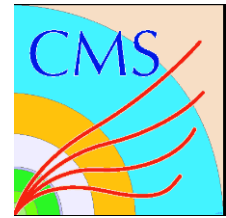


LHCP 2013



Searches for resonances at LHC and Tevatron

Laurent VACAVANT
on behalf of the ATLAS, CDF, CMS and D0 collaborations



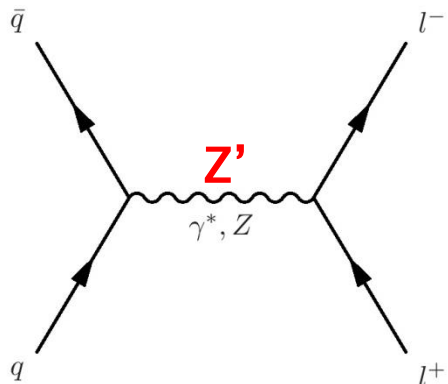
Introduction

- **Motivations for BSM physics** introduced in previous talk (A. Weiler)
- **New massive resonances** are predicted by many BSM scenarios, in particular since many have extended gauge sectors:
 - Sequential SM Z' and W' (motivated e.g. by Little Higgs models)
 - Z' from GUT-inspired theories (E6, SO(10), ...)
 - Extra dimensions: Randall–Sundrum KK gravitons, KK gauge bosons
 - Technicolor, ...
- **Experimental strategy:**
 - generic signatures \rightarrow interpreting results in terms of models
 - looking for the highest energy: most results today from LHC @ 8 TeV
 - challenges: understand objects (trigger, efficiency, resolution) @ very high p_T and tails of SM backgrounds
- **Focus of this talk:** heavy (\sim TeV) resonances, with ll / jj / VV final states
 - non-resonant searches: **next talk** by T. Bose
 - long-lived particles: this afternoon, by S. Haug
 - $t\bar{t}$ -related final states: talk tomorrow, by J. Pilot
 - BSM Higgs: Monday, by M. Flechl
 - parallel talks: this afternoon and Friday afternoon
 - posters: J. Coggeshall (room A), M. Davies (room A), M. Vincter (room C)
 - apologies for the analyses not covered here

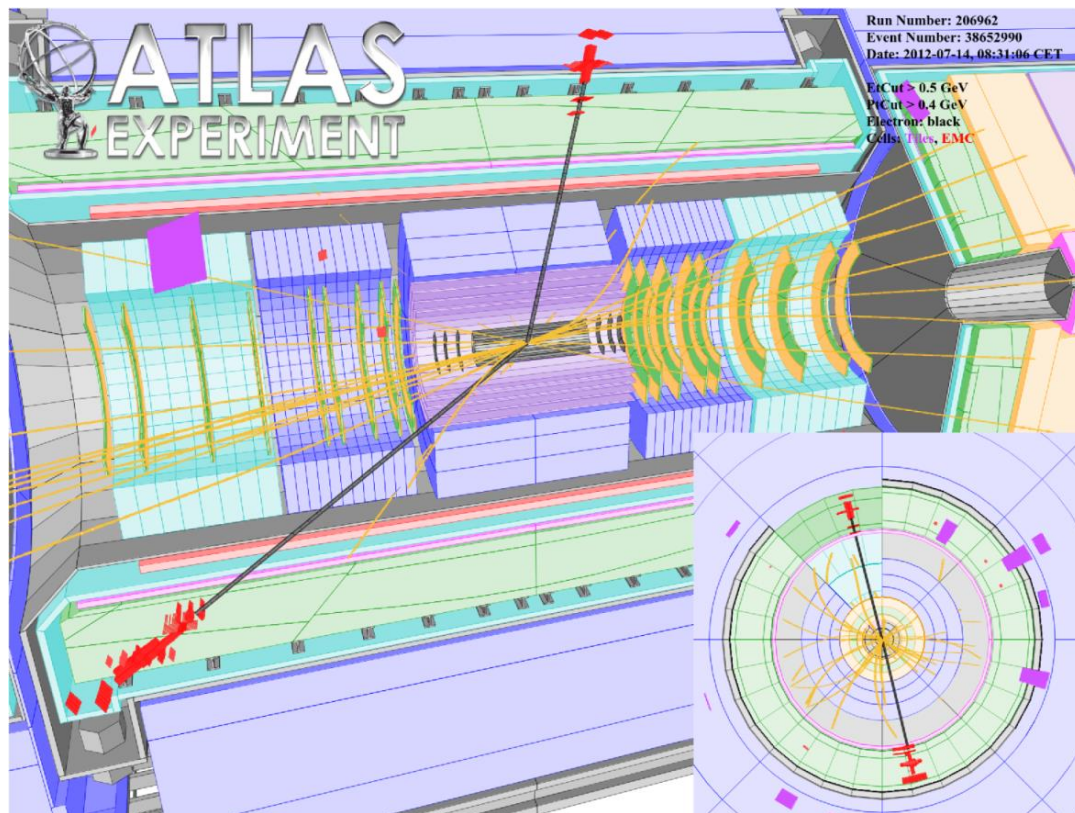
Search for heavy resonances: Dileptons

Models: SSM Z' , RS graviton, GU E6, minimum walking technicolor,...

Search: looking for 'bumps' on top of (tails of) SM Drell-Yan background in $m(\ell\ell)$ distribution



- clean signature: 2 high- p_T leptons (of opposite charge)
- triggering on one of them



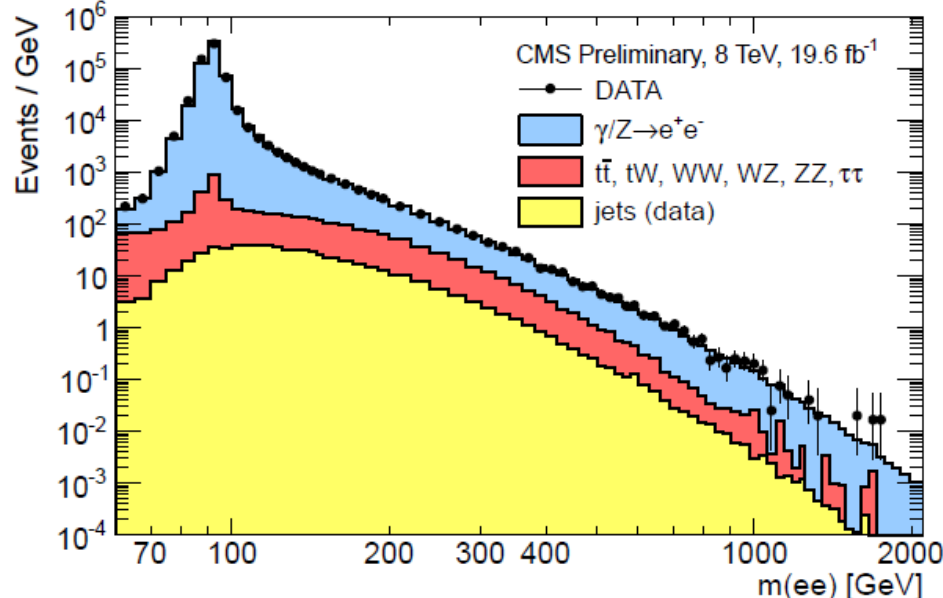
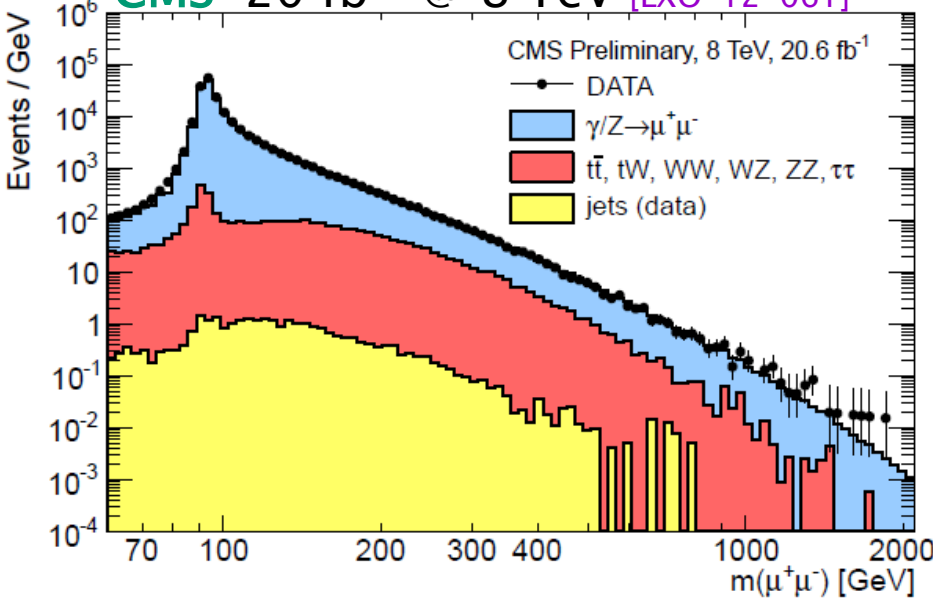
$\mu\mu$ vs ee :

- low μ fake level vs jet background for e
- easier charge ID for μ
- $\gtrsim 2\times$ better energy/mass resolution for e

Highest dielectron invariant mass event in ATLAS: $m(ee)=1.54$ TeV
 $E_T(e_1)=588$ GeV, $E_T(e_2)=584$ GeV

Search for heavy resonances: Dileptons

CMS 20 fb⁻¹ @ 8 TeV [EXO-12-061]



$\mu\mu$ analysis in a nutshell:

- single- μ triggers
 - CMS: $p_T > 40$ GeV, $|\eta| < 2.1$
 - ATLAS: $p_T > 24 + \text{iso} || 36$ GeV, $|\eta| < 2.7$
- combined μ (tracker+MS), quality cuts, muon track isolation
 - CMS: $p_T > 45$ GeV
 - ATLAS: $p_T > 25$ GeV, $|\eta| < 2.4$
- 2 muons of opposite charge

ee analysis in a nutshell:

- trigger on 2 objects:
 - CMS: di-e trigger ($E_T > 35$ GeV)
 - ATLAS: di- γ trigger ($E_T > 35, 25$ GeV)
- 2 offline electrons: q. cuts, track (CMS) or calo (ATLAS) isolation
 - CMS: $E_T > 45$ GeV, $|\eta| < 2.5$
 - ATLAS: $E_T > 45(30)$ GeV, $|\eta| < 2.47$
- no charge requirement

Search for heavy resonances: Dileptons

Physics background estimation:

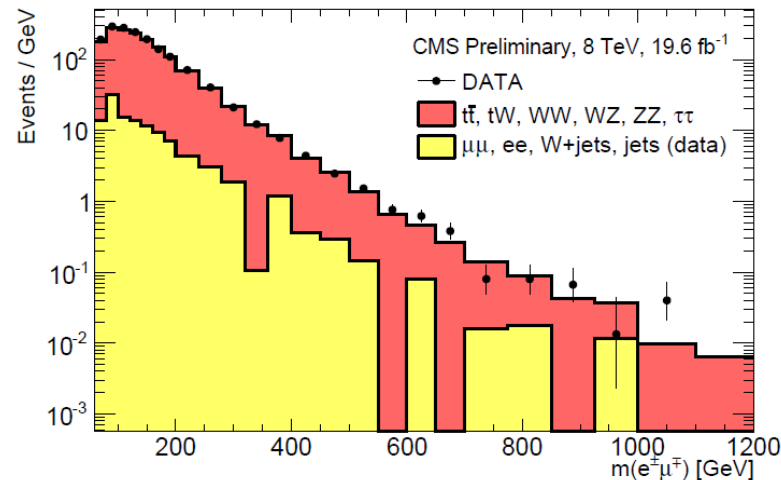
- irreducible Z/γ^* Drell–Yan: Monte–Carlo
- $t\bar{t}$, tW , diboson: Monte–Carlo, cross–checked with opposite flavor analysis in CMS
- normalized to NNLO cross–sections
- overall normalization with data in Z peak region

Instrumental background: jets faking leptons

- data–driven estimation
- for ee : fake rates from loose selection extrapolated to high E_T , normalized in data CR
- for $\mu\mu$: reversed isolation

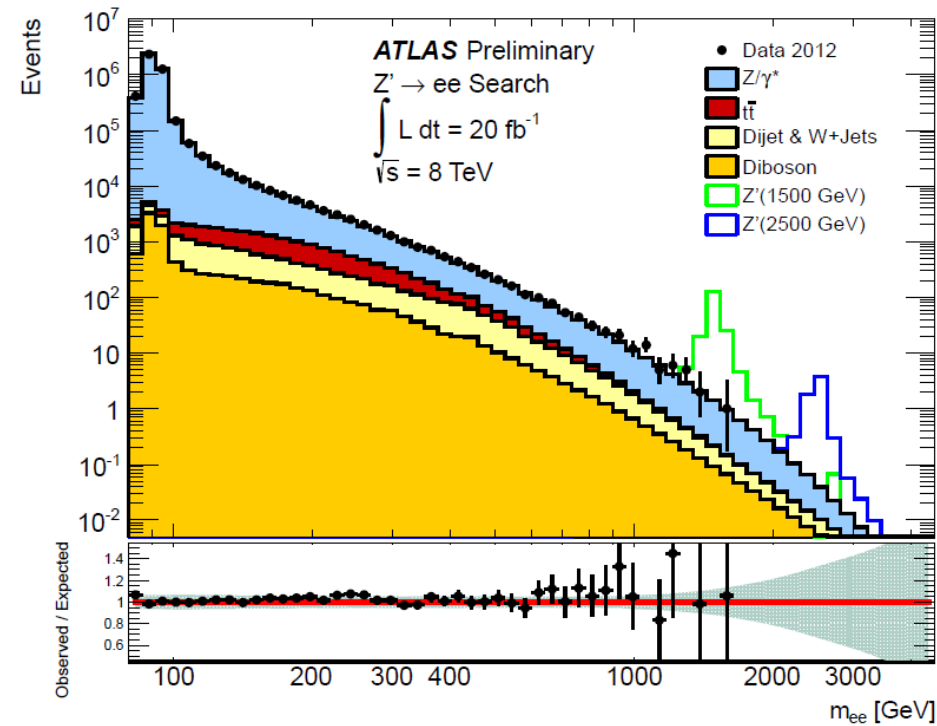
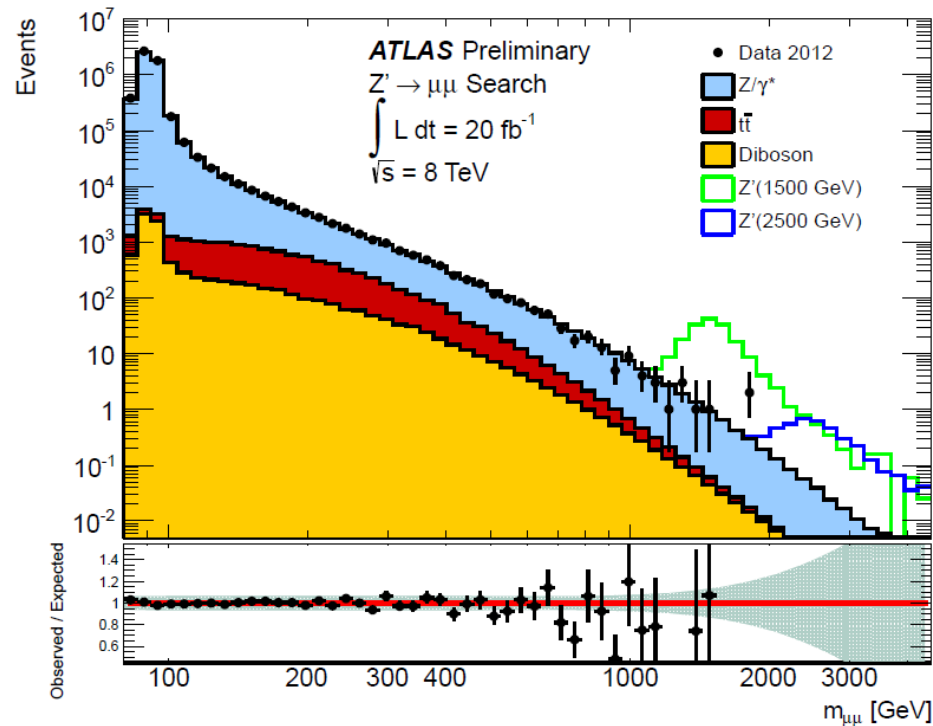
Statistical analysis:

- Different techniques for ATLAS & CMS, in both cases: cancel integrated luminosity uncertainty and reduce uncertainties on acceptance, trigger and lepton effi.
- Differences in signal modeling: narrow resonance à la Z'_ψ for CMS versus full shape of SSM Z' for ATLAS (more conservative)
- Bayesian limit setting procedure
- Main sources of systematics:
 - signal: normalization & lepton efficiency
 - background: PDF choice & variation, jet background (for ee)



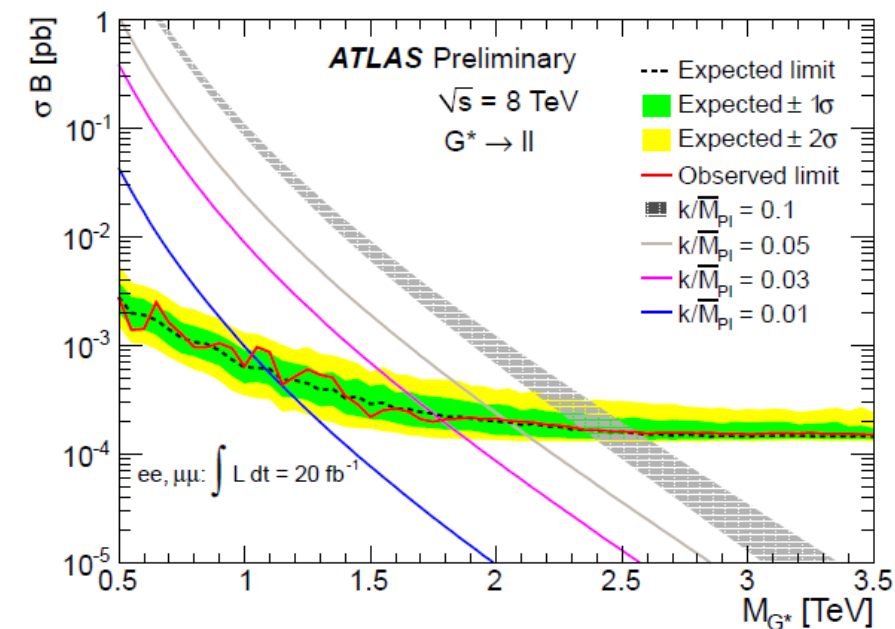
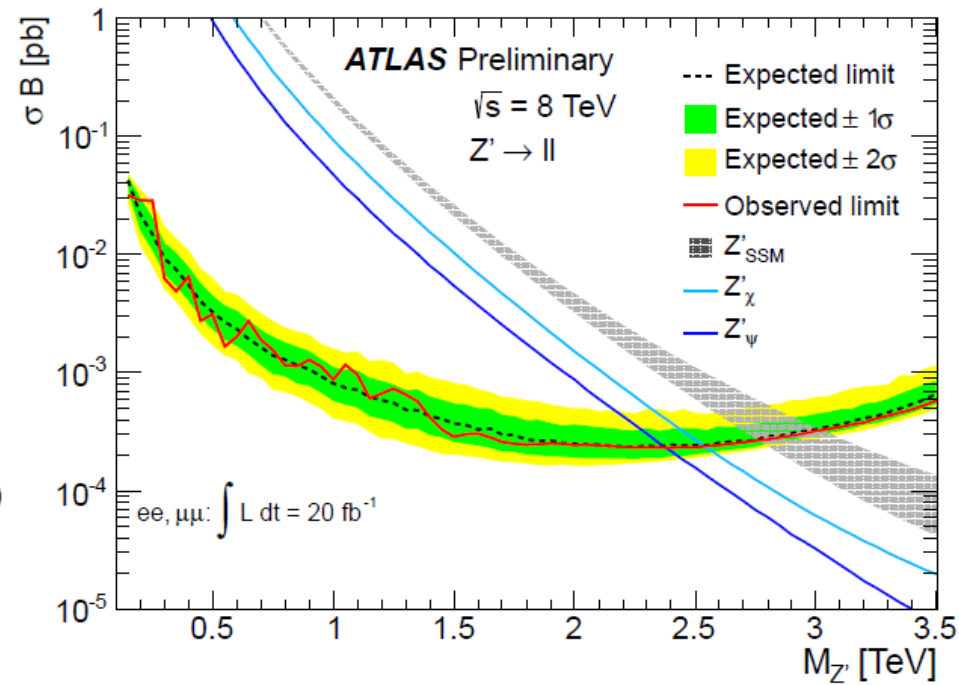
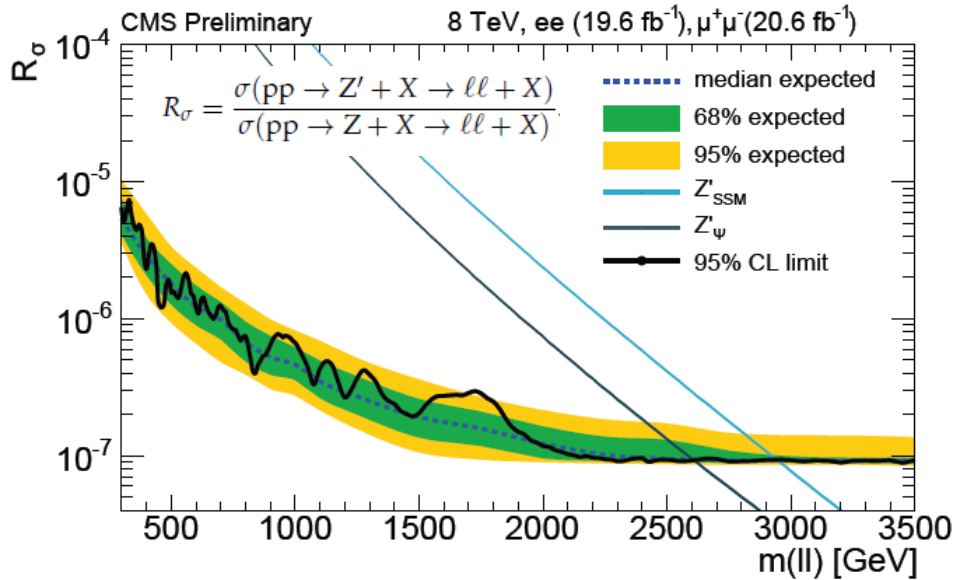
Search for heavy resonances: Dileptons

ATLAS 20 fb^{-1} @ 8 TeV [CONF-2013-017]



- similar results obtained by ATLAS with same amount of data
 - illustration of Z' signals (and impact of resolution on high- p_T e/μ)
- no evidence for a signal with ATLAS either

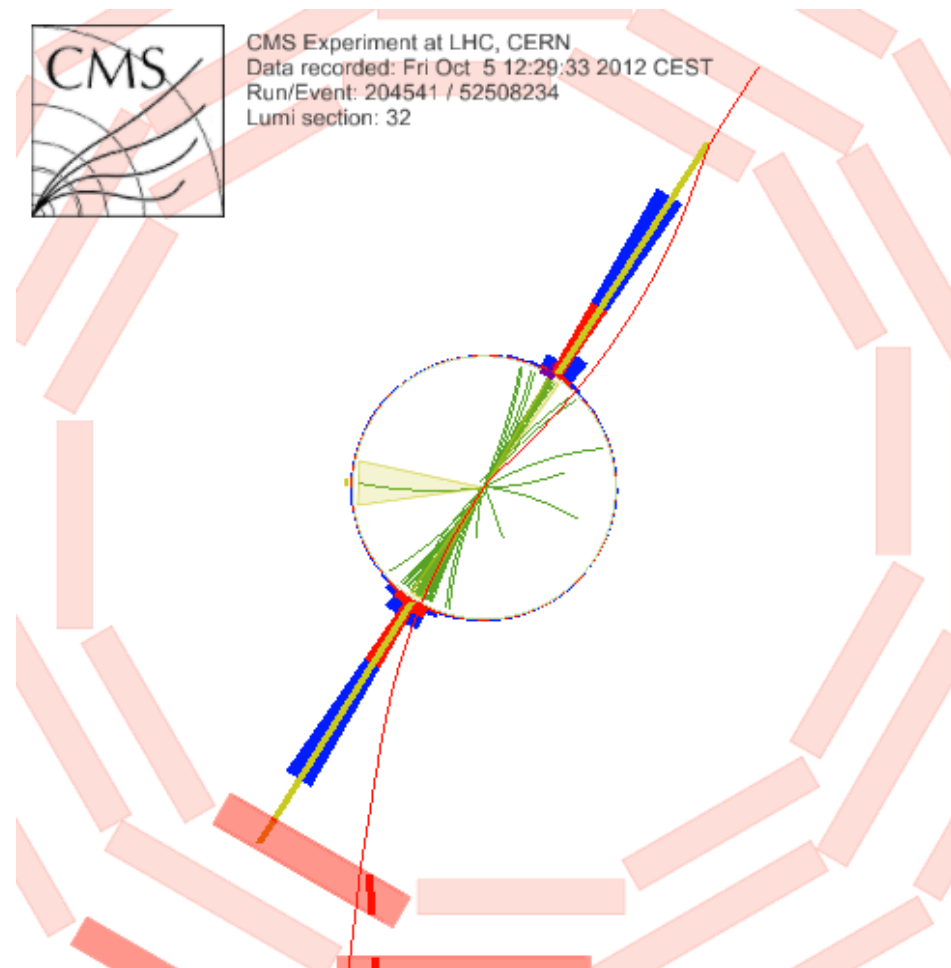
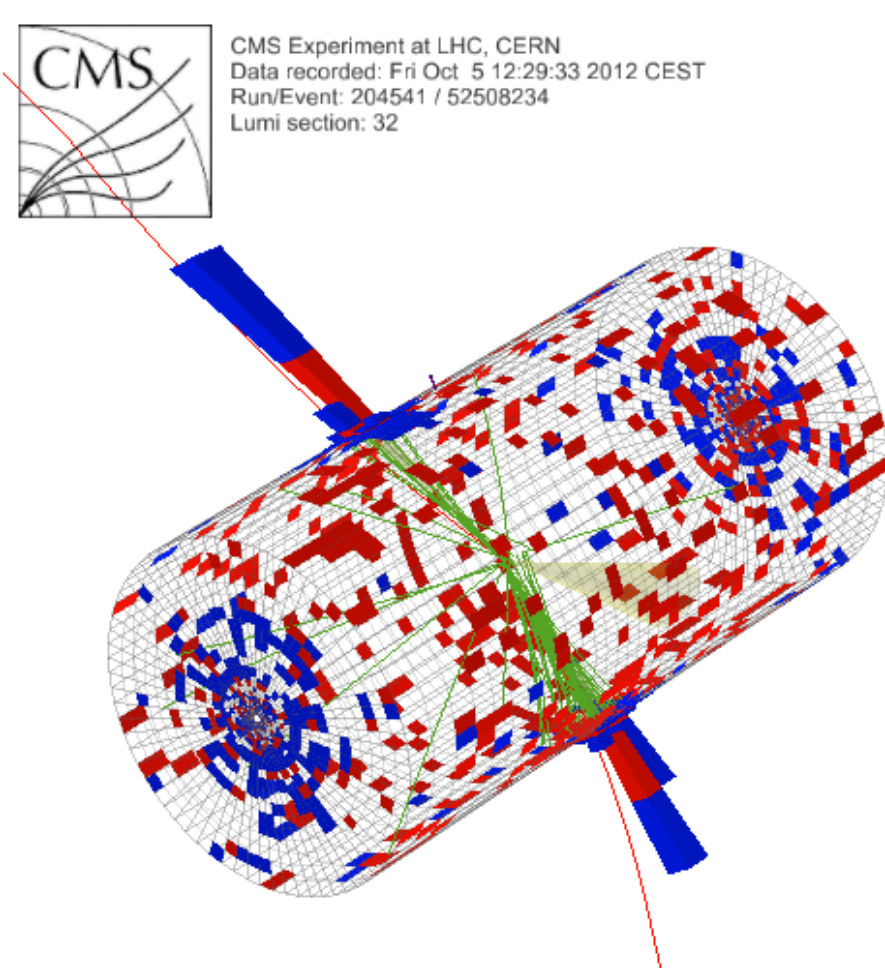
Search for heavy resonances: Dileptons



Observed lower limits (TeV) at 95% CL:

Model	ATLAS	CMS
SSM Z'	2.86	2.96
E6 Z' _ψ	2.38	2.60
RS G* (spin 2) k/M _{PI} =0.1	2.47	

Search for heavy resonances: Dijets



Highest mass dijet event with central jets: $m(jj) = 5.15$ TeV

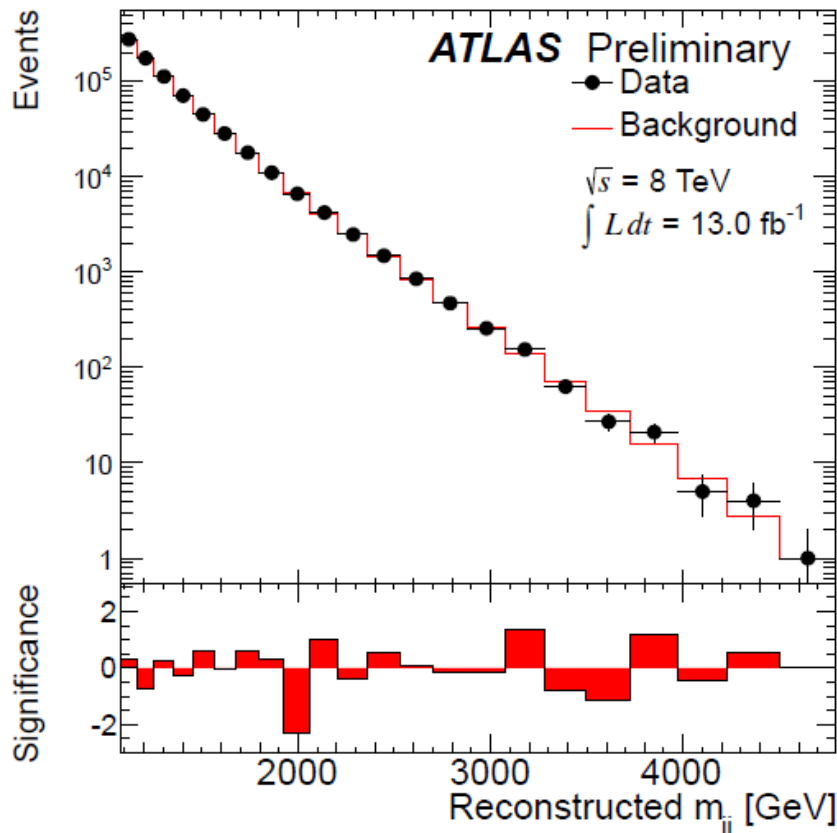
Search for heavy resonances: Dijets

Models: excited quarks q^* , SSM W'/Z' , RS graviton, E6, string, axigluon,...

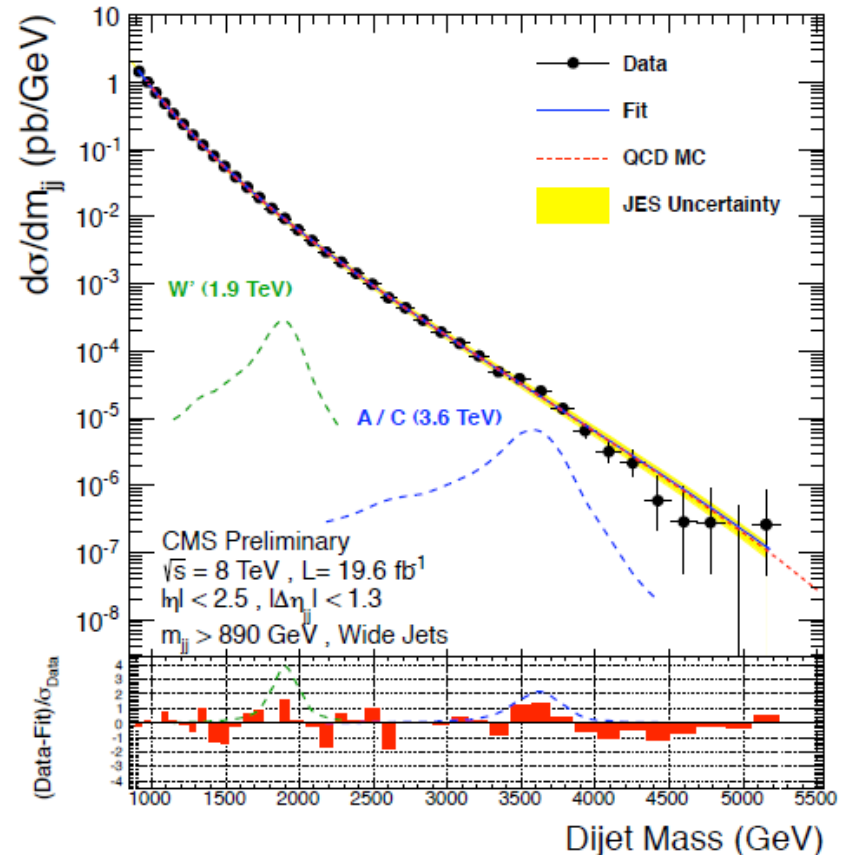
Search: looking for 'bumps' on top of the large QCD background in $m(jj)$

Higher BR than for dileptons, but: large bkgd, lower resolution, trigger threshold.
Main sources of systematic uncertainties: PDF & JES

ATLAS 13 fb^{-1} @ 8 TeV [CONF-2012-148]



CMS 20 fb^{-1} @ 8 TeV [EXO-12-059]



Search for heavy resonances: Dijets

ATLAS versus CMS analysis in a nutshell:

- central 1-jet triggers $E_T \sim 350$ GeV vs $H_T/m(jj)$ at HLT
- anti- k_T $R=0.6$ jets versus wide jets ($R \sim 1.1$)
- in both cases:
 - rapidity cuts to enhance central scattering
 - selection requires $m(jj) \gtrsim 1$ TeV

Search:

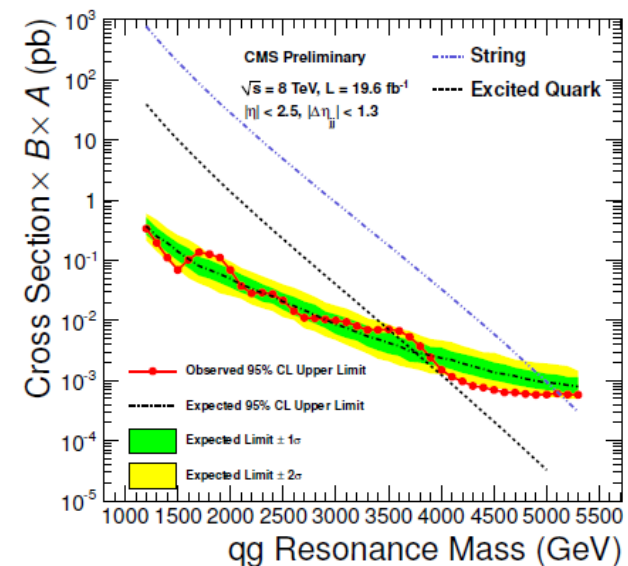
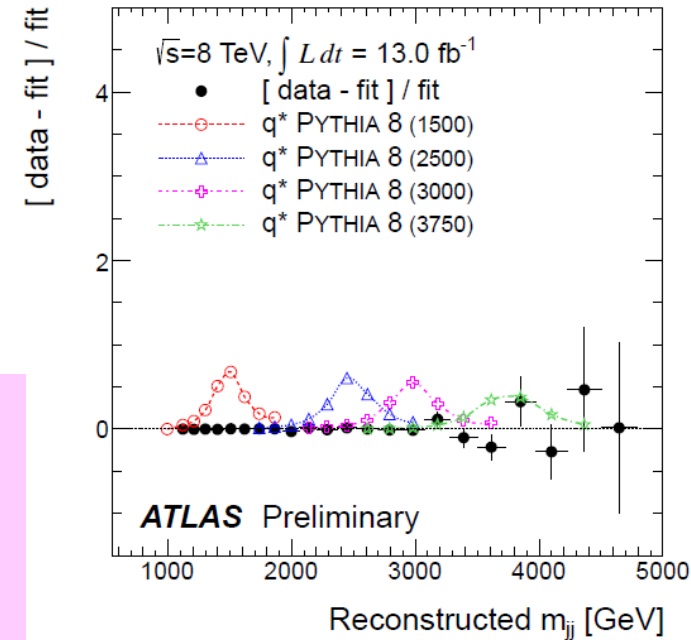
- fit $m(jj)$ data distribution with smooth form:
 - ⊕ no MC QCD uncertainties, reduced sensitivity to JES&lumi,
 - ⊖ uncertainties on fit form, no sensitivity to smooth changes (CI)

$$f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x} \quad x \equiv m_{jj} / \sqrt{s}$$

- binned likelihood fit: χ^2 compatible with bkgd
- ATLAS: BumpHunter for excess of any width
- no signal found

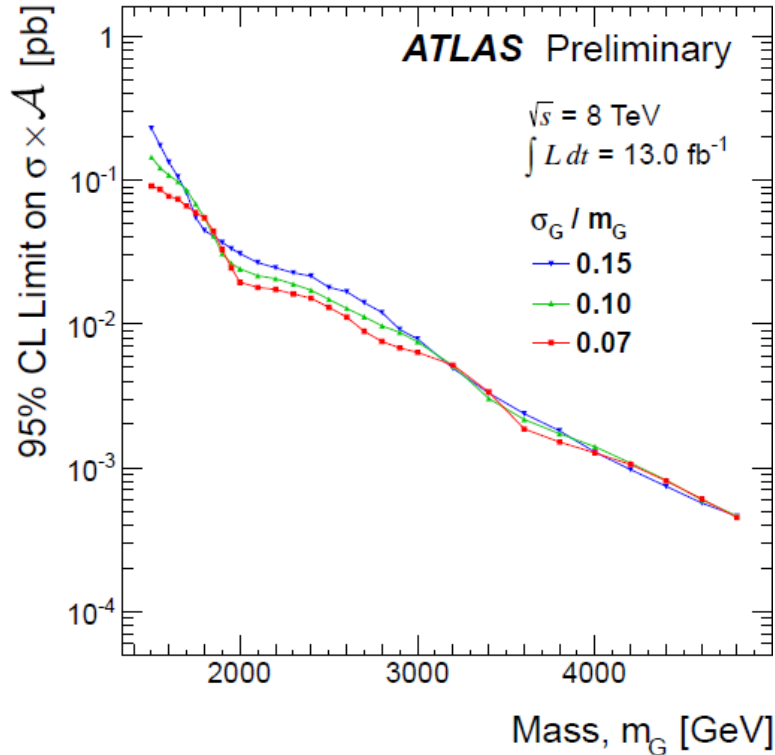
Exclusion:

- bayesian approach
- with Gaussian-like signals
- ATLAS: q^* + model-independent approach
- CMS: many models, separation of q/g final states

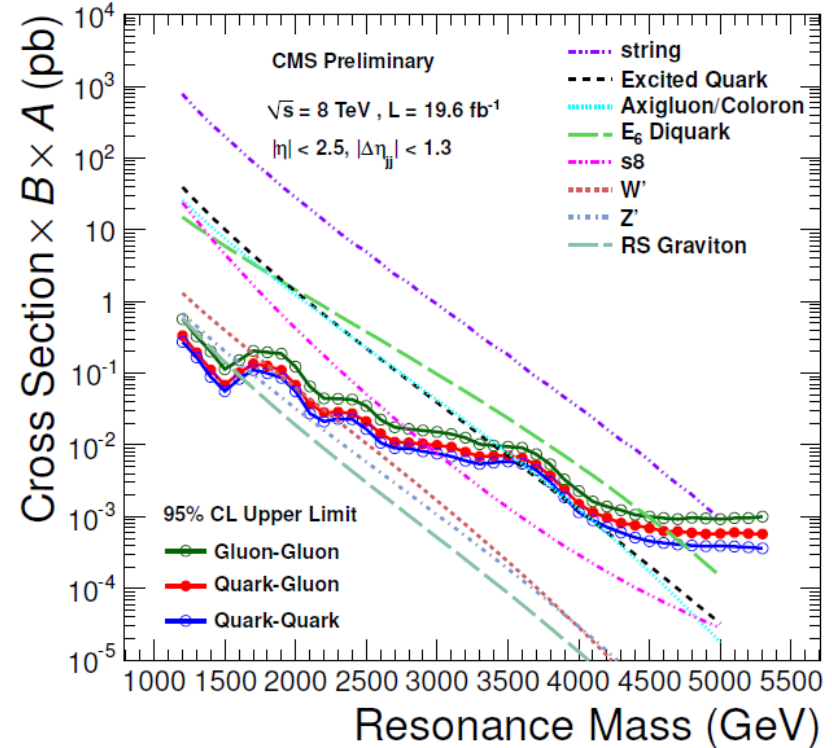


Search for heavy resonances: Dijets

ATLAS 'generic' observed limits:



CMS observed limits:



ATLAS 13 fb⁻¹ @ 8 TeV:

$1 < m(q^*) < 3.84 \text{ TeV}$ (exp 3.70)

$k/M_{\text{Pl}}=0.1$

CMS 20 fb⁻¹ @ 8 TeV

	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]	[1.20,5.00]
Excited Quark (q*)	qg	[1.20,3.50]	[1.20,3.75]
E ₆ Diquark (D)	qq	[1.20,4.75]	[1.20,4.50]
Axigluon (A)/Coloron (C)	q \bar{q}	[1.20,3.60] + [3.90,4.08]	[1.20,3.87]
Color Octet Scalar (s8)	gg	[1.20,2.79]	[1.20,2.74]
W' Boson (W')	q \bar{q}	[1.20,2.29]	[1.20,2.28]
Z' Boson (Z')	q \bar{q}	[1.20,1.68]	[1.20,1.87]
RS Graviton (G)	q \bar{q} +gg	[1.20,1.58]	[1.20,1.43]

Search for heavy resonances: Dijets

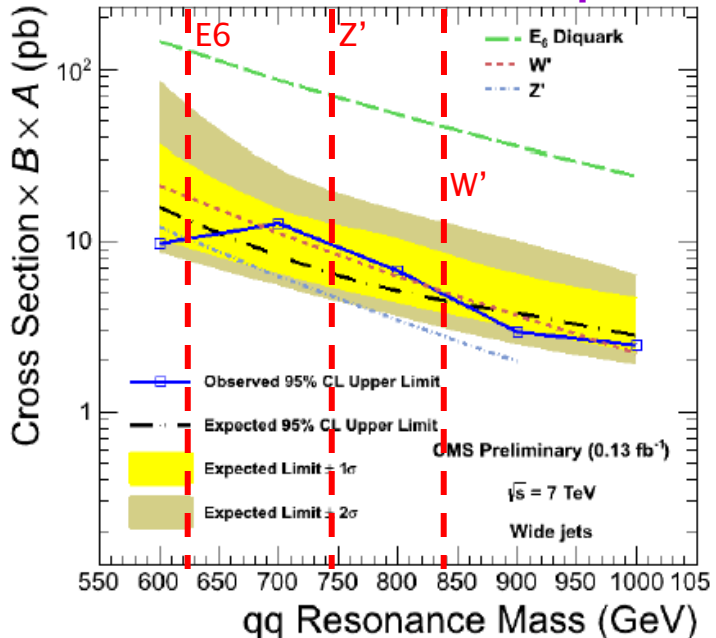
Note:

- high p_T threshold required at LHC for triggers on (single) jets
- therefore mass region below ~ 1 TeV is not probed by current analyses
- \rightarrow searches from Tevatron were still relevant in this region not so long ago
- \rightarrow specific strategies devised at LHC to keep access to this region

CMS: data scouting (since end of 2011)
also data parking (since 2012)

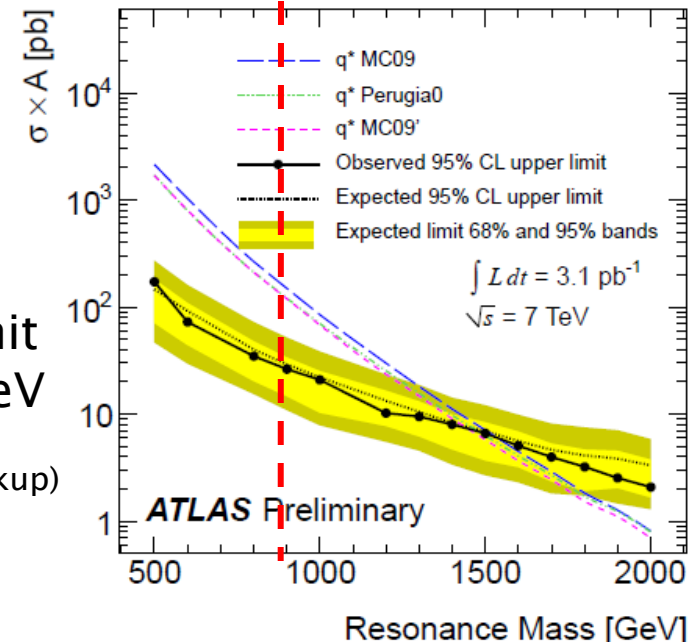
ATLAS: no special trigger in 2011,
also delayed triggers (since 2012)

CMS 0.12 fb^{-1} @ 7 TeV [EXO-11-094]



red dashed lines:
upper excluded limit
CDF 1 fb^{-1} @ 1.96 TeV
[PRD 79, 112002 (2009)]
(more Tevatron results in backup)

ATLAS 3.1 pb^{-1} @ 7 TeV [CONF-2010-093]

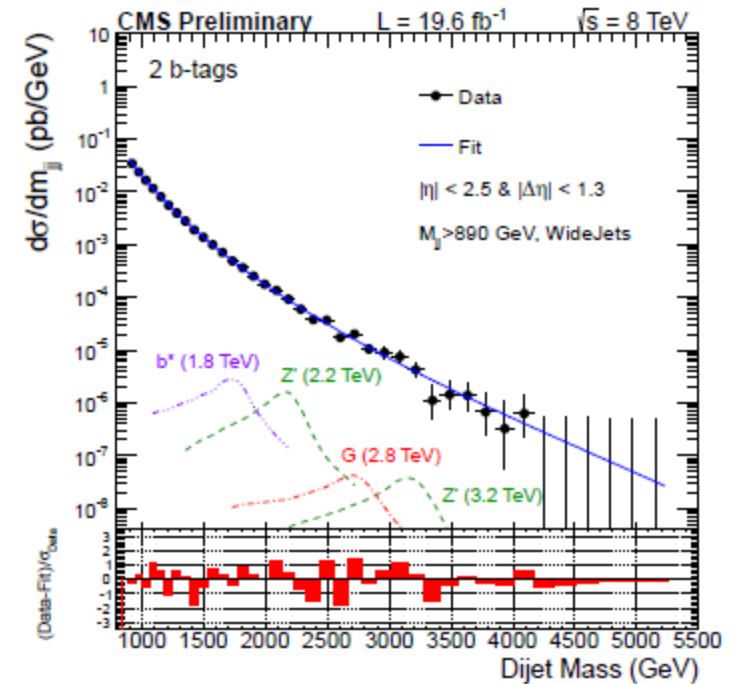
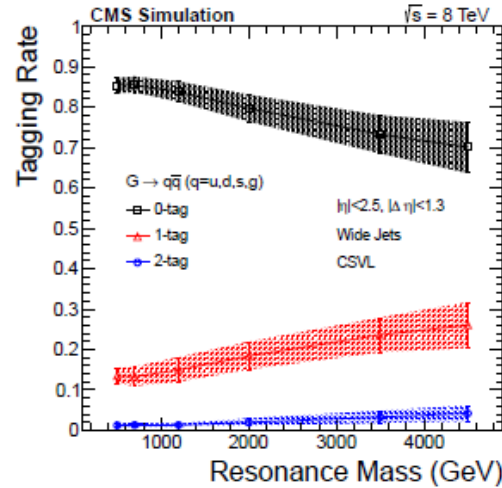
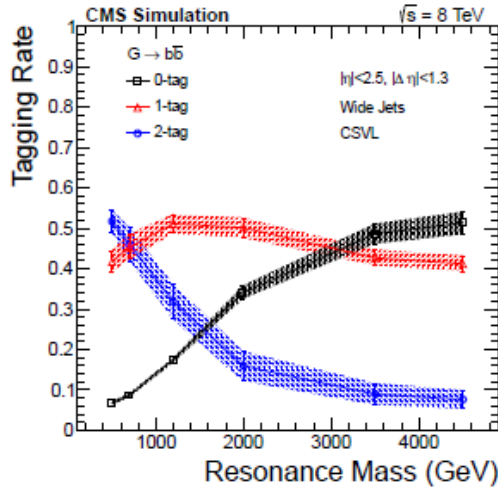


Search for heavy resonances: Dijets (bb)

More specific searches: decays to bb and bg

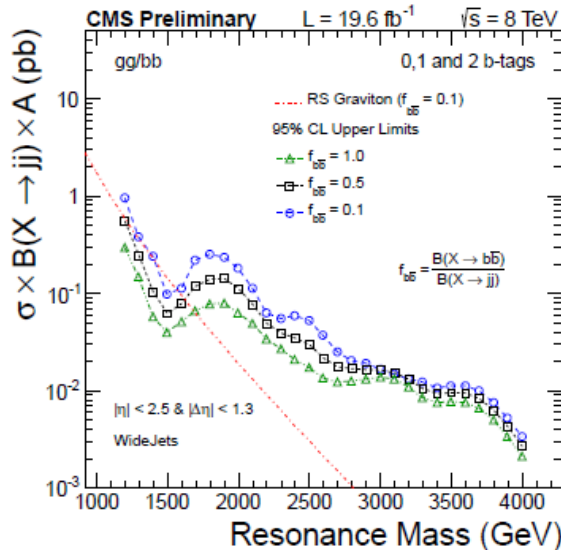
CMS 20 fb⁻¹ @ 8 TeV [EXO-12-023]

requiring 1 or 2 b-tagged jets



Observed 95% C.L. excluded masses (TeV):

	this analysis	untagged
Z' ($f_{bb}=0.2$)	[1.20, 1.68]	[1.20, 1.68]
RS G ($f_{bb}=0.1$) $k/M_{Pl}=0.1$	[1.24, 1.57]	[1.20, 1.58]
$b^* \rightarrow bg$	[1.34, 1.54]	N/A

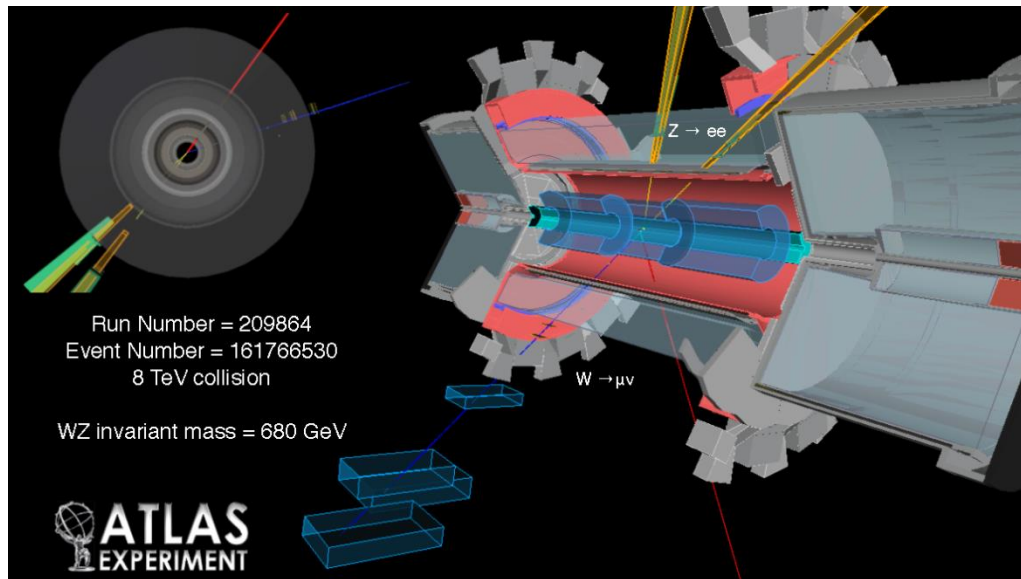


Search for heavy resonances: Dibosons

Models: extended gauge bosons $V' \rightarrow V_1 V_2$, LSTC, KK...

Search: looking for resonances on top of SM diboson background in $m(VV)$

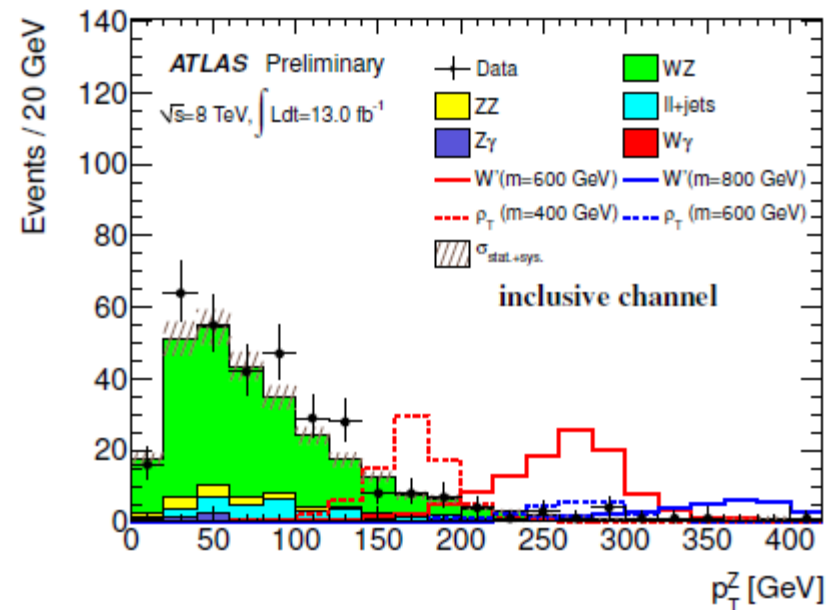
Typically less background than dijets/dileptons. Less branching too...
Background modeling: Monte Carlo with data-driven normalizations for most



Candidate event for $WZ \rightarrow \mu\nu ee$
 $m(WZ) = 680 \text{ GeV}$

ATLAS 13 fb^{-1} @ 8 TeV [CONF-2013-015]

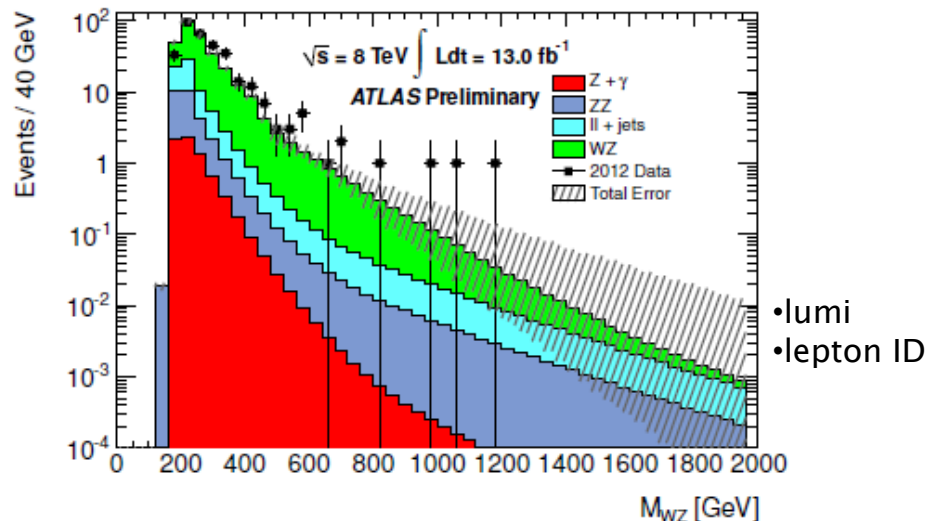
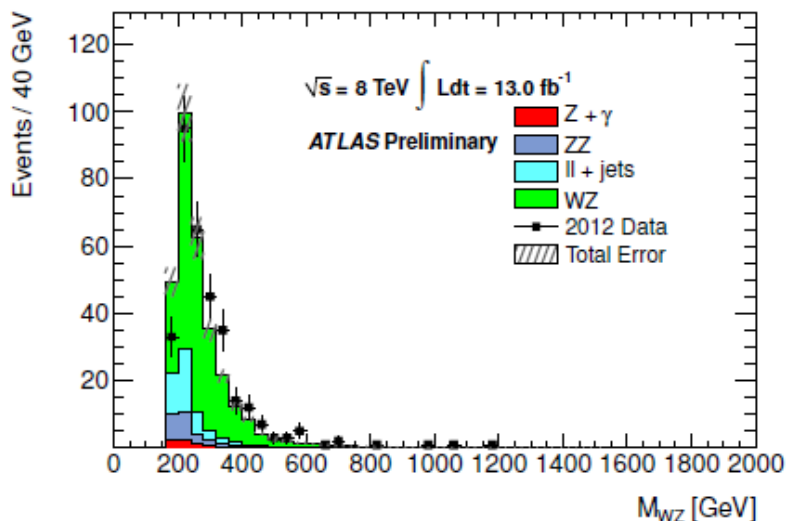
$WZ \rightarrow l\nu l'l'$



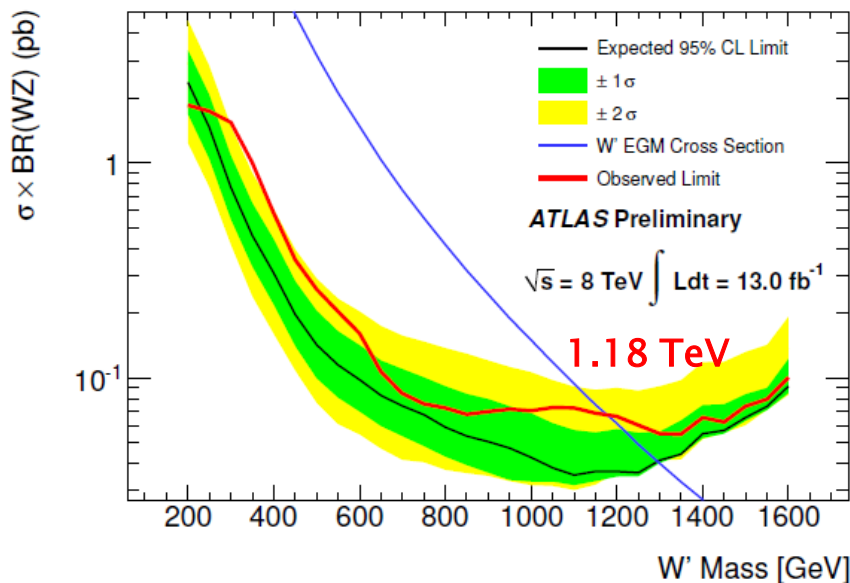
Search for heavy resonances: Dibosons (WZ)

The final VV invariant mass distribution:

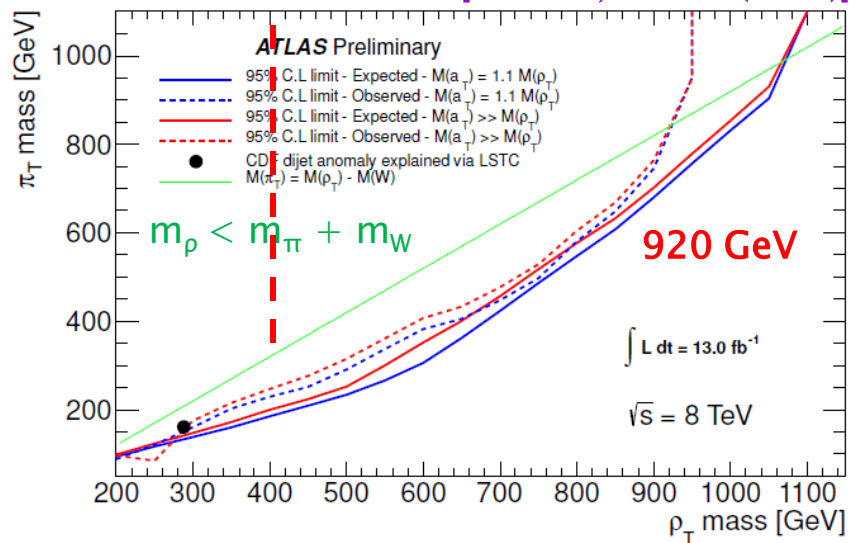
ATLAS 13 fb⁻¹ @ 8 TeV [CONF-2013-015]



Limits (95%CL) on W', technirho masses:

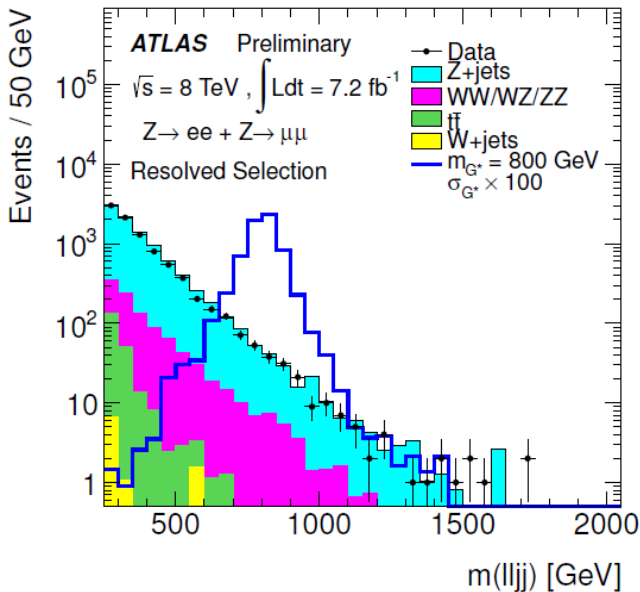


D0 408 GeV [PRL 104,061801 (2010)]



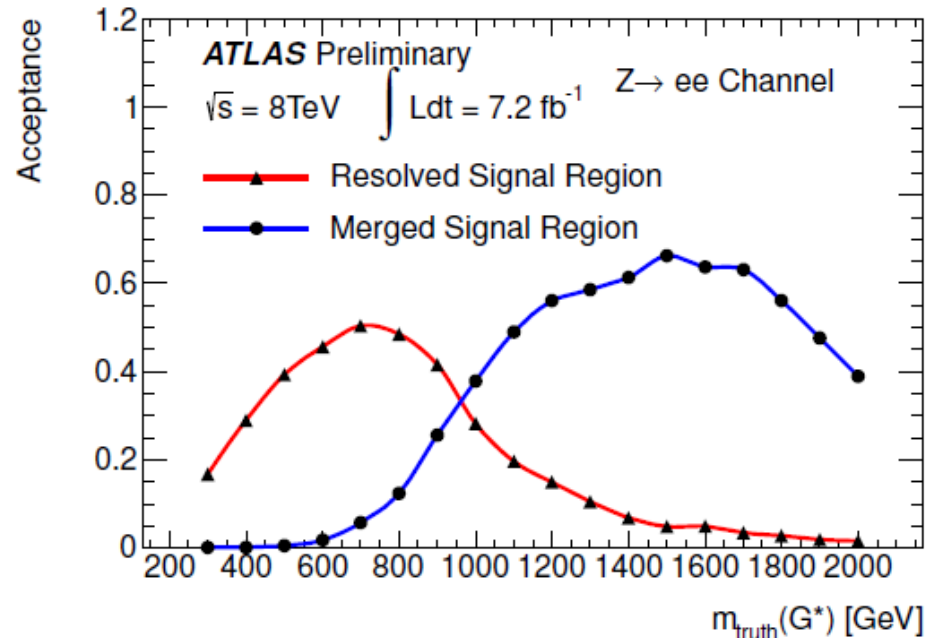
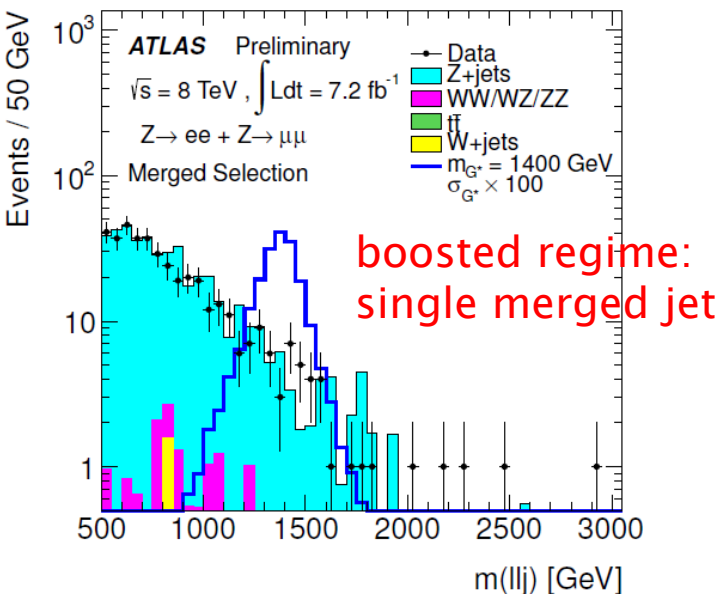
Search for heavy resonances: Dibosons (ZZ)

ATLAS 7 fb⁻¹ @ 8 TeV [CONF-2012-150]



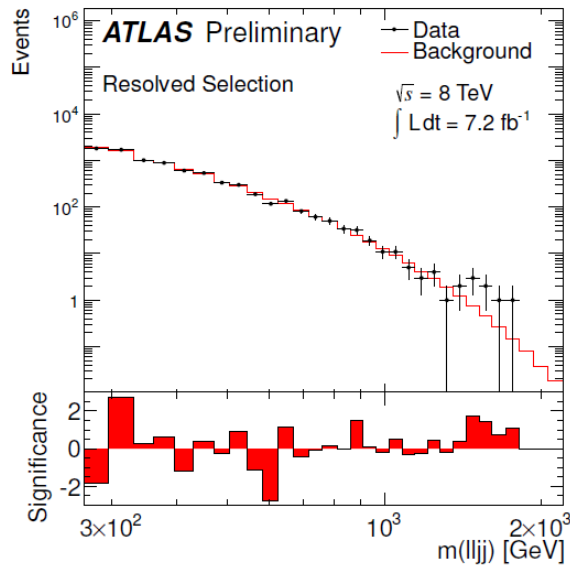
Search for resonant ZZ \rightarrow ll qq:

- 2 lepton channels: $\mu\mu$ & ee
- triggers on single leptons
- jets: 2 kinematical regimes
 - low mass: two anti-kT R=0.4 jets
 - high mass: single jet



Search for heavy resonances: Dibosons (ZZ)

ATLAS 7 fb⁻¹ @ 8 TeV [CONF-2012-150]

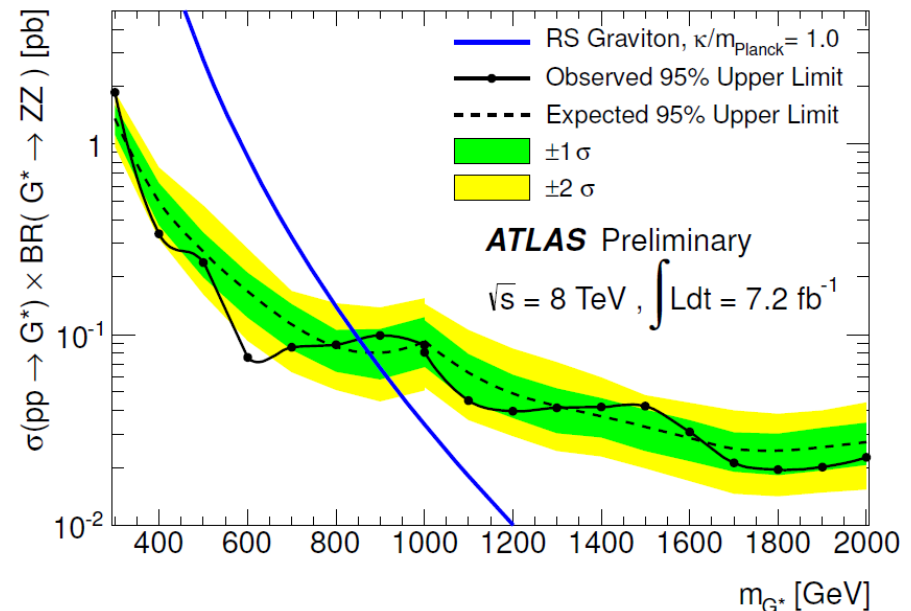
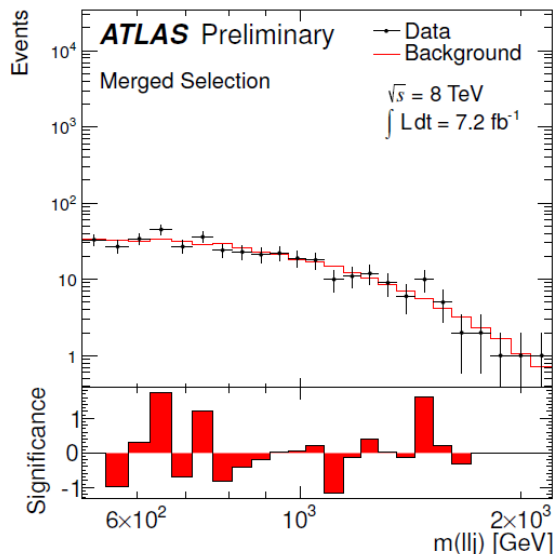


Background modelling: fit to data with same form than for dijets.
Uses BumpHunter as well.

95% CL limits:

m(G) > 850 GeV (exp. 870 GeV) for k/M_{pl}=1.0

(CMS 5 fb⁻¹ @ 7 TeV: 720 GeV [PLB 718,2,307 (2009)])



NB: here “bulk RS” model, different from RS1 in page 7

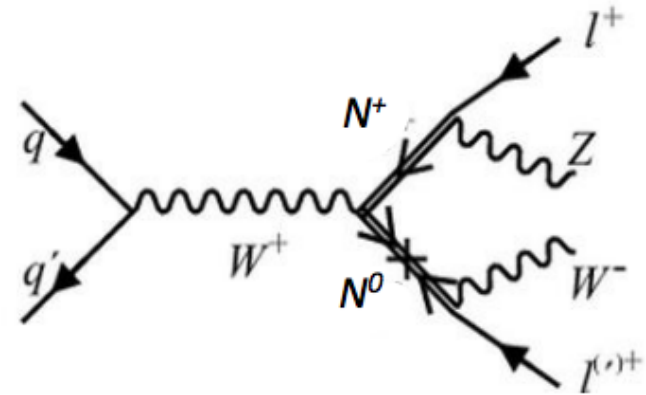
Search for lighter resonances: heavy fermions

See-saw mechanism for ν masses:

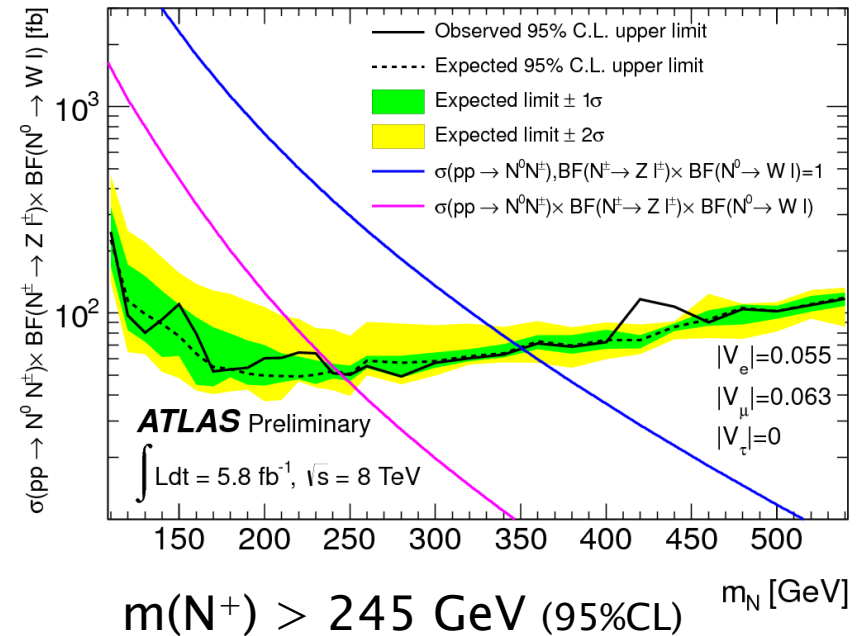
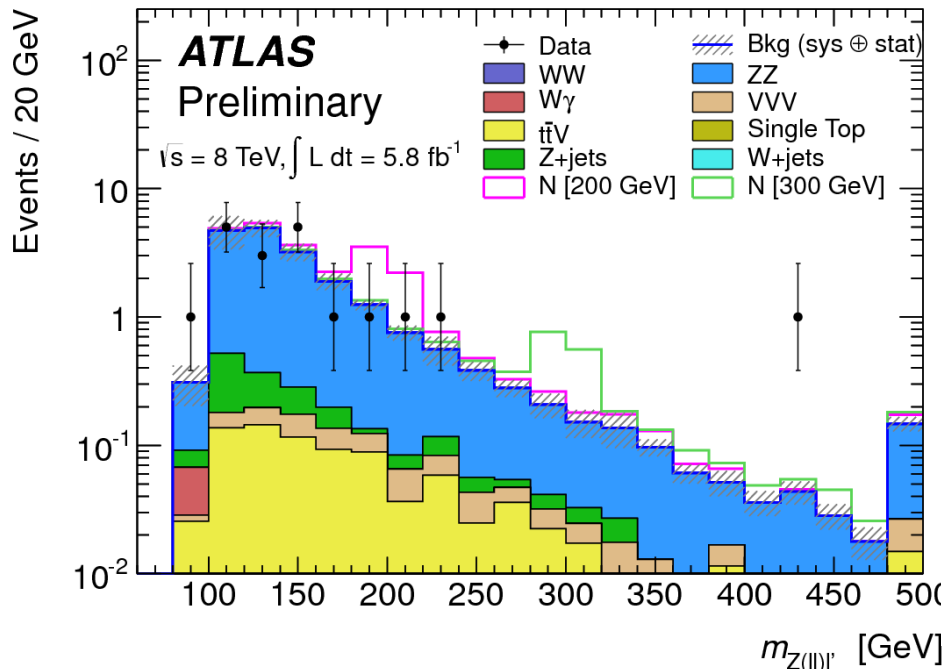
- Type III: 2 fermionic triplets
- N^+ , N^- , N^0 (\sim degenerated in mass)
- $\text{Br}(N^+ \rightarrow Zl^+)$, $\text{Br}(N^0 \rightarrow W^+l^-)$

Signature:

- $Z \rightarrow ll$, plus 2 leptons
- full reconstruction of N^+



ATLAS 5.8 fb⁻¹ @ 8 TeV [CONF-2013-019]



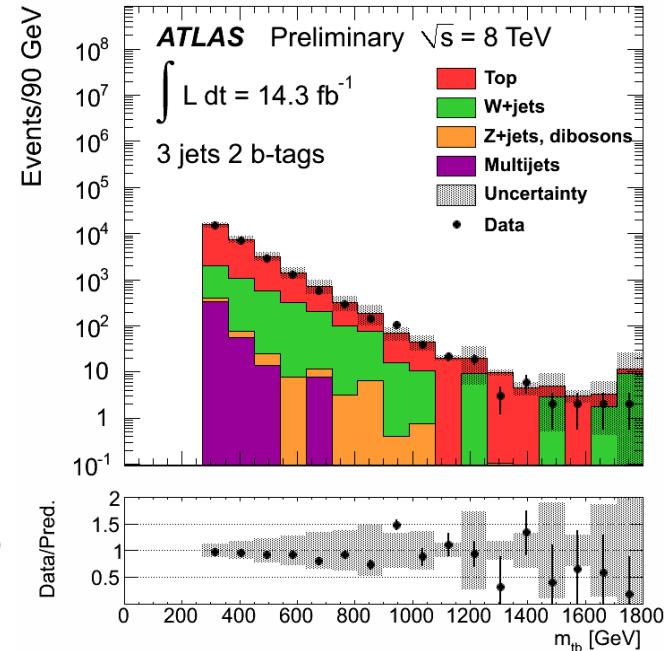
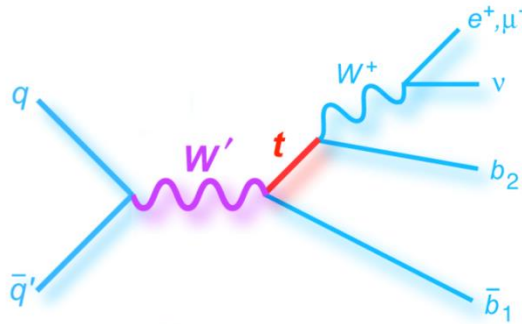
Exclusion plane (m, BR) in the CONF note.

NEW!

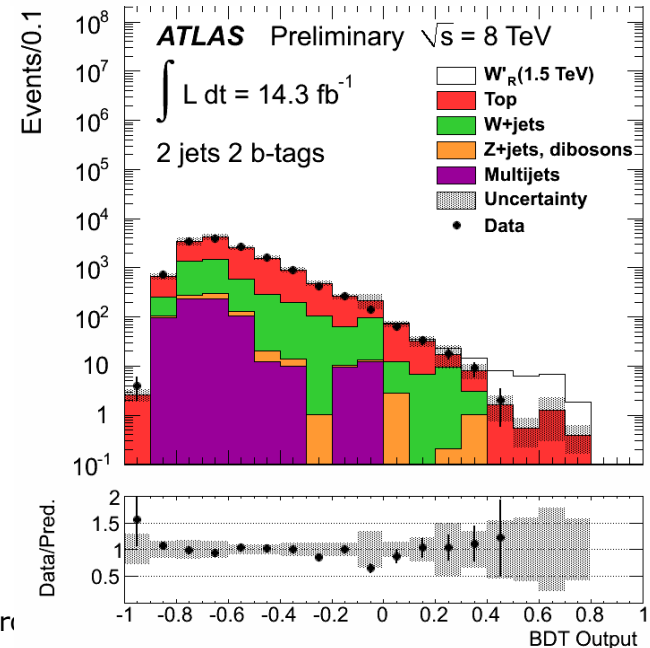
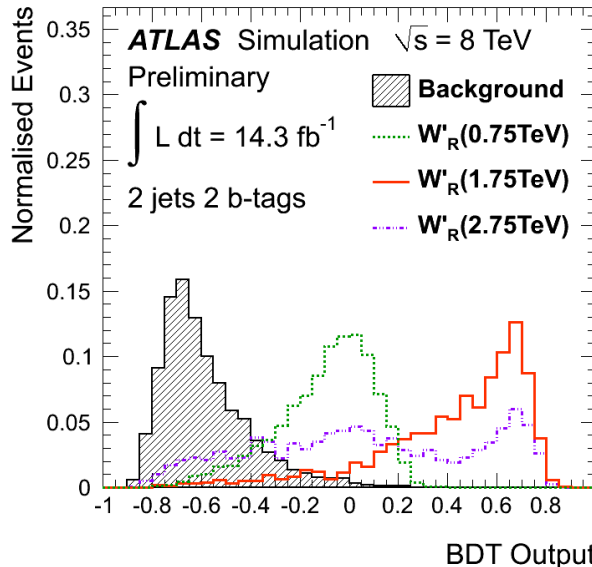
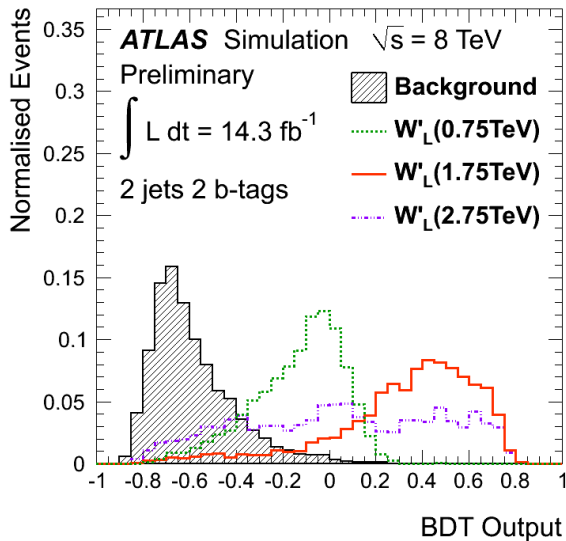
Search for heavy resonances: $W' \rightarrow tb$

ATLAS 14 fb^{-1} @ 8 TeV [CONF-2013-022]

- $W' \rightarrow tb$, W'_L or W'_R
- leptophobic W' , 3rd gen.
- XS: Duffty, Sullivan [PRD 86, 075018 (2012)]
- $0.5 < m(W') < 3 \text{ TeV}$
- 2 flavors of lepton
- 2||3 jets, 1||2 b-tags
- BDT with 14 variables: m_{tb} , $p_T(t)$, $\Delta R(l, b_2)$, H_T , m_{bb}



Expected BDT outputs:



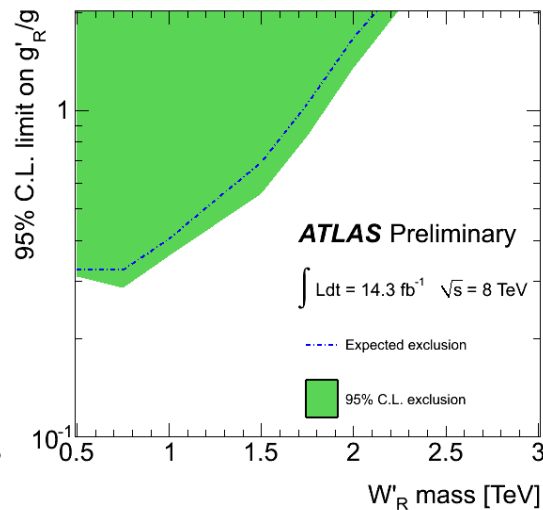
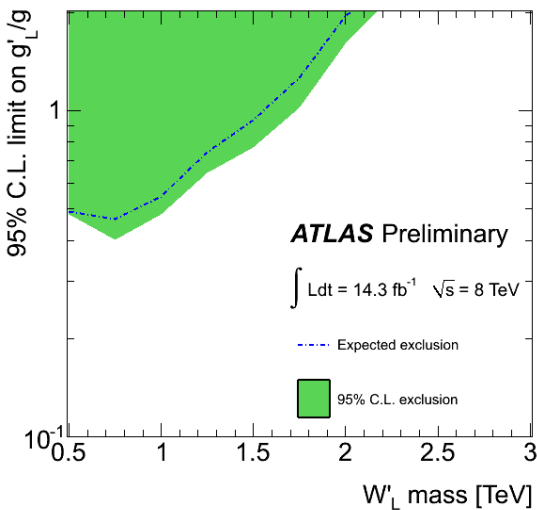
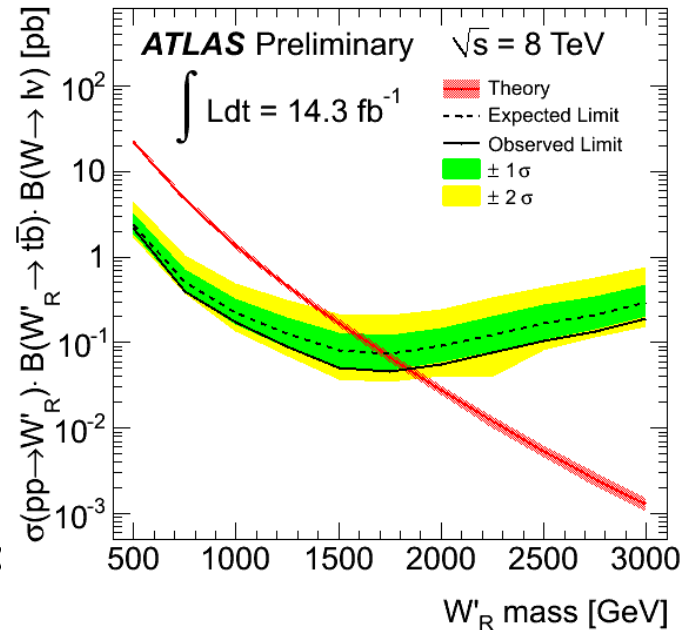
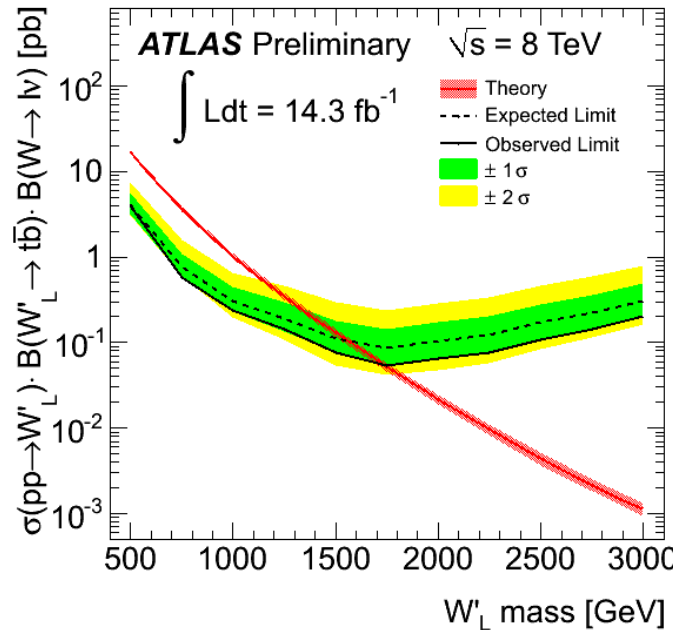
NEW!

Search for heavy resonances: $W' \rightarrow tb$

ATLAS 14 fb⁻¹ @ 8 TeV [CONF-2013-022]

95% CL limits:

- $m(W'_L) > 1.74$ TeV (exp. 1.74 TeV)
- $m(W'_R) > 1.84$ TeV (exp. 1.84 TeV)



CMS 20 fb⁻¹ @ 8 TeV [B2G-12-010]

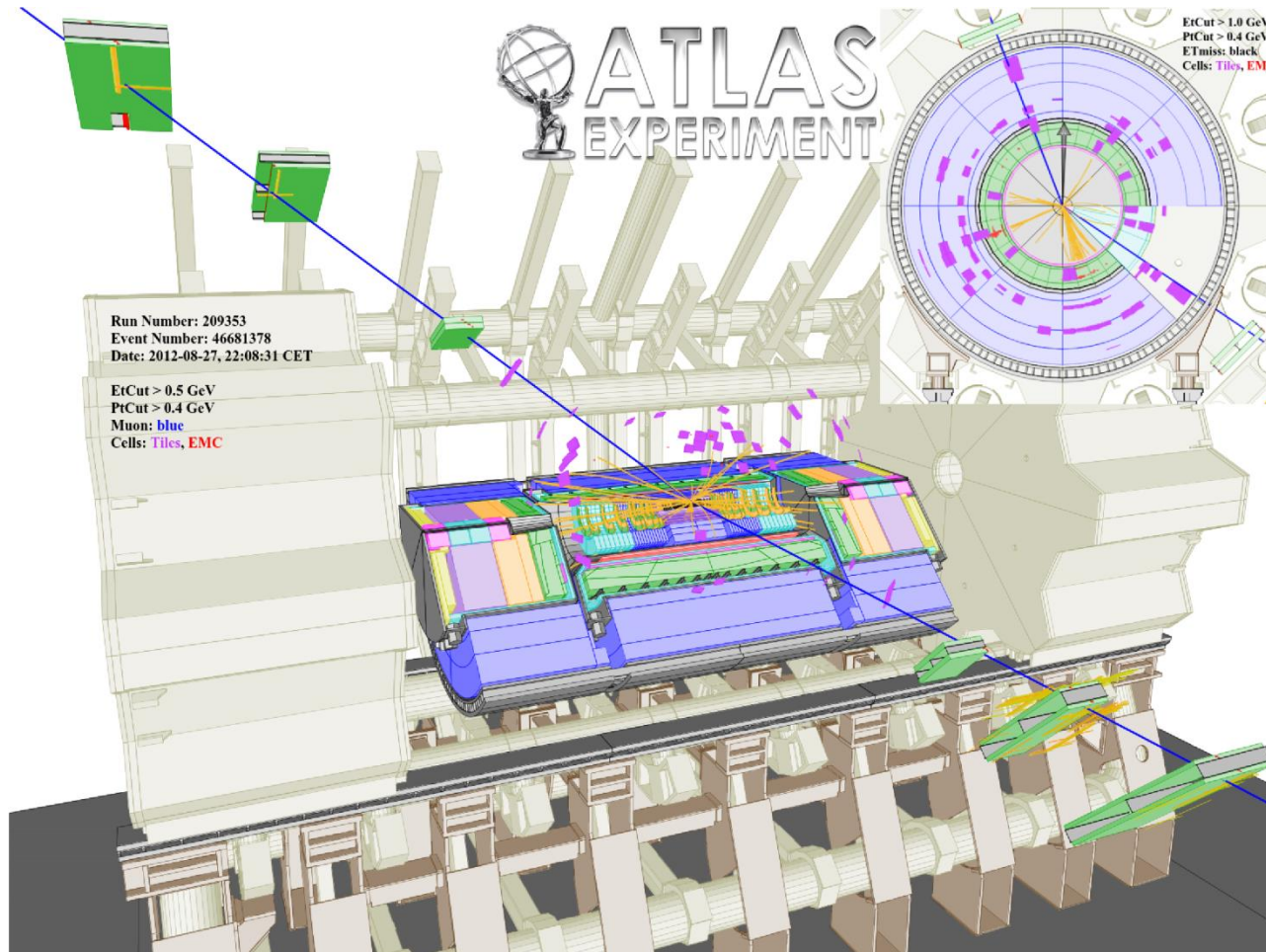
- see next talk by Tulika Bose
- $m(W'_R) > 2.03$ TeV

Conclusion

- Building on the searches done at the Tevatron with CDF and D0, ATLAS and CMS at LHC are now exploring the energy frontier
- At the end of the 1st LHC run, and in particular thanks to the 8 TeV data ($\sim 20 \text{ fb}^{-1}$ per experiment), many searches for exotic resonances are reaching the multi-TeV region. More information:
 - <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>
 - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>
 - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>
- So far no discovery unfortunately... A few (95%CL) limits to take away:
 - SSM Z' : $m(Z') > 2.96 \text{ TeV}$ (dileptons)
 - RS G ($k/M_{\text{Pl}}=0.1$): $m(G) > 2.47 \text{ TeV}$ (dileptons)
 - excited quarks: $m(q^*) > 3.84 \text{ TeV}$ (dijets)
- Prospects:
 - finish the analyses with LHC Run 1 data !
 - the next LHC run at 13/14 TeV will significantly increase the reach for these searches.

Backup

Search for heavy resonances: Dileptons

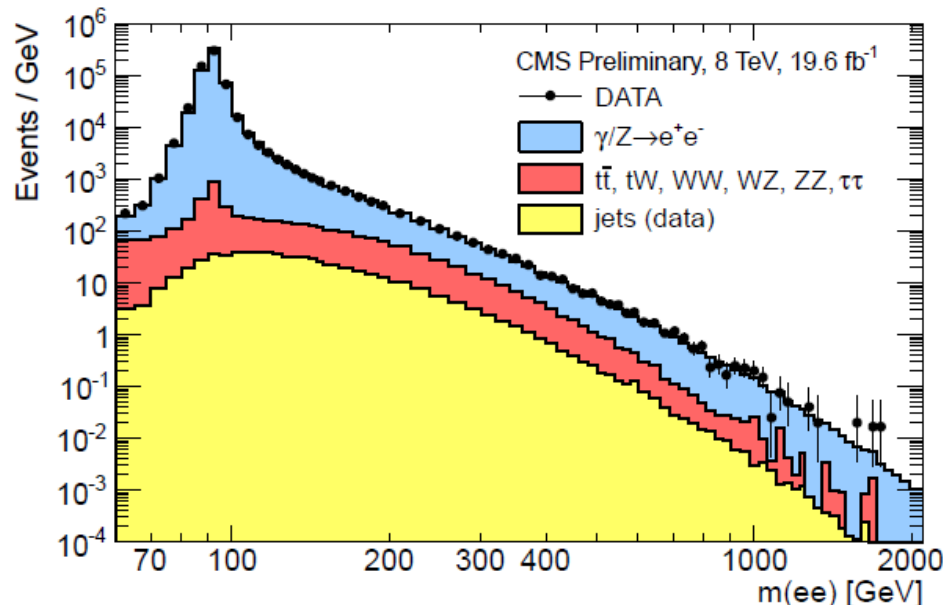
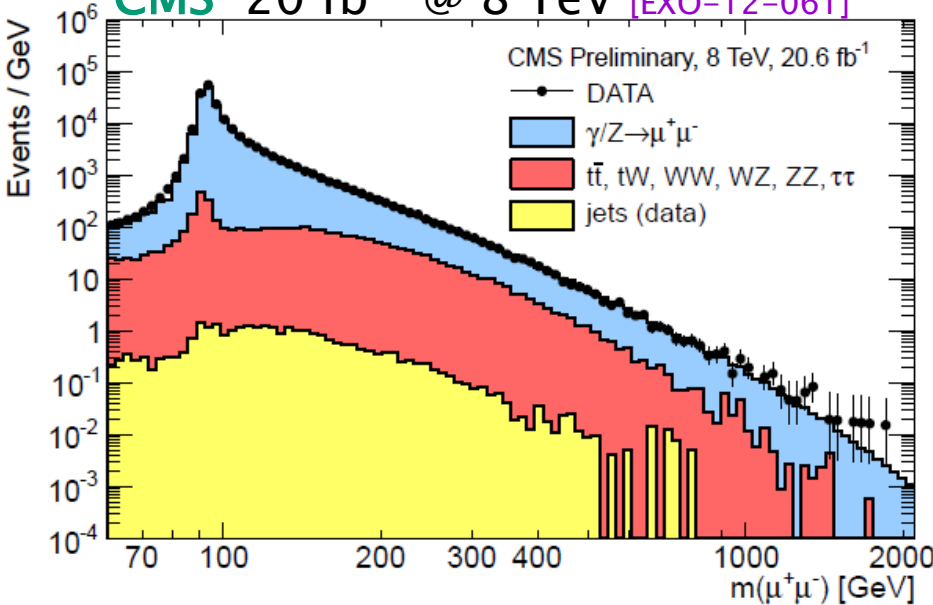


Highest dimuon invariant mass event in ATLAS: $m(\mu\mu)=1.84$ TeV

$p_T(\mu_1)=653$ GeV, $p_T(\mu_2)=646$ GeV

Search for heavy resonances: Dileptons

CMS 20 fb⁻¹ @ 8 TeV [EXO-12-061]



CMS $\mu\mu$ analysis in a nutshell:

- single- μ trigger ($p_T > 40$ GeV, $|\eta| < 2.1$)
- combined μ (tracker+MS), $p_T > 45$ GeV, quality cuts, isolation
- 2 muons of opposite charge

ATLAS $\mu\mu$ analysis in a nutshell:

- single- μ triggers ($p_T > 24 + \text{iso} || 36$ GeV)
- combined μ , $p_T > 25$ GeV, $|\eta| < 2.4$, quality cuts, isolation
- 2 muons of opposite charge

CMS ee analysis in a nutshell:

- di- e trigger ($E_T > 35$ GeV, e -shape+track)
- clusters: $E_T > 45$ GeV, $|\eta| < 2.5$ (- 1.44, 1.56), quality cuts, track isolation (5 GeV $\Delta R = 0.3$)
- no charge requirement

ATLAS ee analysis in a nutshell:

- di- γ trigger ($E_T^1 > 35$ GeV, $E_T^2 > 25$ GeV)
- 2 e : $E_T > 45(30)$ GeV, $|\eta| < 2.47$ (- 1.37, 1.52), quality cuts, calo isolation (\neq for the 2 e)
- no charge requirement

Search for heavy resonances: Dijets

ATLAS analysis in a nutshell:

- central 1-jet triggers $E_T \sim 350$ GeV
- ≥ 2 anti- k_T $R=0.6$ jets with $|y_j| < 2.8$, $|y^*| < 0.6$ and $m(jj) > 1$ TeV
- \rightarrow min jet $p_T \sim 150$ GeV

CMS analysis in a nutshell:

- trigger: loose jet L1, HLT: $H_T > 650$ GeV
- $m(jj) > 750$ GeV
- PFjets combined in wide-jets ($R \sim 1.1$)
- $|\Delta\eta| < 1.3$ and $m(jj) > 0.89$ TeV

Search:

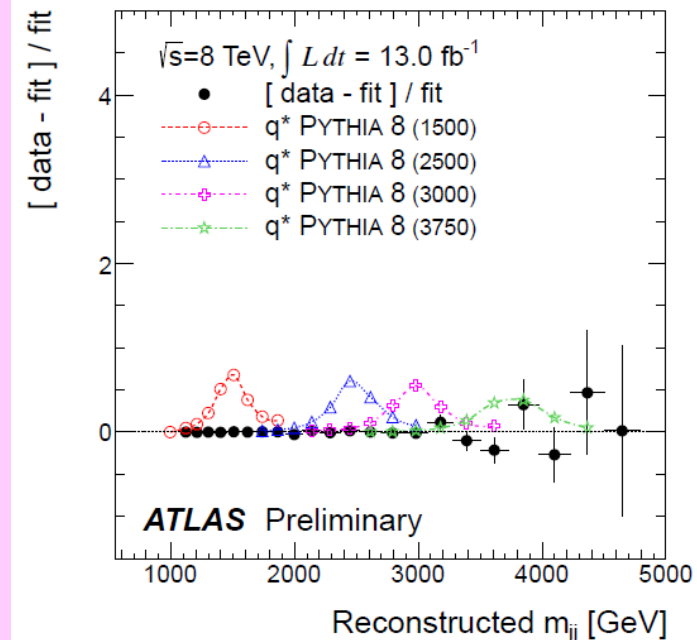
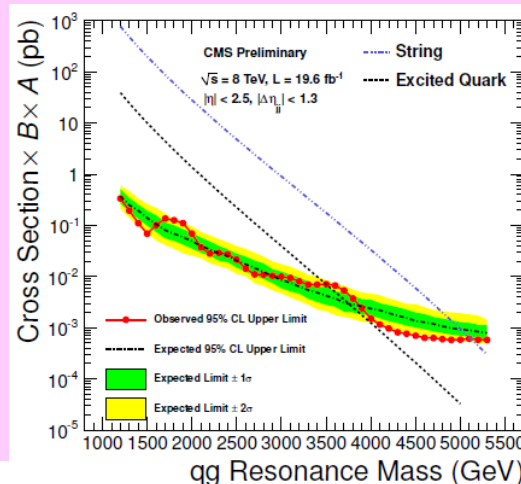
- fit $m(jj)$ data distribution with smooth form: \oplus no MC QCD uncertainties, reduced sensitivity to JES&lumi, \ominus uncertainties on fit form, limited sensitivity to smooth changes (e.g. contact interaction)

$$f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x} \quad x \equiv m_{jj} / \sqrt{s}$$

- binned likelihood fit: χ^2 compatible with bkgd
- ATLAS: BumpHunter for excess of any width
- no signal found

Exclusion:

- bayesian approach
- with Gaussian-like signals
- ATLAS: q^* + model-independent approach
- CMS: many models, separation of q/g final states



Search for heavy resonances: Dijets

Important note:

- high p_T threshold required at LHC for triggers on (single) jets
- therefore mass region below ~ 1 TeV is not probed by current analysis
- \rightarrow searches from Tevatron were still relevant in this region not so long ago

Observed 95% C.L. excluded masses (GeV):

Model	Tevatron exclusion	LHC exclusion
Excited quark q^*	[260, 870] (CDF)	[1000, 3840] (ATLAS)
E6 diquark D	[290, 630] (CDF)	[1200, 4750] (CMS)
Axigluon/coloron	[260, 1250] (CDF)	[1200, 3600] + [3900, 4080] (CMS)
W'	[280, 840] (CDF†)	[1200, 2290] (CMS)
Z'	[320, 740] (CDF‡)	[1200, 1680] (CMS*)

CDF 1 fb⁻¹ @ 1.96 TeV [PRD 79, 112002 (2009)]

CMS 20 fb⁻¹ @ 8 TeV [EXO-12-059]
ATLAS 13 fb⁻¹ @ 8 TeV [CONF-2012-148]

†: more stringent limit (1 TeV) from D0 W' to electron analysis [PRL 100, 031804 (2008)]

‡: more stringent limit (923 GeV) from CDF Z' to electrons analysis [PRL 99, 171802 (2007)]

*: more stringent limit from LHC dilepton analyses as we saw

NEW!

Search for heavy resonances: $W' \rightarrow tb$



Control regions:

