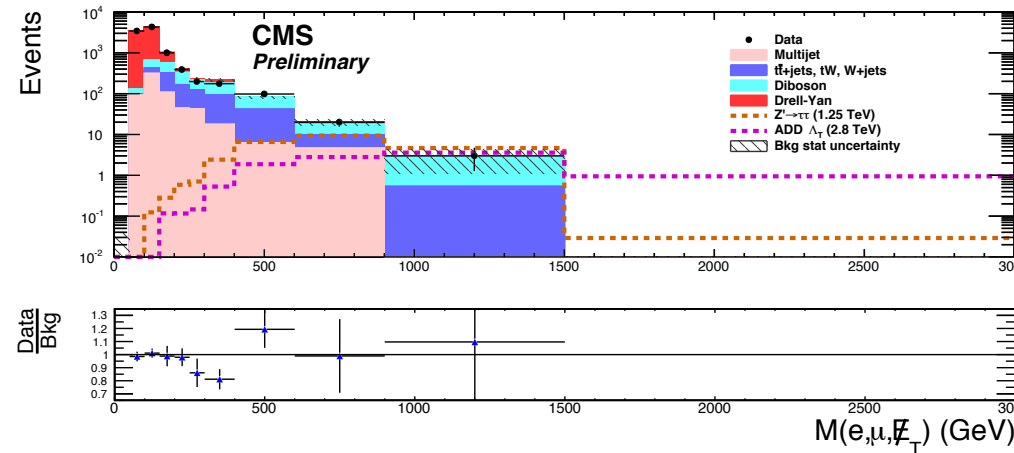
- Dominant systematic uncertainties: PDFs for background modeling, Signal efficiency for ATLAS, data driven background estimates for CMS.

Ditau resonances



19.7 fb⁻¹ (8 TeV)

19.7 fb⁻¹ (8 TeV)



• Exclusion limits:

ATLAS: $m(Z'_{\text{SSM}}) > 2.02 \text{ TeV}$

CMS: $m(Z'_{\text{SSM}}) > 1.30 \text{ TeV}$

ULB Lepton flavour violating resonances

- Results from ATLAS and CMS
- ATLAS considers $e\text{-}\mu$, $e\text{-}\tau$, and $\mu\text{-}\tau$ final states
- CMS consider $e\text{-}\mu$ final states
- Kinematic selections:

arXiv:1503.054420

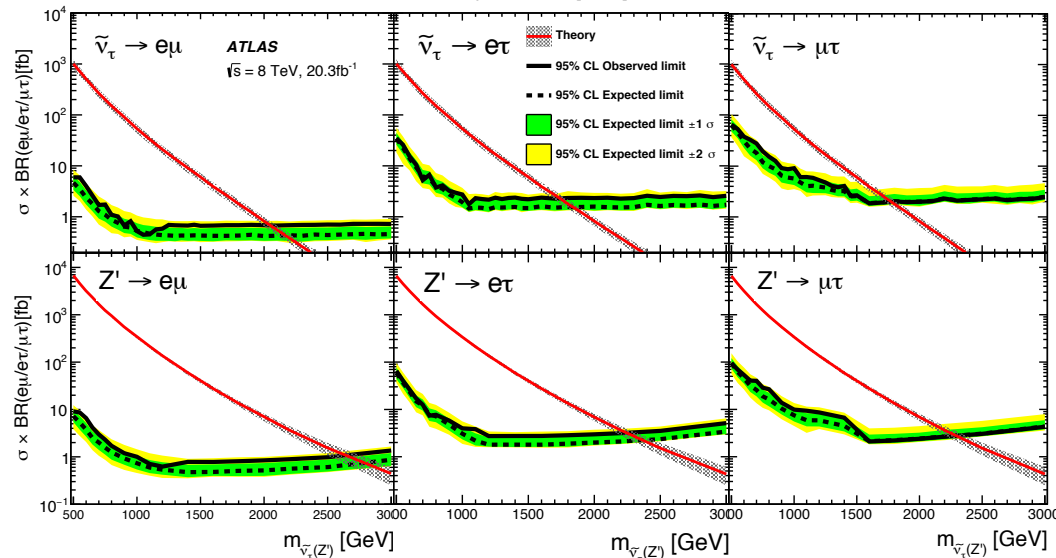
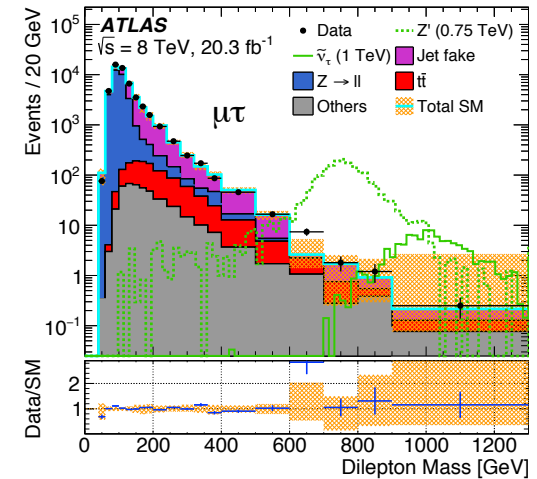
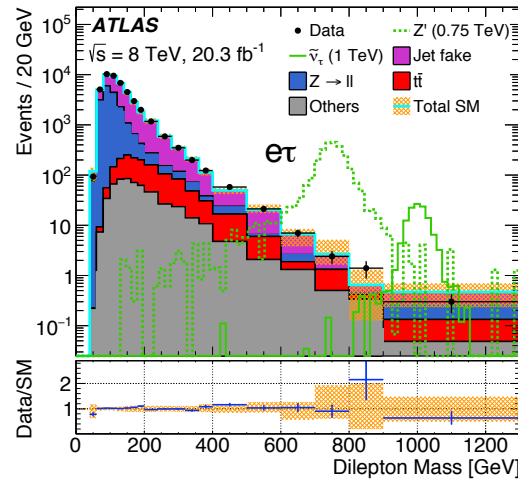
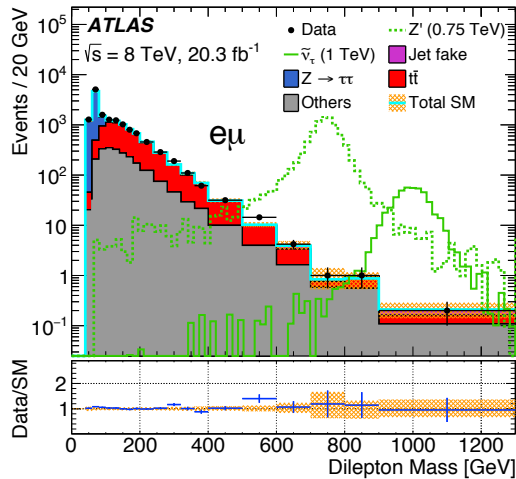
arXiv:1504.055115

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

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

ULB Lepton flavour violating resonances

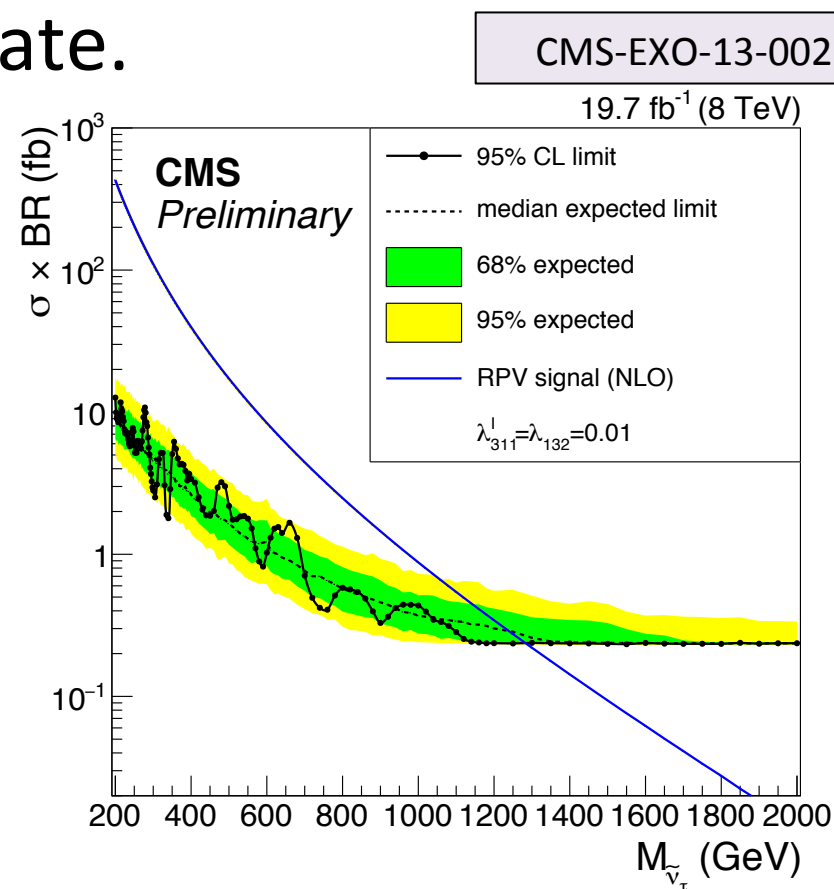
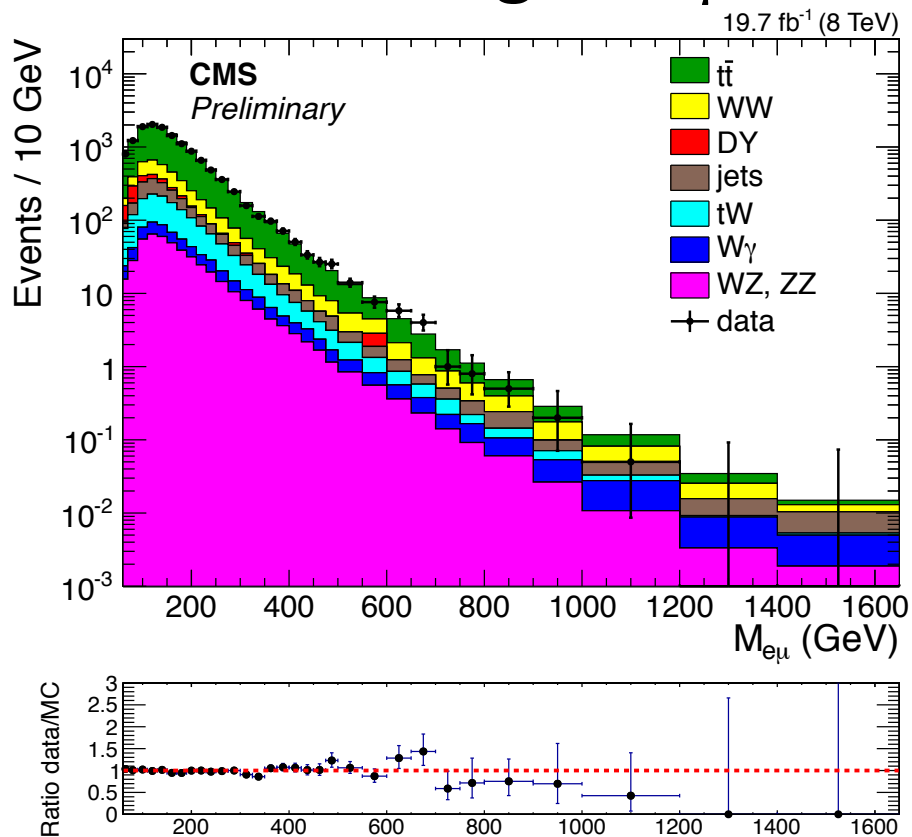
- ATLAS investigates $e\mu$, $e\tau$, $\mu\tau$ final states.



- Limits: \sim
 - $e\mu$: $m(\nu_\tau) > 2.0$ TeV
 - $e\tau$: $m(\nu_\tau) > 1.7$ TeV
 - $\mu\tau$: $m(\nu_\tau) > 1.7$ TeV

ULB Lepton flavour violating resonances

- CMS investigate $e\mu$ final state.

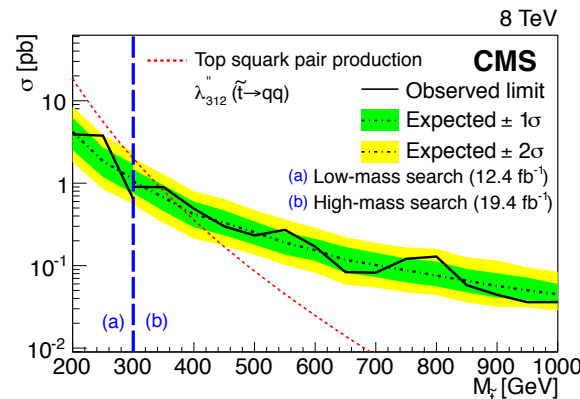
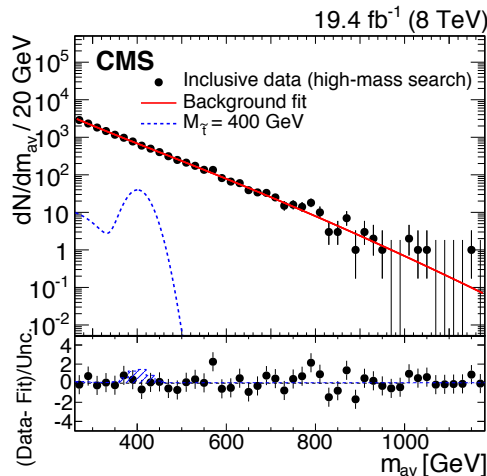


Limit: $m(\tilde{\nu}_\tau) > 2.1$ TeV

ULB Further multi-jet resonances

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

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

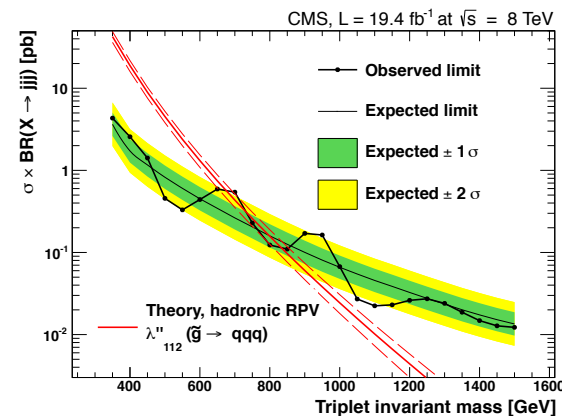
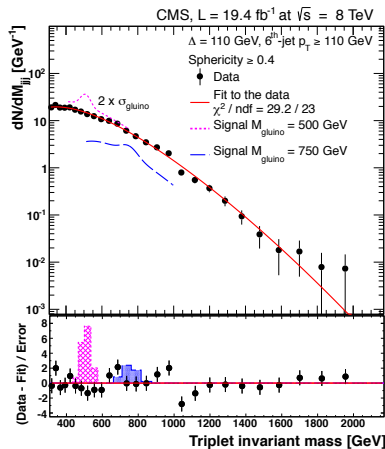


Phys. Lett. B 730 (2014) 193

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

