

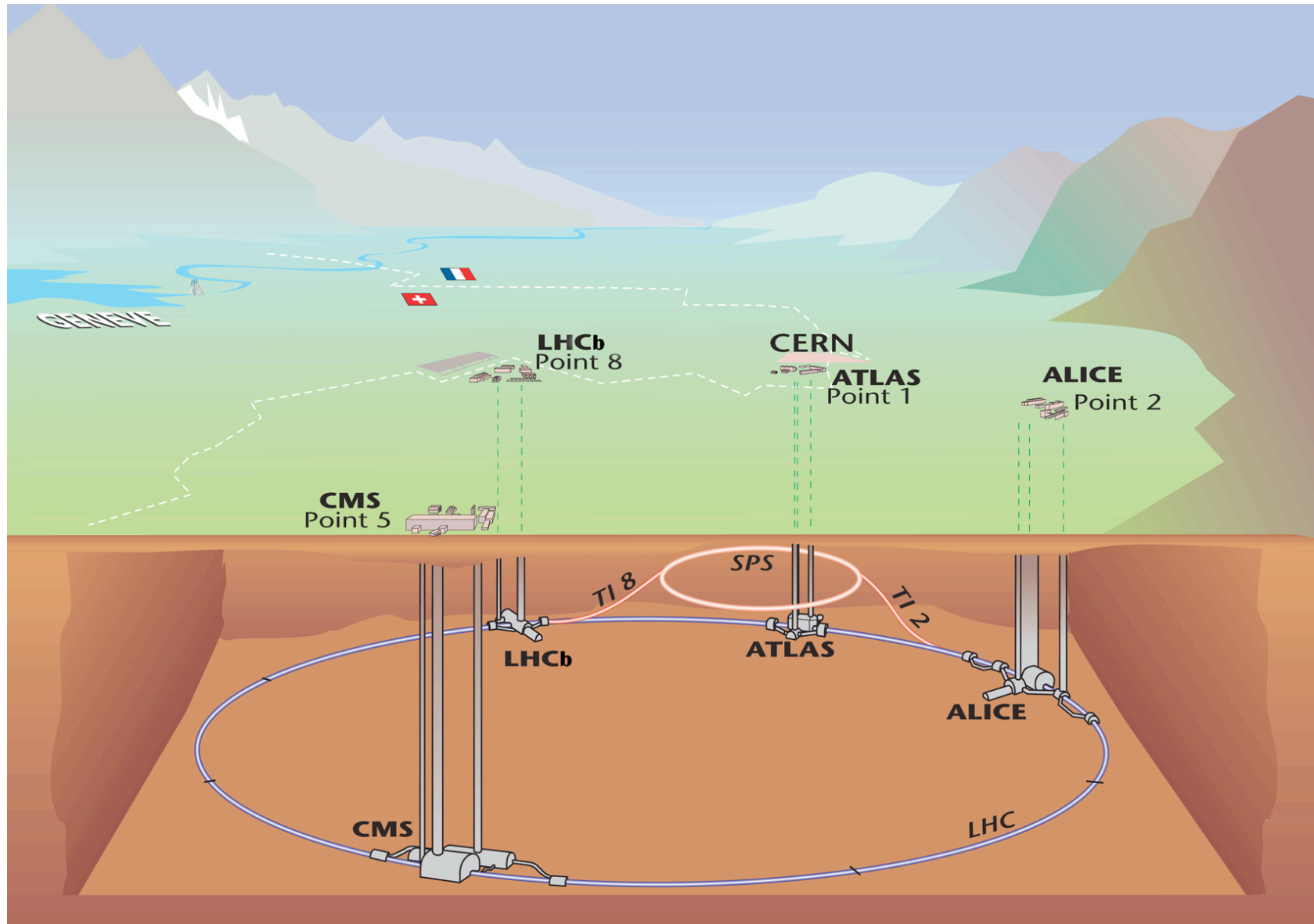
# ATLAS at the LHC – Latest Results from Run 2

Oliver Stelzer-Chilton  
(TRIUMF)

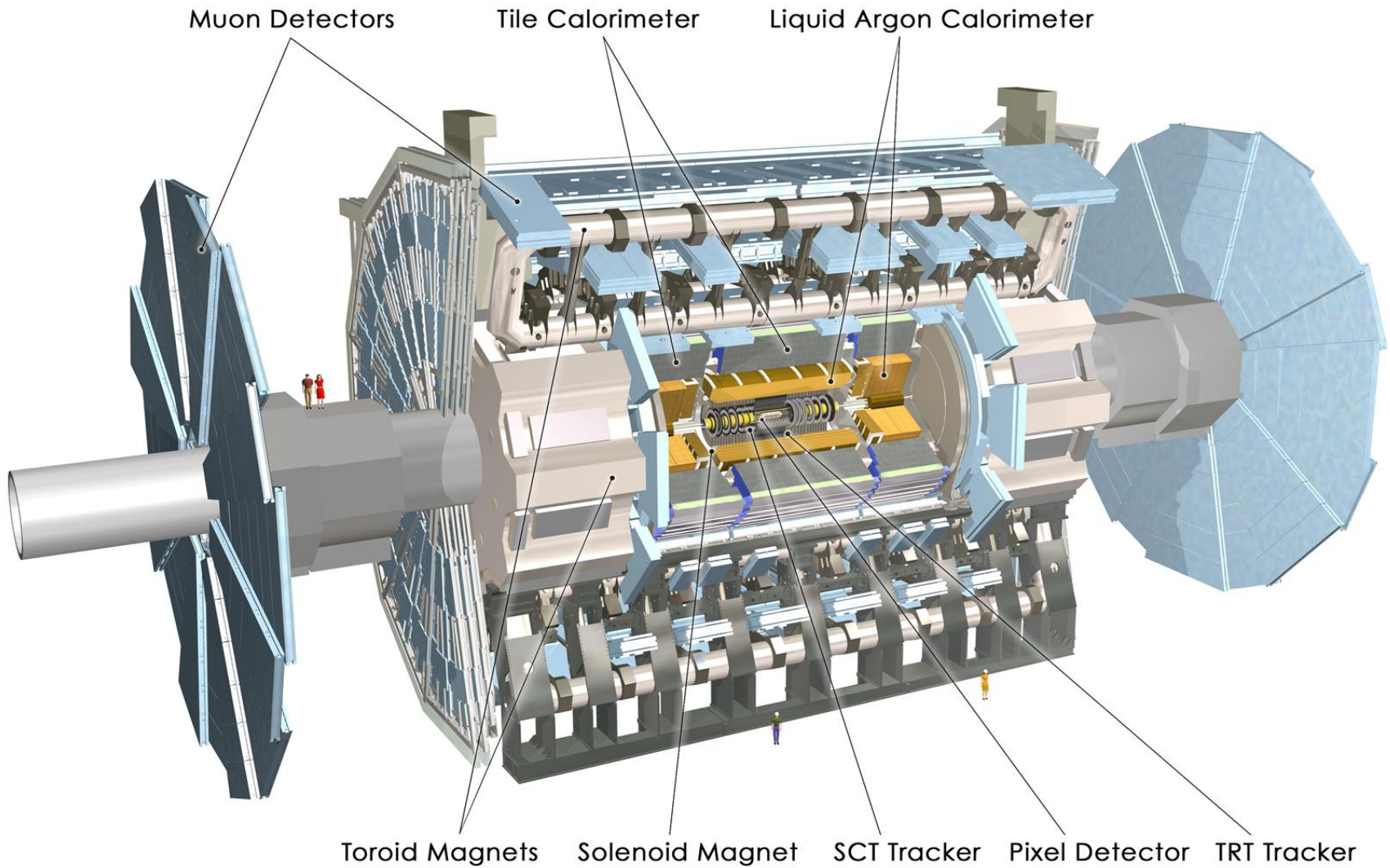
*39<sup>th</sup> Symposium on  
Nuclear Physics*

Cocoyoc, Mexico 2016

# The Large Hadron Collider



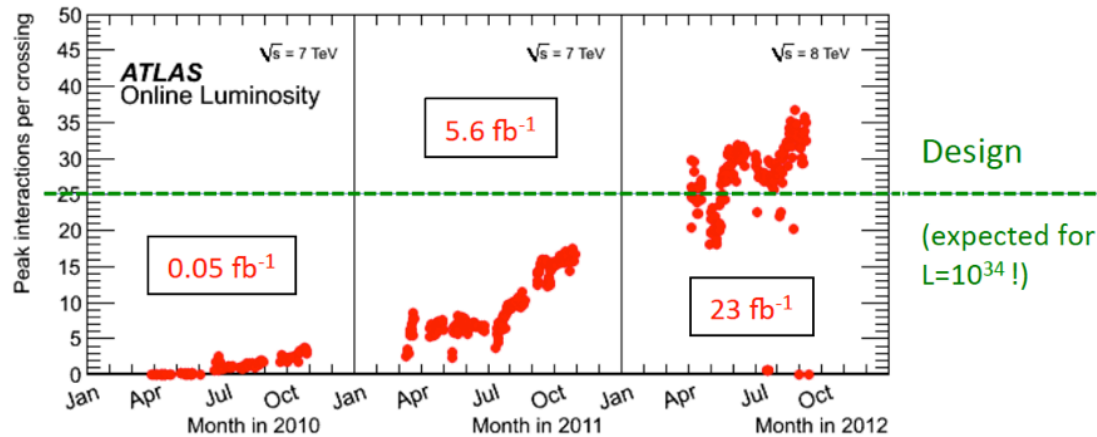
# The ATLAS Detector



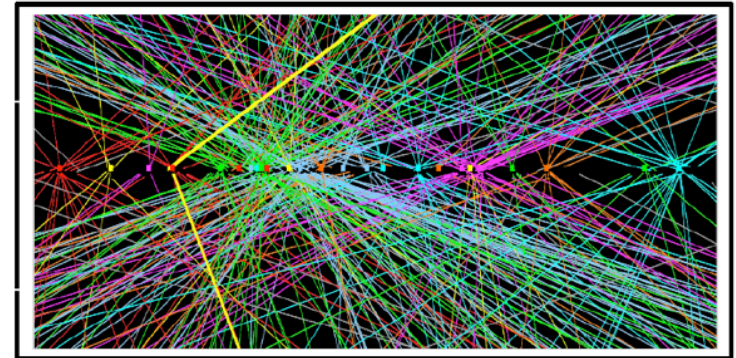
# LHC in Run 1



- LHC delivered 30 fb<sup>-1</sup>



O(25) Pile Up (PU) events

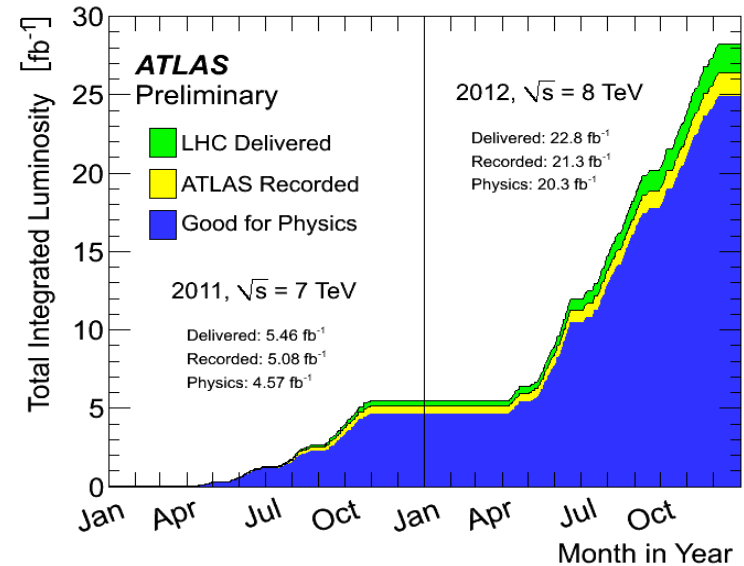
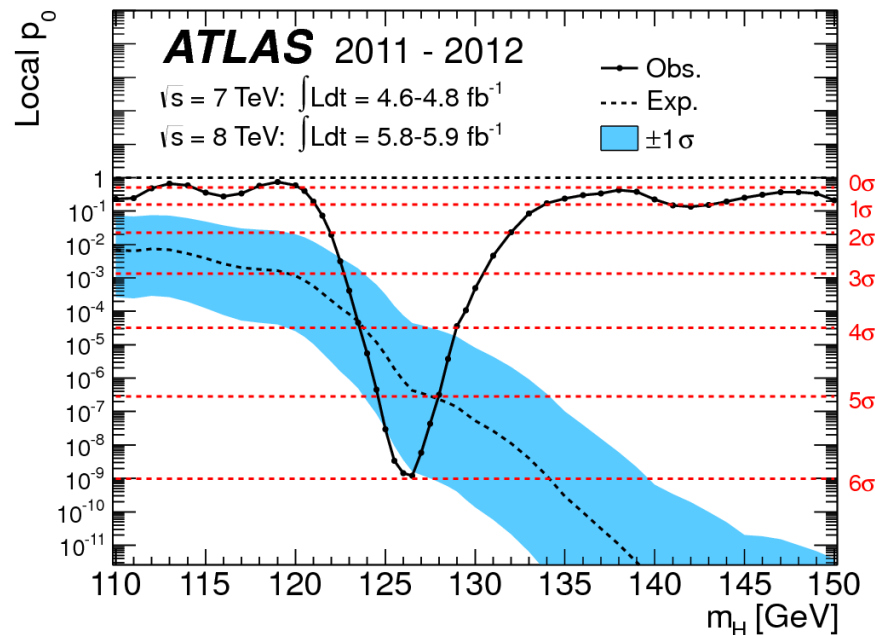


- Trigger challenge
  - Select 400 out of 40M collisions/s and keep the “New Physics”
- Computing challenge
  - Reconstruct, store and distribute 400 complex events per second
- Very stable performance
  - Data taking efficiency ~94%
  - Data quality selection ~94%



## ■ Run 1 Highlight

- A new particle was found:  
“Observation of a New Particle in the Search for the Standard Model Higgs Boson”



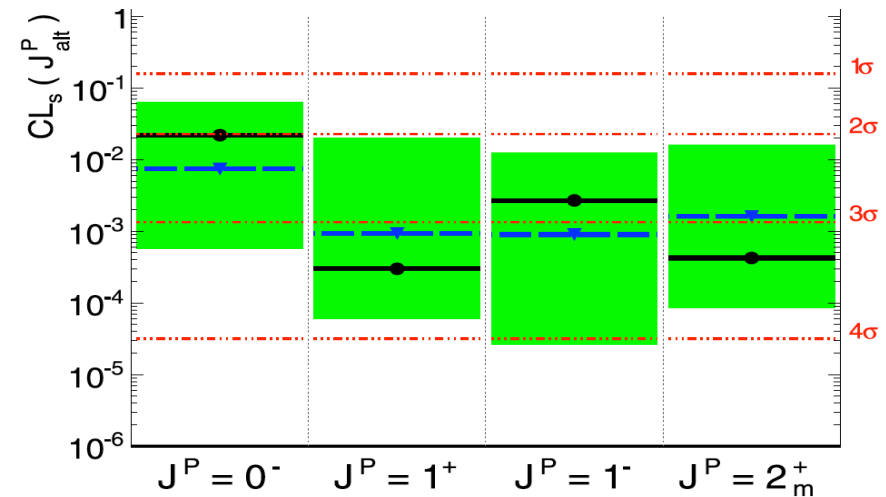
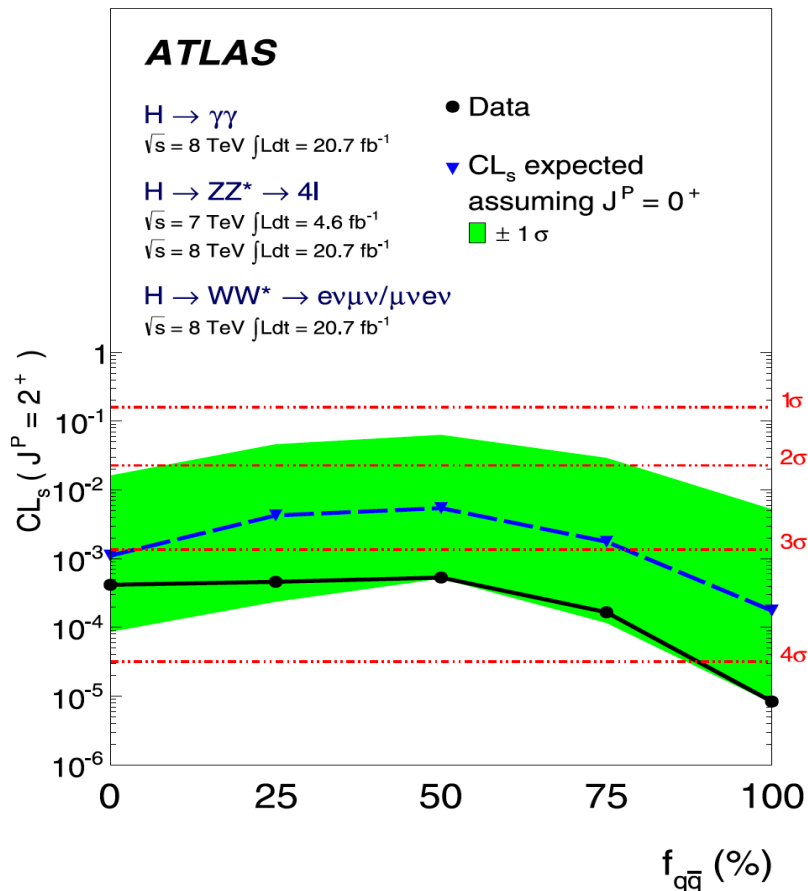
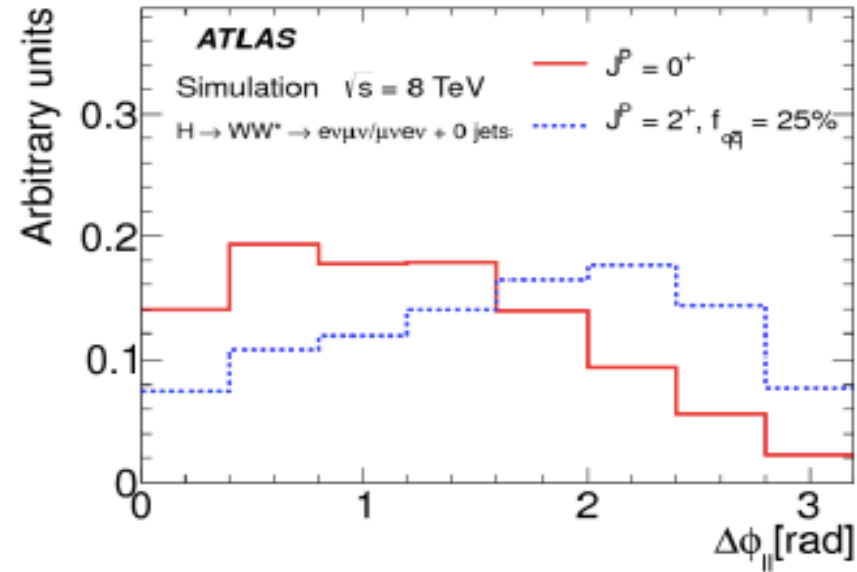
# Higgs Boson: Spin and Parity



Phys. Lett. B 726 (2013), 120-144

## ■ Reject alternative models

- $J^P = 0^-, 1^\pm, 2^+$
- It's "a Higgs boson!"



# Higgs Boson: Coupling

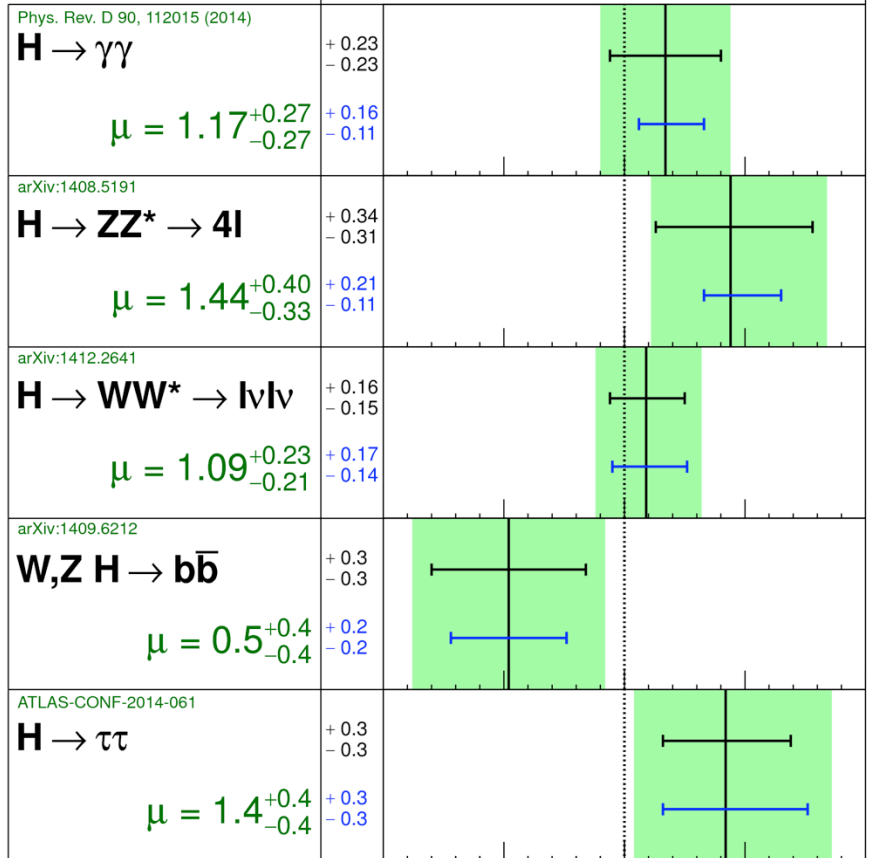
ATLAS-CONF-2015-044



**ATLAS Prelim.**

$m_H = 125.36 \text{ GeV}$

—  $\sigma(\text{stat.})$  Total uncertainty  
 —  $\sigma(\text{sys inc.})$   
 —  $\sigma(\text{theory})$   $\pm 1\sigma$  on  $\mu$

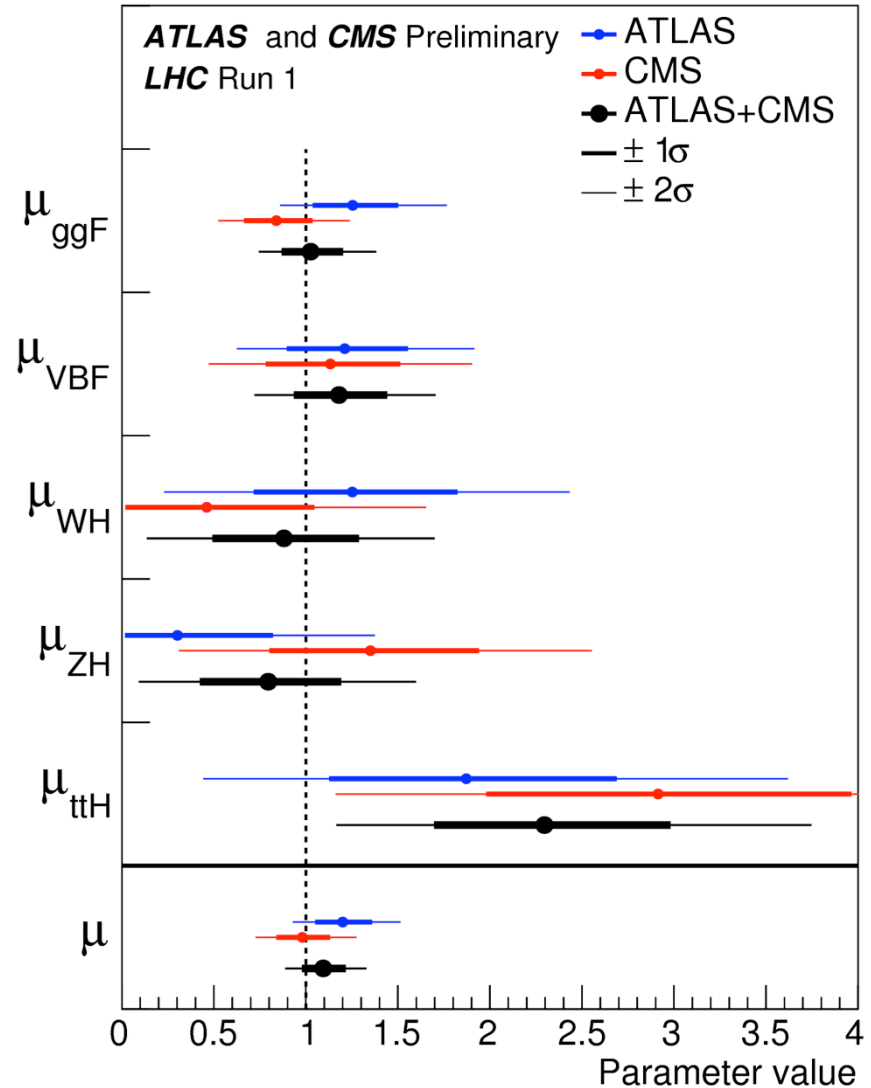


$\sqrt{s} = 7 \text{ TeV} \int \mathcal{L} dt = 4.5\text{-}4.7 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV} \int \mathcal{L} dt = 20.3 \text{ fb}^{-1}$

Signal strength ( $\mu$ )

released 12.01.2015

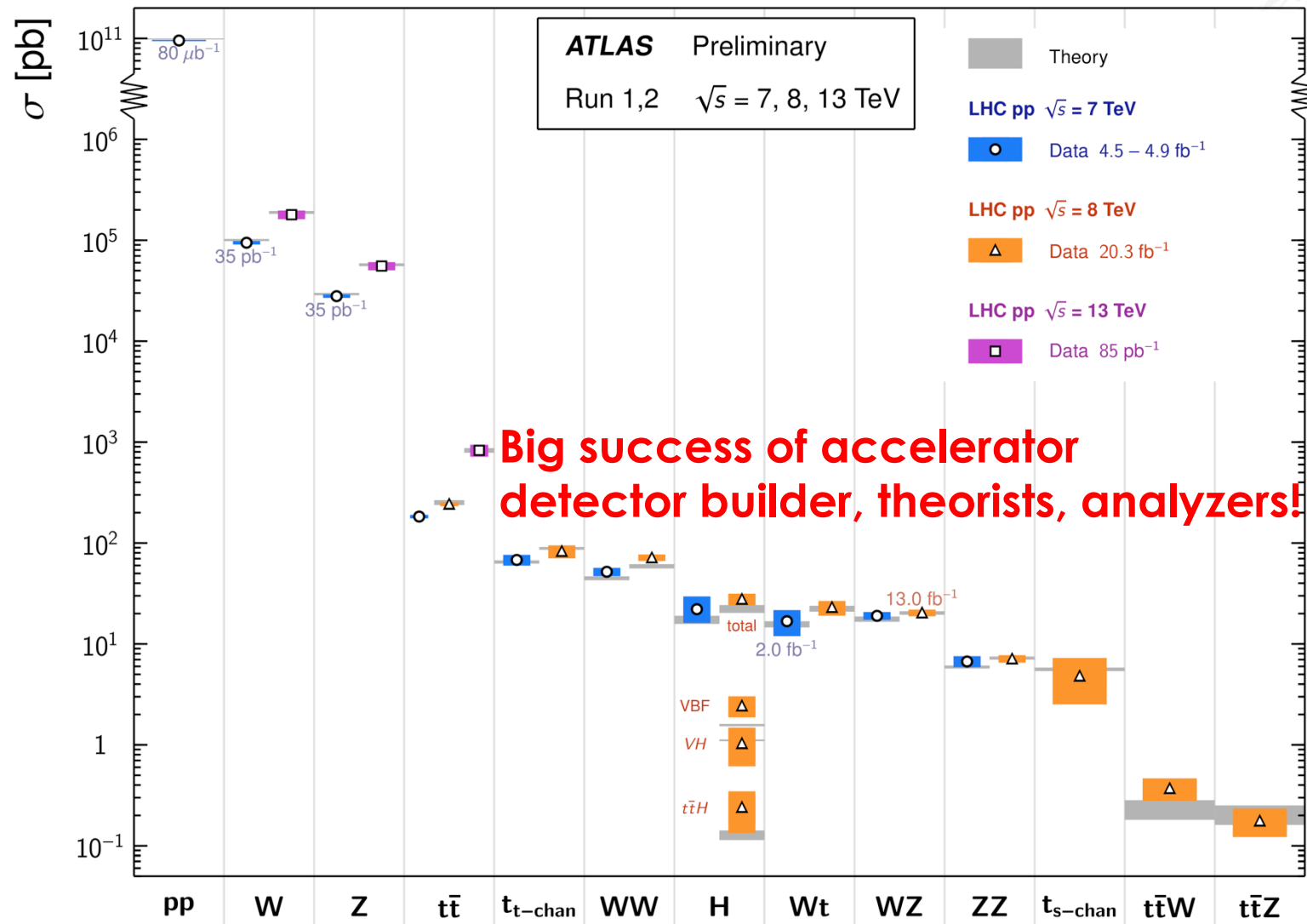


# Standard Model Measurements



## Standard Model Total Production Cross Section Measurements

Status: Nov 2015

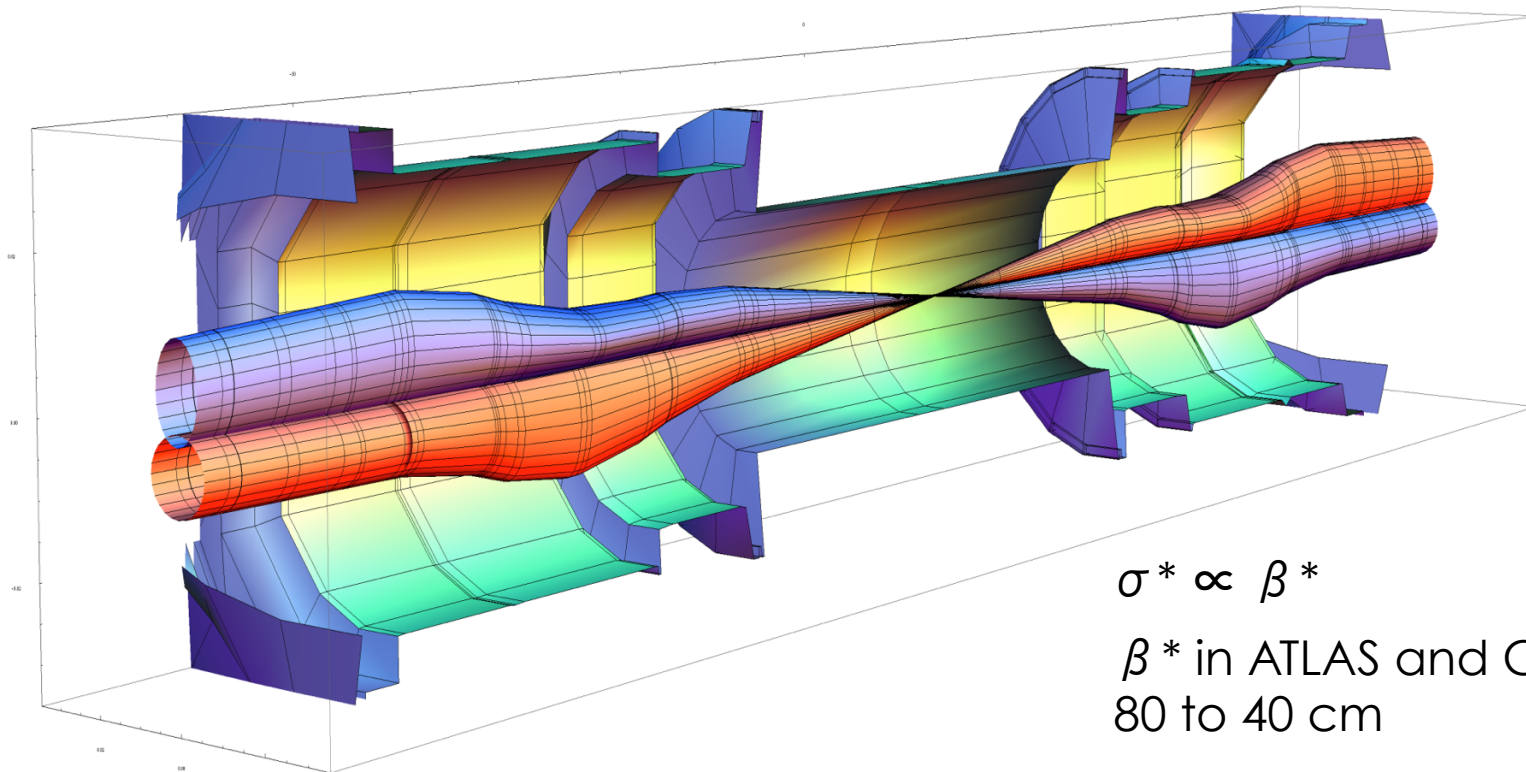


<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/>



# LHC in 2015

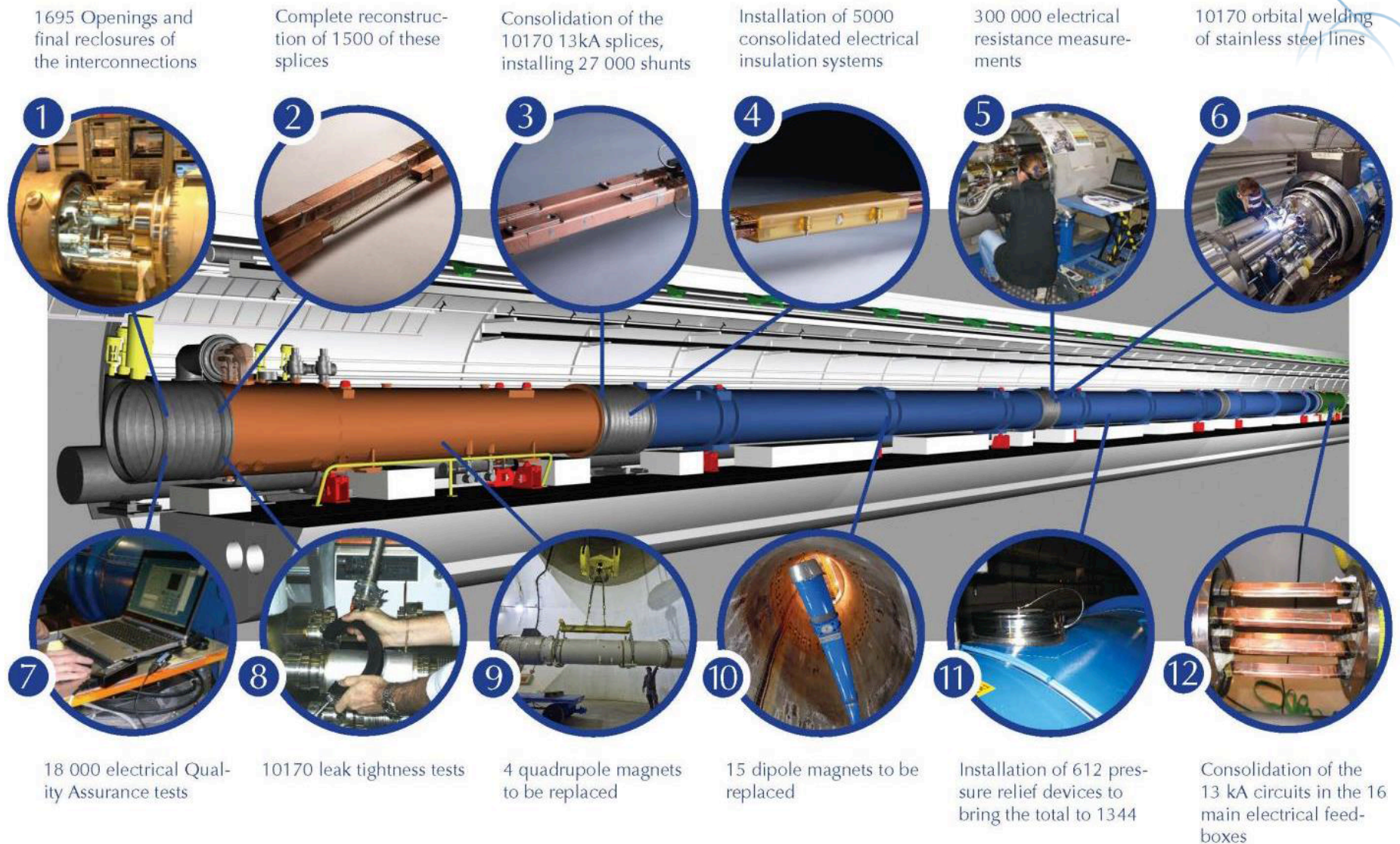
- The goal for Run 2 luminosity is  $1.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ 
  - Operation with 25 ns bunch spacing (2800 bunches), giving an estimated pile-up of 40 events per bunch crossing
- Energy 13 TeV, 6.5 TeV per beam
  - Nominal bunch intensity:  $1.15 \times 10^{11}$  protons per bunch



$$\sigma^* \propto \beta^*$$

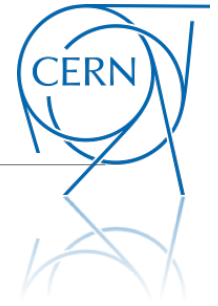
$\beta^*$  in ATLAS and CMS:  
80 to 40 cm

# Long Shutdown 1, 2013-2014





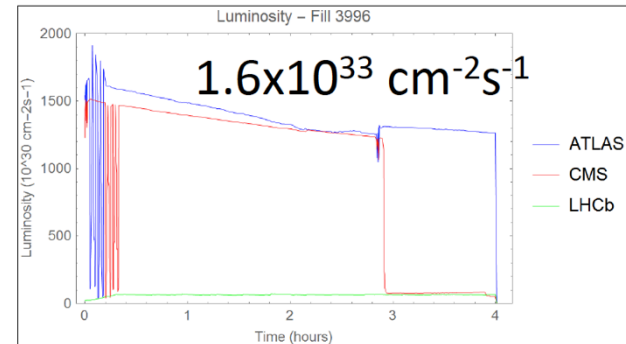
# LHC in Run 2



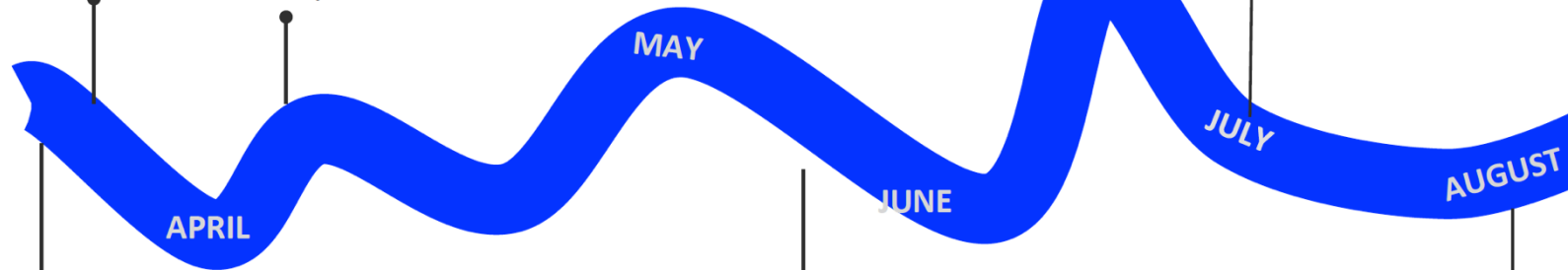
5<sup>th</sup> April  
first beam



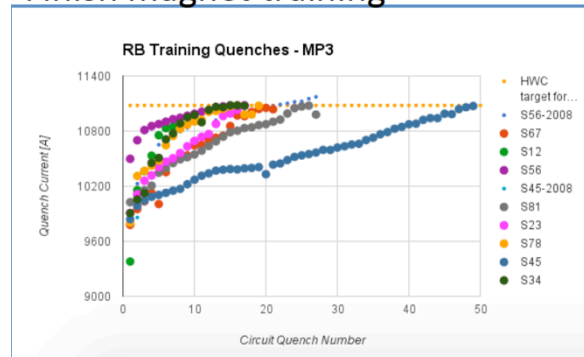
10<sup>th</sup> April: 6.5 TeV for the first time



July 14<sup>th</sup>: 476b (50 ns)



Finish magnet training



3<sup>rd</sup> June: First Stable Beams



25 ns  
219 bunches

Sergio Bertolucci  
LHCP 2015

2015

# ATLAS in Run 2: Improvements



## ■ Detectors

- IBL, 4<sup>th</sup> innermost layer of pixels (3.3 cm, 2<sup>nd</sup> layer at 5.05 cm)
- Consolidation, muon coverage, LAr and Tile calorimeters

## ■ Infrastructure

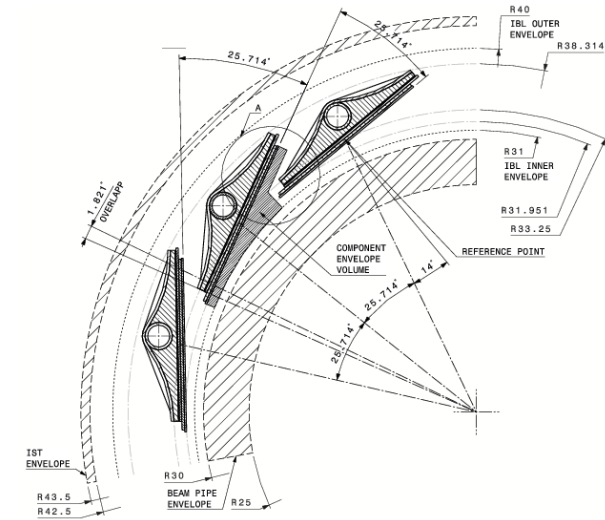
- New beam pipe, muon chamber shielding, new pixel services

## ■ Trigger

- Increased L1 rate from 75kHz to 100 kHz
- New Central Trigger Processor
- Merged L2 and HLT

## ■ Software

- Improved reconstruction software
- New analysis framework and data format

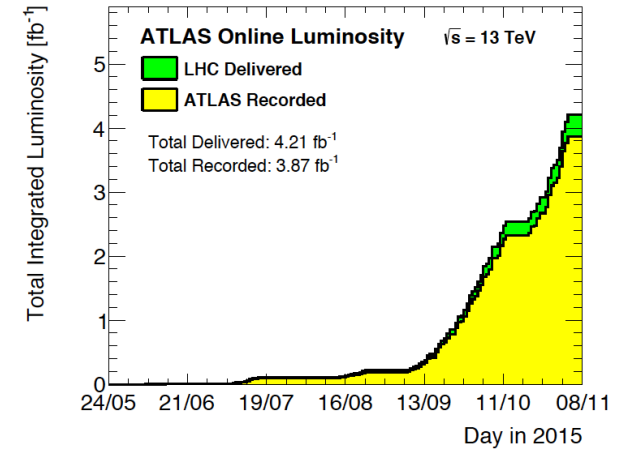




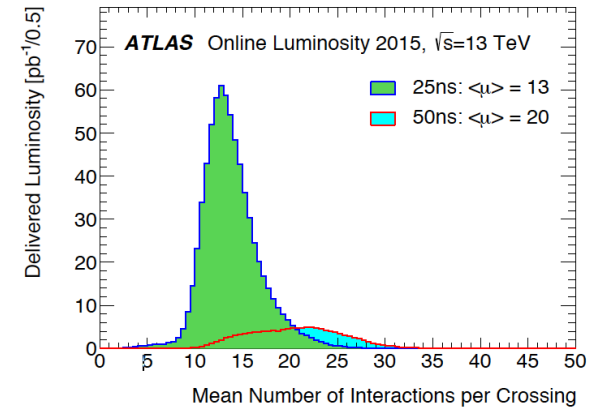
# 2015 Run in Review



- 13 TeV pp 2015 Dataset
  - **50 ns data:**  $100 \text{ pb}^{-1}$  ( $\mu \sim 20$ )
  - **25 ns data:**  $4 \text{ pb}^{-1}$  ( $\mu \sim 13$ )
  - Highest instantaneous luminosity  
 $5.1 \times 10^{33} \text{ cm}^2\text{s}^{-1}$  (Run 1:  $7\text{--}8 \times 10^{33} \text{ cm}^2\text{s}^{-1}$ )
- Heavy Ion  $677 \text{ pb}^{-1}$  collected



*Data taking efficiency of 95%*



**Run 1: 8 TeV ( $\mu \sim 21$ ) and 7 TeV ( $\mu \sim 9$ )**

**ATLAS: Pileup at Run-2 less critical than at Run-1**

PbPb  
collision  
at 1.1 PeV

Events  
With charged  
track  
Multiplicities  
of up to 10k  
tracks



# Tracking Performance

ATLAS-CONF-2015-064



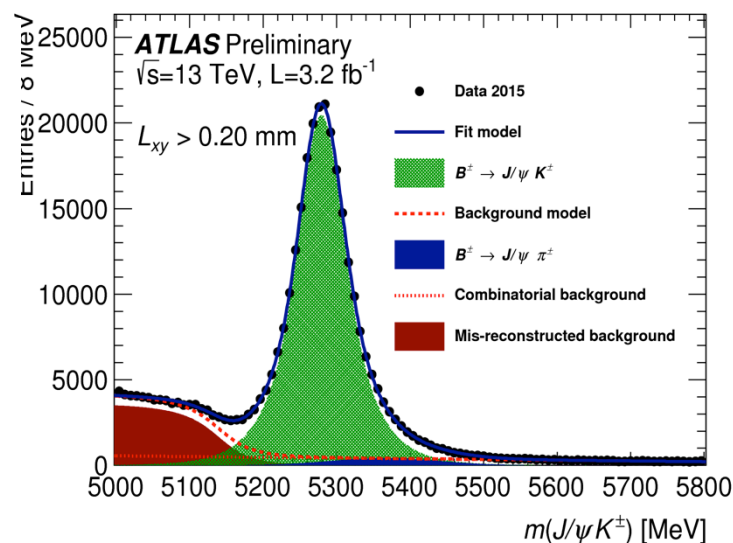
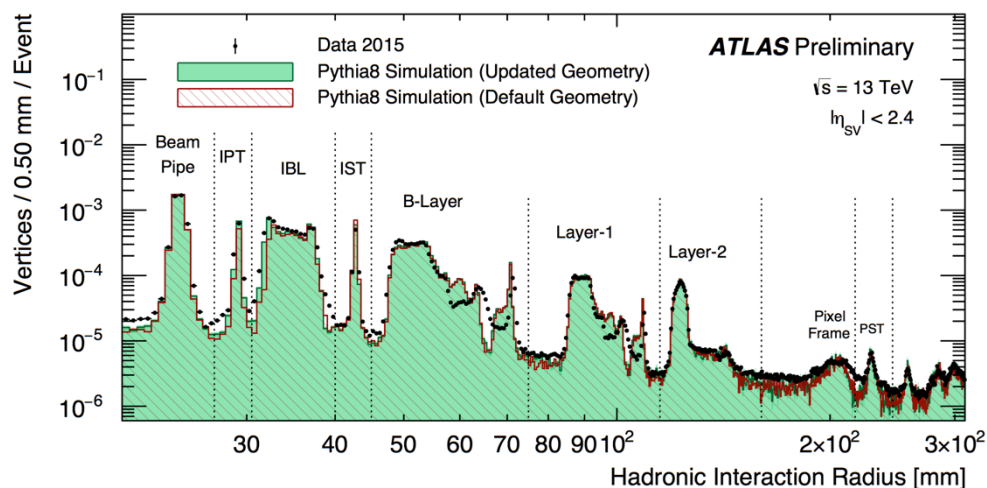
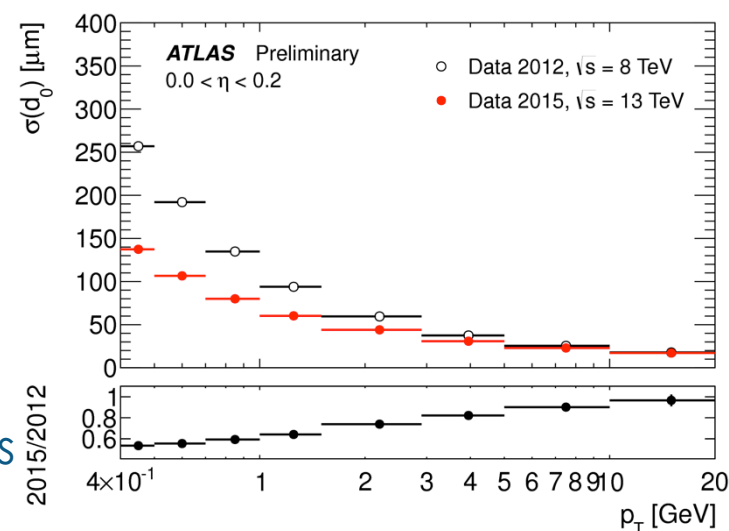
- Improved tracking performance due to IBL

- Alignment and tracking performance check with  $B^\pm \rightarrow J/\psi K^\pm$  mass

- $m(B^\pm) = 5279.32 \pm 0.10(\text{stat}) \pm 0.22(\text{syst}) \text{ MeV}$

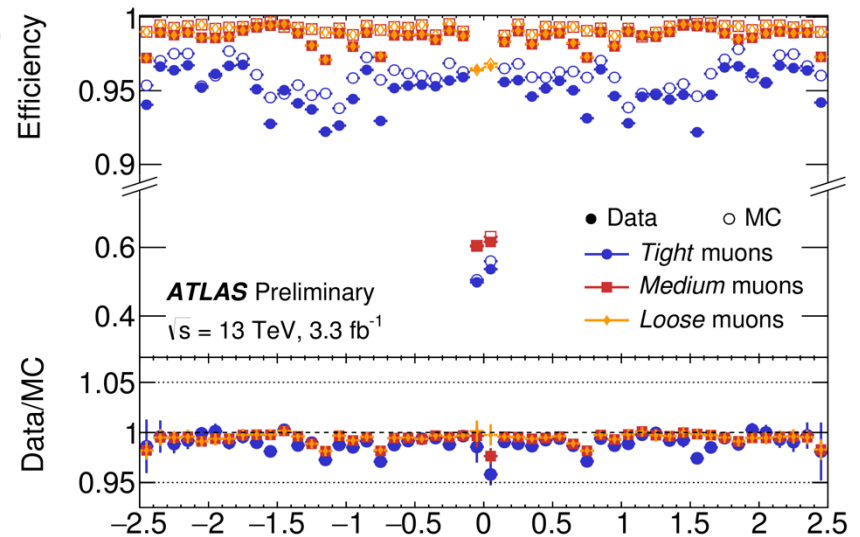
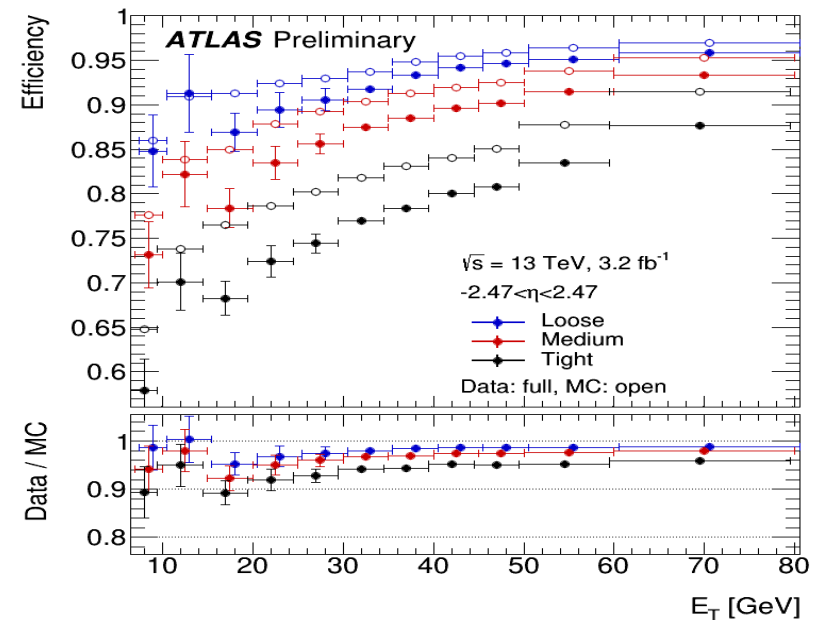
- Additional material due to IBL, services and new beam pipe

- Material studies using hadronic interactions and conversions



# Combined Performance

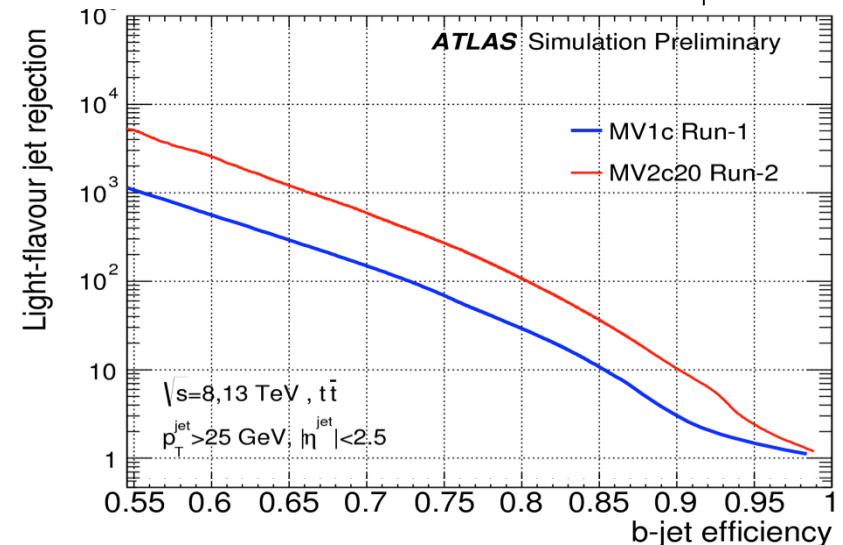
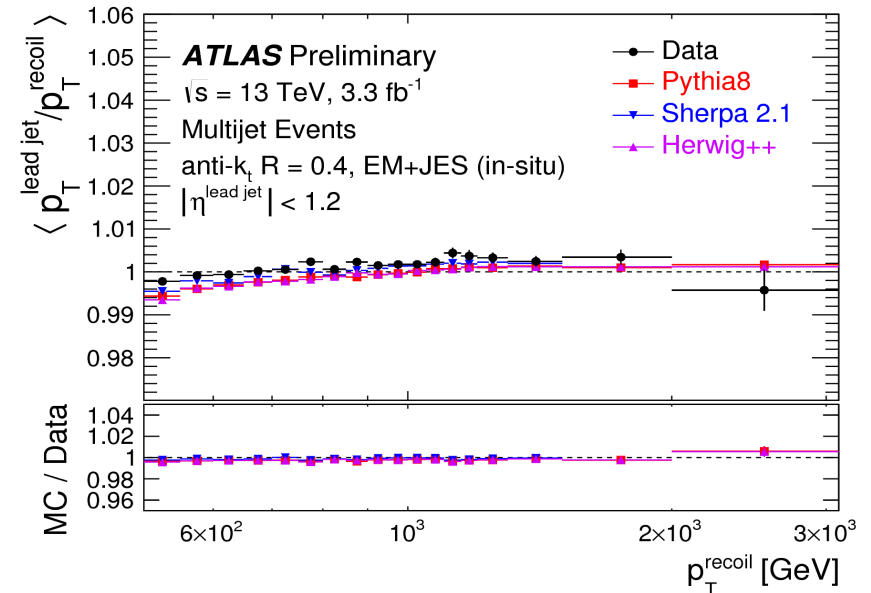
- **Electrons** efficiency, full 2015 data driven measurements
- **Photon** efficiency, from Run 1 and MC extrapolation
- Calibration
  - Based on Run 1 with MC extrapolation, checked with Run 2
- **Muon** efficiency (tag and probe) and energy scale / resolution calibration with Z and J/ψ data
- Alignment with toroid off data
  - Close to design performance
  - O(10%) relative resolution for TeV muons



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/December2015-13TeV>

# Combined Performance

- **Jets** MC extrapolated from Run 1
  - Many checks in Run-2 data
    - JES balance photon-jet
    - JES balance with multi-jet
- **MET** extrapolated from Run 1
  - multiple checks in data
- **Flavour Tagging**
  - Improvements from IBL and new algorithms
  - Improved light jet rejection by 4
  - MC calibration checked with top quark events
  - Fully consistent within uncertainties



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/December2015-13TeV>



# W and Z Cross Sections

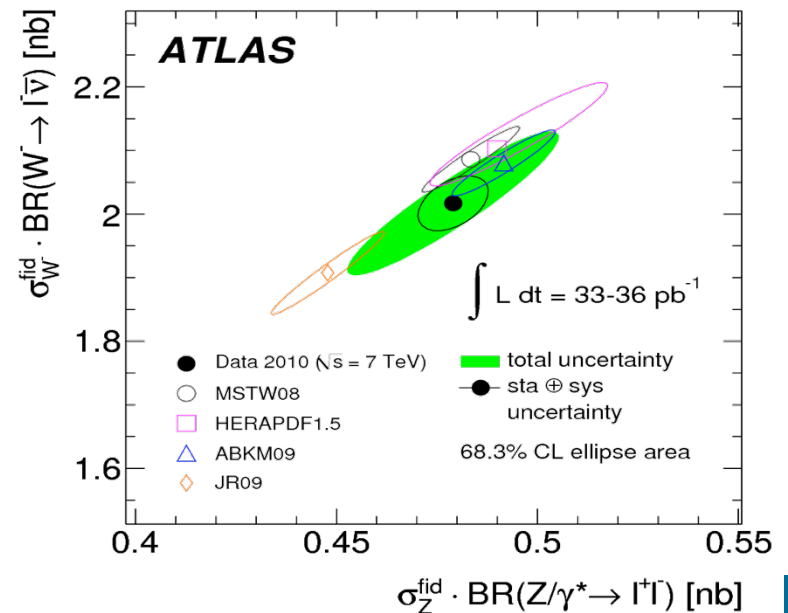
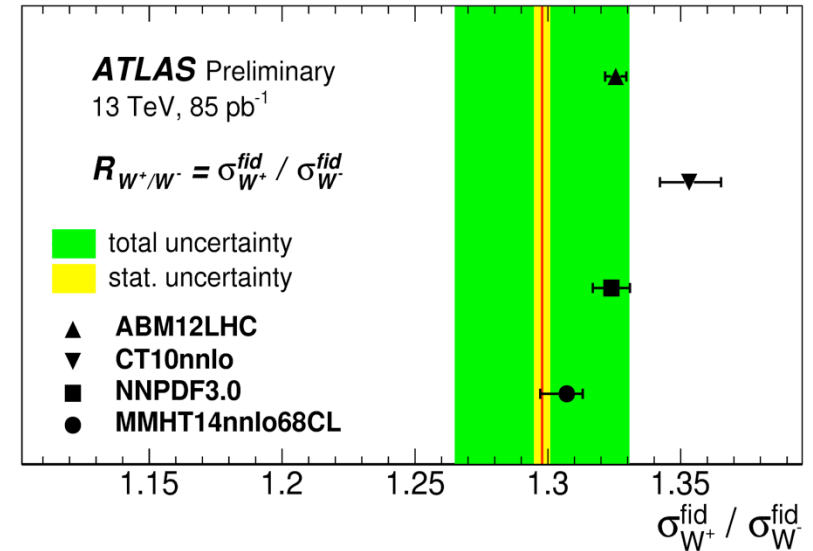
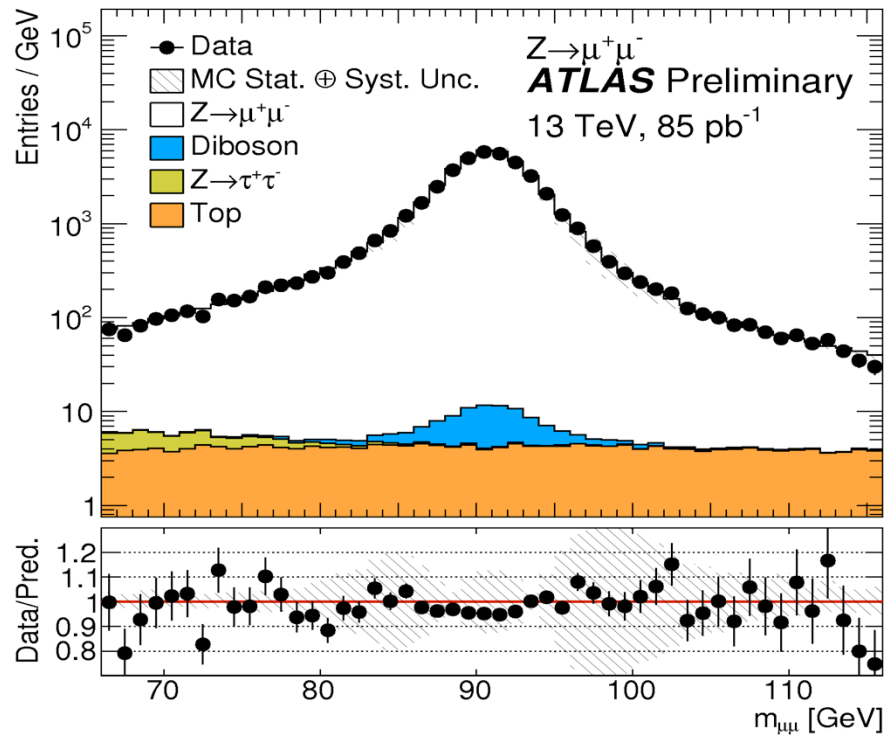
ATLAS-CONF-2015-039

## ■ Proton Structure

- Probed by various hard processes

## ■ W, Z, jets...

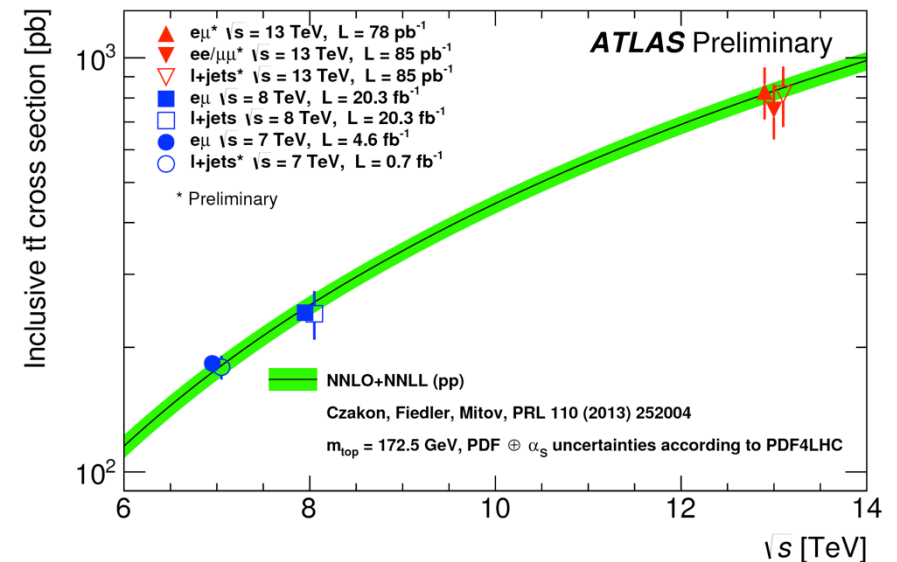
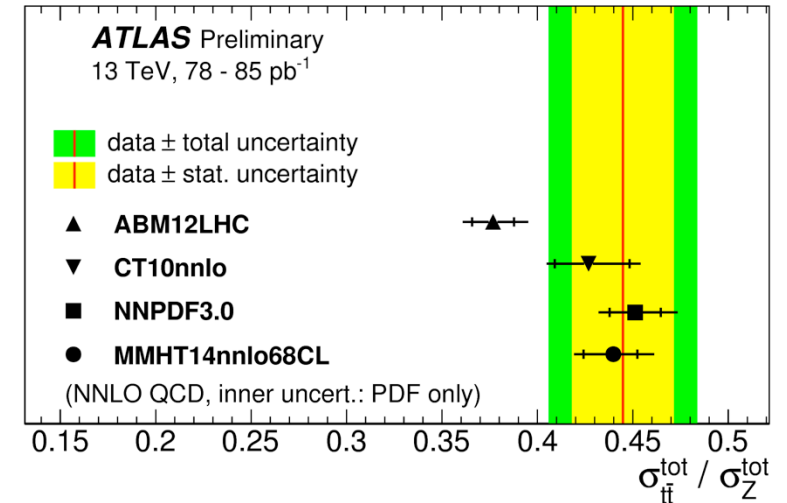
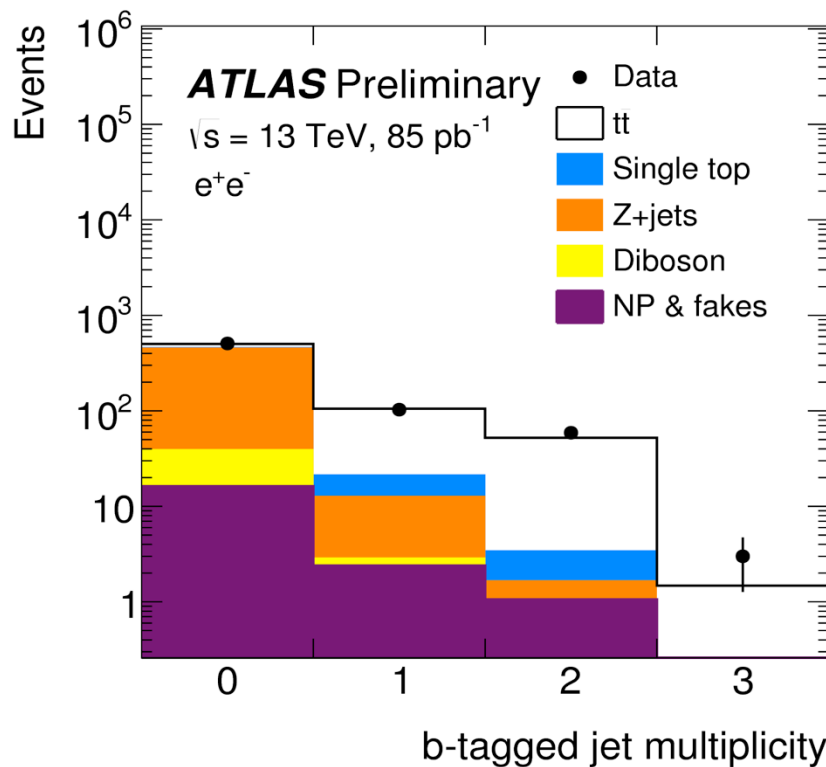
- Include in global PDF fits



# Top Quark

ATLAS-CONF-2015-049

- Top quark cross section consistent with NNLO+NNLL QCD calculations
- Probe as a function of center of mass energy



# Higgs in Run 2

ATLAS-CONF-2015-059  
ATLAS-CONF-2015-060

- Mass taken to be ATLAS-CMS combined measurement

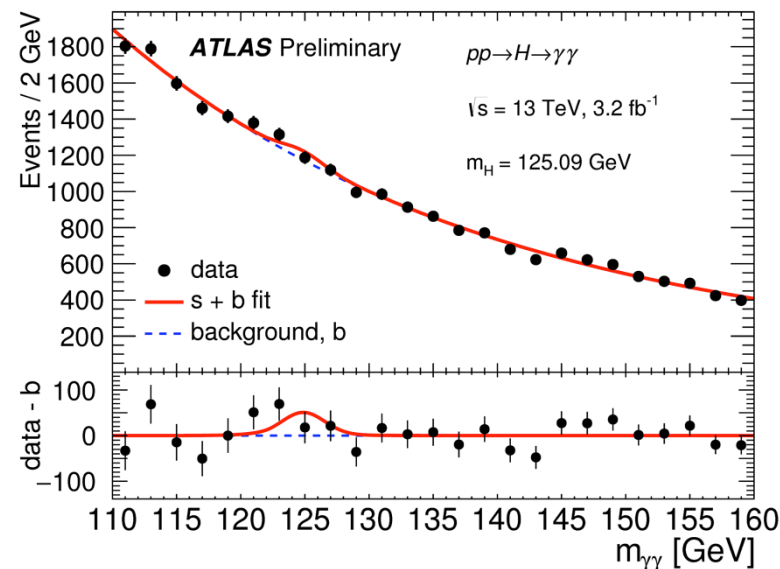
- $m_H = 125.09 \pm 0.24 \text{ GeV}$

Phys. Rev. Lett. 114, 191803

- Diphoton channel

- Sensitivity to SM Higgs:  $1.9\sigma$

- Observed:  $1.5\sigma$

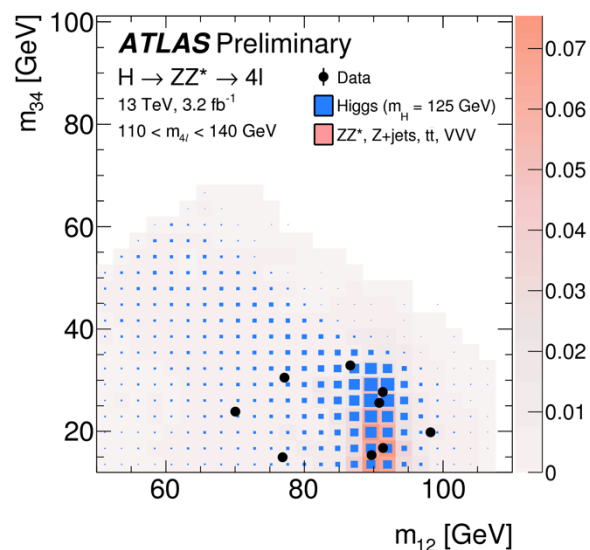
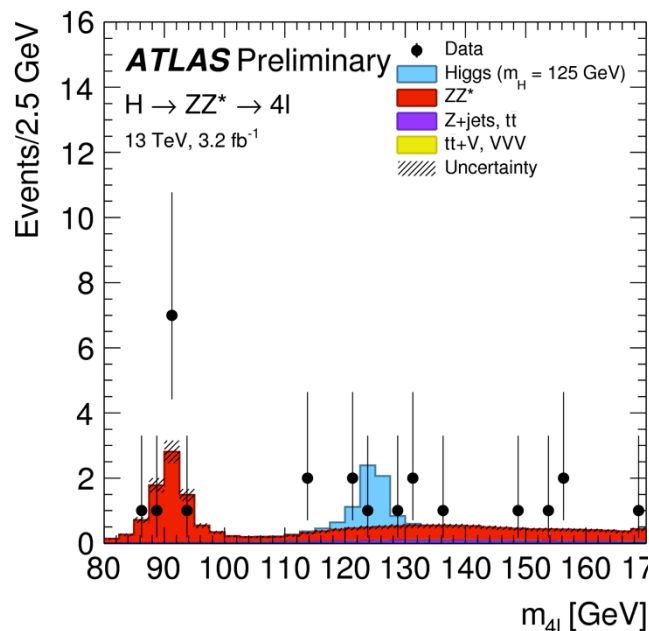


- Four lepton channel

- Fully inclusive

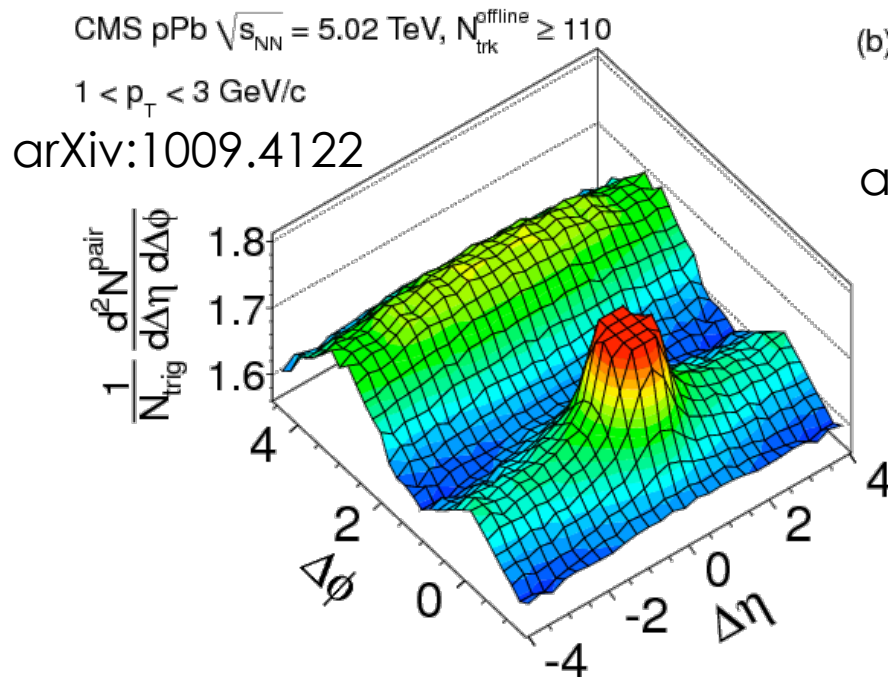
- Sensitivity:  $2.8\sigma$

- Observed:  $0.7\sigma$

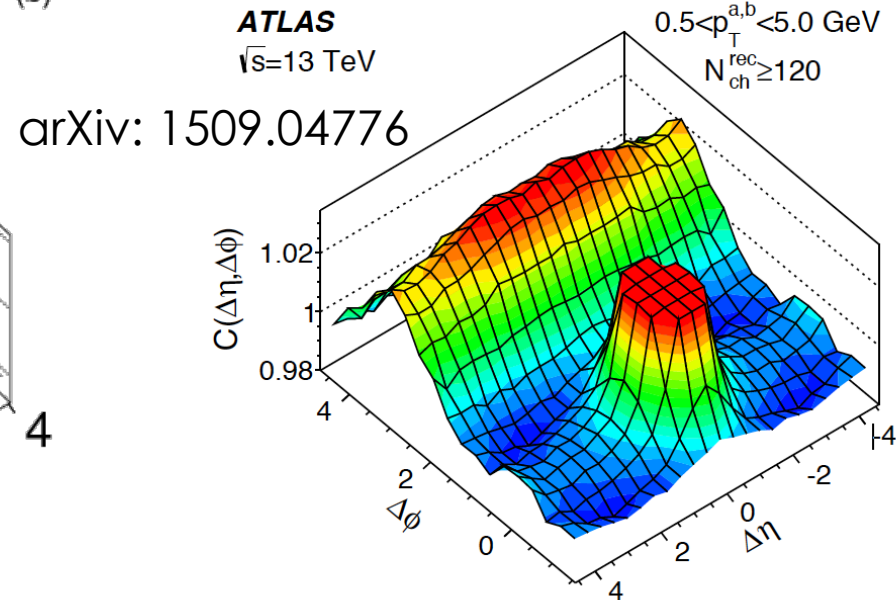


# Long Range Elliptic Anisotropies

- Same-side ridge in high multiplicity events in p-p system, seen by ATLAS now at 13 TeV
  - Two particle correlations as a function of azimuthal angle and pseudorapidity
- Collectivity in small systems?
  - Testing ridges in pp and p-Pb collisions might give insight in underlying physics and may help distinguish between competing explanations

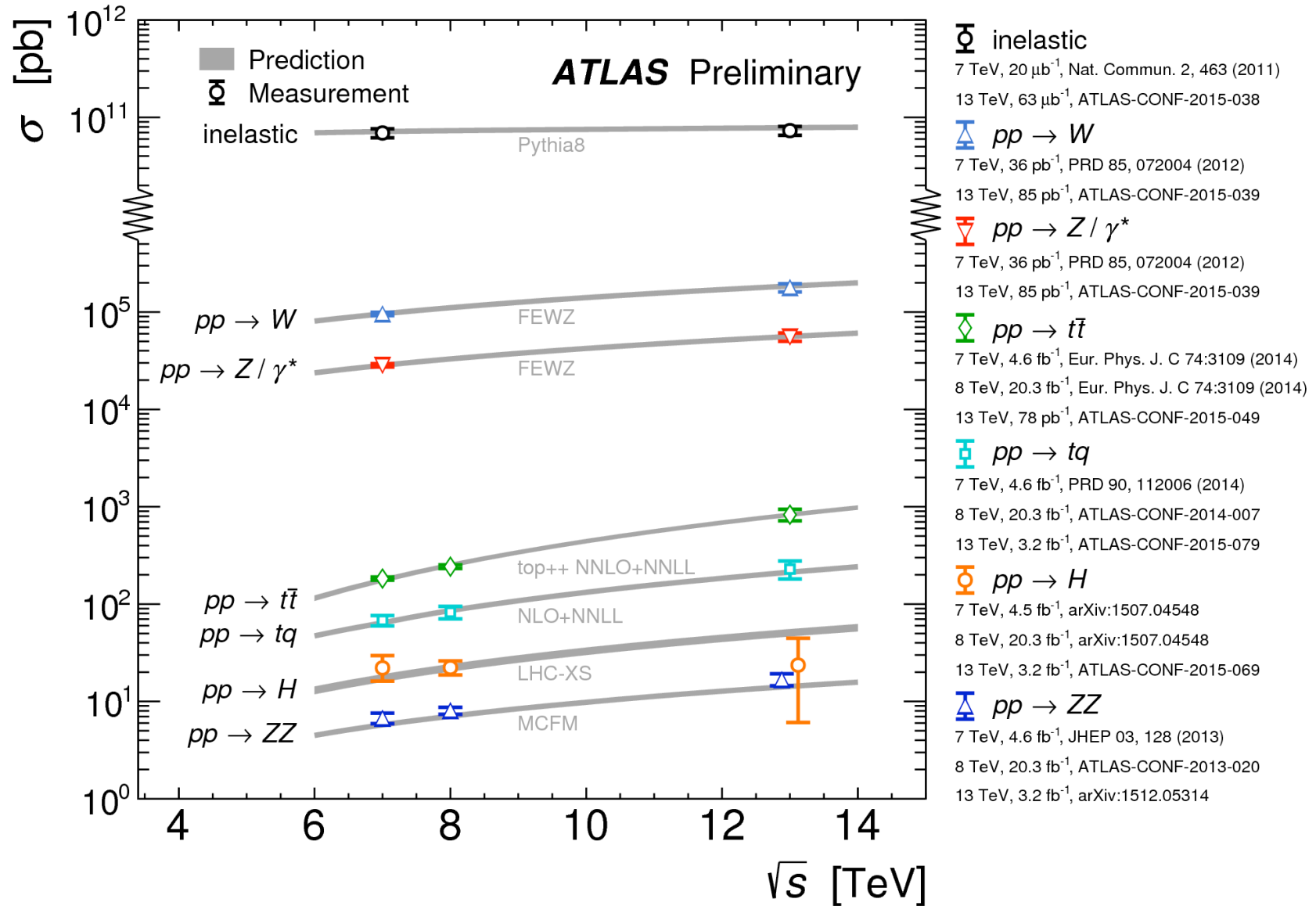


(b)





# Summary of Total Run 2 Cross Sections



<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/>

# Motivation for New Physics

Now that we found a Higgs, we know there has to be New Physics

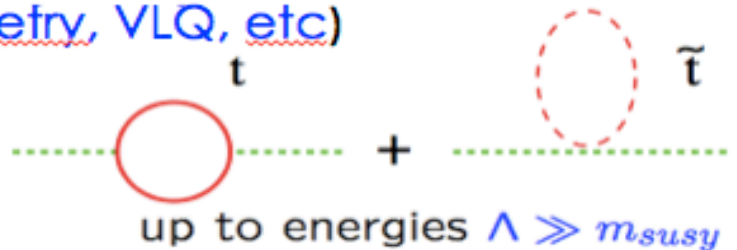
## Option A

D. Morrissey

- Introduce **new particles** with mass  $M \sim \text{TeV}$  to cancel off quantum corrections above this scale (e.g. SuperSymmetry, VLQ, etc)

## Option B

- Physics “as we know it” ends at scale  $\Lambda \sim \text{TeV}$ .
    - e.g. Warped / Large Extra Dimensions
      - $\Lambda \sim$  scale of new spacetime structure/quantum gravity
    - e.g. New Strong Dynamics / Technicolour
      - $\Lambda \sim$  new strong coupling scale, composite higgs
- => **Many new resonances** with masses near  $\Lambda$



## Option C

- Multiverse, our universe *happens to be observable*
  - weak scale has its special value “by accident”

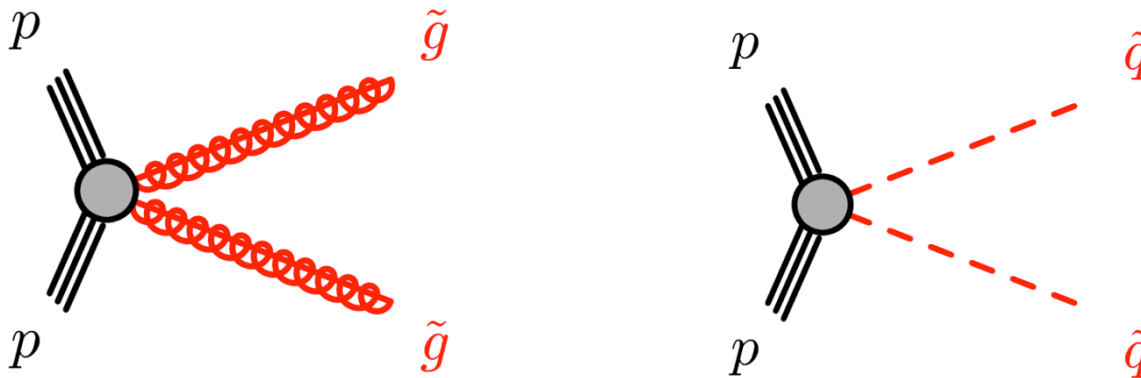
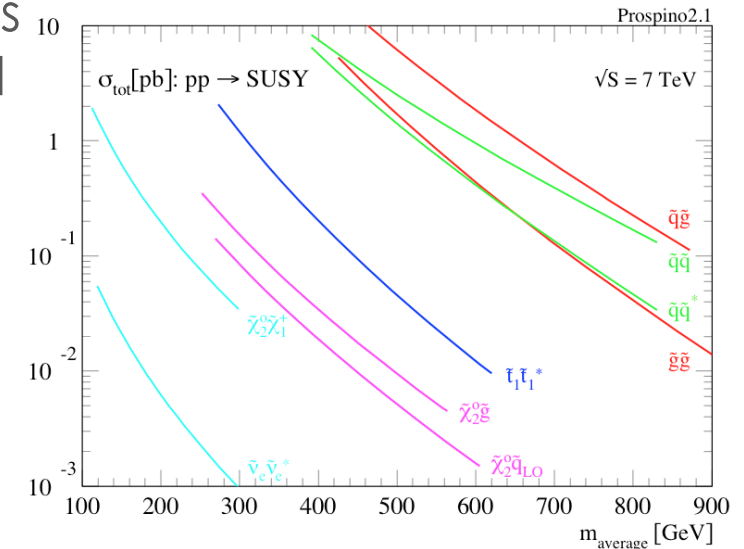


=> *Still need to explain: dark matter, matter/antimatter excess, etc.*

# Early Searches for SUSY



- At this early stage of Run 2, main focus is on strong production of Gluinos and Squarks
- Ratio of 13 TeV / 8 TeV cross sections
  - Squark and gluino 1.5 TeV: **35**
  - Squark and gluino 1 TeV: **15**
- 44 signal regions covered, large number of decay chains including jets, MET, leptons, b-jets

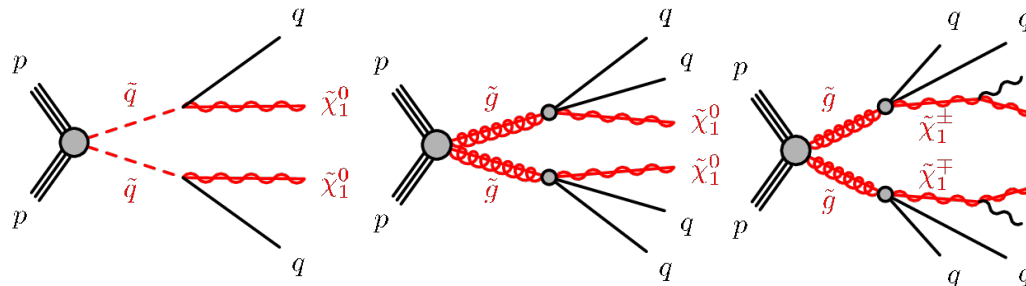


# Strongly Produced SUSY

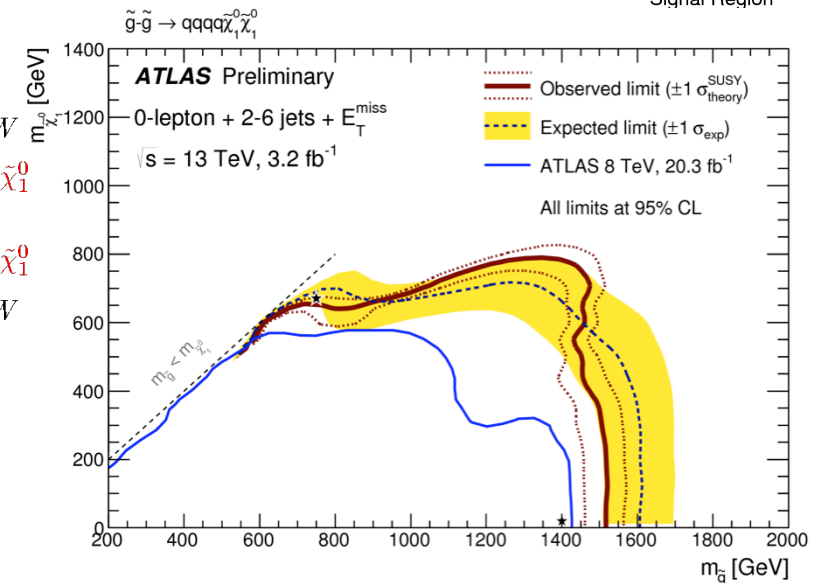
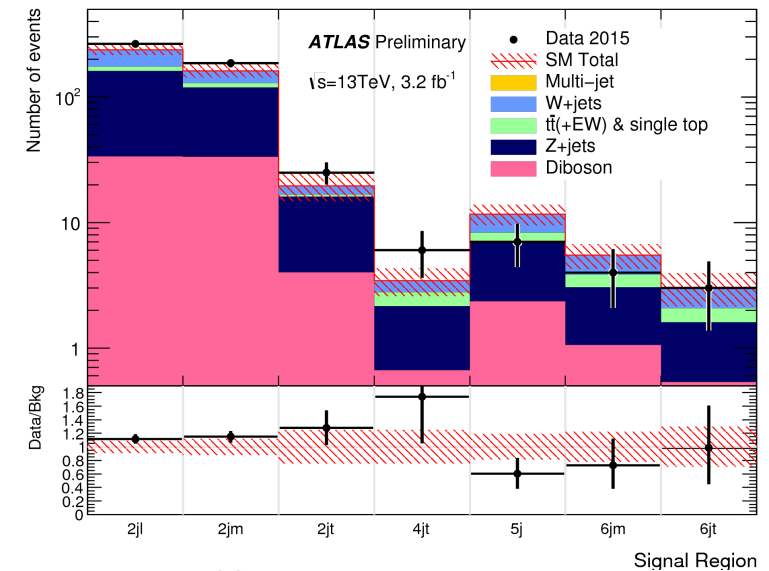
ATLAS-CONF-2015-062

- Search for squarks and gluinos in 6 signal regions aiming at simplest production and decay modes
  - 2-6 jets and Missing Energy

- 44 signal regions covered, large number of decay chains including jets, MET, leptons, b-jets



- Background estimates from dedicated control regions



Limits on gluino mass reach 1.5 TeV

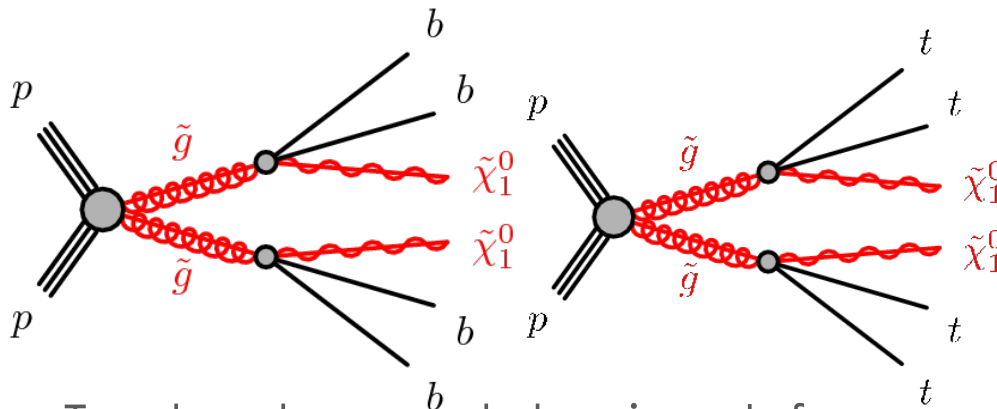


# Strongly Produced SUSY II

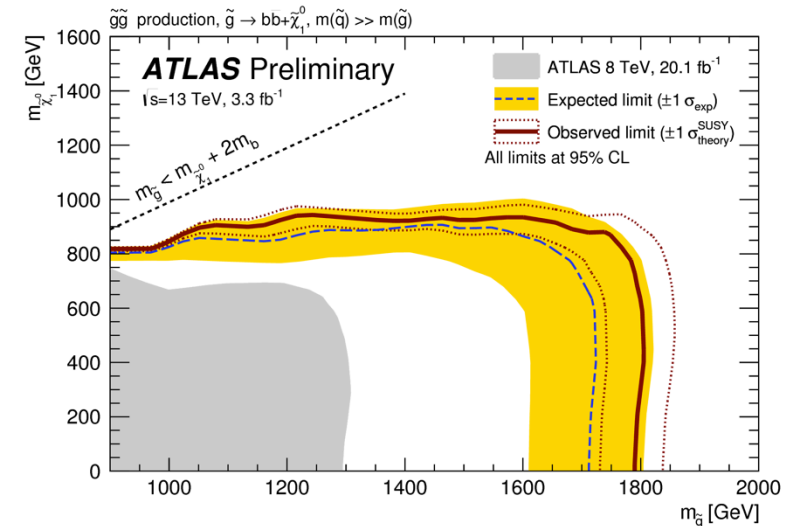
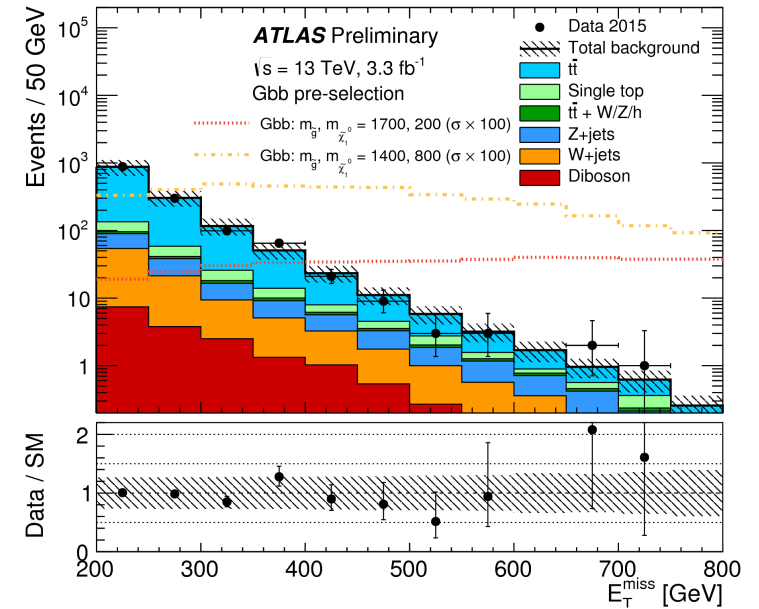
ATLAS-CONF-2015-067

- Search for gluinos in 8 signal regions with multiple b-jets aiming at decays b and top quarks
  - Multi-b signatures

- Signal categories, no lepton and 1 lepton, MET and multiple jets including b-jets



- Top background dominant, from MET control region

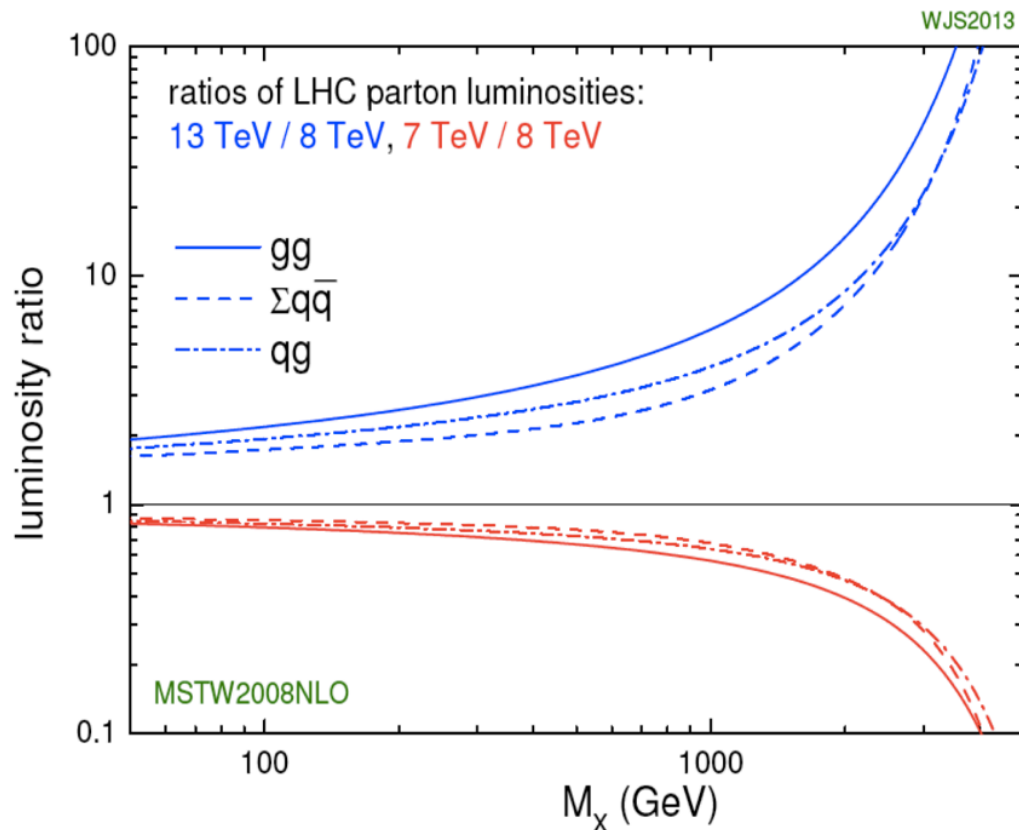


Limits on gluino mass reach 1.8 TeV

# Early Searches for New Phenomena



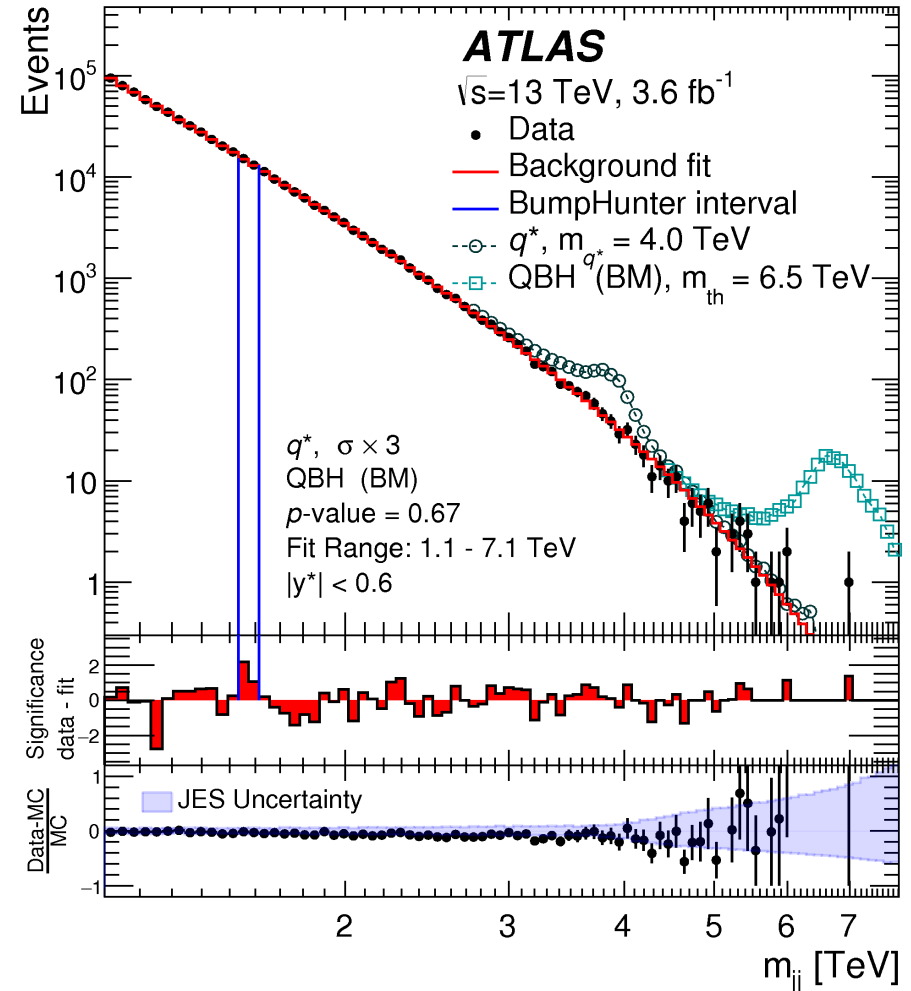
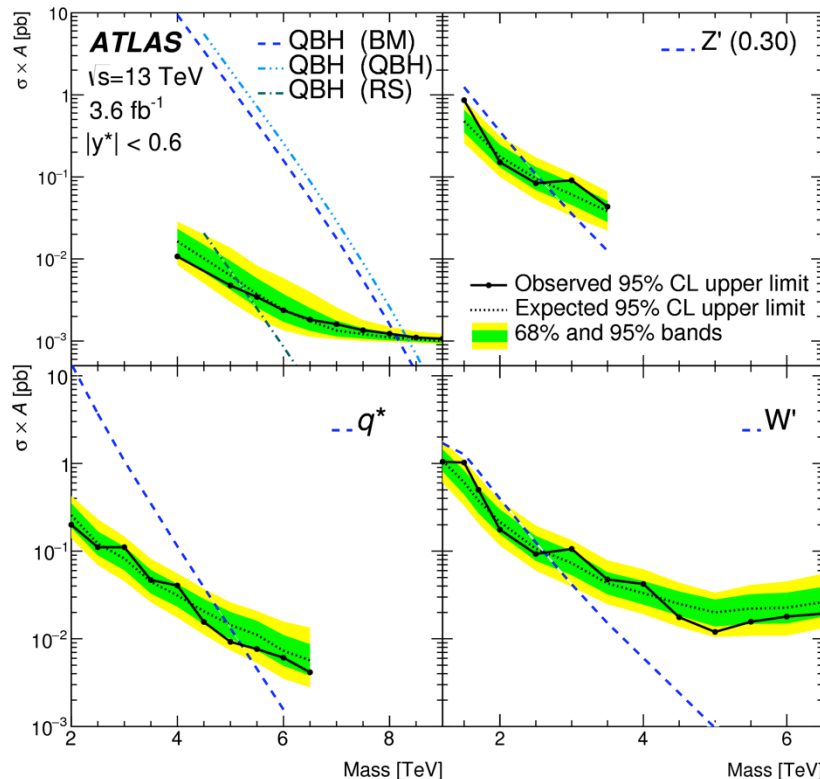
- Ratio of 13 TeV / 8 TeV cross sections
  - $Z'$  at 3 TeV: **20**
  - Excited quark  $q^*$  at 4 TeV: **56**
  - Quantum Black Hole at 5 TeV: **370**
  - Quantum Black Hole at 6 TeV: **9000**



# Dijet Resonance Search

arXiv:1512.01530

- Search for peak in invariant mass spectrum
- QBH, excited quarks,  $W'$ ,  $Z'$
- Background using simple analytic fit function



Limits on QBH reaching 8 TeV



ATLAS  
EXPERIMENT  
<http://atlas.ch>

Run: 280673  
Event: 1273922482  
2015-09-29 15:32:53 CEST

## *Di-Jet Event*

*Highest Mass Central Dijet*

$$pT_1 = pT_2 = 3.2 \text{ TeV}$$

$$m_{jj} = 6.9 \text{ TeV}$$

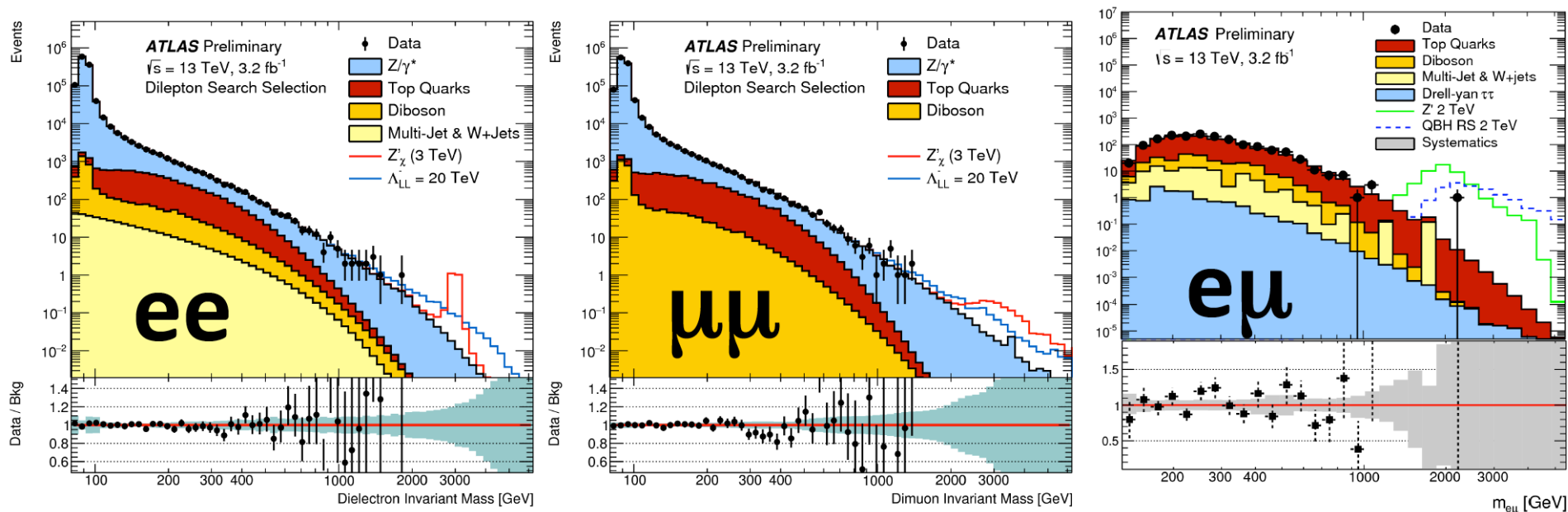
$$MET = 46 \text{ GeV}$$



# Dilepton Resonance Search

ATLAS-CONF-2015-070  
ATLAS-CONF-2015-072

- Main background DY taken from MC
  - corrected at NNLO using mass dependent k-factor



- Search for  $Z'$ 
  - Same flavor ( $ee$ ,  $\mu\mu$ )
    - 95 % CL limit on SSM  $Z$  at 3.4 TeV (2.9 TeV from Run 1)
  - Opposite flavor ( $e\mu$ )
    - 95 % CL limit on SSM LFV  $Z$  at 3.0 TeV (2.5 TeV from Run 1)

# Di-Electron Event

High Mass Dielectron

$ET_1 = 370 \text{ GeV}$   $ET_2 = 246 \text{ GeV}$

$m_{ee} = 1.8 \text{ TeV}$

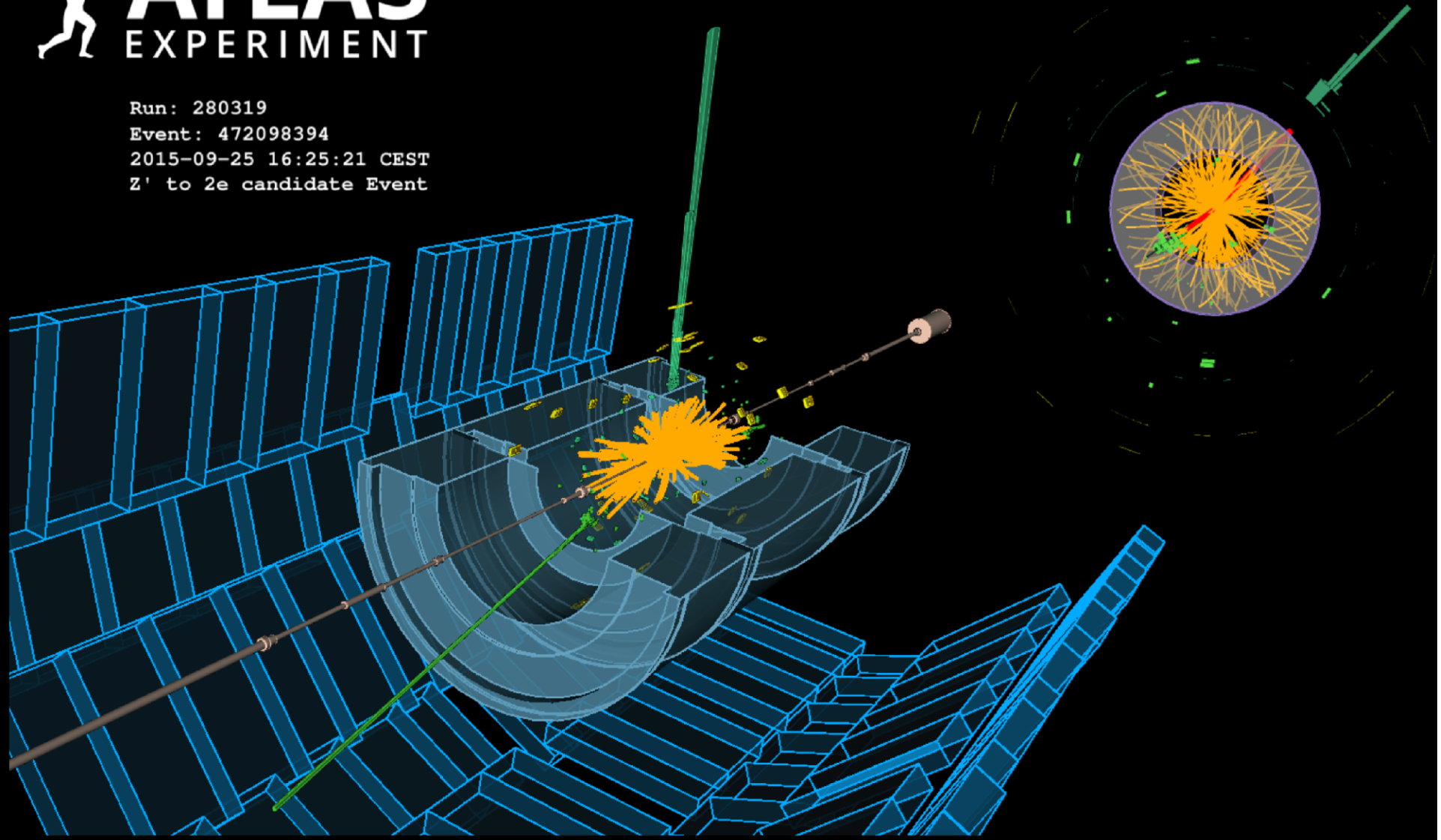


Run: 280319

Event: 472098394

2015-09-25 16:25:21 CEST

Z' to 2e candidate Event

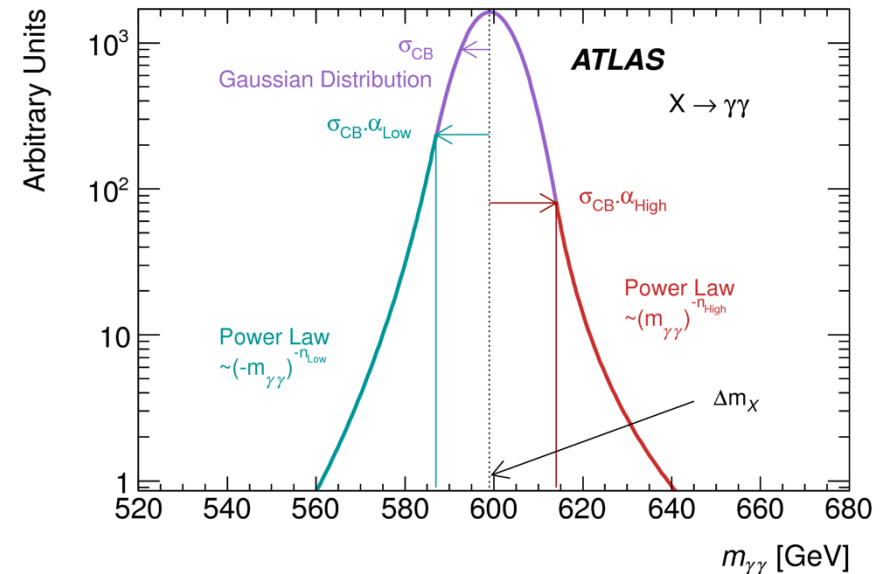


# Diphoton Resonance Search

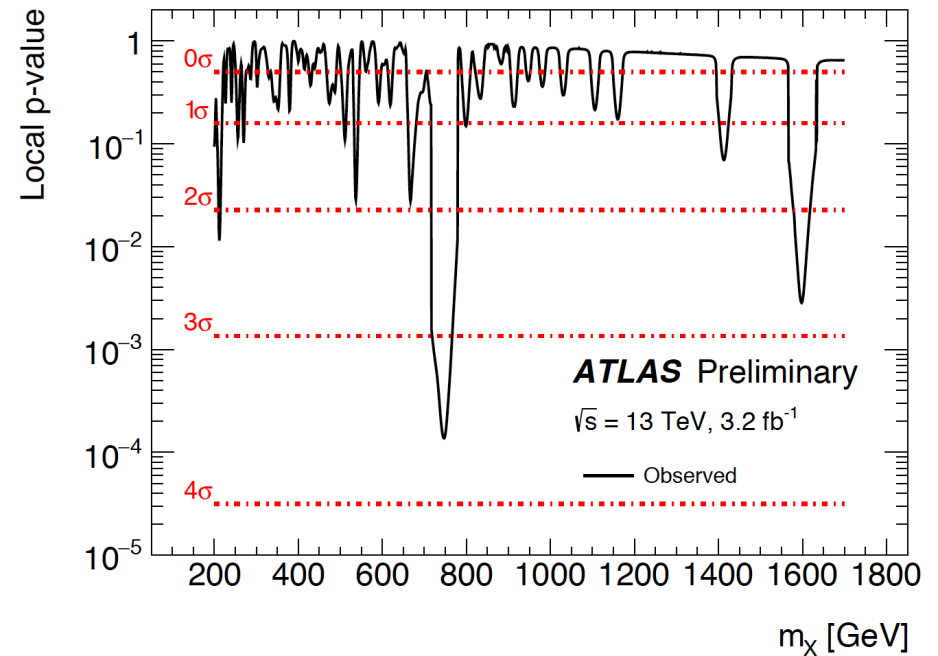
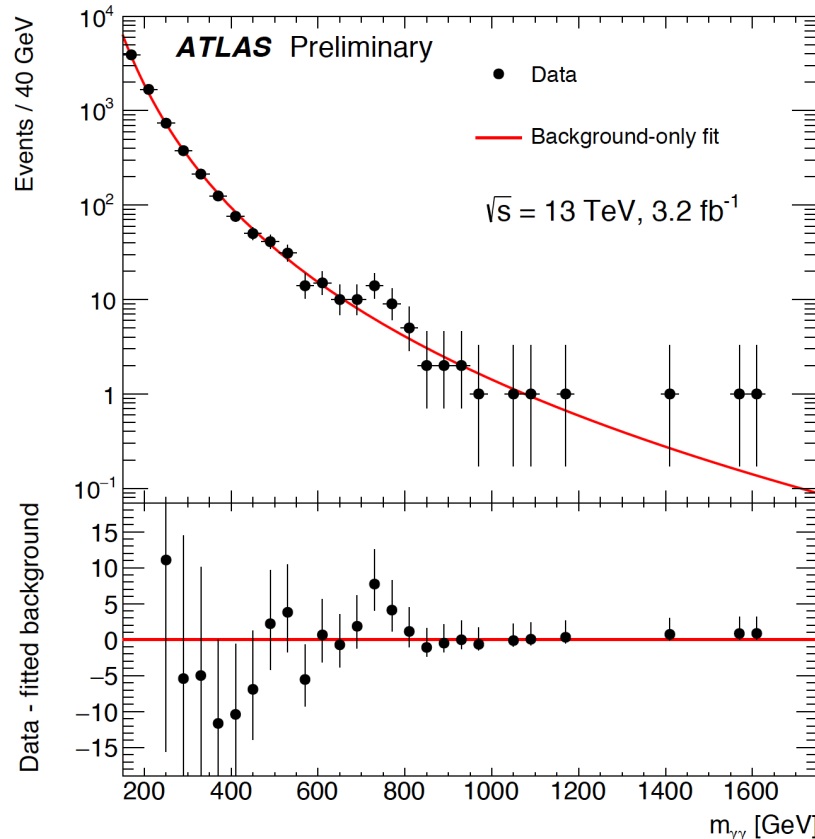
- Inclusive search, optimized for scalar resonance
  - Typical prompt photon purity 90%
- Background using analytic fit function similar to dijet search

$$f_{bkg}(x; b, \{a_k\}) = (1 - x^{1/3})^b x^{\sum_{j=0}^k a_j \log(x)^j}$$

- Signal Model use double sided Crystal Ball function
- Narrow width approximation
- Large width
  - Use parameters from fitting simulated samples with different widths up to 25% resonance mass



- Events with mass  $> 200$  GeV are included in unbinned fit



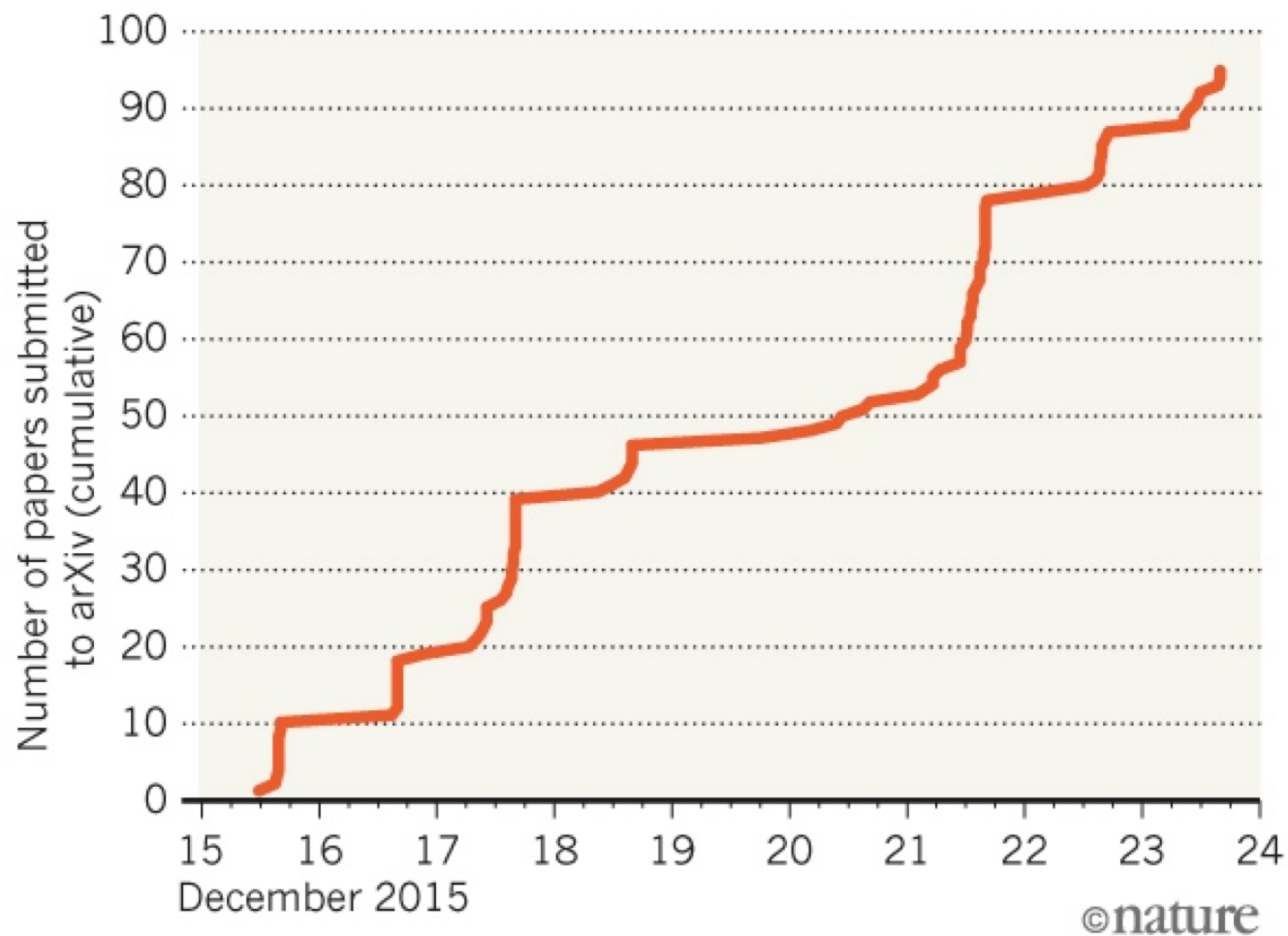
- Data prefers a width of 6% under the LW hypothesis
- Local significance increases to  $3.9\sigma$
- Including LEE in mass and width of up to 10%, global significance is  $2.3\sigma$
- In NWA, an excess of  $3.6\sigma$  local is observed at a mass of 750 GeV
- Including LEE in range 0.2-2 TeV, global significance is  $2.0\sigma$



# Theory Community

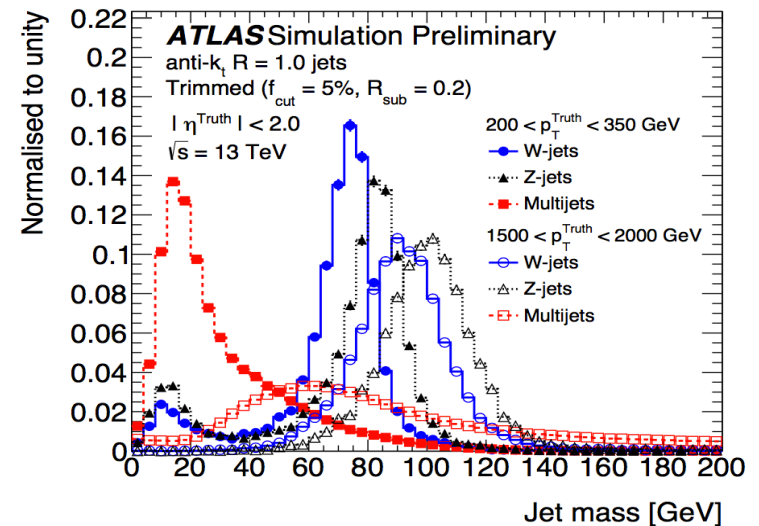
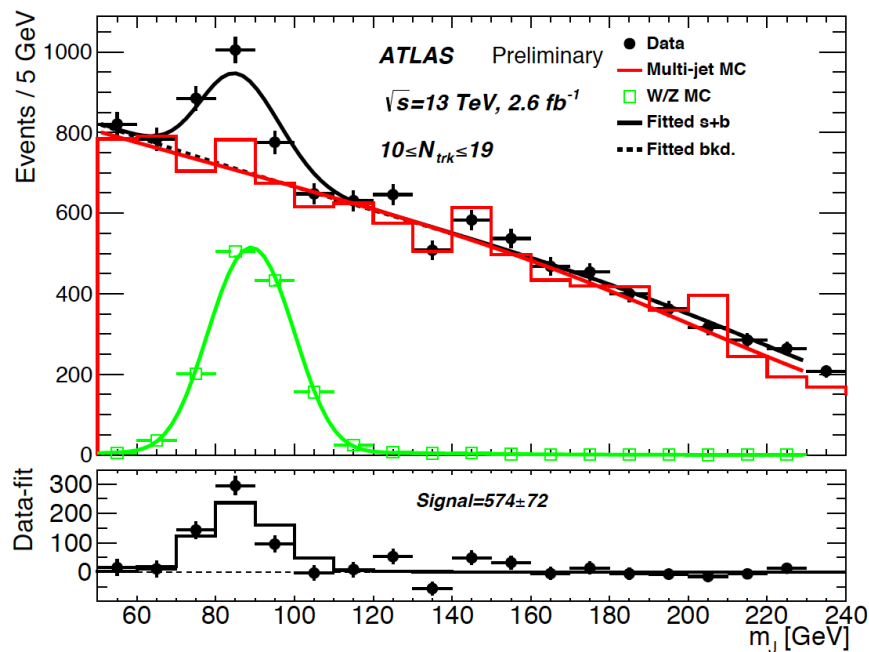
## HINT OF NEW BOSON SPARKS FLOOD OF PAPERS

In just 9 days, physicists have posted 95 papers on the arXiv preprint server about tantalizing results at the Large Hadron Collider.



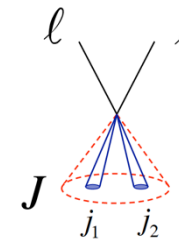
# Diboson Search with Jet Substructure

- Nominal boson tagging
  - Anti- $k_T$  jets  $R=1.0$
  - $p_T$  dependent selection on energy correlation, separately for W and Z
- W and Z peak in data from dijet events!

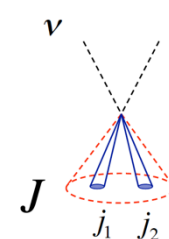


## Various VV final states

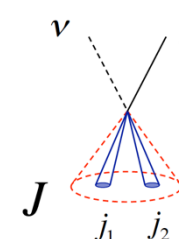
ZV (with Z to dilepton)



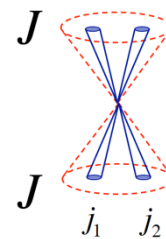
ZV (with Z to  $\nu\nu$ )



WV (with W to  $\ell\nu$ )



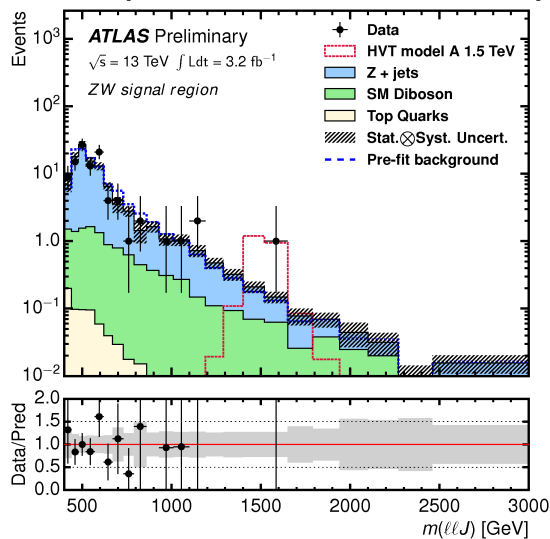
VV to JJ



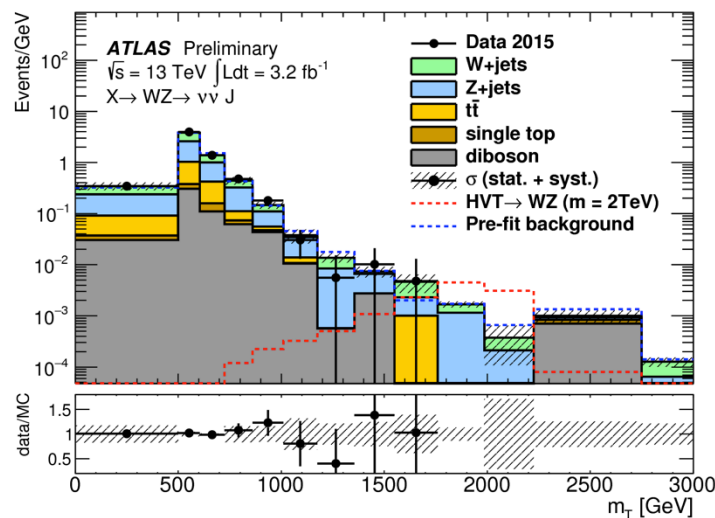
# Diboson Resonance Search

## ■ Signal regions

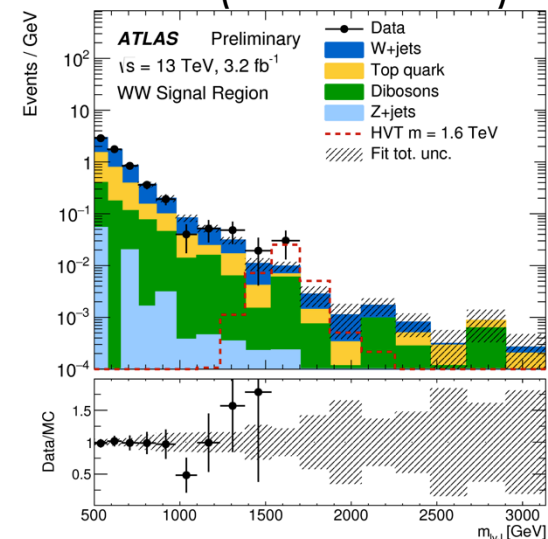
### ZV (with Z to dilepton)



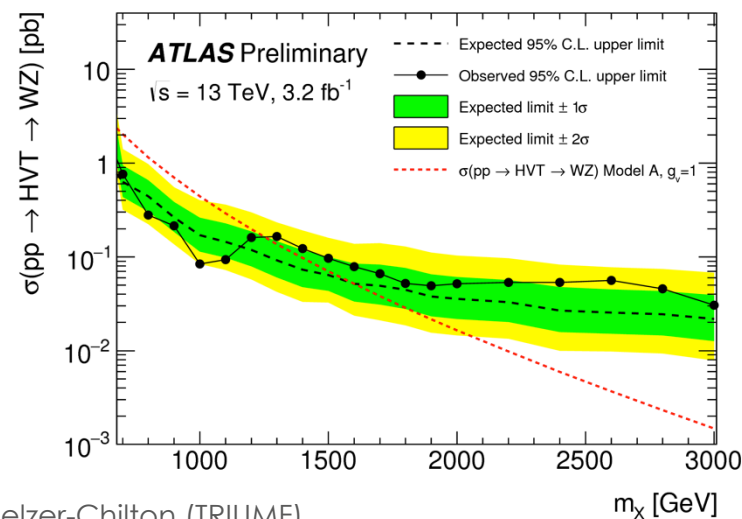
### ZV (with Z to neutrinos)



### WV (with W to $\ell\nu$ )



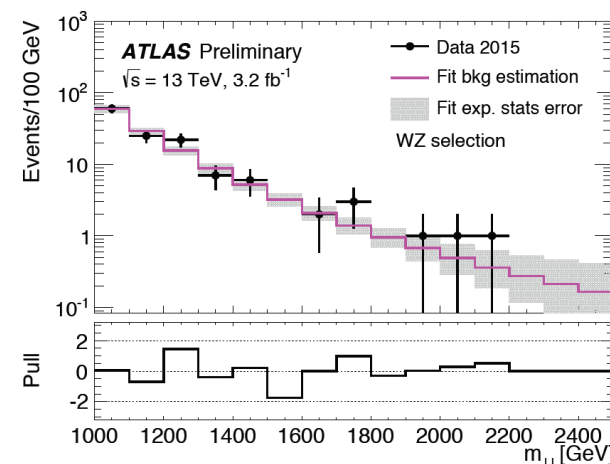
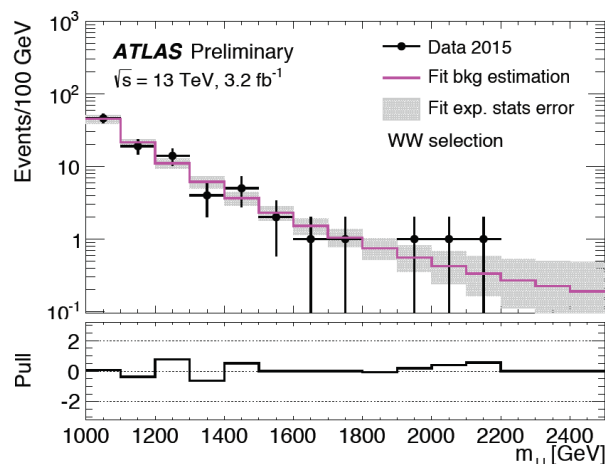
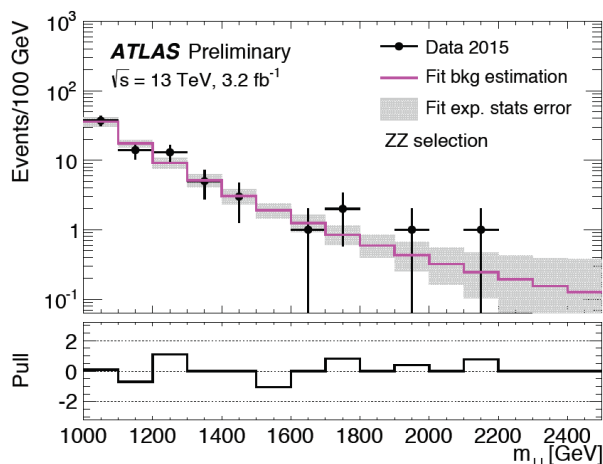
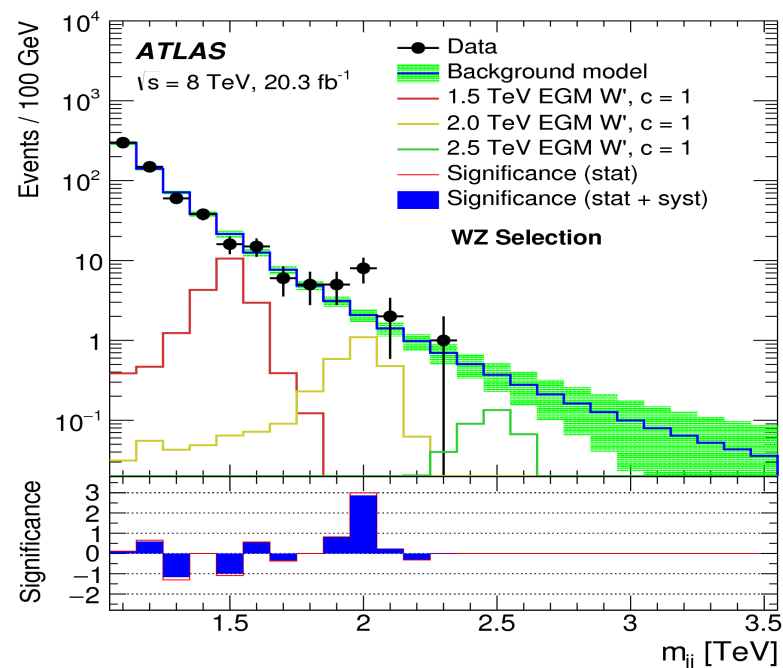
- All analyses have similar sensitivity ranging between 1.4-1.6 TeV for HVT addition vector boson
- Interpretations also in Higgs and spin-2 Gravitons



# Diboson Resonance Search

ATLAS-CONF-2015-073

- Modest excess in Run 1
  - $3.4\sigma$  local /  $2.5\sigma$  global
- Run 2 analysis very similar
  - Functional fit to background
- No significant excess observed
  - Sensitivity not high enough to probe Run 1, thus consistent





# Summary



- ATLAS made major changes to detector (IBL), trigger/DAQ, and software frameworks during long shutdown
- ATLAS and LHC working well at 13 TeV with 25ns collisions
- Run 2 is well underway!
  - Many new results public with full 2015 dataset  
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic>
  - Cross sections for many new physics increased significantly
  - Modest excesses need more data
- Eagerly awaiting a much larger Run 2



# Pentaquarks

arXiv:1507.03414

- Discovery of a new class of QCD bound states by LHCb

- I am a member of the ATLAS collaboration, but figured I had to cover this at a Nuclear Physics conference

- See talk by C. Ramirez

- Satisfactory fit of the structures seen in the  $J/\psi$  p mass spectrum it is necessary to include two Breit-Wigner amplitude states

- Significance is  $> 9.0 \sigma$

