

# Searches for Exotic Resonances and Decays at the HL-LHC: Experimental Prospects

Chris Pollard

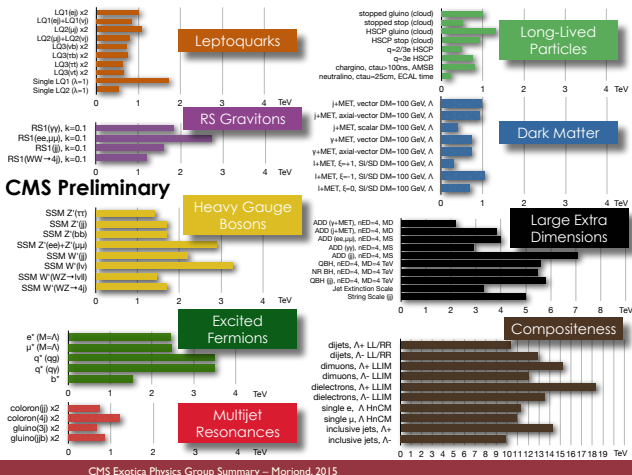
University of Glasgow  
for CMS and ATLAS

2015 05 12



# Introduction I

Run I was successful in that we searched over a wide range of final states, excluding parameter space on a huge number of BSM models.



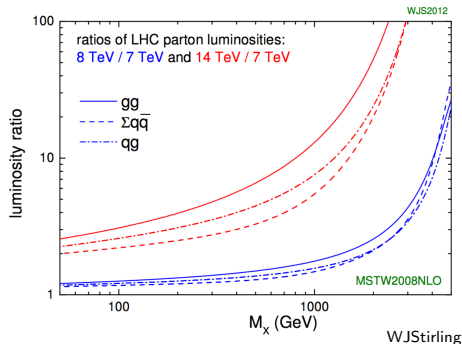
CMS Exotica Physics Group Summary – Moriond, 2015

# Introduction II

Run II has more in store:

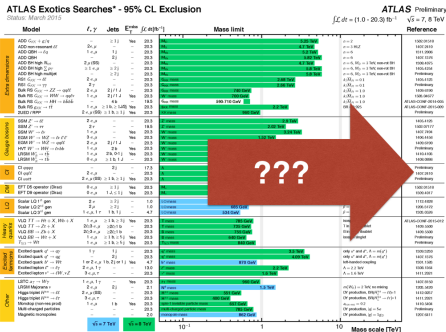
- ▶ 8 TeV  $\rightarrow$  14 TeV: higher high-mass cross sections
- ▶ More luminosity
- ▶ Better reconstruction and analysis techniques \*
- ▶ More and better models. . . \*

\* no pressure.



## Introduction III

Run II has more in store... but not so fast!



<sup>a</sup>Only a selection of the available mass limits on new states or phenomena is shown.

- ▶ How much does even more luminosity buy us?
- ▶ Obviously helpful for measurements and rare process discovery.
- ▶ How much will we push out mass limits?
- ▶ Is this the correct metric?
- ▶ Will we find something in the first  $300\text{fb}^{-1}$ ?

- Common Issues
- Dijet resonances
- Dilepton resonances
- $t\bar{t}$  resonances
- Single-lepton searches

# Common issues

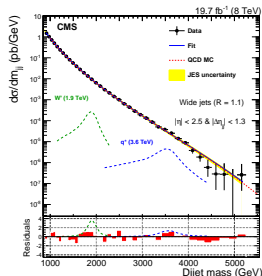
“What will we gain from more luminosity” is not a trivial question to answer. There are many common issues that we need to keep in mind when trying to estimate what we can see with  $3000\text{fb}^{-1}$ :

- ▶ What will our detectors look like?
- ▶ How do we model their performance?
- ▶ How well will we be able to identify and reconstruct objects at very high- $p_T$ ?
  - ▶  $b$ -jets
  - ▶ top quarks (hadronic and leptonic)
  - ▶ H,W,Z bosons
  - ▶ etc.
- ▶ Do we have any handle on what our systematic uncertainties will be?
- ▶ Pileup.

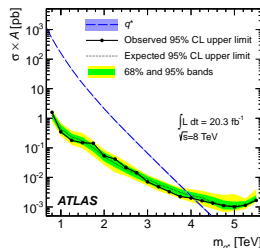
# Dijet resonances

- ▶ Search for new resonances decaying to two partons
- ▶ Generally highest mass reach searches at the LHC
- ▶ Basic approach: fit data to smooth function; search for bumps
- ▶ Dominant systematic: jet energy scale

Going to spend a little extra time on this final state because it's a good example.



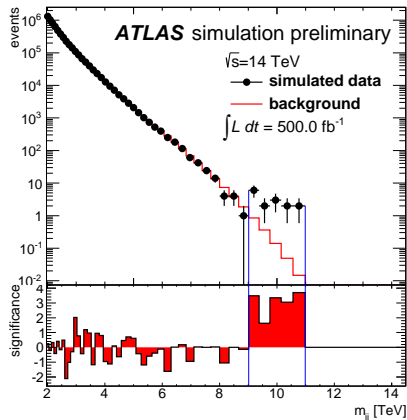
10.1103/PhysRevD.91.052009



PRD 91, 052007 (2015)

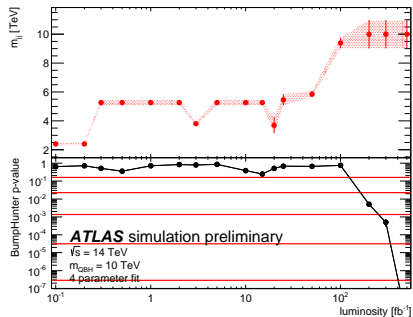
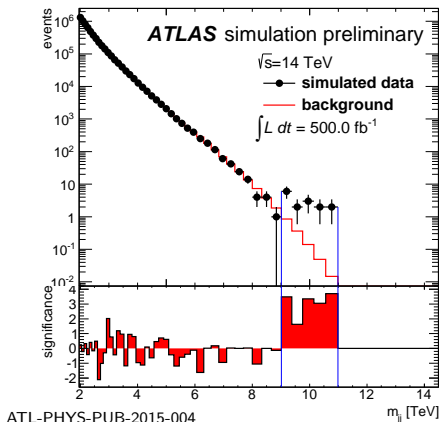
# Dijet resonances: 14 TeV

- ▶ Recent studies show expected sensitivity at 14 TeV with integrated luminosity
- ▶ Two signal models consistent with 8 TeV searches: excited quarks ( $q^*$ ) and quantum black holes (QBH)
- ▶ anti- $k_t$   $R = 0.4$  jets
- ▶ Signal predictions injected into  $m_{jj}$  spectrum to predict discovery potential
- ▶ 8 TeV limits:  $\sim 4$  TeV  $q^*$ ,  $\sim 6$  TeV QBH



ATL-PHYS-PUB-2015-004

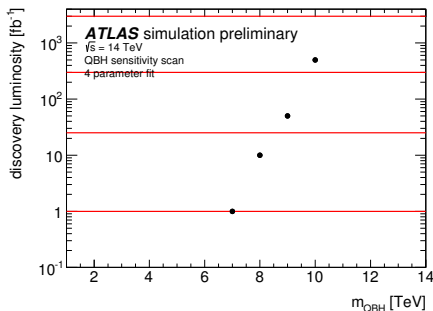
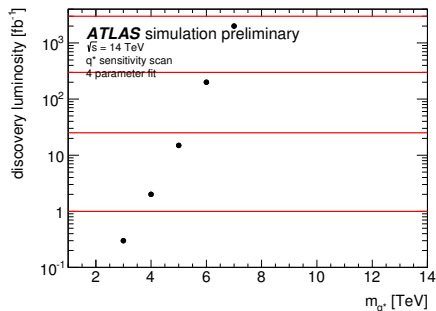
# Dijet resonances: injecting signal



mass and p-value of the most significant bump with injected 10 TeV QBH signal as a function of integrated luminosity

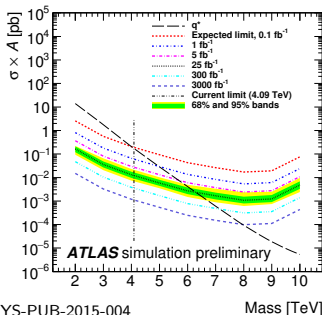
# Dijet discovery luminosities at 14 TeV

This process is iterated—approximately exponential dependence of  $5\sigma$  discovery luminosity on  $m_\chi$ .



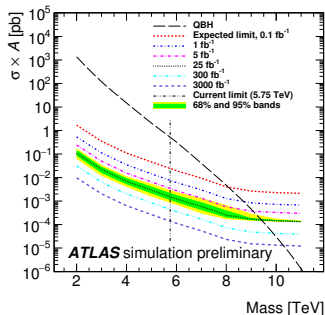
ATL-PHYS-PUB-2015-004

# Dijet limits at 14 TeV



ATL-PHYS-PUB-2015-004

Mass [TeV]



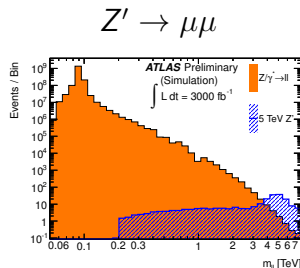
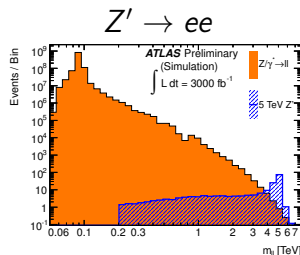
Mass [TeV]

- ▶ Run I limits superseded very quickly; it's difficult to push out mass limits beyond a certain point.
- ▶ Continuing to push down cross section limits and discovery potential (previous slide) also important.

integrated luminosity [fb <sup>-1</sup> ]	$m_{q^*}$ [TeV]	$m_{QBH}$ [TeV]
0.1	4.0	8.2
1	5.0	8.9
5	5.9	9.2
25	6.6	9.7
300	7.4	10.0
3000	8.0	10.1

# Dilepton resonances: 14 TeV

- ▶ Another search with high mass reach
- ▶ Only one type of reconstructed object (two channels)
- ▶  $Z/\gamma^*$  the dominant background.
- ▶  $ee$  mass resolution gets better with resonance mass.
- ▶  $m_{\mu\mu}$  resolution deteriorates, but somewhat made up for by higher efficiency.



ATL-PHYS-PUB-2013-003

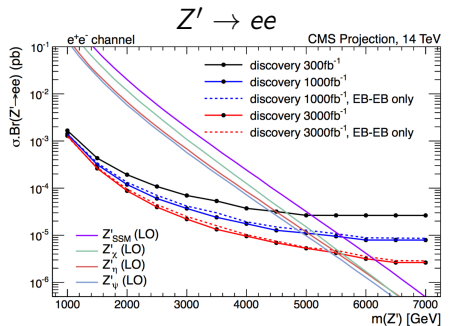
# Dilepton resonances: 14 TeV

Projected limits:

model	300 fb <sup>-1</sup>	1000 fb <sup>-1</sup>	3000 fb <sup>-1</sup>
$Z'_{SSM} \rightarrow ee$	6.5	7.2	7.8
$Z'_{SSM} \rightarrow \mu\mu$	6.4	7.1	7.6

(current limits:  $\sim 3$  TeV)

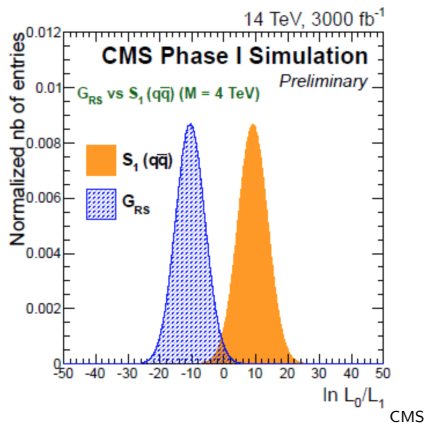
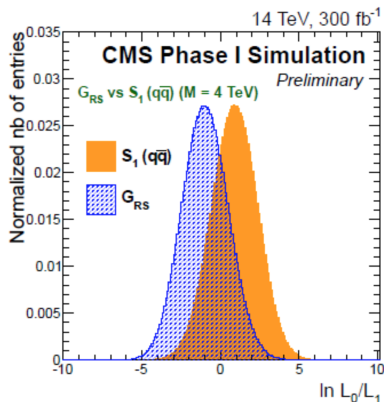
- ▶ 1-1.5 TeV increase in exclusion reach with 3000fb<sup>-1</sup> over 300fb<sup>-1</sup>
- ▶ Similar improvement in discovery reach



CMS-NOTE-2013-002

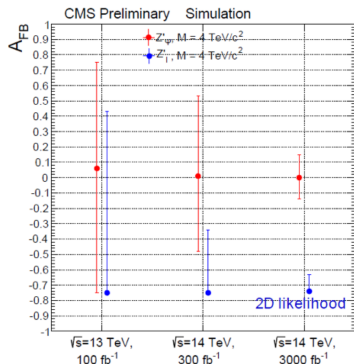
# $Z' \rightarrow ee$ : telling the difference

If we do see an excess in the  $m_{ee}$  spectrum, how well can we characterize it?

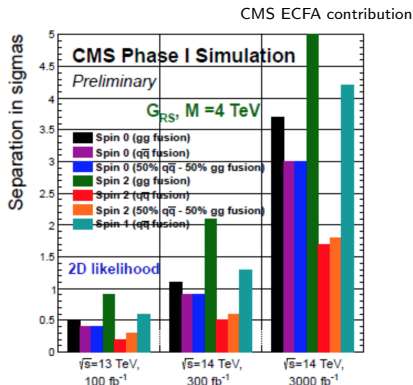


$300\text{fb}^{-1} \rightarrow 3000\text{fb}^{-1}$ : separation between spin-0 and spin-1 resonances

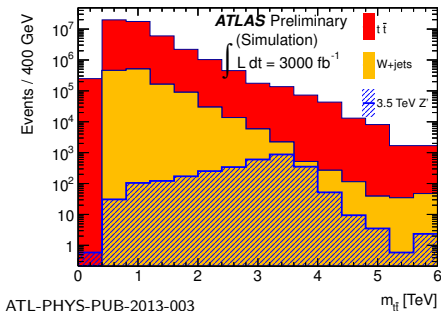
# $Z' \rightarrow ee$ : telling the difference



$A_{FB}$  for two spin-1  $Z'$  bosons

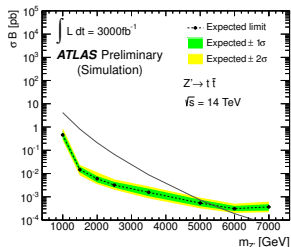
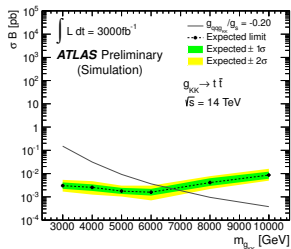


Sensitivity to differences between  $G_{RS}$  and other dilepton resonances

$t\bar{t}$  resonances: 14 TeV

ATL-PHYS-PUB-2013-003

- ▶  $t\bar{t}$  resonances: proxy for searches with complicated final states
- ▶  $\ell$ +jets selection:
  - ▶ One lepton
  - ▶  $E_T^{\text{miss}} > 50 \text{ GeV}$
  - ▶ One anti- $k_t$  0.4 jet
  - ▶ One anti- $k_t$  1.0 jet with  $m_{\text{jet}} > 120 \text{ GeV}$
- ▶ Two signal benchmarks: narrow  $Z'$ , wide Randall-Sundrum Kaluza-Klein gluon

$t\bar{t}$  resonances: 14 TeV

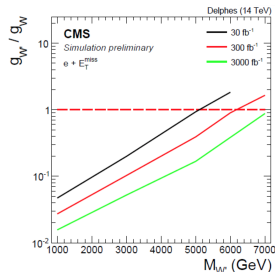
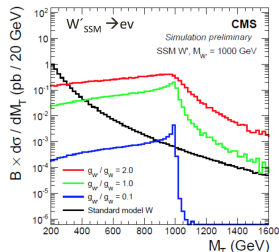
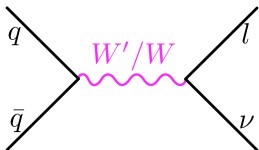
model	300 fb <sup>-1</sup>	1000 fb <sup>-1</sup>	3000 fb <sup>-1</sup>
$g_{KK}$	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\text{topcolor}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

$\ell$ +jets (dilepton) channel  
current limits:  $\sim 2$  TeV

- ▶ 2+ TeV increase in mass reach with 3000fb<sup>-1</sup> over 300fb<sup>-1</sup>
- ▶ No systematic uncertainties are included in the limits.

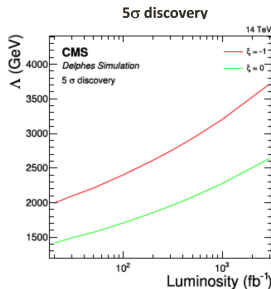
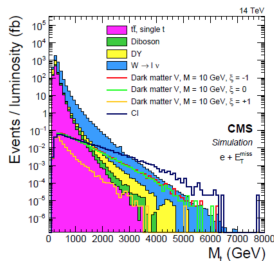
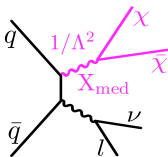
# $W' \rightarrow e\nu$ : 14 TeV

- ▶ Search for an excess in the  $m_{T,e\nu}$  spectrum due to a new resonance
- ▶ Only electron channel shown here (much better  $m_T$  resolution than  $\mu$  channel).
- ▶  $W \rightarrow e\nu$  the dominant background.

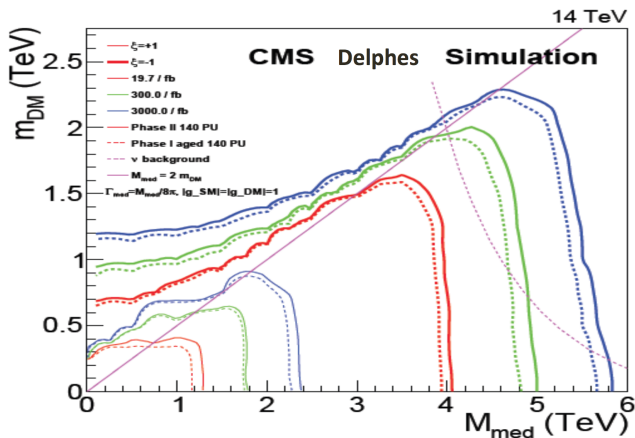


# Non-resonant $e\nu$ production

- ▶ Search for a non-resonant excess in the  $m_{T,e\nu}$  spectrum due to a new dark particle or contact interaction
- ▶  $W \rightarrow e\nu$  still the dominant background.
- ▶  $\xi = +1, 0, -1 \rightarrow$  negative, zero, positive interference



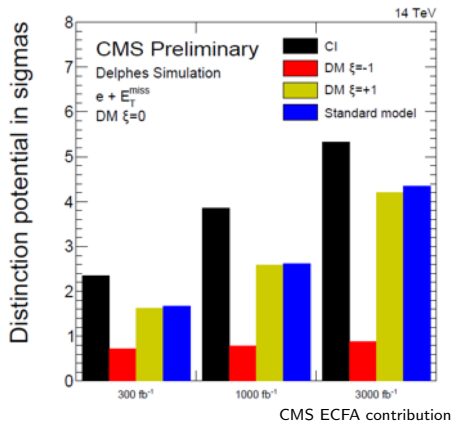
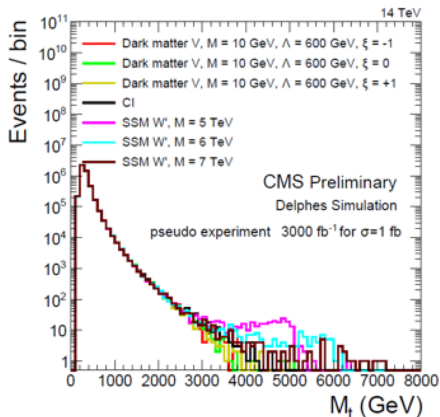
# Dark matter exclusion reach



CMS

With  $3000\text{fb}^{-1}$  we can push into the region that is difficult to exclude with direct searches due to the  $\nu$  background. (simplified mode)

## Distinguishing $e + E_T^{miss}$ signals



If we do see an excess in the  $m_{T, e\nu}$  spectrum, how well can we characterize it?

# Summary

- ▶ The HL-LHC isn't going to push out mass limits as quickly as a higher-energy collider. . .
- ▶ . . . but a lot can still be gained.
- ▶ Models with smaller cross sections can be better probed with more luminosity. . .
- ▶ . . . although to predict our sensitivity we probably need at least a vague idea of systematic uncertainties.
- ▶ It's not clear how well we will reconstruct very high- $p_T$  objects, e.g. leptons near jets, high- $p_T$  substructure, high- $p_T$   $b$ -jets.
- ▶ We have an idea of our mass reach for a few key searches with  $3000\text{fb}^{-1}$ .
- ▶ We are beginning to understand how well we could characterize new physics.
- ▶ There's still a lot to do. . .