# Search Analyses at the LHC

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CoEPP summer school, February 20th, 2017

ATLAS EXPERIMENT

- A attempt to find a result that is inconsistent with the Standard Model (SM) picture of particle physics, with a significant level of precision
- That could be:
  - Evidence of a new particle(s) that is(are) not present in the SM
  - Evidence of an anomalous distribution that hints at a new interaction/mechanism
  - Measurement of a SM property (branching fraction, coupling etc) that is in disagreement with the SM
  - Anything else?

- A question I'd like you to ponder is

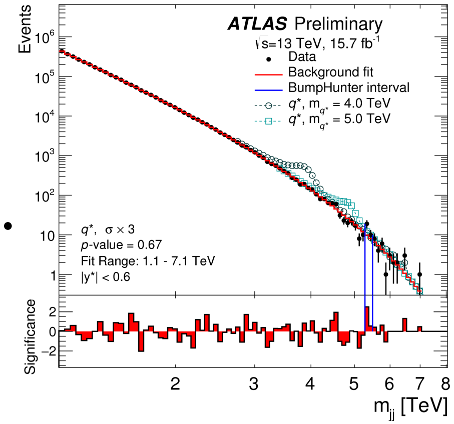
*How would we "know" if we have seen such a signal?*

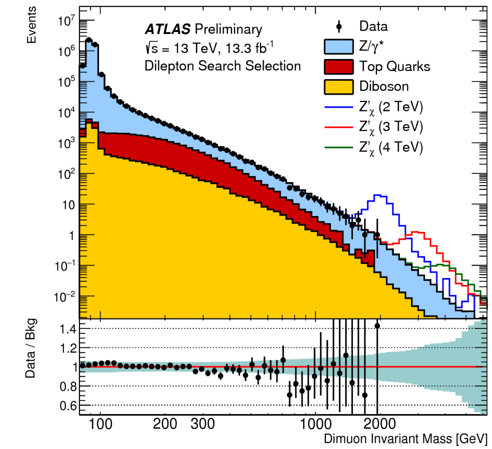
# What is a "search for new physics"

**new particle**(s):

Expect a resonance in some distribution of final state objects.

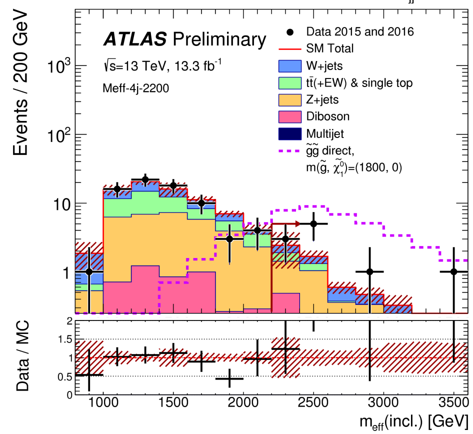
Can use it to measure mass of NP

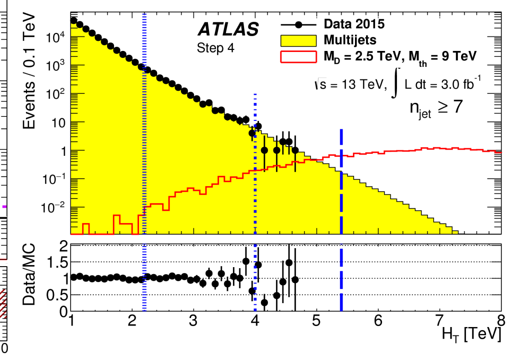



**anomalous distribution**:

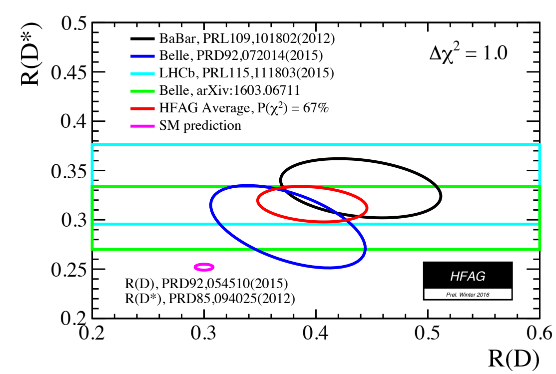
Some inclusive distribution that has a different shape between signal and background (but doesn't have to be a peak)



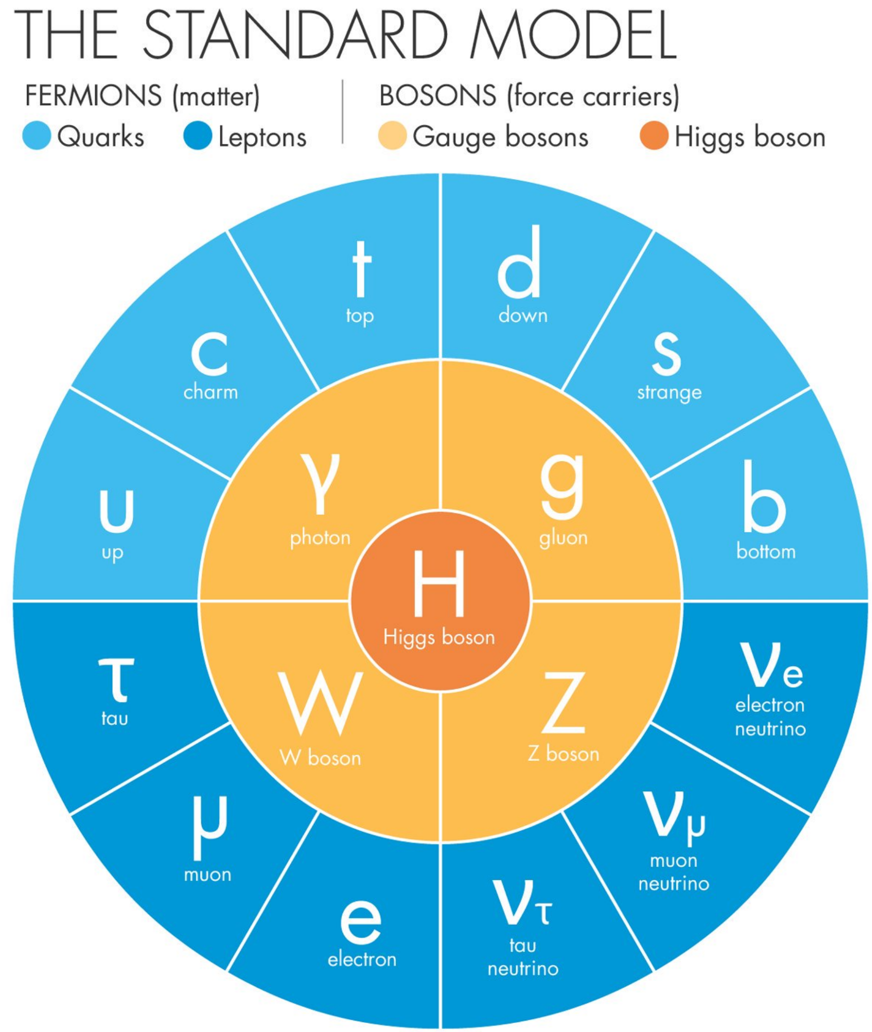

**SM property:**

Accurate measure of branching fraction, property etc



# Searches vs Standard Model

- The standard model is standing up to intense scrutiny
- A variety of precision measurements show excellent agreement with calculations at several collision energies
- Almost all searches we perform have some amount of model dependence i.e. you search for a specific signal topology
- But…..
- We DO NOT KNOW what new physics will look like (…and we want to cast a wide net)

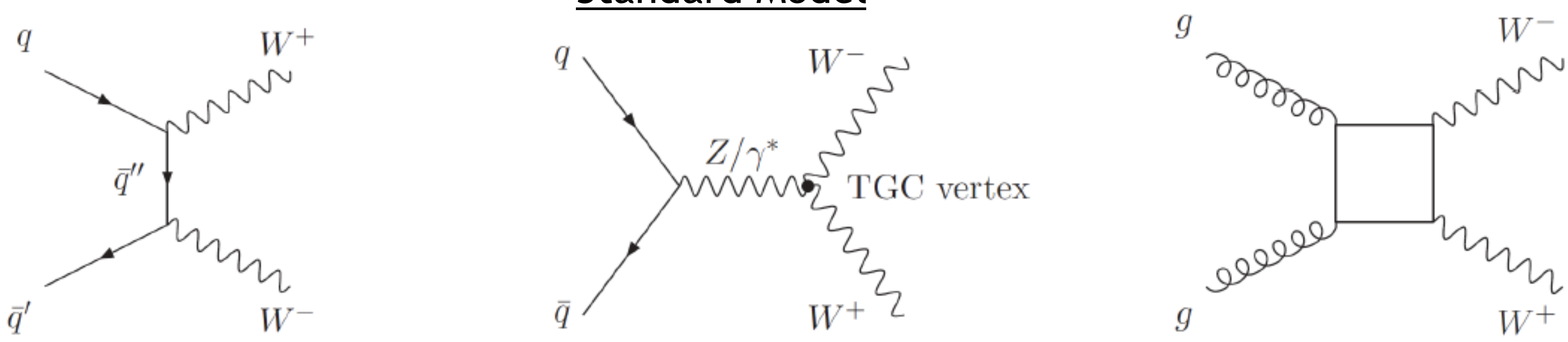


# (Maybe obvious) statements about "Searches"

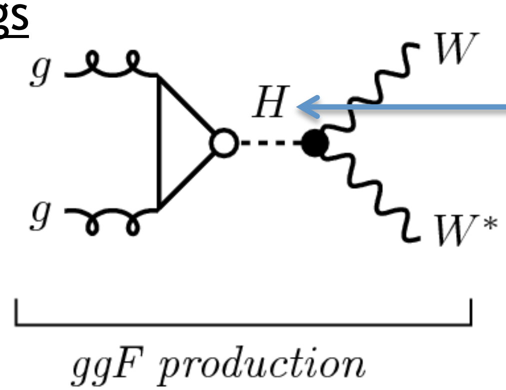
- Any new physics will either be produced in conjunction with/or decay to Standard Model particles – ***these are what we measure***
  - Whether performing a search or not we measure Standard Model objects
  - To search for something new there has to be a difference, or differences, between the new physics and the Standard Model
  - Exploiting the differences as efficiently as possible is what makes one analysis better than another
- We DO NOT KNOW what new physics will look like!!!
  - The searches we perform are based on our prejudices and we interpret them in only a specific number of signal scenarios
- The *partitioning* of many analyses within ATLAS/CMS is *largely arbitrary* and often not based on physics principles
  - Example "X" -> $W^+W^-$ -> $l^+\nu\ l^-\nu$ => is it SM/Exotics/Higgs/SUSY?

"X" -> $W^+W^-$ -> $l^+\nu\ l^-\nu$ => is it SM/Exotics/Higgs/SUSY?

## Standard Model



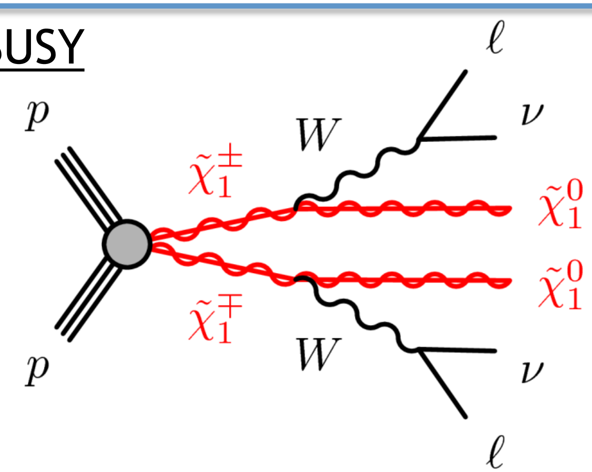

## Higgs




## EXOTICS

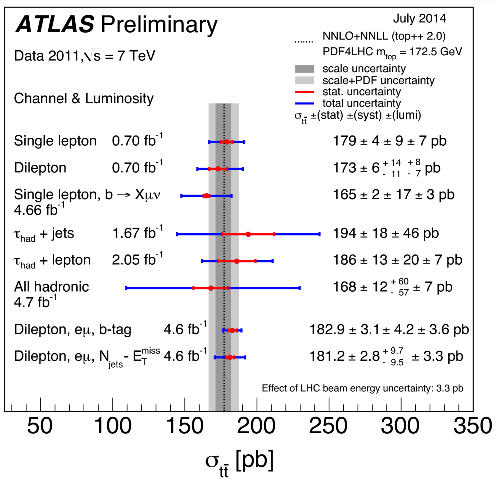
Swap "H" for "X" - a new particle

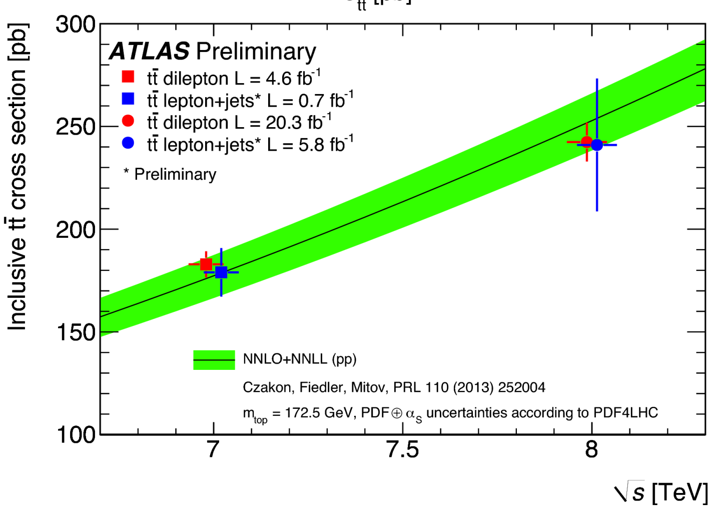
## SUSY

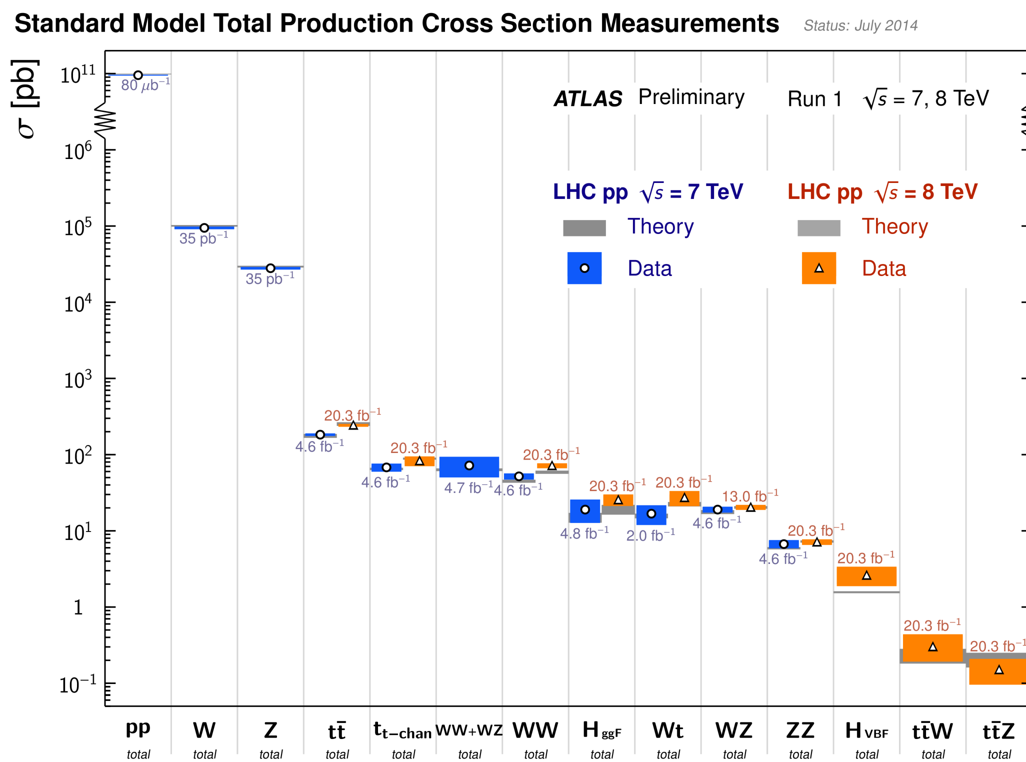


ATLAS EXPERIMENT

Precision measurements of boson, ttbar, single top and di-boson cross sections




Crucial to demonstrate detector performance and measure Standard Model to great accuracy

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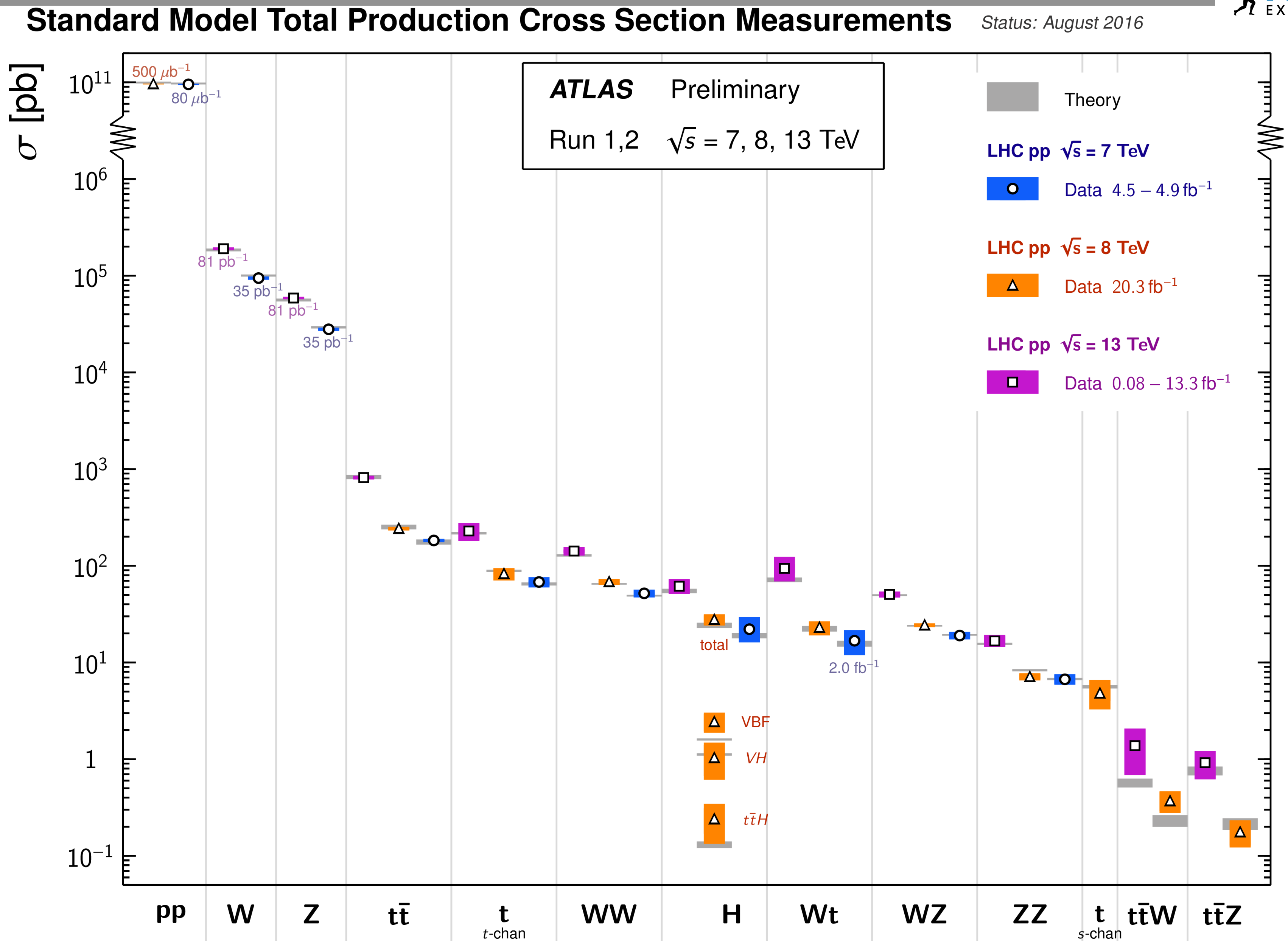
# If {no discoveries of new physics} then……

….keep increasing the energy….

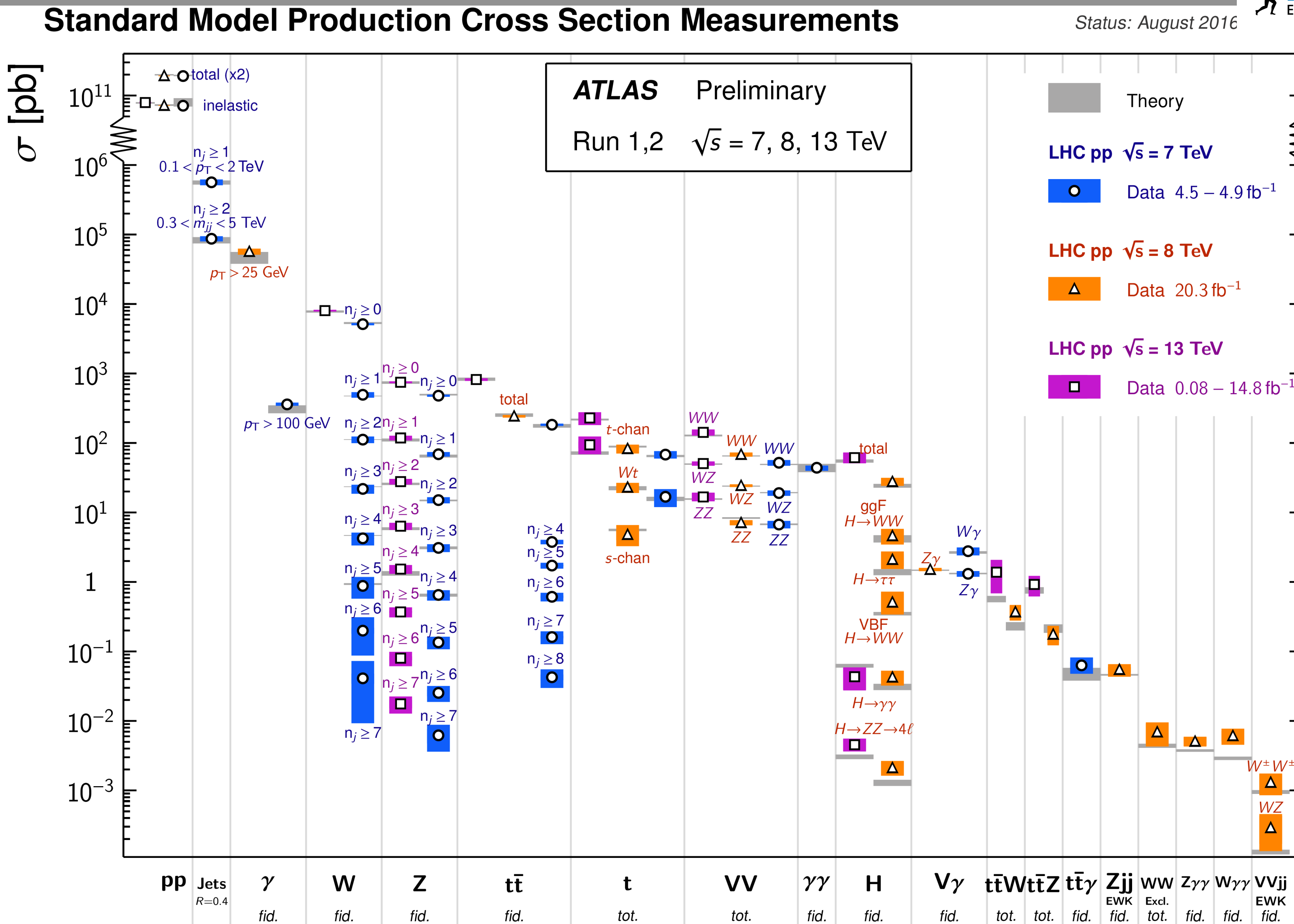
2011 -> 2012 -> 2015+

7 TeV -> 8TeV -> **13TeV**

# Understanding the Standard Model Backgrounds



# Understanding the Standard Model Backgrounds

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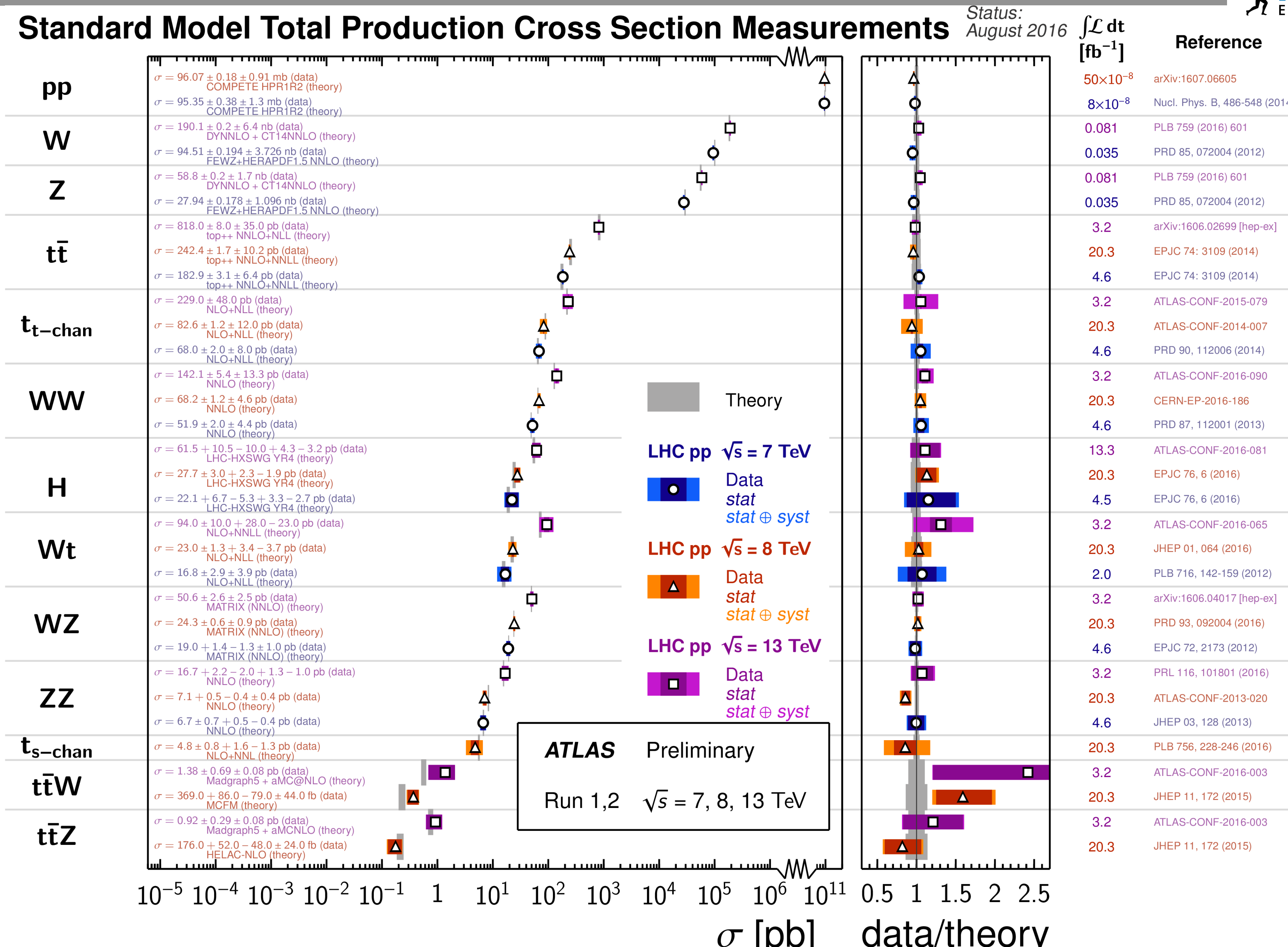
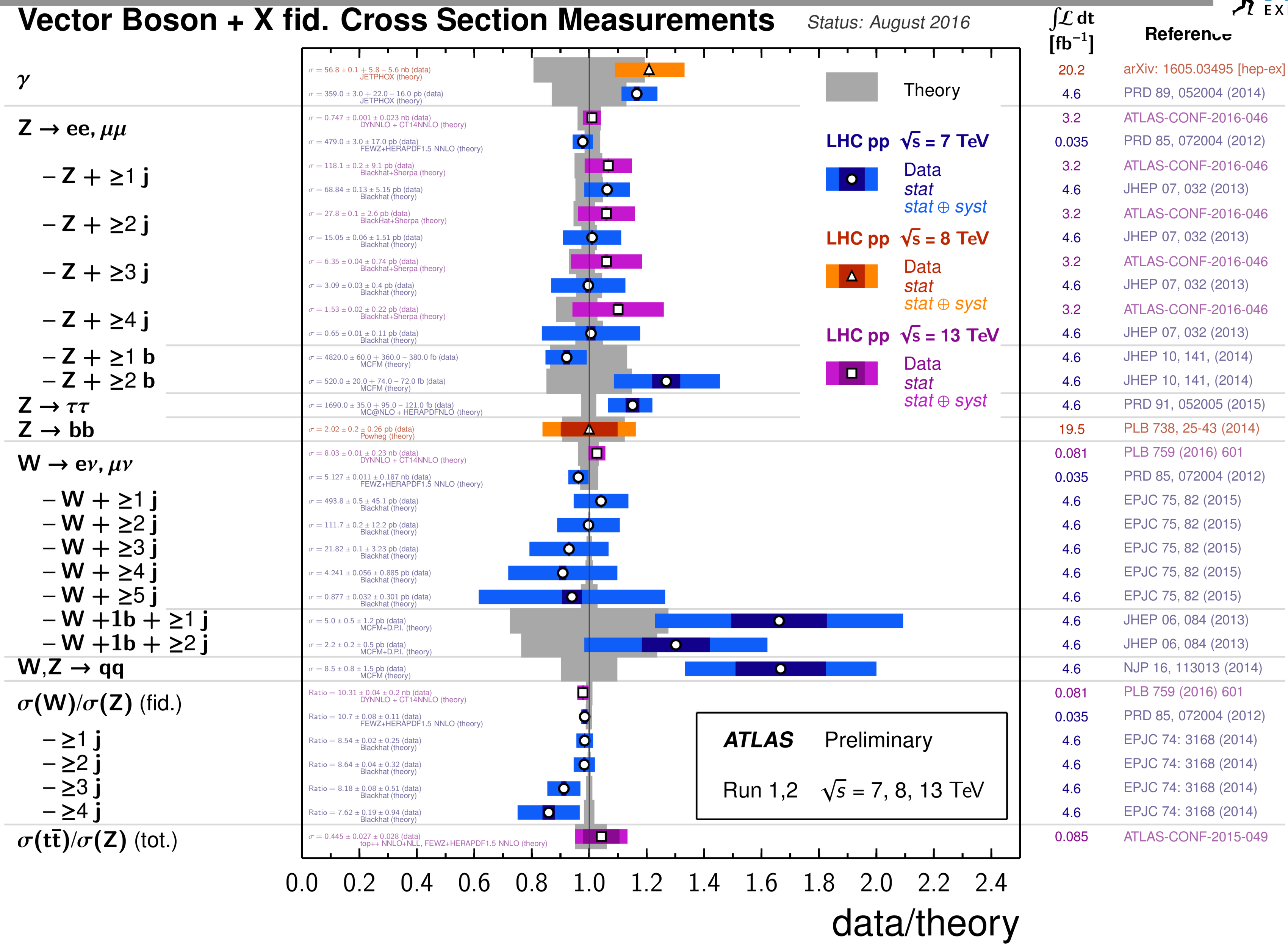
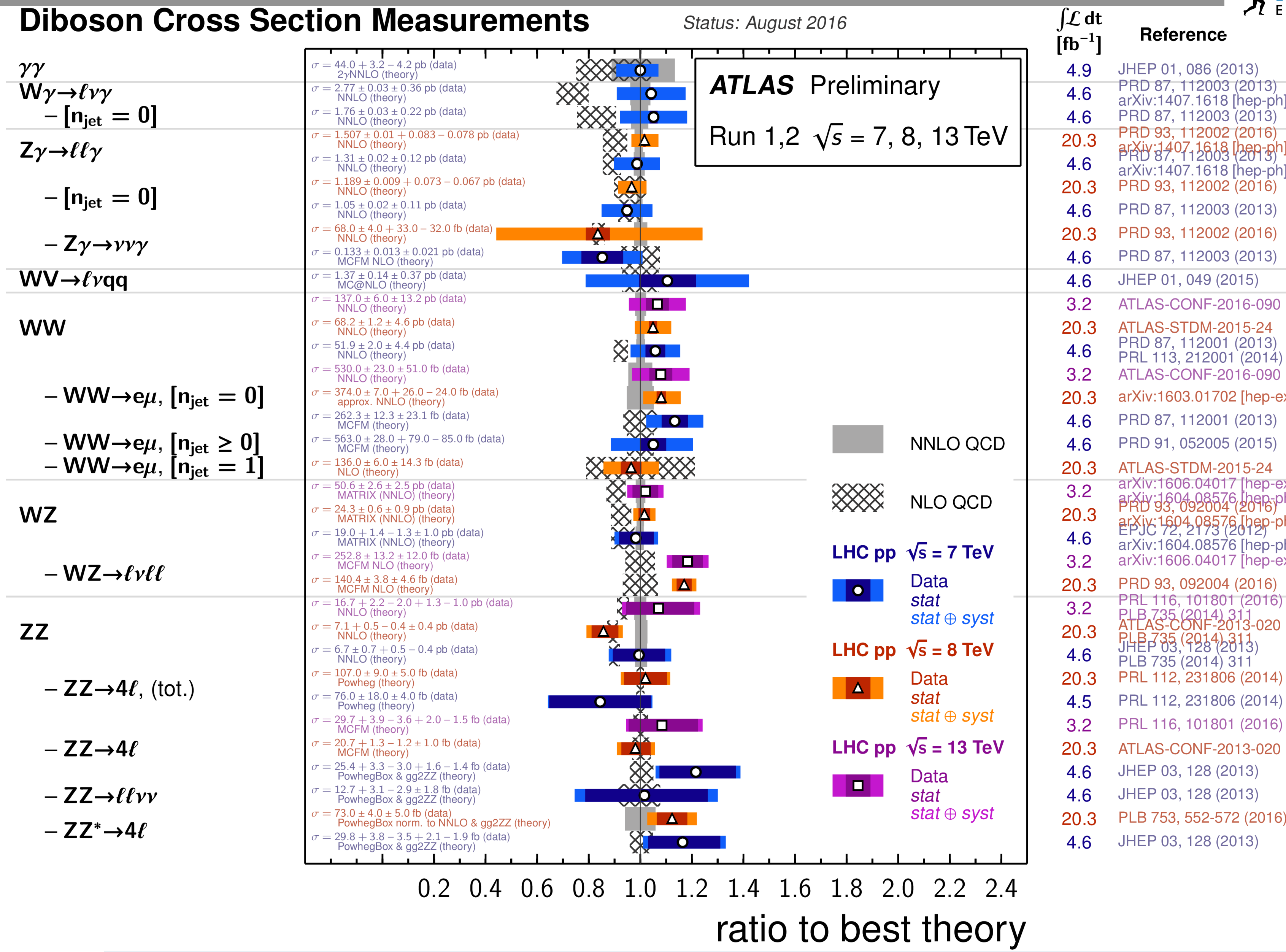
# Understanding the Standard Model Backgrounds

ATLAS EXPERIMENT

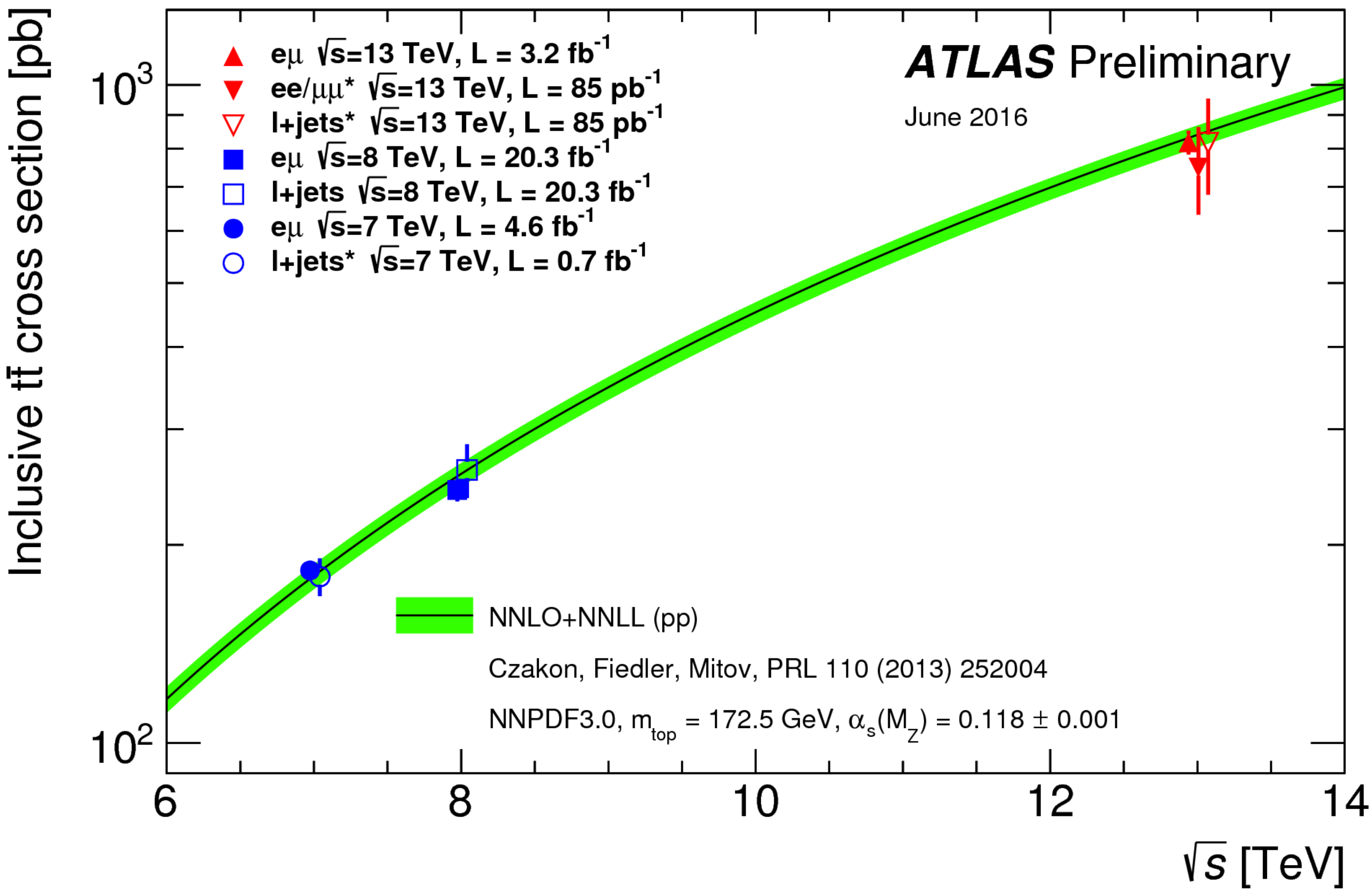


# Understanding the Standard Model Backgrounds

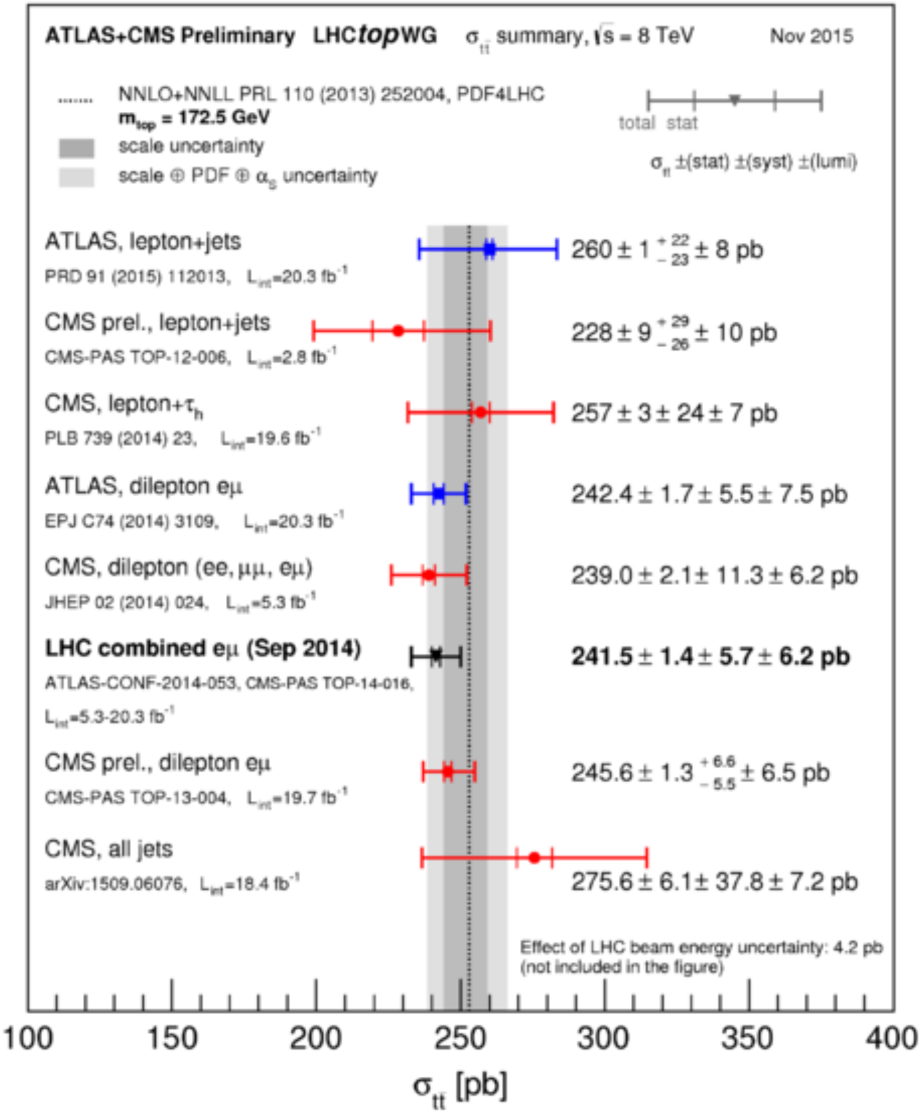


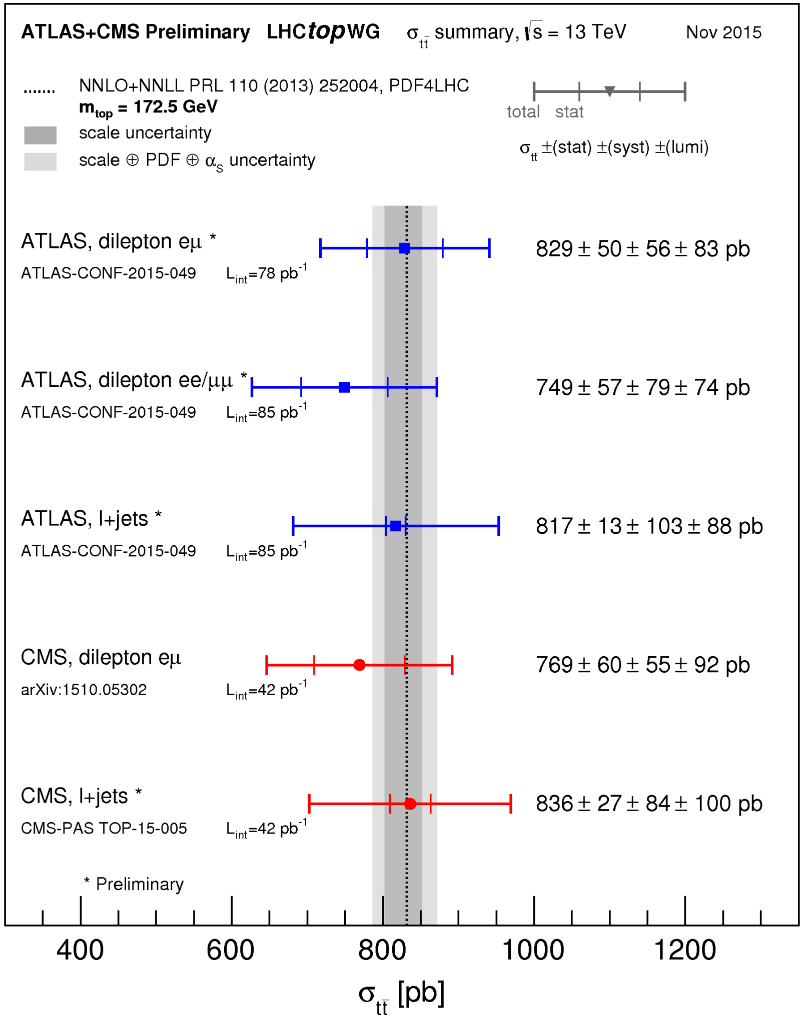

Diboson Cross Section Measurements
Status: August 2016
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
∫ℒ dt [fb⁻¹]
Reference
γγ
Wγ→ℓνγ
– [njet = 0]
Zγ→ℓℓγ
– [njet = 0]
– Zγ→ννγ
WV→ℓνqq
WW
– WW→eμ, [njet = 0]
– WW→eμ, [njet ≥ 0]
– WW→eμ, [njet = 1]
WZ
– WZ→ℓνℓℓ
ZZ
– ZZ→4ℓ, (tot.)
– ZZ→4ℓ
– ZZ→ℓℓνν
– ZZ*→4ℓ
σ = 44.0 + 3.2 − 4.2 pb (data) 2γNNLO (theory) | 4.9 | JHEP 01, 086 (2013)
σ = 2.77 ± 0.03 ± 0.36 pb (data) NNLO (theory) | 4.6 | PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
σ = 1.76 ± 0.03 ± 0.22 pb (data) NNLO (theory) | 4.6 | PRD 87, 112003 (2013)
σ = 1.507 ± 0.01 + 0.083 − 0.078 pb (data) NNLO (theory) | 20.3 | PRD 93, 112002 (2016) arXiv:1407.1618 [hep-ph]
σ = 1.31 ± 0.02 ± 0.12 pb (data) NNLO (theory) | 4.6 | PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
σ = 1.189 ± 0.009 + 0.073 − 0.067 pb (data) NNLO (theory) | 20.3 | PRD 93, 112002 (2016)
σ = 1.05 ± 0.02 ± 0.11 pb (data) NNLO (theory) | 4.6 | PRD 87, 112003 (2013)
σ = 68.0 ± 4.0 + 33.0 − 32.0 fb (data) NNLO (theory) | 20.3 | PRD 93, 112002 (2016)
σ = 0.133 ± 0.013 ± 0.021 pb (data) MCFM NLO (theory) | 4.6 | PRD 87, 112003 (2013)
σ = 1.37 ± 0.14 ± 0.37 pb (data) MC@NLO (theory) | 4.6 | JHEP 01, 049 (2015)
σ = 137.0 ± 6.0 ± 13.2 pb (data) NNLO (theory) | 3.2 | ATLAS-CONF-2016-090
σ = 68.2 ± 1.2 ± 4.6 pb (data) NNLO (theory) | 20.3 | ATLAS-STDM-2015-24
σ = 51.9 ± 2.0 ± 4.4 pb (data) NNLO (theory) | 4.6 | PRD 87, 112001 (2013) PRL 113, 212001 (2014)
σ = 530.0 ± 23.0 ± 51.0 fb (data) NNLO (theory) | 3.2 | ATLAS-CONF-2016-090
σ = 374.0 ± 7.0 + 26.0 − 24.0 fb (data) approx. NNLO (theory) | 20.3 | arXiv:1603.01702 [hep-ex]
σ = 262.3 ± 12.3 ± 23.1 fb (data) MCFM (theory) | 4.6 | PRD 87, 112001 (2013)
σ = 563.0 ± 28.0 + 79.0 − 85.0 fb (data) MCFM (theory) | 4.6 | PRD 91, 052005 (2015)
σ = 136.0 ± 6.0 ± 14.3 fb (data) NLO (theory) | 20.3 | ATLAS-STDM-2015-24
σ = 50.6 ± 2.6 ± 2.5 pb (data) MATRIX (NNLO) (theory) | 3.2 | arXiv:1606.04017 [hep-ex] arXiv:1604.08576 [hep-ph]
σ = 24.3 ± 0.6 ± 0.9 pb (data) MATRIX (NNLO) (theory) | 20.3 | PRD 93, 092004 (2016) arXiv:1604.08576 [hep-ph]
σ = 19.0 + 1.4 − 1.3 ± 1.0 pb (data) MATRIX (NNLO) (theory) | 4.6 | EPJC 72, 2173 (2012) arXiv:1604.08576 [hep-ph]
σ = 252.8 ± 13.2 ± 12.0 fb (data) MCFM NLO (theory) | 3.2 | arXiv:1606.04017 [hep-ex]
σ = 140.4 ± 3.8 ± 4.6 fb (data) MCFM NLO (theory) | 20.3 | PRD 93, 092004 (2016)
σ = 16.7 + 2.2 − 2.0 + 1.3 − 1.0 pb (data) NNLO (theory) | 3.2 | PRL 116, 101801 (2016) PLB 735 (2014) 311
σ = 7.1 + 0.5 − 0.4 ± 0.4 pb (data) NNLO (theory) | 20.3 | ATLAS-CONF-2013-020 PLB 735 (2014) 311
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data) NNLO (theory) | 4.6 | JHEP 03, 128 (2013) PLB 735 (2014) 311
σ = 107.0 ± 9.0 ± 5.0 fb (data) Powheg (theory) | 20.3 | PRL 112, 231806 (2014)
σ = 76.0 ± 18.0 ± 4.0 fb (data) Powheg (theory) | 4.5 | PRL 112, 231806 (2014)
σ = 29.7 + 3.9 − 3.6 + 2.0 − 1.5 fb (data) MCFM (theory) | 3.2 | PRL 116, 101801 (2016)
σ = 20.7 + 1.3 − 1.2 ± 1.0 fb (data) MCFM (theory) | 20.3 | ATLAS-CONF-2013-020
σ = 25.4 + 3.3 − 3.0 + 1.6 − 1.4 fb (data) PowhegBox & gg2ZZ (theory) | 4.6 | JHEP 03, 128 (2013)
σ = 12.7 + 3.1 − 2.9 ± 1.8 fb (data) PowhegBox & gg2ZZ (theory) | 4.6 | JHEP 03, 128 (2013)
σ = 73.0 ± 4.0 ± 5.0 fb (data) PowhegBox norm. to NNLO & gg2ZZ (theory) | 20.3 | PLB 753, 552-572 (2016)
σ = 29.8 + 3.8 − 3.5 + 2.1 − 1.9 fb (data) PowhegBox & gg2ZZ (theory) | 4.6 | JHEP 03, 128 (2013)
NNLO QCD
NLO QCD
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4
ratio to best theory

# Understanding the Standard Model Backgrounds



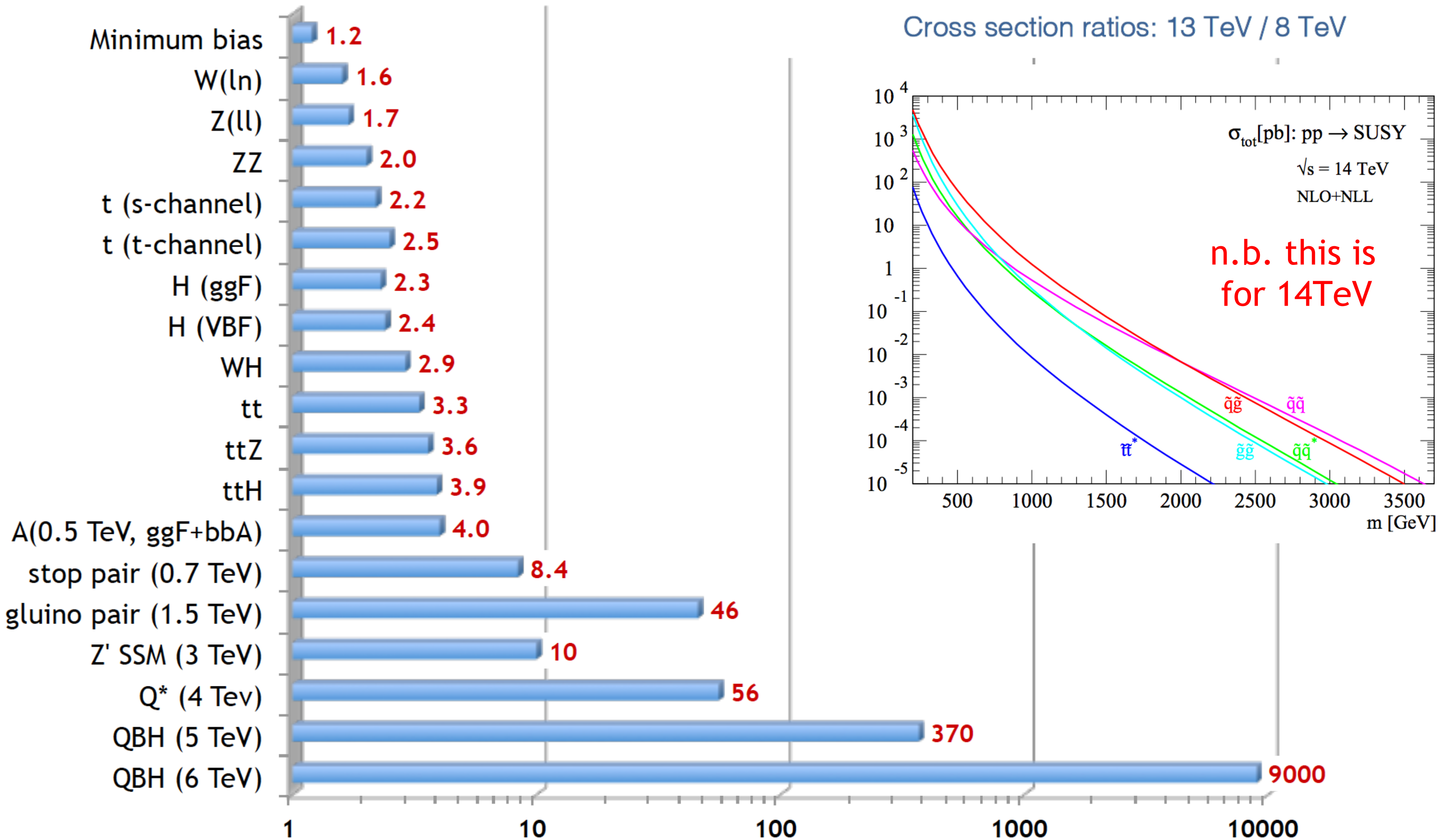
# Understanding the Standard Model Backgrounds



## Hugely increased potential for discovery of heavy particles at 13 TeV

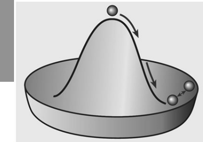
*But life may also become harder for states lighter than tt*



# HIGGS Physics and Searches

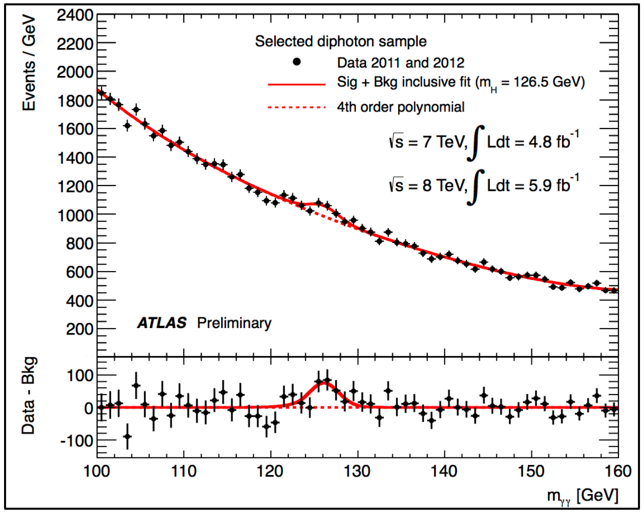
- We've discovered the Higgs – can't search for it anymore
- If you're working on Higgs physics you are either:
  a) Making as precise a measurement as possible of the Standard Model (both ***production***: ttH, VH and ***decay:*** H->WW, H->ττ, H->μμ, H->Zγ etc)
  b) Searching for BSM Higgs
     - $H^{+}$->$\tau^{+}\nu$ or $H^{+}$->tb (charged Higgs)
     - H->τe or τμ (Lepton Flavour Violation)
     - H/h/A->f fbar (where f is 'fermion')
     - H/h/A-> B Bbar (where B is 'boson')
- For the most part there's overlap with the exotics program here

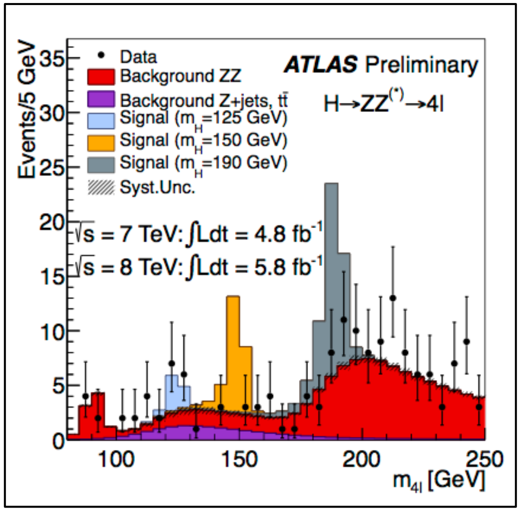
# LHC Run 1 Higgs Results

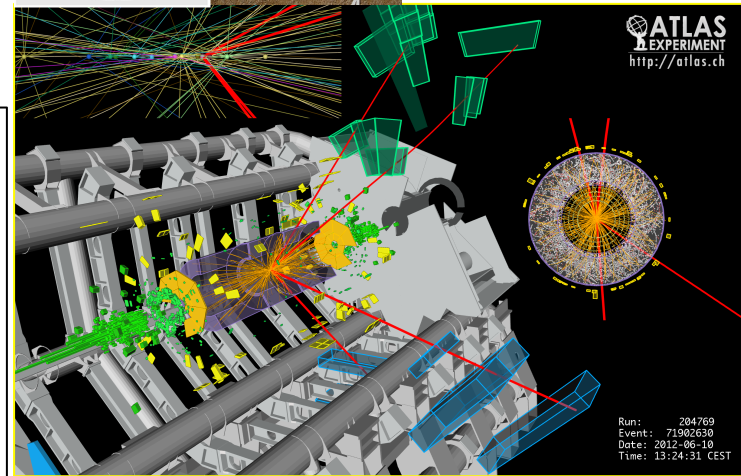


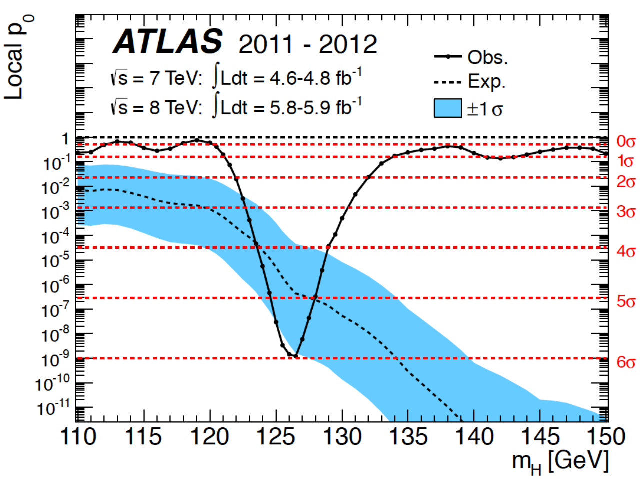

Run 1 highlights!!

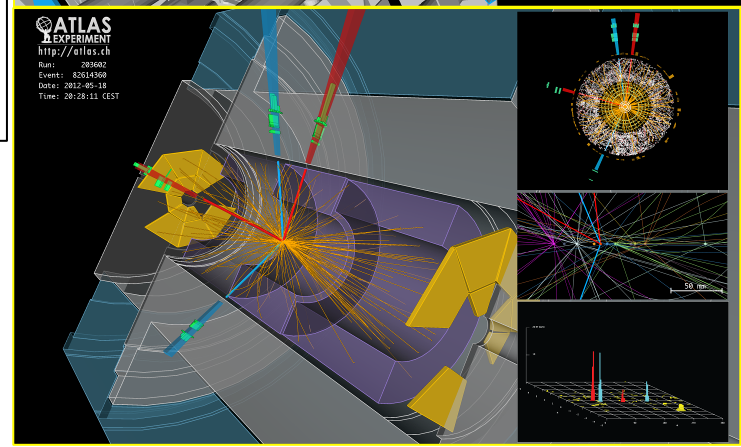
## Higgs Boson discovered!




**Francois Englert and Peter Higgs shared the 2013 Nobel Prize for the discovery**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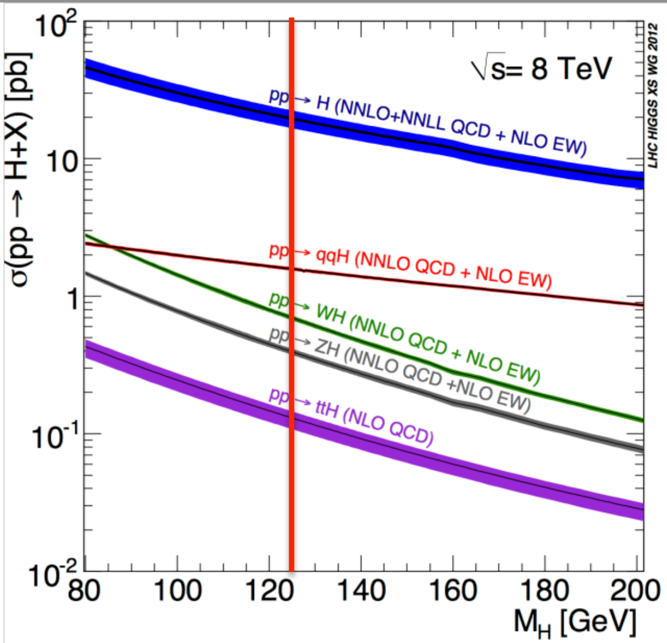
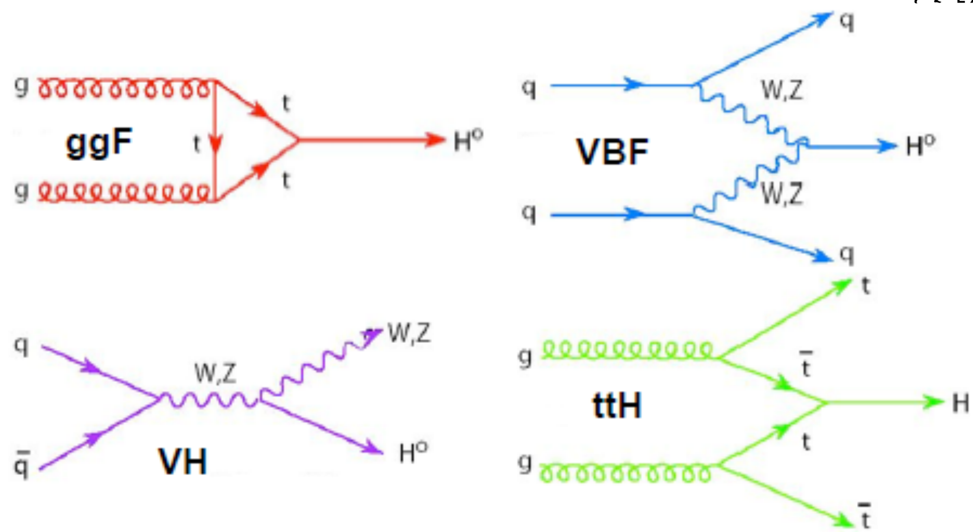
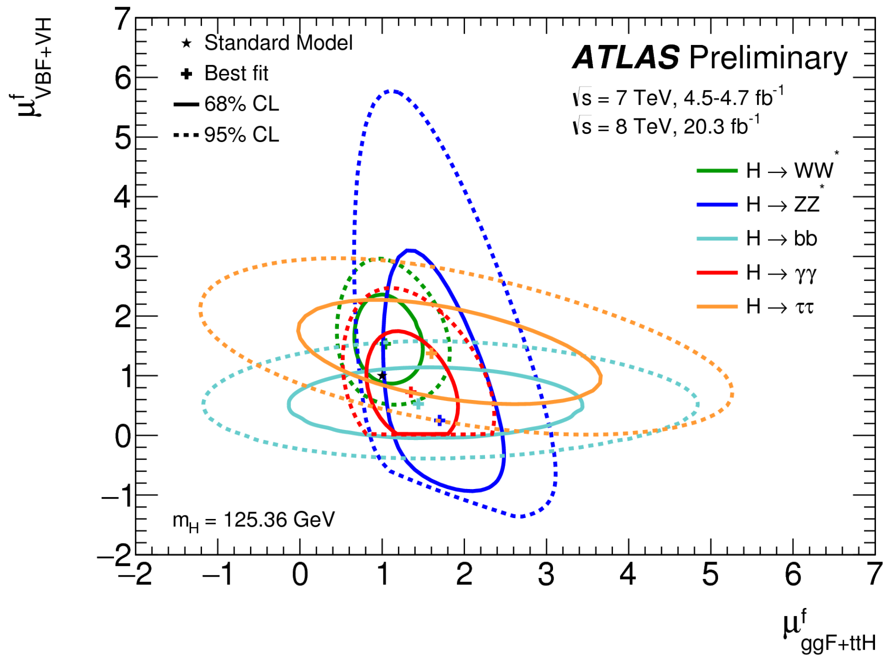
# The Higgs Boson - Production modes

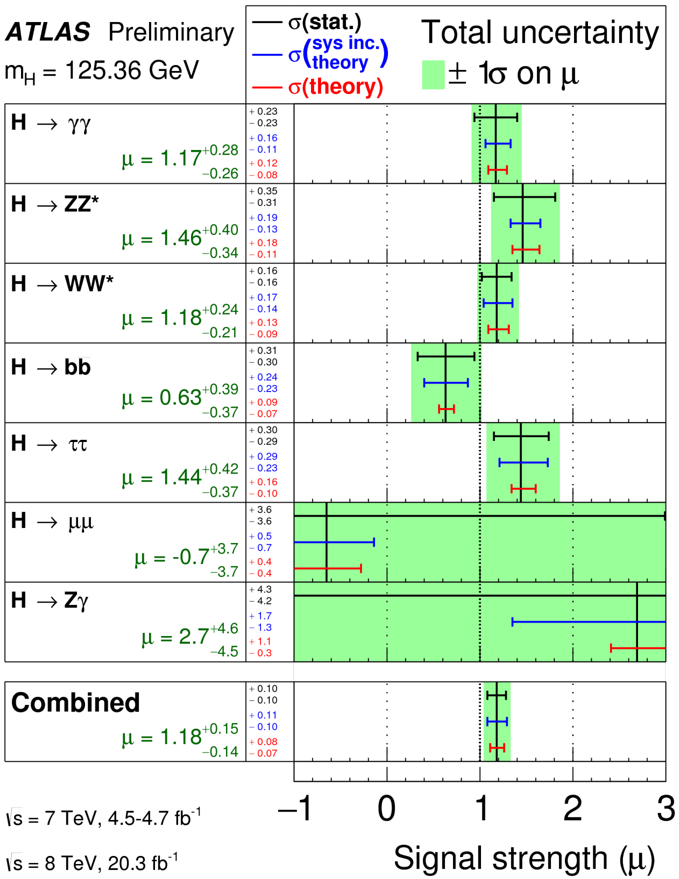



- gluon-gluon fusion (ggF) dominant
- Several measurements of vector-boson fusion (VBF)
- Data not yet very sensitive to VH and ttH

- Combine VBF and VH (both scale with V-H coupling)
- Combine ggF and ttH (both scale with t-H coupling)






| Analysis<br>Categorisation or final states | Signal<br>Strength | Significance [$\sigma$] | $\int \mathcal{L}dt$ (fb$^{-1}$)<br>7 TeV | 8 TeV |
|---|---|---|---|---|
| $H \to \gamma\gamma$ [12] | $1.17 \pm 0.27$ | 5.2 (4.6) | 4.5 | 20.3 |
| $ttH$: leptonic, hadronic | | | ✓ | ✓ |
| $VH$: one-lepton, dilepton, $E_T^{miss}$, hadronic | | | ✓ | ✓ |
| VBF: tight, loose | | | ✓ | ✓ |
| ggF: 4 $p_{Tt}$ categories | | | ✓ | ✓ |
| $H \to ZZ^* \to 4\ell$ [13] | $1.44^{+0.40}_{-0.33}$ | 8.1 (6.2) | 4.5 | 20.3 |
| VBF | | | ✓ | ✓ |
| $VH$: hadronic, leptonic | | | ✓ | ✓ |
| ggF | | | ✓ | ✓ |
| $H \to WW^*$ [14, 15] | $1.16^{+0.24}_{-0.21}$ | 6.5 (5.9) | 4.5 | 20.3 |
| ggF: (0-jet, 1-jet) $\otimes$ ($ee + \mu\mu$, $e\mu$) | | | ✓ | ✓ |
| ggF: $\geq$ 2-jet and $e\mu$ | | | | ✓ |
| VBF: $\geq$ 2-jet $\otimes$ ($ee + \mu\mu$, $e\mu$) | | | ✓ | ✓ |
| $VH$: opposite-charge dilepton, three-lepton, four-lepton | | | ✓ | ✓ |
| $VH$: same-charge dilepton | | | | ✓ |
| $H \to \tau\tau$ [17] | $1.43^{+0.43}_{-0.37}$ | 4.5 (3.4) | 4.5 | 20.3 |
| Boosted: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ | | | ✓ | ✓ |
| VBF: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ | | | ✓ | ✓ |
| $VH \to Vb\bar{b}$ [18] | $0.52 \pm 0.40$ | 1.4 (2.6) | 4.7 | 20.3 |
| $0\ell$ ($ZH \to \nu\nu bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V$ > and < 120 GeV | | | ✓ | ✓ |
| $1\ell$ ($WH \to \ell\nu bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V$ > and < 120 GeV | | | ✓ | ✓ |
| $2\ell$ ($ZH \to \ell\ell bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V$ > and < 120 GeV | | | ✓ | ✓ |

The Higgs Boson is no longer a discovery – it is a precision measurement!

# The Higgs Boson – ATLAS + CMS combined

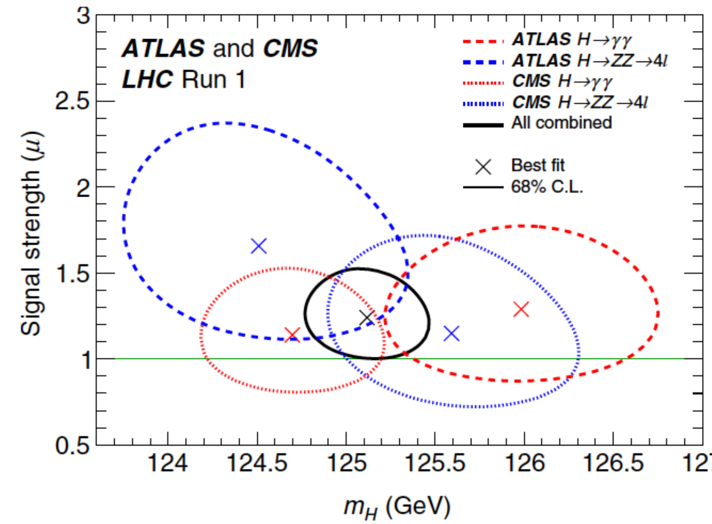
**Combined Measurement of the Higgs Boson Mass in $pp$ Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments**

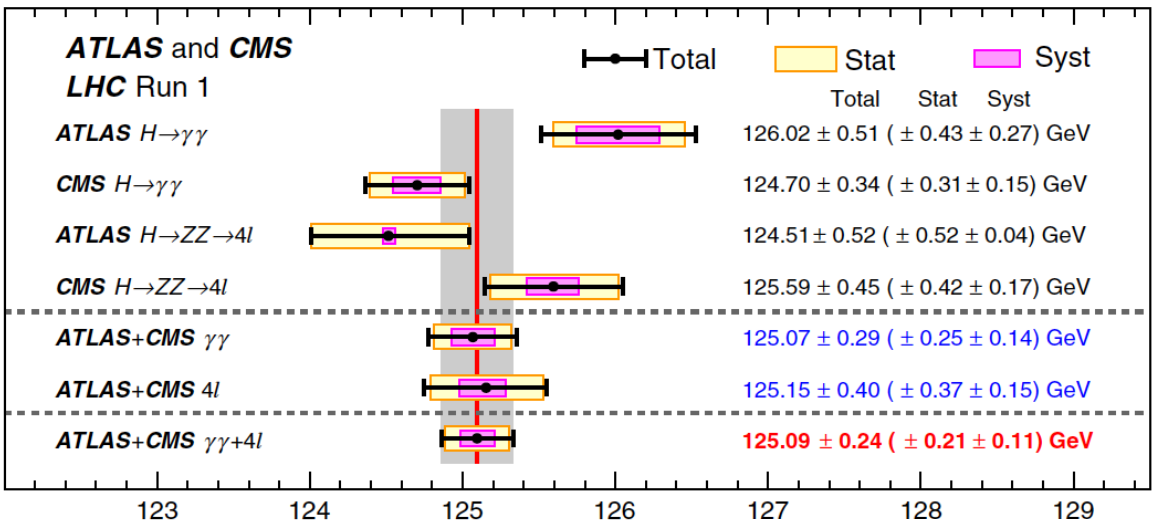
G. Aad *et al.*[*]

(ATLAS Collaboration)[†]
(CMS Collaboration)[‡]
(Received 25 March 2015; published 14 May 2015)

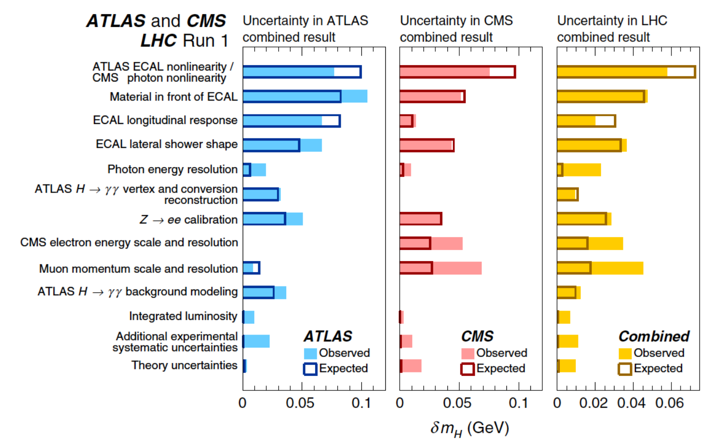
A measurement of the Higgs boson mass is presented based on the combined data samples of the ATLAS and CMS experiments at the CERN LHC in the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ decay channels. The results are obtained from a simultaneous fit to the reconstructed invariant mass peaks in the two channels and for the two experiments. The measured masses from the individual channels and the two experiments are found to be consistent among themselves. The combined measured mass of the Higgs boson is $m_H = 125.09 \pm 0.21\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst})$ GeV.

…only 5,154 authors!
Adelaide lead institution ☺



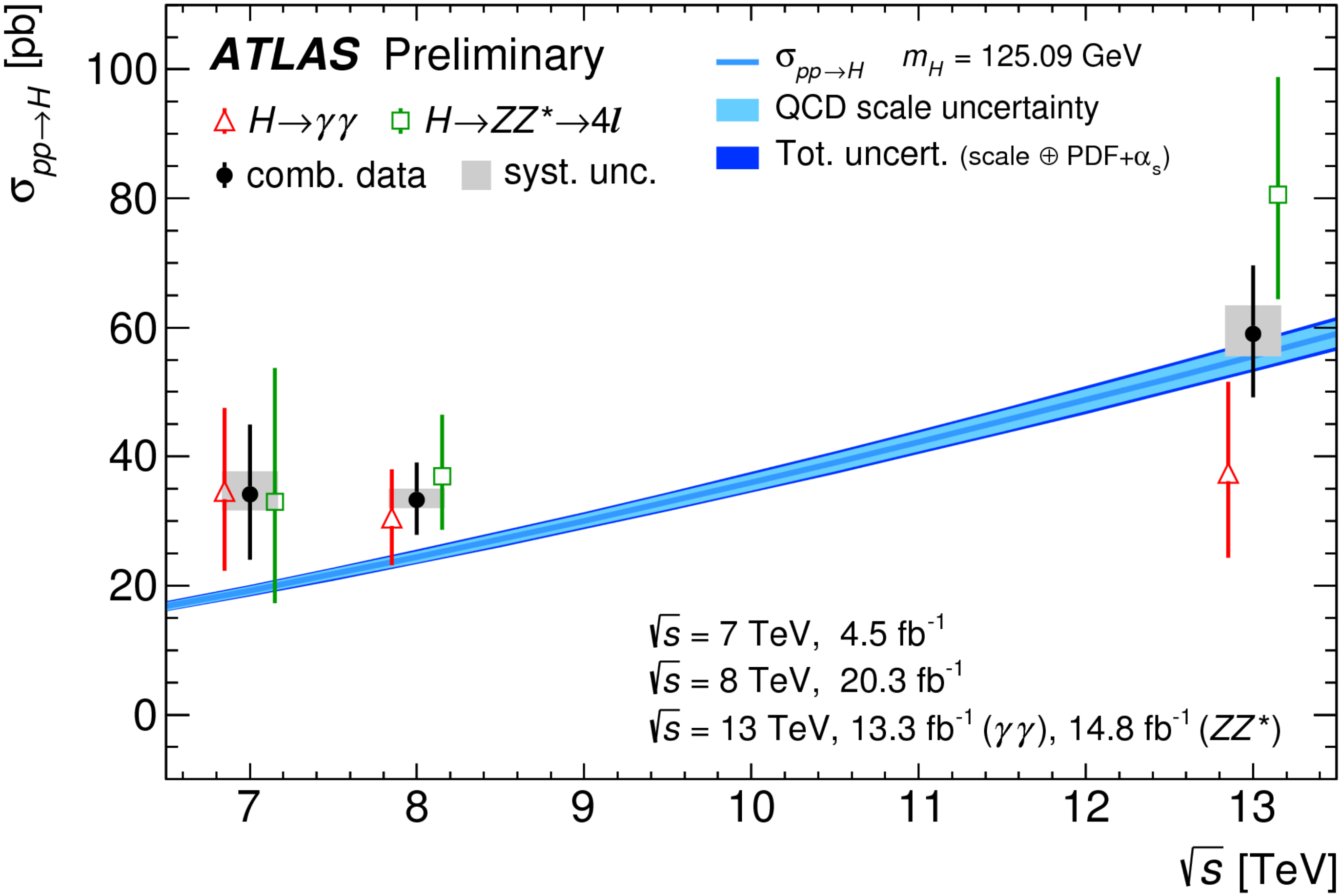




$m_H$ (GeV)

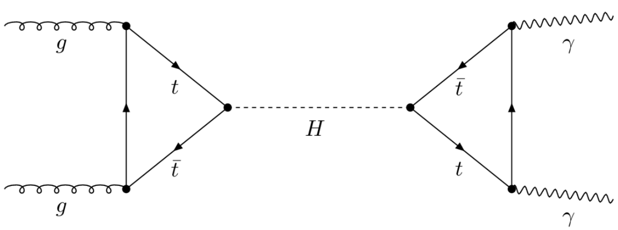



$$m_H = 125.09 \pm 0.24\ \mathrm{GeV}$$
$$= 125.09 \pm 0.21\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst})\ \mathrm{GeV}$$

The Higgs Boson is no longer a discovery – it is a precision measurement!




Higgs combination looks in good agreement with expectation at 13 TeV……..bad news if you wanted to see effects of something showing up in loops



# SUPERSYMMETRY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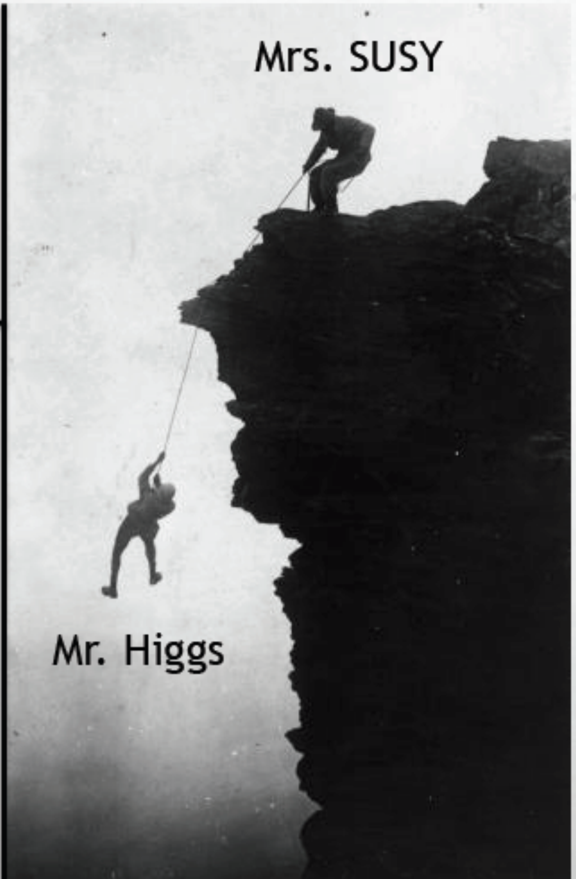
imgflip.com

*The scalar precipice*



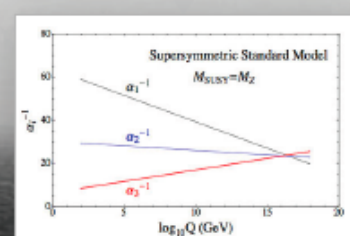

EW scale$^{-1}$

GUT scale$^{-1}$

Fundamental scalar length scale

***If weak-scale SUSY existed, it could …***

- Moderate the hierarchy problem by cancelling quadratic divergence of SM scalar
- Equalise the number of fermionic and bosonic degrees of freedom, render existence of scalar particles natural
- Realise grand unification of the gauge couplings
- Provide a suitable dark matter candidate




slide by Andreas Hoecker

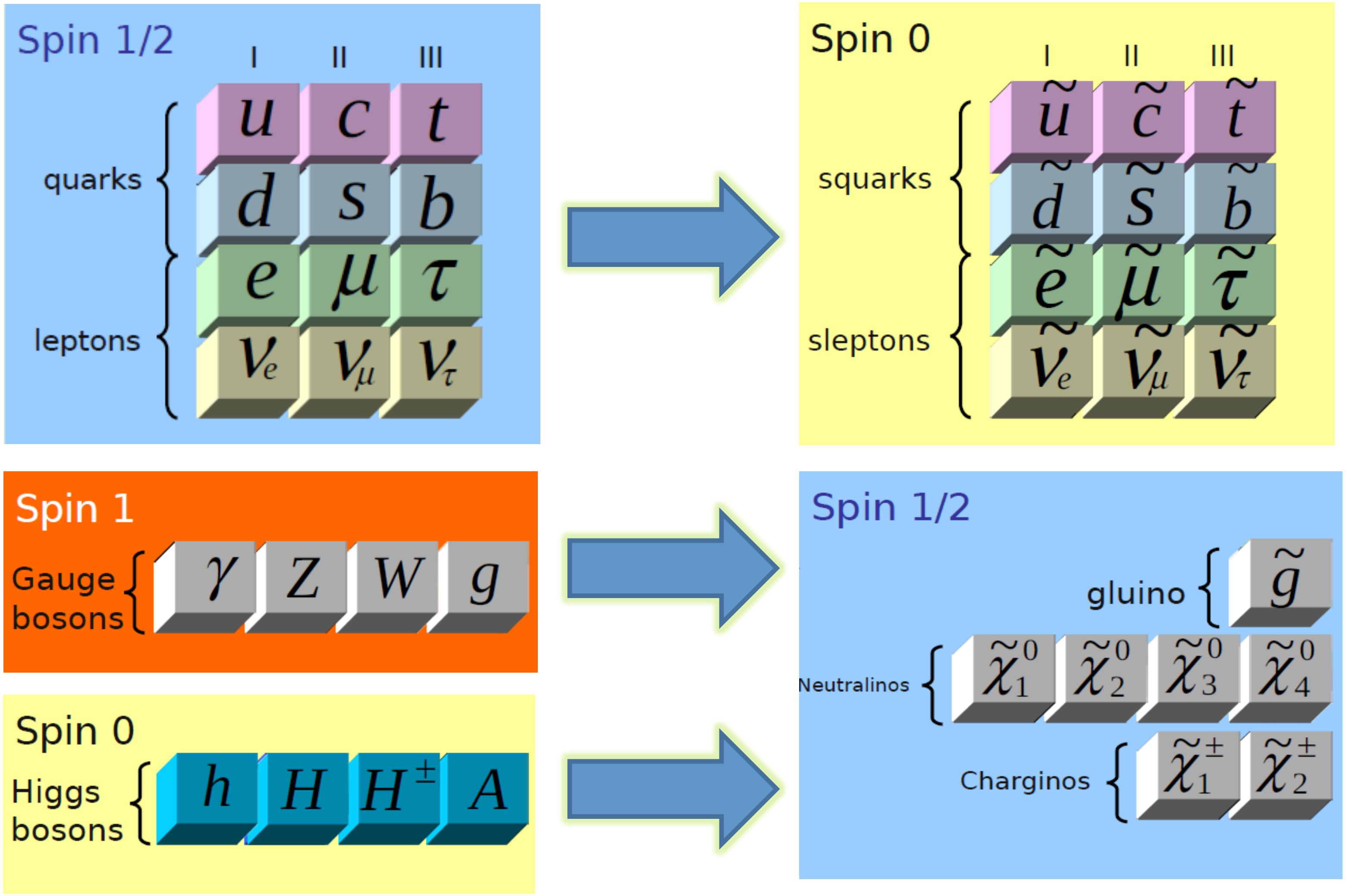



illustration by M-H Genest

Standard Model → SUSY

Laughter → SLaughter

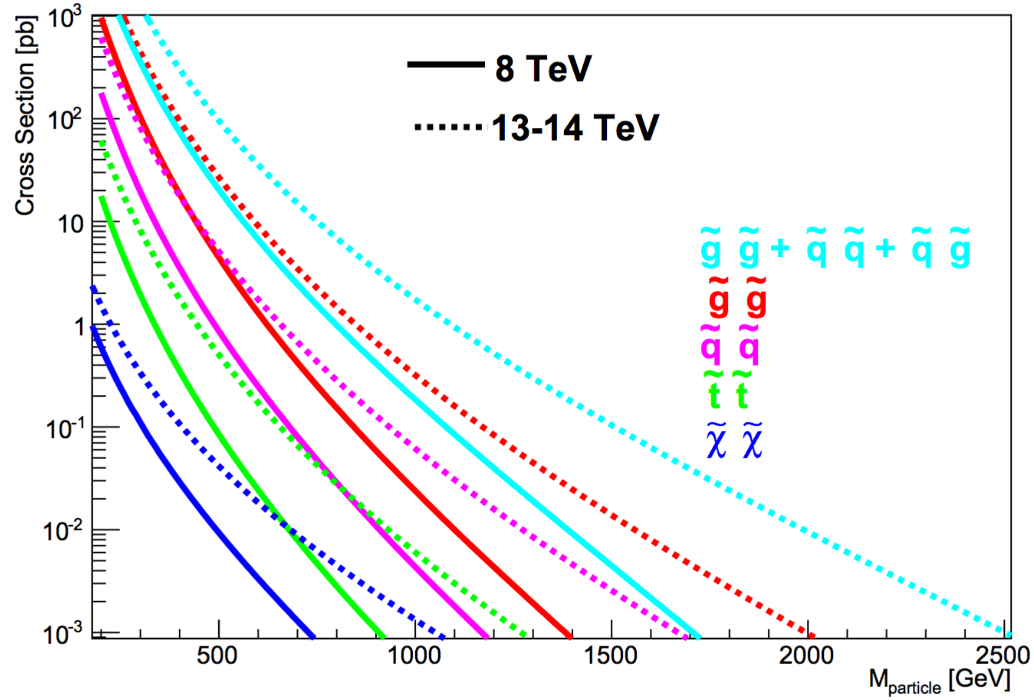
Franz Anthony Winner of ‘Collision 2015’

SUSY ~duplicates spectrum of particle states wrt. Standard Model

Sparticle decays produce SM objects: (**b**/**c**-)jets, leptons, τ, γ, invisible (MET), …

Cancellation of the top loop correction to the Higgs mass **requires (relatively) light susy… perhaps particularly third generation squarks**

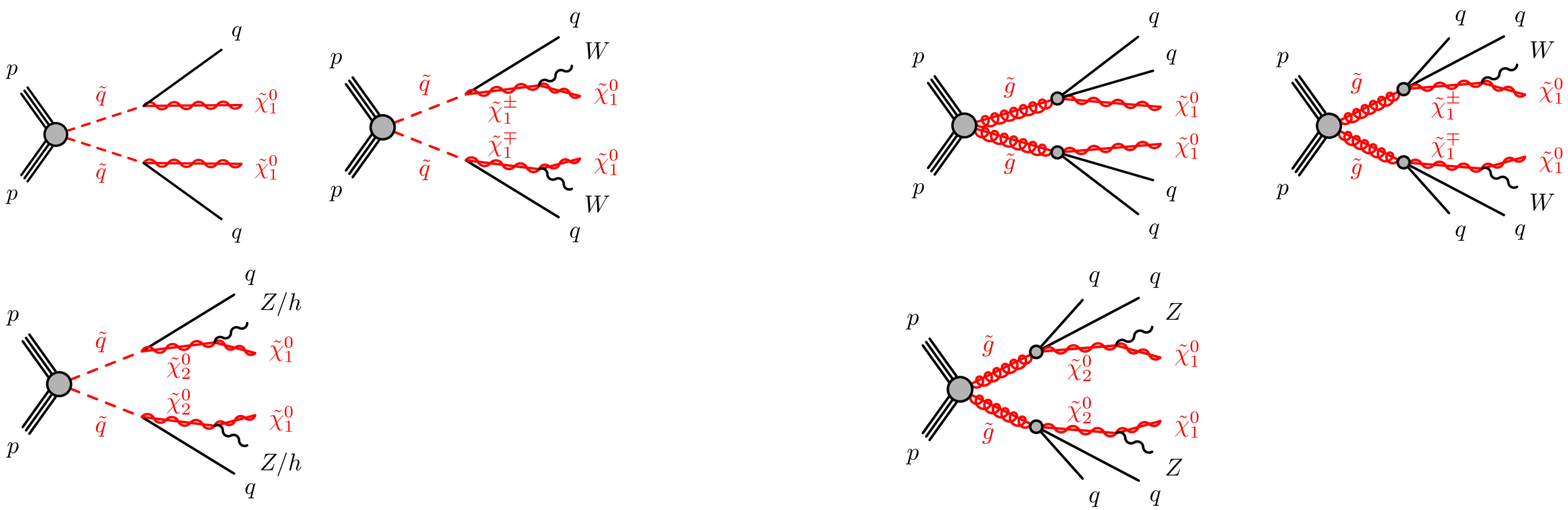
**But, direct production cross section is relatively small** compared to light squark and gluino



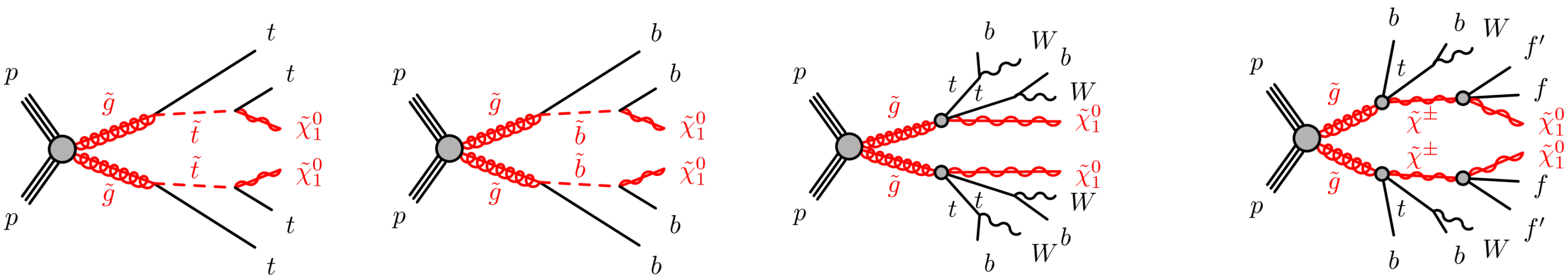

Dedicated searches required

The early focus of Run2 is on strong production with squarks/ gluinos

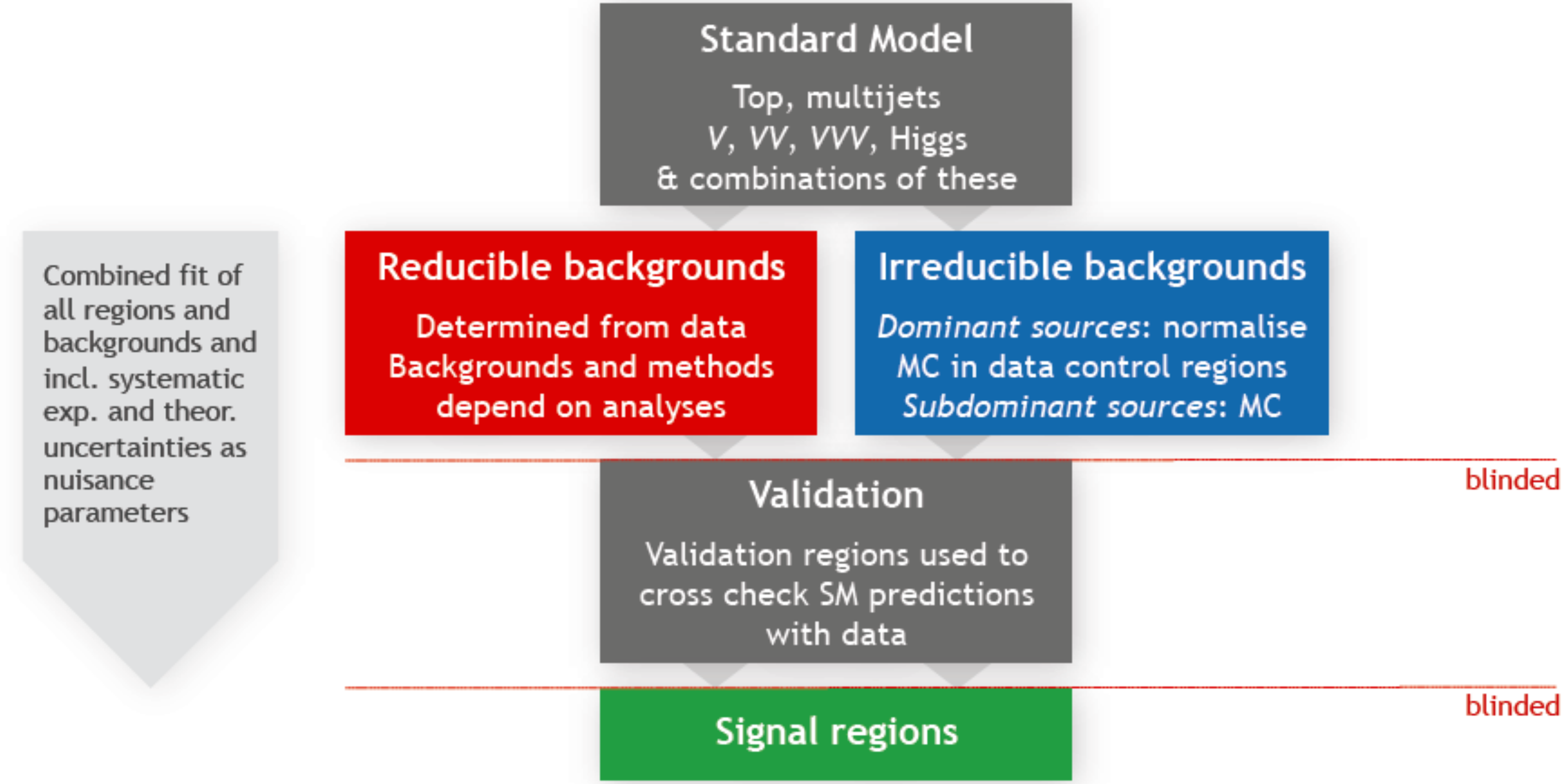
## Squark and Gluino mediated light jets




## Gluino mediated third generation



# SUSY searches rely primarily on the <u>understanding of the SM backgrounds</u>

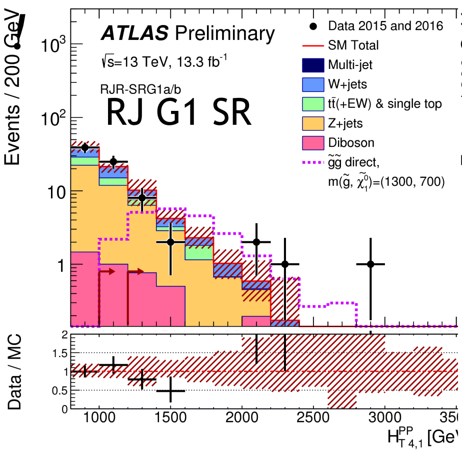


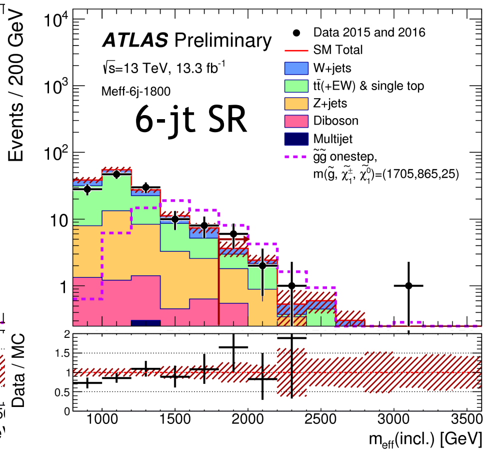
# SUSY: Strong Production

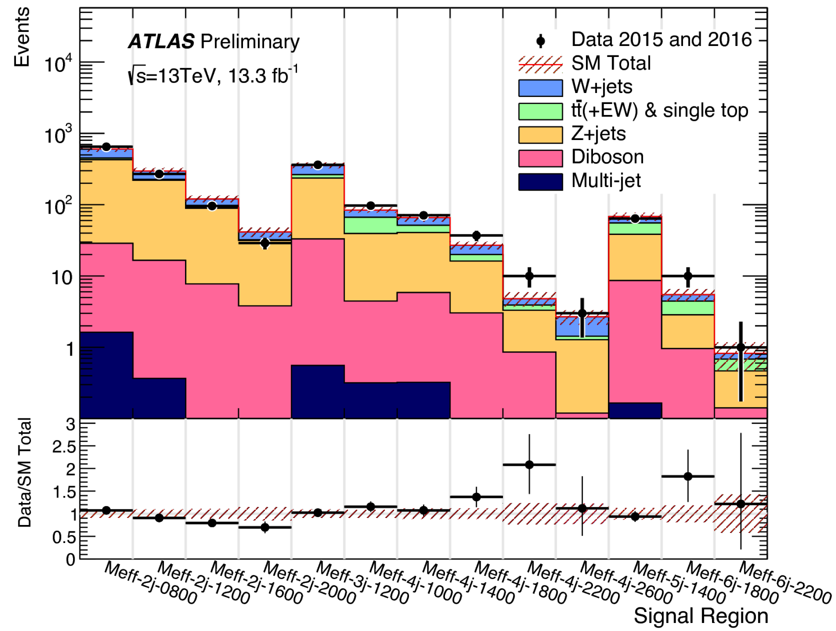
ATLAS EXPERIMENT

Squark and Gluino mediated light jets. The workhorse of the SUSY group – if you predict an excess in many/most channels you often have to reconcile it with the results here.

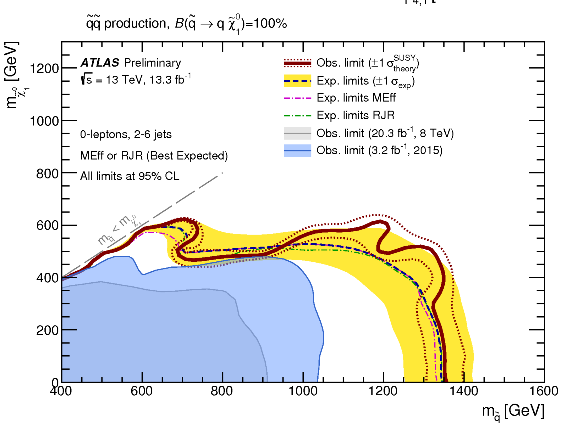
*No excess observed so far in 2015/2016*

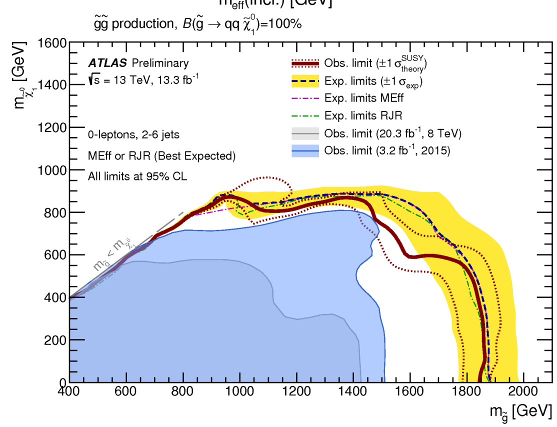


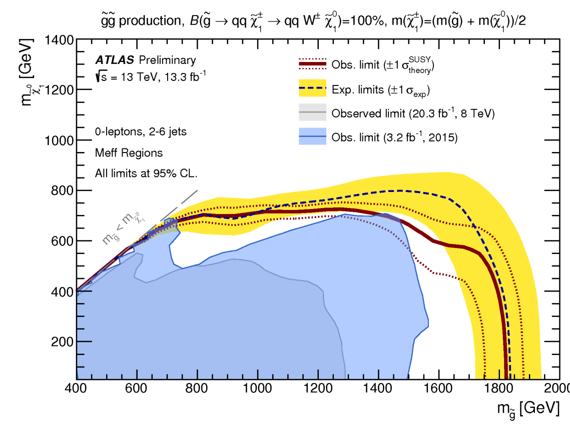




***Always caveats!*** Be careful making blanket interpretations of any SUSY search

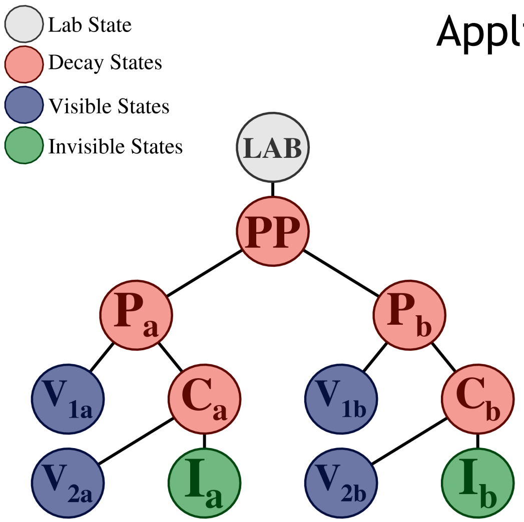


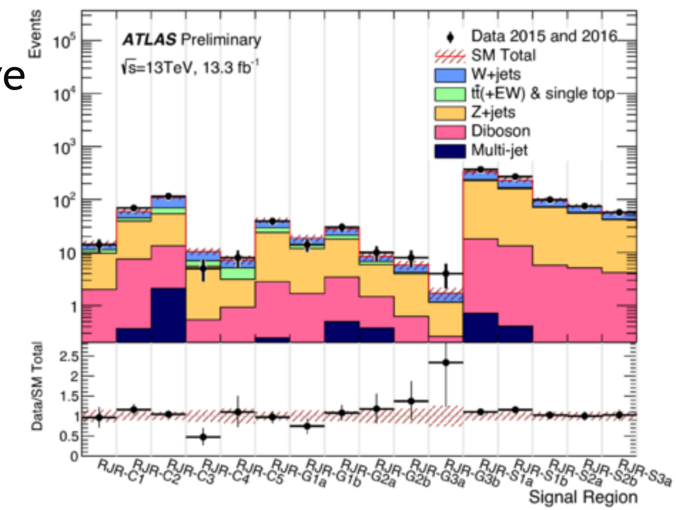
# SUSY: Recursive Jigsaw Reconstruction

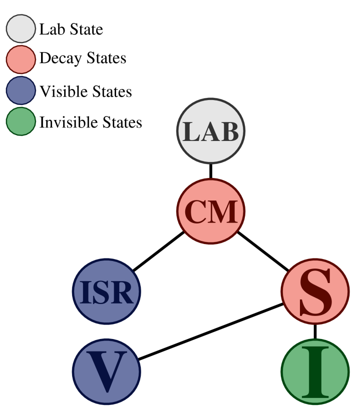
ATLAS EXPERIMENT




Application to open final states

- Apply a *decay tree* to decompose information event-by-event
- Partition the MET using a series of *jigsaw rules*
- Extract a basis of variables sensitive to mass scales, but also properties of particles (decay angles, ratios of scales etc)
- Construct signal regions sensitive

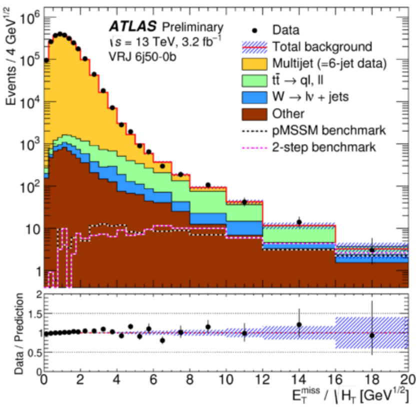


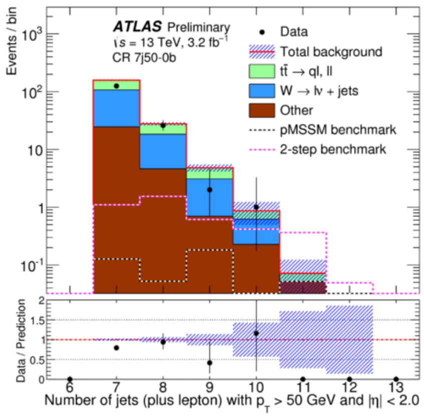



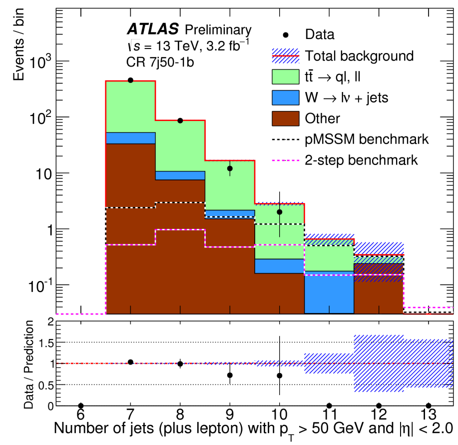

Application to compressed scenarios ( 25 GeV < Δm < 200 GeV)

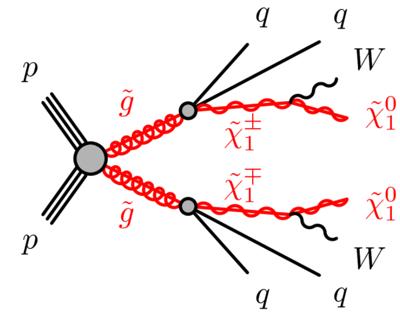
- Leverage large pT ISR system, simple additional complementary variables
- Apply a dedicated decay tree to categorize jets as ISR-like or not
- Improved sensitivity for light squark, stop and gluino pair-production

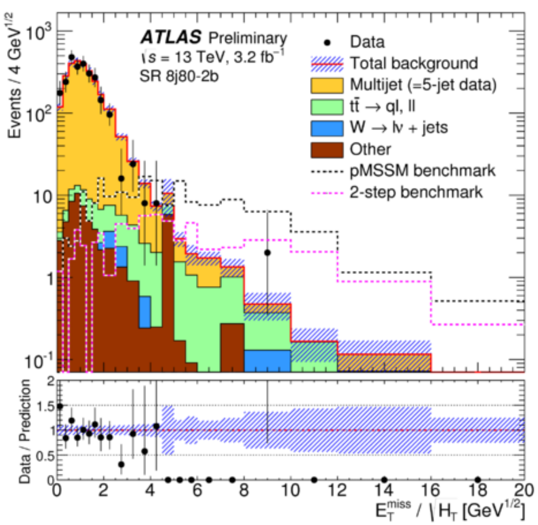
# Squark and Gluino mediated light jets: 7-10 jets and 0 leptons



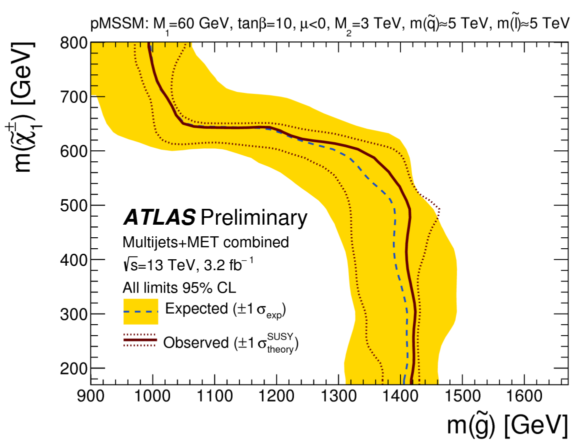



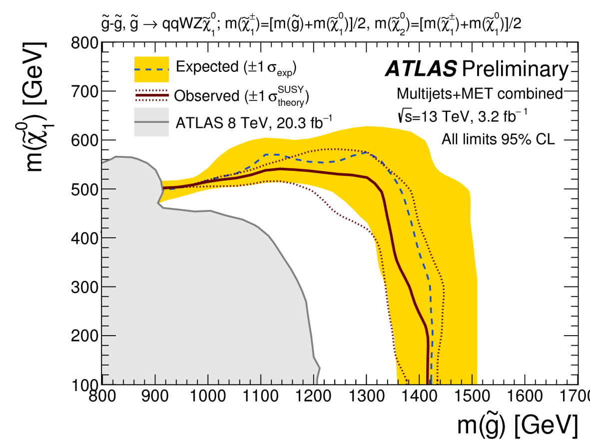





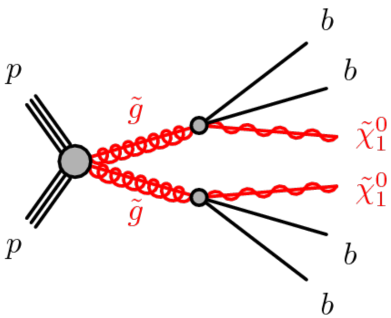

As we increase the number of steps in the decay chain we increase the number of objects

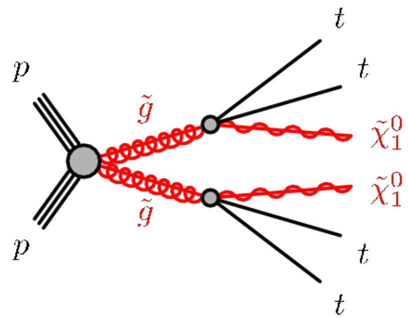


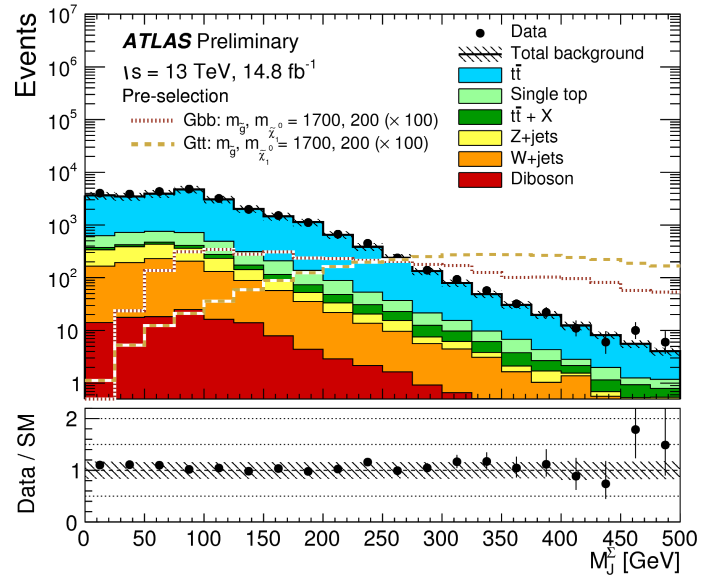



# SUSY: Strong Production – multi b-jet signatures

**Search for gluino** production in 8 signal regions with multiple b-jets aiming at decays with b and top quarks



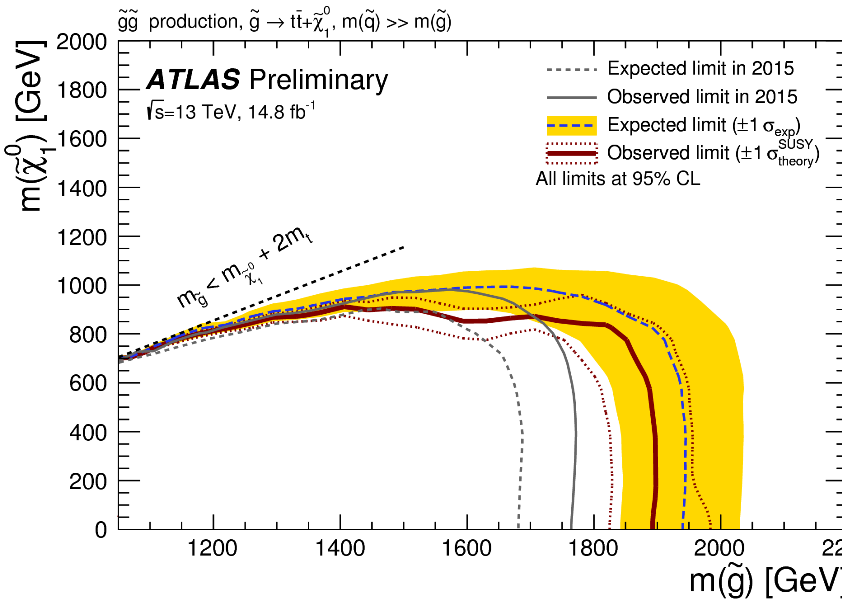




## Signal categories

- 0L and 1L (specific for multi-top signals)
- Number of jets, b-jets and MET

## Improvements to the analysis

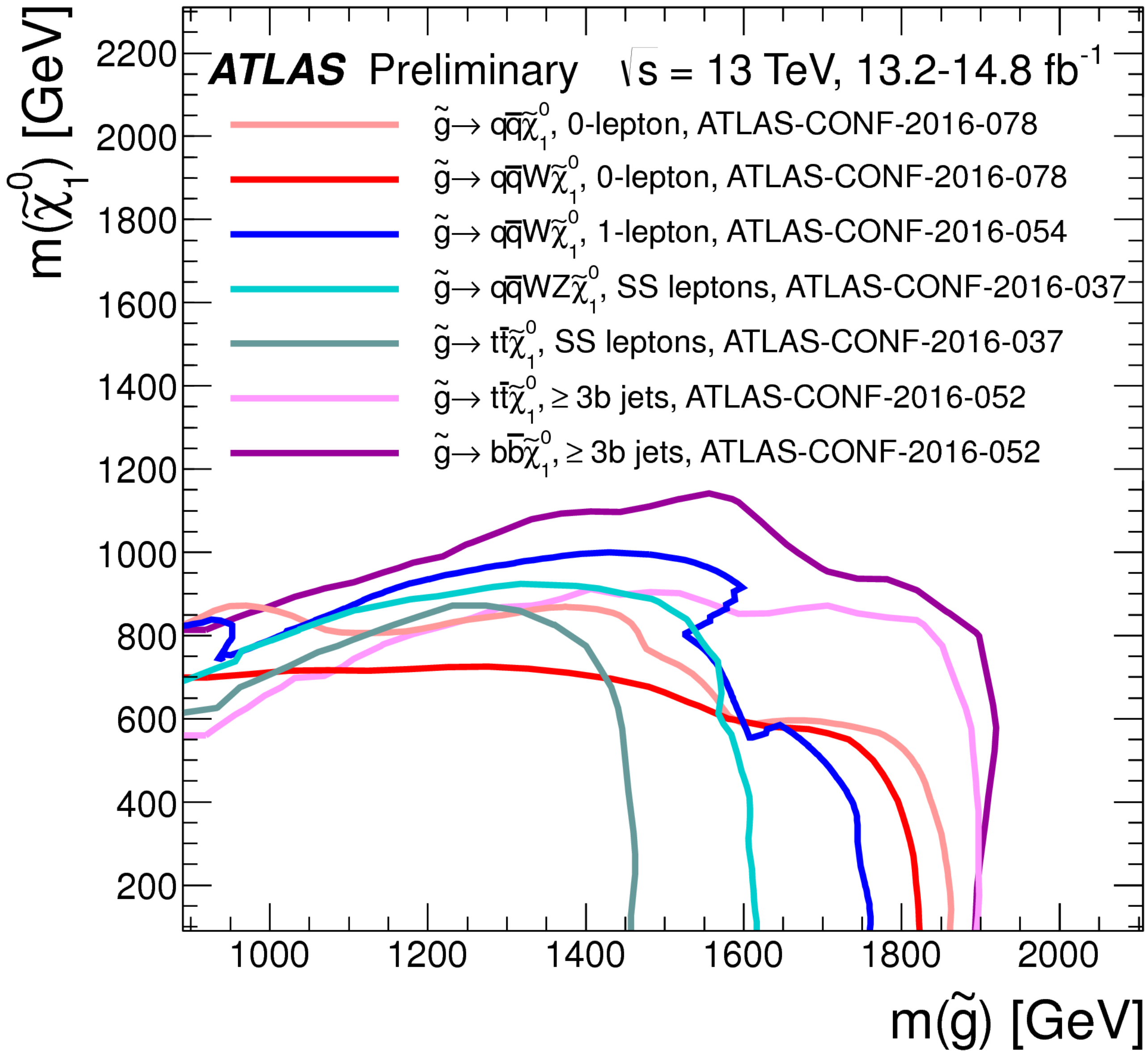
Use of boosted tops, New selection cuts




## Backgrounds

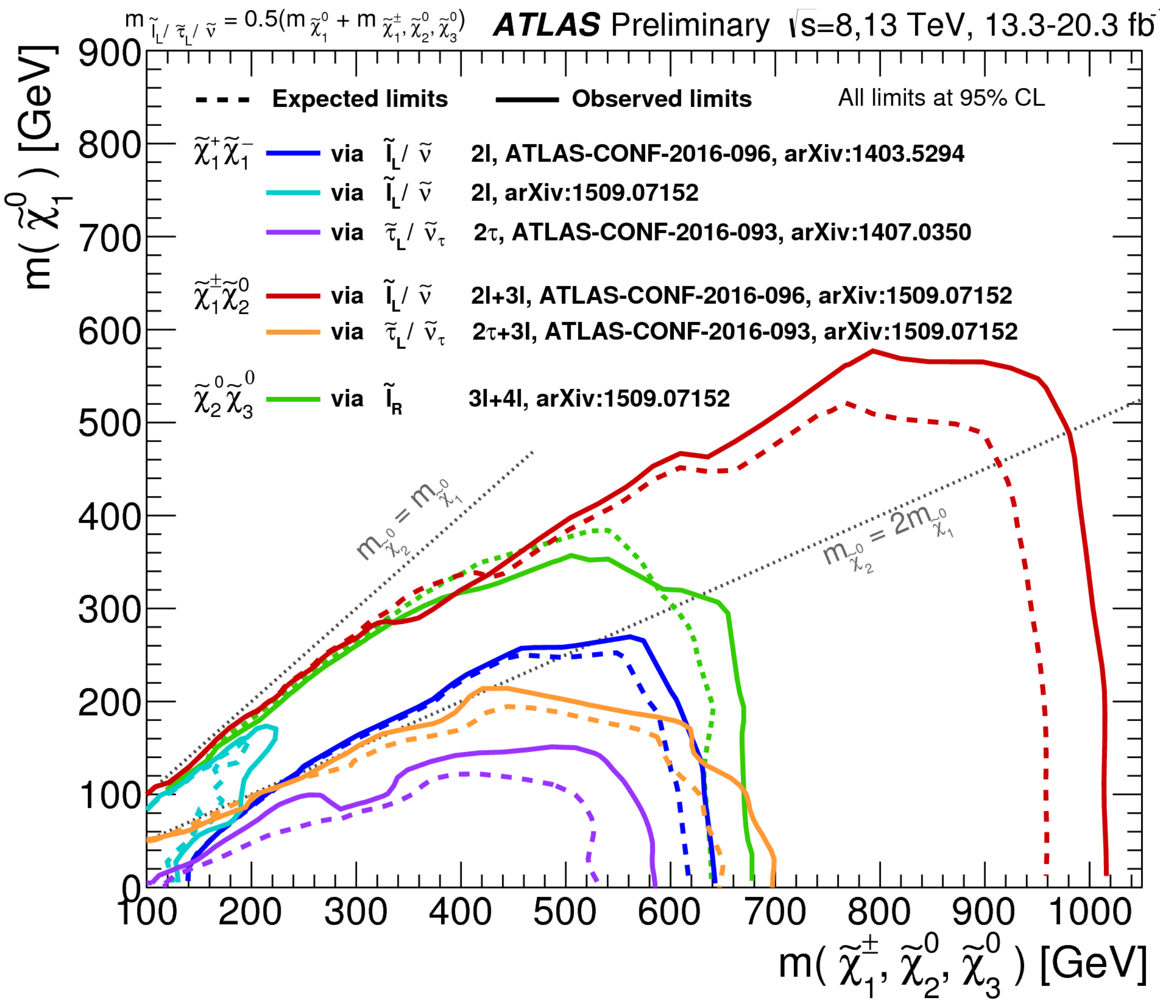
Top background (dominant) from CRs (in MET)

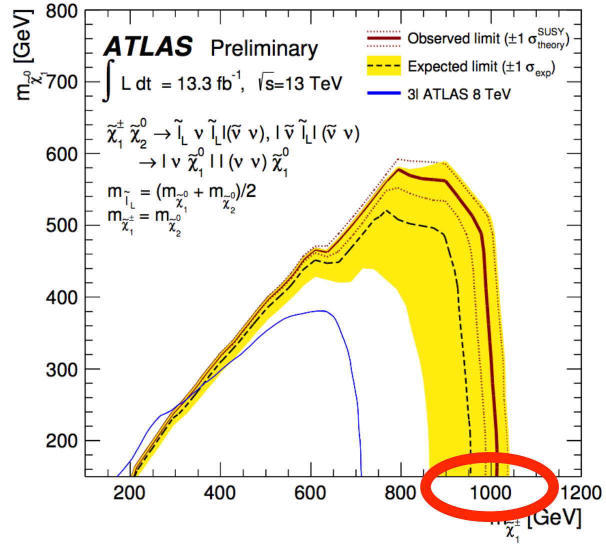
*Other backgrounds from MC*

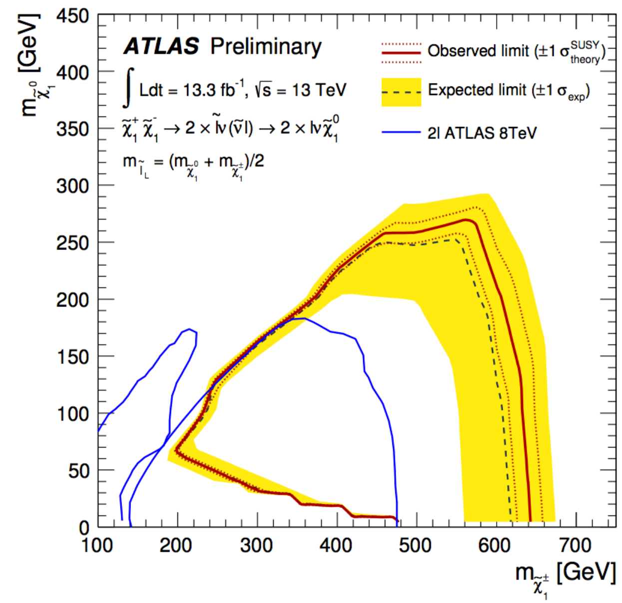


ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 13.2-14.8 fb$^{-1}$
$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$, 0-lepton, ATLAS-CONF-2016-078
$\tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$, 0-lepton, ATLAS-CONF-2016-078
$\tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$, 1-lepton, ATLAS-CONF-2016-054
$\tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$, SS leptons, ATLAS-CONF-2016-037
$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$, SS leptons, ATLAS-CONF-2016-037
$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$, $\geq$ 3b jets, ATLAS-CONF-2016-052
$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$, $\geq$ 3b jets, ATLAS-CONF-2016-052
$m(\tilde{\chi}_1^0)$ [GeV]
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
1000
1200
1400
1600
1800
2000
$m(\tilde{g})$ [GeV]

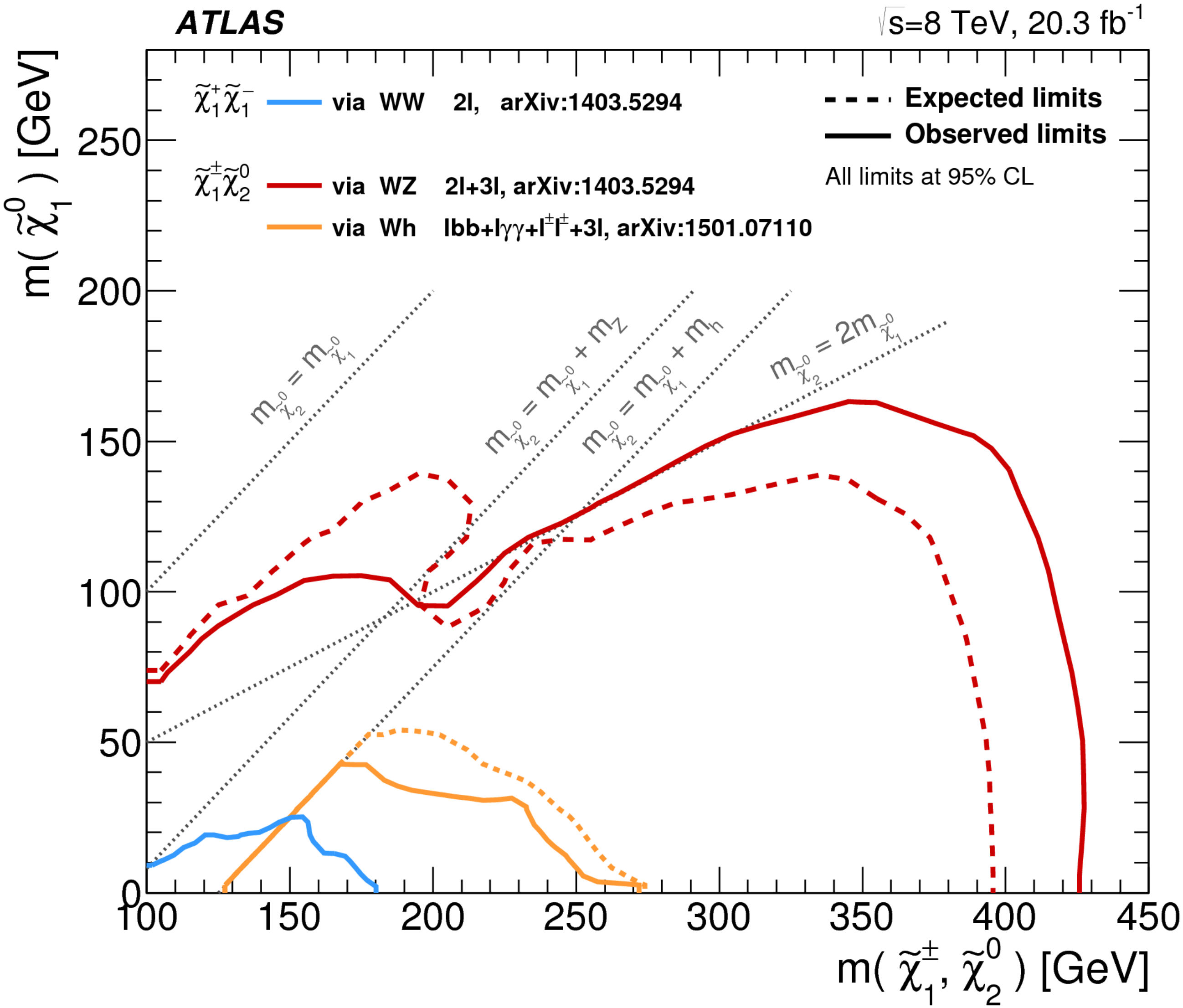
# SUSY: Electroweak Production



# SUSY: Electroweak Production

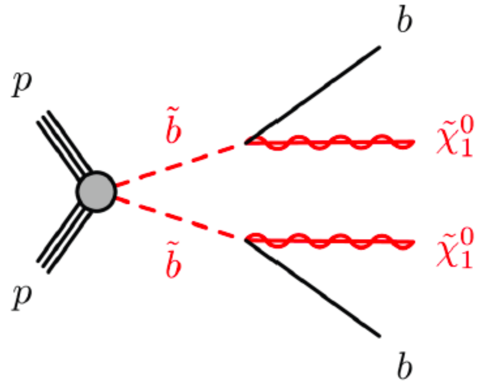


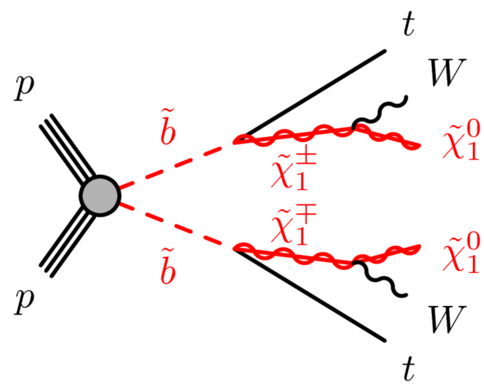

Currently being updated by the Adelaide group.

Stay tuned for more news in the coming weeks when we unblind the data!

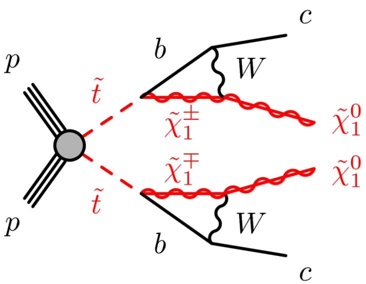
ATLAS EXPERIMENT

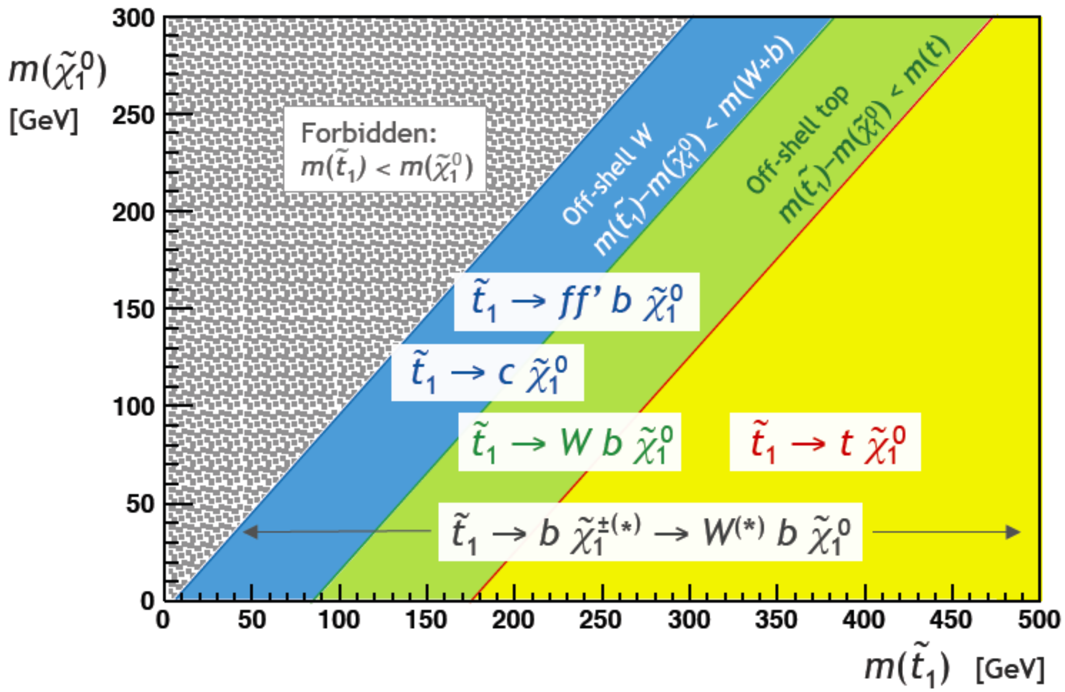
scalar bottom searches

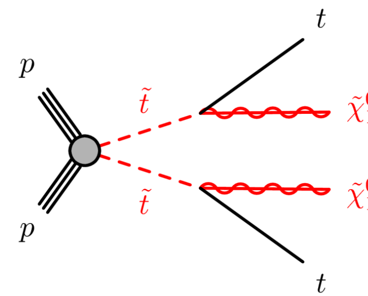


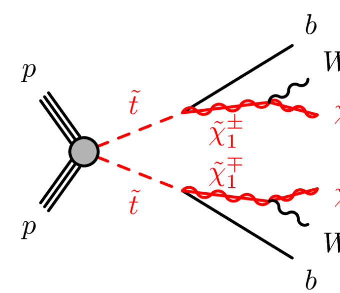




scalar top searches

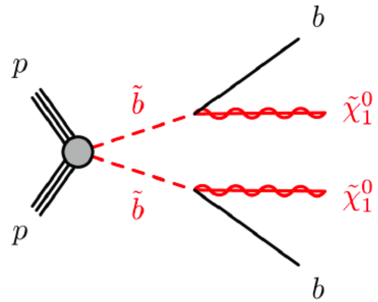


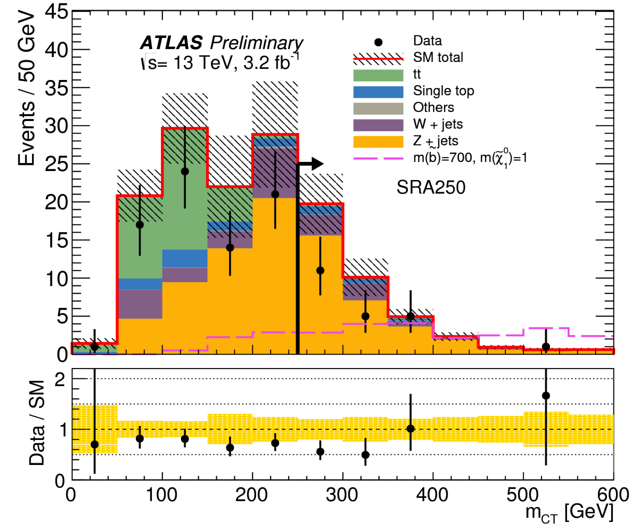



# Scalar bottom searches – still no excess at 13TeV

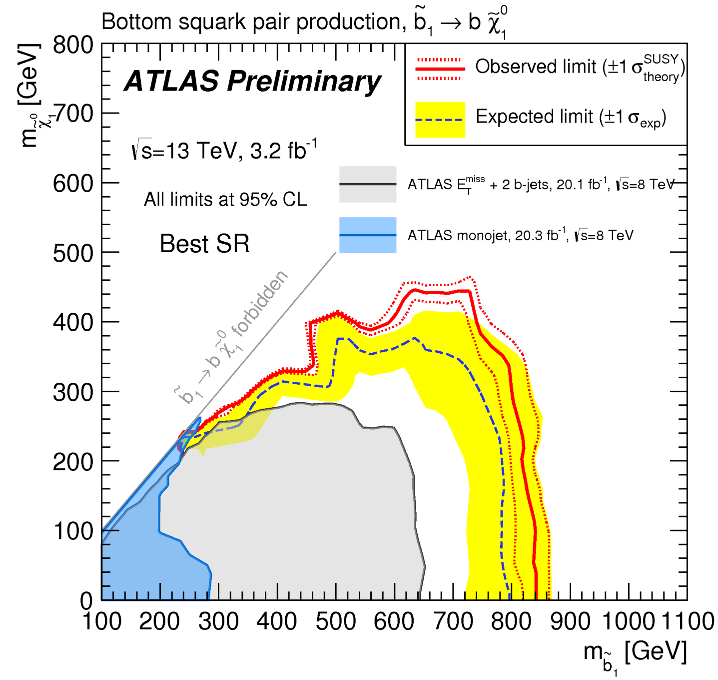



$$m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [p_T(v_1) - p_T(v_2)]^2$$

$$H_{T,3} = \sum_{i=4}^{n} (p_T^{\text{jet}})_i$$




0 lepton + 2 b-jets + MET
Primary signature for direct sbottom production
Direct Stop sensitivity for small $\Delta m(\tilde{\chi}^{\pm}, \tilde{\chi}^0)$ in $\tilde{t}_1 \to b\tilde{\chi}^{\pm}$




## Analysis method:

- Trigger: $E_T^{miss}$
- Selection: $E_T^{miss}$, 2-b-jets, lepton veto
- Large $\Delta m(b_1,\chi^0_1)$: large $m_{CT}$, $m_{bb}$ > 200GeV, 3rd jet veto
- Small $\Delta m(b_1,\chi^0_1)$: require an anti- b-tagged ISR jet, large $H_{T,3}$ and $E_T^{miss}$
- Main backgrounds: Z(νν)+bjets, W+bjets, tt

from Z(ll)+bjets control region

from single lep or e/μ control region

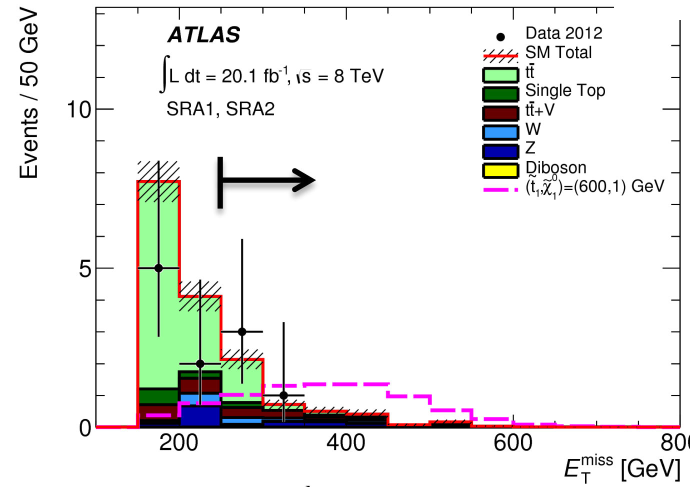

THE UNIVERSITY of ADELAIDE
CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

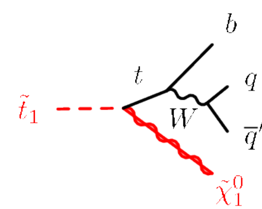
# 0lepton + 6 jets (2 b-jets) +$E_T^{miss}$ analyses

| | |
|---|---|
| Trigger | $E_T^{miss}$ |
| $N_{lep}$ | 0 |
| $b$-tagged jets | $\geq 2$ |
| $E_T^{miss}$ | $> 150 GeV$ |
| $\left\|\Delta\phi\left(\text{jet}, \mathbf{p}_T^{miss}\right)\right\|$ | $> \pi/5$ |
| $\left\|\Delta\phi\left(\mathbf{p}_T^{miss}, \mathbf{p}_T^{miss,track}\right)\right\|$ | $< \pi/3$ |
| $m_T^{b,\,min}$ | $> 175$ GeV |

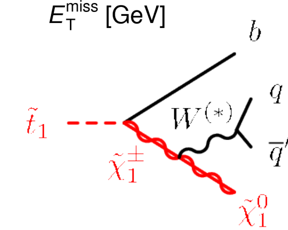
| | SRA1 | SRA2 | SRA3 | SRA4 |
|---|---|---|---|---|
| anti-$k_t$ $R = 0.4$ jets | $\geq 6$, $p_T > 80, 80, 35, 35, 35, 35$ GeV | | | |
| $m_{bjj}^0$ | $< 225$ GeV | | [50,250] GeV | |
| $m_{bjj}^1$ | $< 250$ GeV | | [50,400] GeV | |
| $\min[m_T(\text{jet}^i, \mathbf{p}_T^{miss})]$ | – | | $> 50$ GeV | |
| $\tau$ veto | yes | | | |
| $E_T^{miss}$ | $> 150$ GeV | $> 250$ GeV | $> 300$ GeV | $> 350$ GeV |

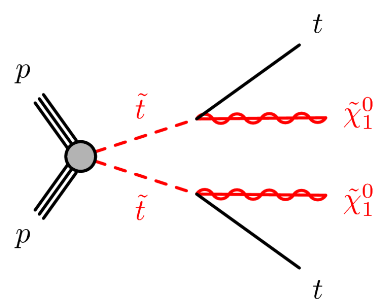
One example of selection showing fully resolved signal regions




AND/
OR

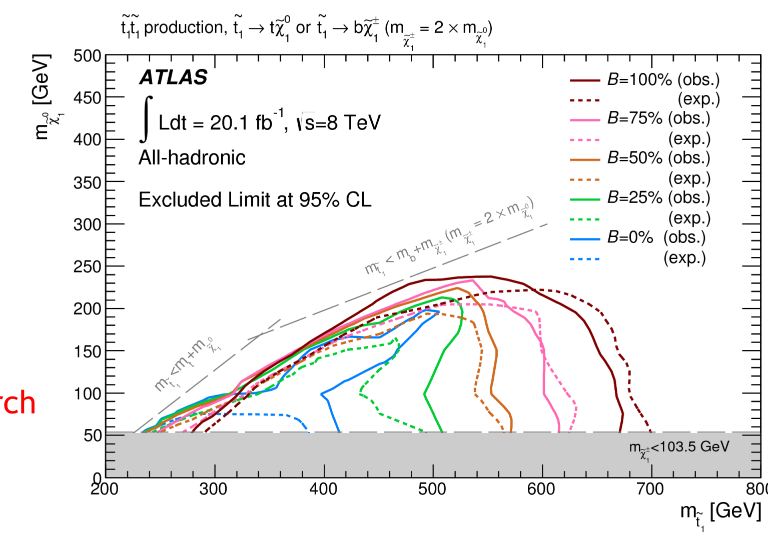


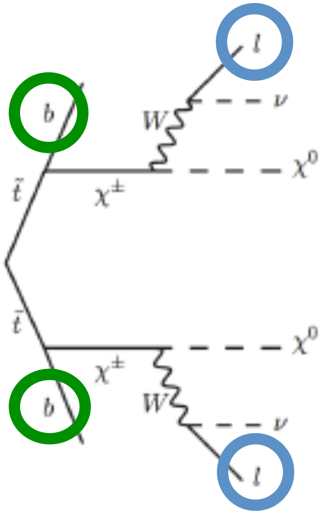

## Main Backgrounds

- Semileptonic tt with one missing (or hadronic tau) lepton: normalise with 1-lepton control region (CR) in data
- Z(vv)+j normalise with Z(ll) CR
- tt + W/Z taken from MC

Challenging fully hadronic search exploiting large MET regime, sensitive to t+LSP decays



ATLAS EXPERIMENT



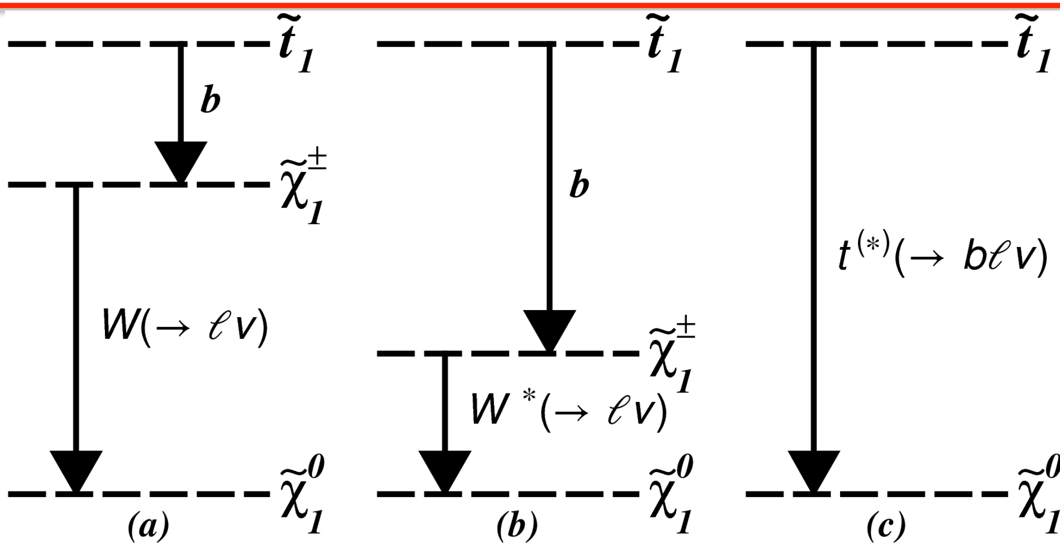

- For pair-produced particles with identical decay chains the variable

$$m_{T2}^2(p_T^\alpha, p_T^\beta, p_T^{\text{miss}}) = \min_{\mathbf{q}_T^{\prime(1)} + \mathbf{q}_T^{\prime(2)} = p_T^{miss}} \left[\max\left(M_T^2(\mathbf{p}_T^\alpha, \mathbf{q}_T^{\prime(1)}; m_\alpha, m_\chi), M_T^2(\mathbf{p}_T^\beta, \mathbf{q}_T^{\prime(2)}; m_\beta, m_\chi)\right)\right]$$

is bounded from above by the parent mass.

$m_{T2}(l_1, l_2, E_T^{Miss})$ bounded by W mass for WW, Wt, $t\bar{t}$

$m_{T2}(b_1, b_2, l_1 + l_2 + E_T^{Miss})$ bounded by top mass for $t\bar{t}$




- Asks for large $m_{T2}(l_1, l_2, E_T^{Miss})$
- Four signal regions, one without jets: sensitive also to small $m(\tilde{t}) - m(\tilde{\chi}_1^\pm)$

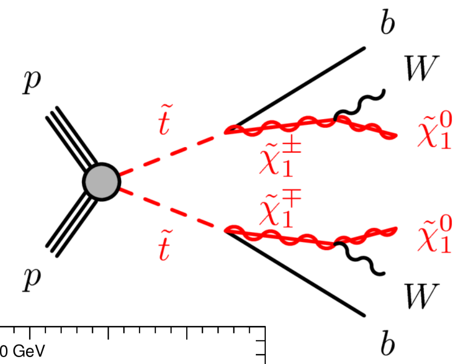
- Asks for 2 b-jets and large $m_{T2}(b_1, b_2, l_1 + l_2 + E_T^{Miss})$

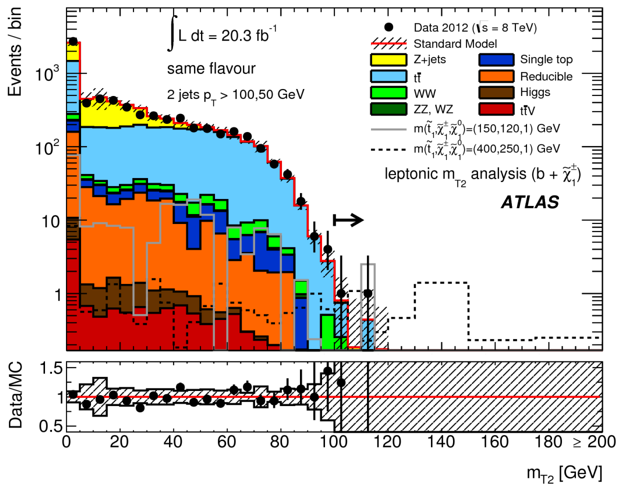
# 2lepton + (b) jets + $E_T^{miss}$ analyses

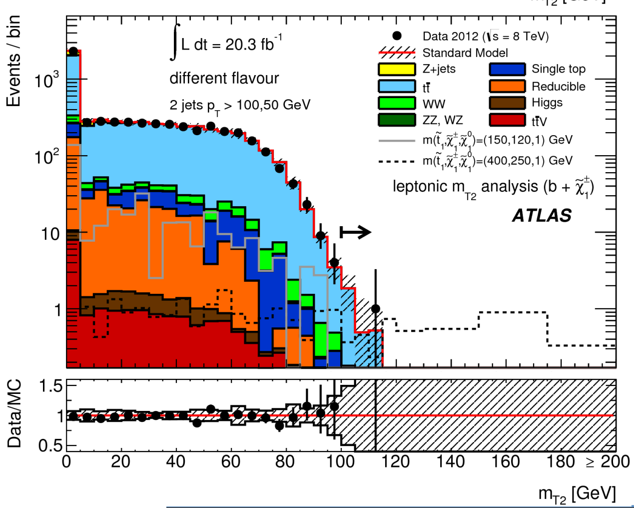
## 2 leptons (+jets) + MET

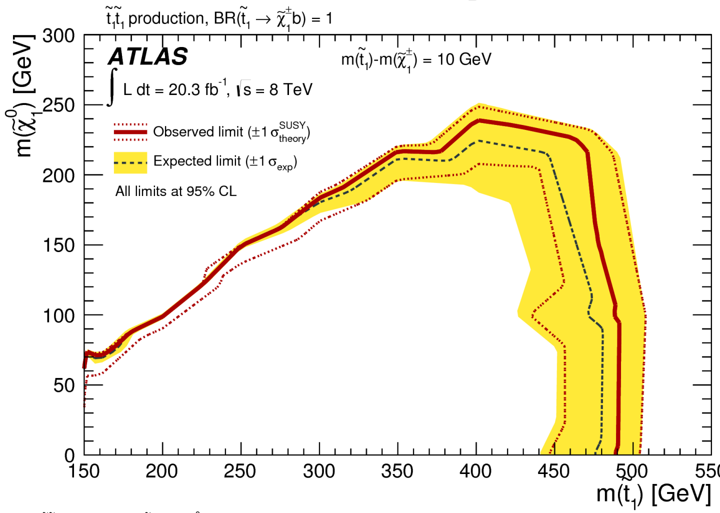
Analysis mainly targets $\tilde{t}_1 \to b\tilde{\chi}^{\pm}$

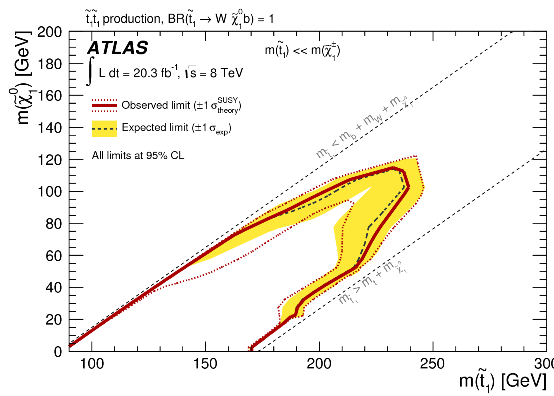
Complements bb + $E_T^{miss}$ analysis for large $\Delta m(\tilde{\chi}^{\pm}, \tilde{\chi}^{0})$

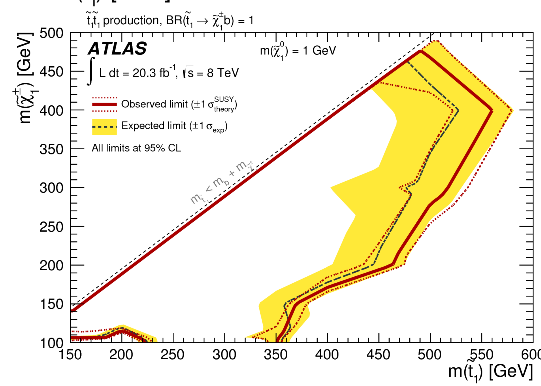




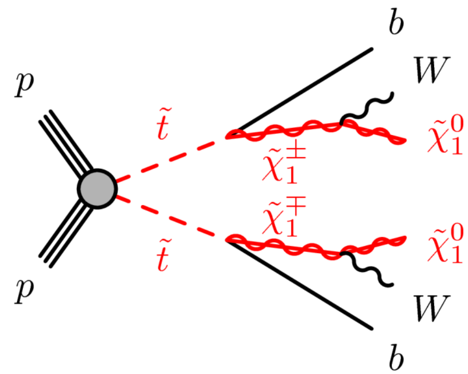



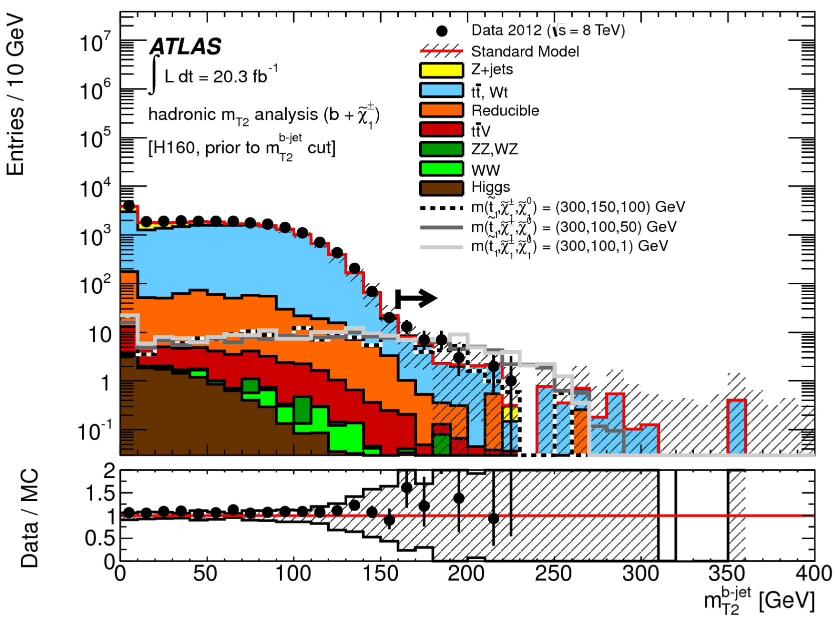

**Limits placed in various kinematic scenarios**

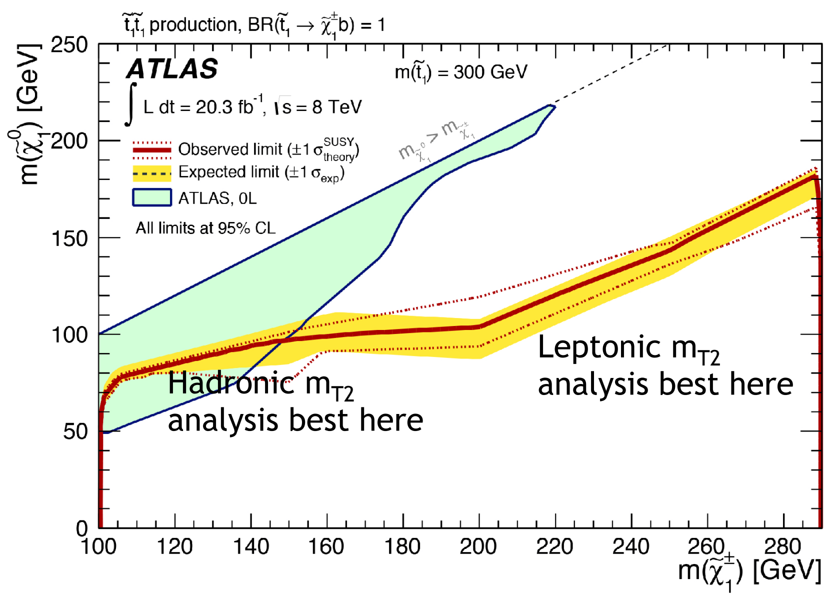
**Selections:**

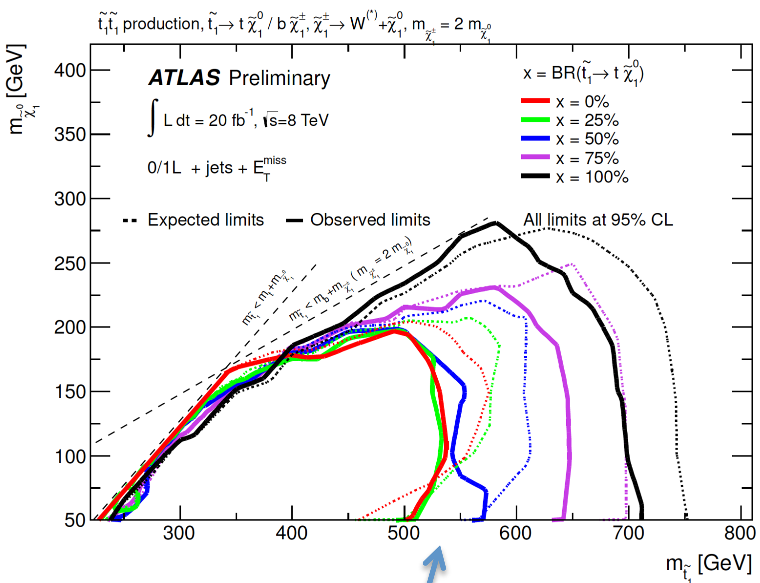
- 2leptons and 2 b-jets
- Leading lepton $p_T$ < 60 GeV
- $m_{T2}(ll, E_T^{miss})$ < 90 GeV
- $m_{T2}(bb, l_1+l_2+E_T^{miss})$ > 160 GeV

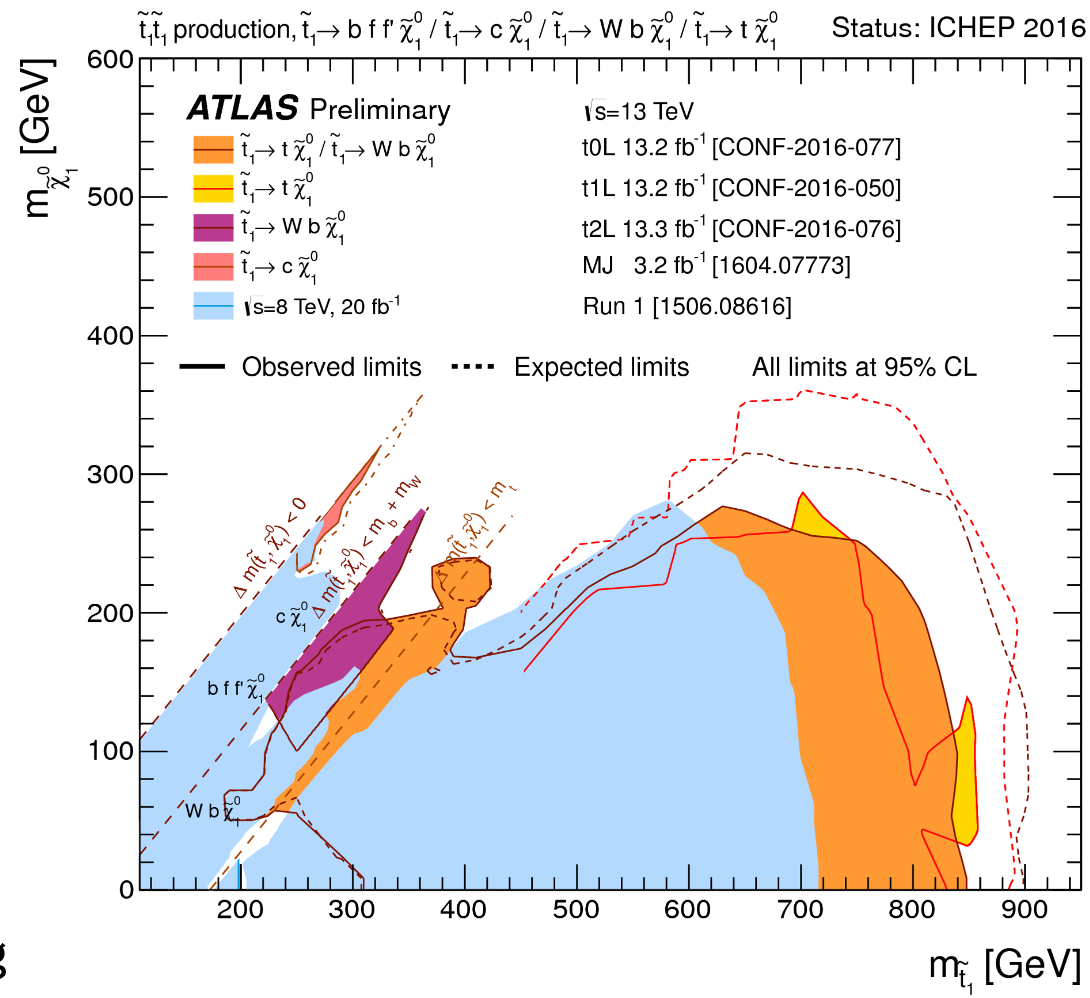
- Main backgrounds (single top and top pairs) normalized in dedicated 1b control region



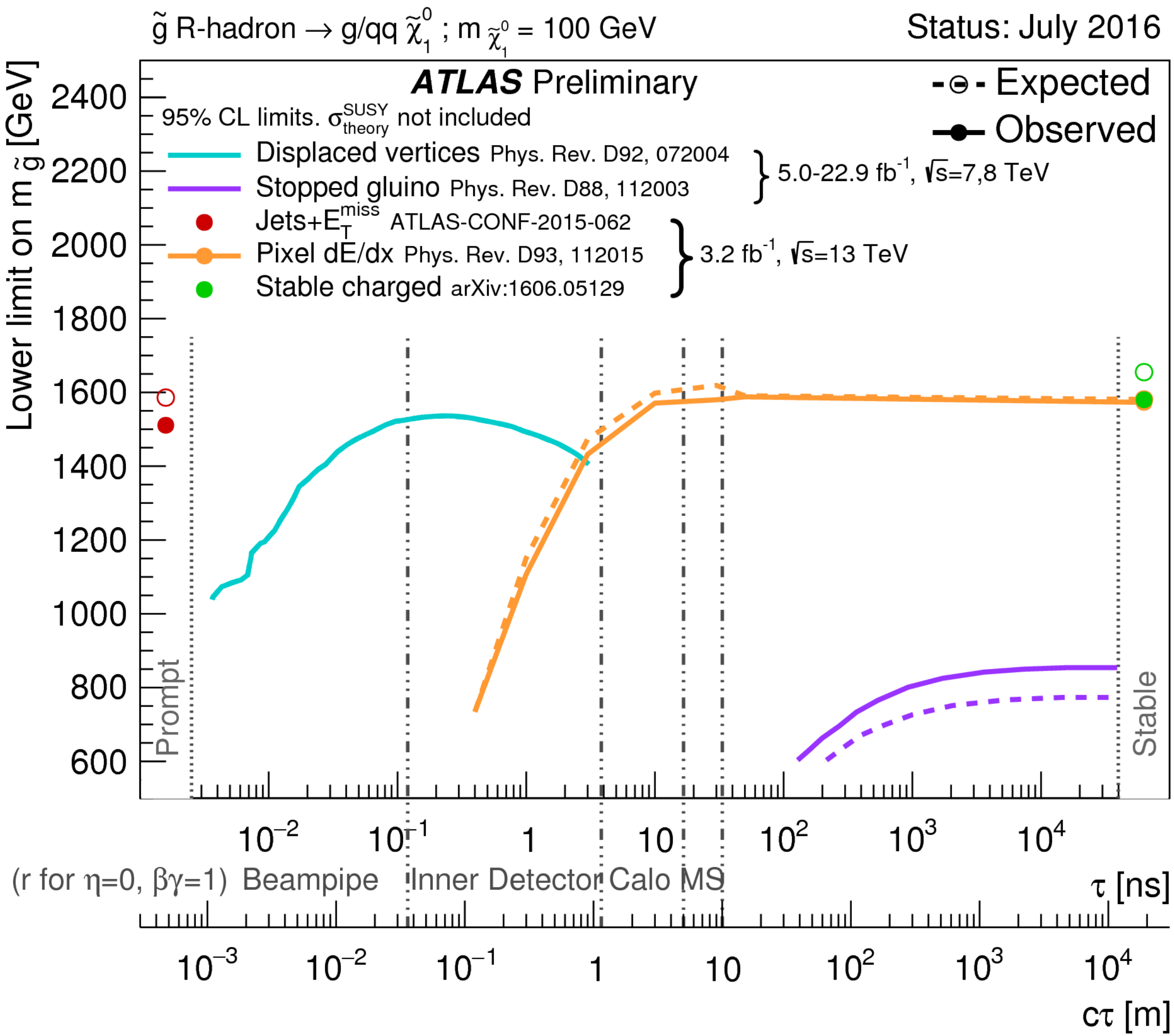





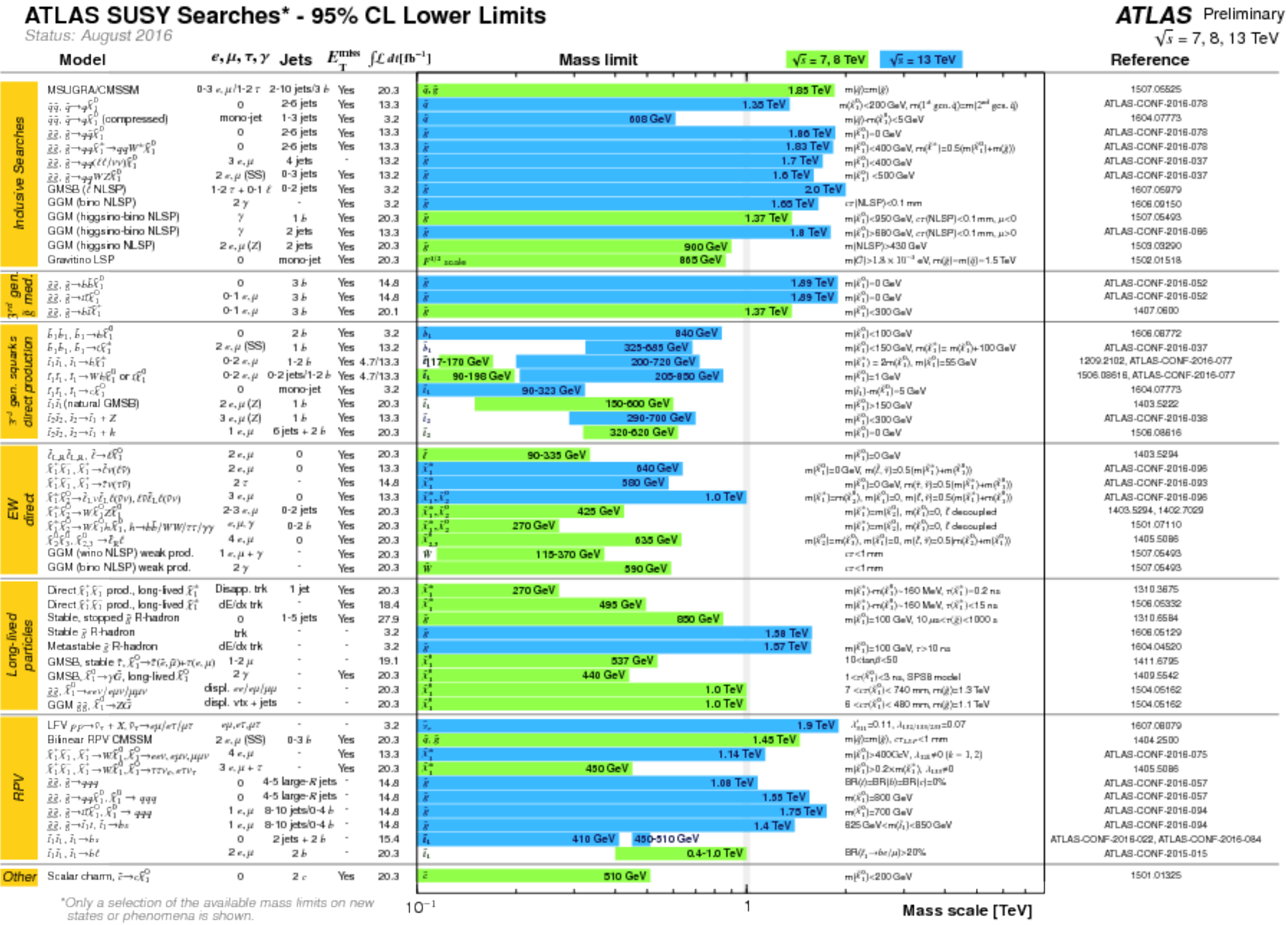




Simply altering the stop branching fractions alter the limits severely

# SUSY: Long-lived particles



ATLAS EXPERIMENT

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# EXOTICA

- What makes something "Exotic"?
- If ≠ SUSY .and. ≠ HIGGS .then. EXOTICA!
- More generally SUSY tends to have large missing momentum and Exotics doesn't necessarily (although R-Parity Violation and Long-lived SUSY mess with this paradigm)
- Also, Exotics is the place where non-SM resonance searches are performed (although they overlap with BSM Higgs)
- Take >=2 SM objects, plot the invariant mass and look for a bump - Easy ☺ (Maybe 😐)
- For the sake of time I won't survey the huge number of searches performed in these groups

# Exotics: Run1 summary

ATLAS EXPERIMENT

## ATLAS Exotics Searches* - 95% CL Exclusion

Status: July 2015

**ATLAS** Preliminary

$\int \mathcal{L}\, dt = (4.7 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

| | Model | $\ell, \gamma$ | Jets | $E_T^{miss}$ | $\int \mathcal{L}\, dt [\text{fb}^{-1}]$ | Limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Extra dimensions | ADD $G_{KK} + g/q$ | – | ≥ 1 j | Yes | 20.3 | $M_D$ 5.25 TeV | $n = 2$ | 1502.01518 |
| | ADD non-resonant $\ell\ell$ | 2e, $\mu$ | – | – | 20.3 | $M_S$ 4.7 TeV | $n = 3$ HLZ | 1407.2410 |
| | ADD QBH $\to \ell q$ | 1 e, $\mu$ | 1 j | – | 20.3 | $M_{th}$ 5.2 TeV | $n = 6$ | 1311.2006 |
| | ADD QBH | – | 2 j | – | 20.3 | $M_{th}$ 5.82 TeV | $n = 6$ | 1407.1376 |
| | ADD BH high $N_{trk}$ | 2 $\mu$ (SS) | – | – | 20.3 | $M_{th}$ 4.7 TeV | $n = 6$, $M_D = 3$ TeV, non-rot BH | 1308.4075 |
| | ADD BH high $\sum p_T$ | ≥ 1 e, $\mu$ | ≥ 2 j | – | 20.3 | $M_{th}$ 5.8 TeV | $n = 6$, $M_D = 3$ TeV, non-rot BH | 1405.4254 |
| | ADD BH high multijet | – | ≥ 2 j | – | 20.3 | $M_{th}$ 5.8 TeV | $n = 6$, $M_D = 3$ TeV, non-rot BH | 1503.08988 |
| | RS1 $G_{KK} \to \ell\ell$ | 2 e, $\mu$ | – | – | 20.3 | $G_{KK}$ mass 2.68 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1405.4123 |
| | RS1 $G_{KK} \to \gamma\gamma$ | 2 $\gamma$ | – | – | 20.3 | $G_{KK}$ mass 2.66 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1504.05511 |
| | Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$ | 2 e, $\mu$ | 2 j / 1 J | – | 20.3 | $G_{KK}$ mass 740 GeV | $k/\overline{M}_{Pl} = 1.0$ | 1409.6190 |
| | Bulk RS $G_{KK} \to WW \to qq\ell\nu$ | 1 e, $\mu$ | 2 j / 1 J | Yes | 20.3 | W' mass 760 GeV | $k/\overline{M}_{Pl} = 1.0$ | 1503.04677 |
| | Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$ | – | 4 b | – | 19.5 | $G_{KK}$ mass 500-720 GeV | $k/\overline{M}_{Pl} = 1.0$ | 1506.00285 |
| | Bulk RS $g_{KK} \to t\bar{t}$ | 1 e, $\mu$ | ≥ 1 b, ≥ 1J/2j | Yes | 20.3 | $g_{KK}$ mass 2.2 TeV | BR = 0.925 | 1505.07018 |
| | 2UED / RPP | 2 e, $\mu$ (SS) | ≥ 1 b, ≥ 1 j | Yes | 20.3 | KK mass 960 GeV | | 1504.04605 |
| Gauge bosons | SSM $Z' \to \ell\ell$ | 2 e, $\mu$ | – | – | 20.3 | Z' mass 2.9 TeV | | 1405.4123 |
| | SSM $Z' \to \tau\tau$ | 2 $\tau$ | – | – | 19.5 | Z' mass 2.02 TeV | | 1502.07177 |
| | SSM $W' \to \ell\nu$ | 1 e, $\mu$ | – | Yes | 20.3 | W' mass 3.24 TeV | | 1407.7494 |
| | EGM $W' \to WZ \to \ell\nu\,\ell'\ell'$ | 3 e, $\mu$ | – | Yes | 20.3 | W' mass 1.52 TeV | | 1406.4456 |
| | EGM $W' \to WZ \to qq\ell\ell$ | 2 e, $\mu$ | 2 j / 1 J | – | 20.3 | W' mass 1.59 TeV | | 1409.6190 |
| | EGM $W' \to WZ \to qqqq$ | – | 2 J | – | 20.3 | W' mass 1.3-1.5 TeV | | 1506.00962 |
| | HVT $W' \to WH \to \ell\nu bb$ | 1 e, $\mu$ | 2 b | Yes | 20.3 | W' mass 1.47 TeV | $g_V = 1$ | 1503.08089 |
| | LRSM $W'_R \to t\bar{b}$ | 1 e, $\mu$ | 2 b, 0-1 j | Yes | 20.3 | W' mass 1.92 TeV | | 1410.4103 |
| | LRSM $W'_R \to t\bar{b}$ | 0 e, $\mu$ | ≥ 1 b, 1 J | – | 20.3 | W' mass 1.76 TeV | | 1408.0886 |
| CI | CI $qqqq$ | – | 2 j | – | 17.3 | $\Lambda$ 12.0 TeV | $\eta_{LL} = -1$ | 1504.00357 |
| | CI $qq\ell\ell$ | 2 e, $\mu$ | – | – | 20.3 | $\Lambda$ 21.6 TeV | $\eta_{LL} = -1$ | 1407.2410 |
| | CI $uutt$ | 2 e, $\mu$ (SS) | ≥ 1 b, ≥ 1 j | Yes | 20.3 | $\Lambda$ 4.3 TeV | $\lvert C_{LL}\rvert = 1$ | 1504.04605 |
| DM | EFT D5 operator (Dirac) | 0 e, $\mu$ | ≥ 1 j | Yes | 20.3 | $M_*$ 974 GeV | at 90% CL for $m(\chi) < 100$ GeV | 1502.01518 |
| | EFT D9 operator (Dirac) | 0 e, $\mu$ | 1 J, ≤ 1 j | Yes | 20.3 | $M_*$ 2.4 TeV | at 90% CL for $m(\chi) < 100$ GeV | 1309.4017 |
| LQ | Scalar LQ 1st gen | 2 e | ≥ 2 j | – | 20.3 | LQ mass 1.05 TeV | $\beta = 1$ | Preliminary |
| | Scalar LQ 2nd gen | 2 $\mu$ | ≥ 2 j | – | 20.3 | LQ mass 1.0 TeV | $\beta = 1$ | Preliminary |
| | Scalar LQ 3rd gen | 1 e, $\mu$ | ≥1 b, ≥3 j | Yes | 20.3 | LQ mass 640 GeV | $\beta = 0$ | Preliminary |
| Heavy quarks | VLQ $TT \to Ht + X$ | 1 e, $\mu$ | ≥ 2 b, ≥ 3 j | Yes | 20.3 | T mass 855 GeV | T in (T,B) doublet | 1505.04306 |
| | VLQ $YY \to Wb + X$ | 1 e, $\mu$ | ≥ 1 b, ≥ 3 j | Yes | 20.3 | Y mass 770 GeV | Y in (B,Y) doublet | 1505.04306 |
| | VLQ $BB \to Hb + X$ | 1 e, $\mu$ | ≥ 2 b, ≥ 3 j | Yes | 20.3 | B mass 735 GeV | isospin singlet | 1505.04306 |
| | VLQ $BB \to Zb + X$ | 2/≥3 e, $\mu$ | ≥2/≥1 b | – | 20.3 | B mass 755 GeV | B in (B,Y) doublet | 1409.5500 |
| | $T_{5/3} \to Wt$ | 1 e, $\mu$ | ≥ 1 b, ≥ 5 j | Yes | 20.3 | $T_{5/3}$ mass 840 GeV | | 1503.05425 |
| Excited fermions | Excited quark $q^* \to q\gamma$ | 1 $\gamma$ | 1 j | – | 20.3 | $q^*$ mass 3.5 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1309.3230 |
| | Excited quark $q^* \to qg$ | – | 2 j | – | 20.3 | $q^*$ mass 4.09 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1407.1376 |
| | Excited quark $b^* \to Wt$ | 1 or 2 e, $\mu$ | 1 b, 2 j or 1 j | Yes | 4.7 | $b^*$ mass 870 GeV | left-handed coupling | 1301.1583 |
| | Excited lepton $\ell^* \to \ell\gamma$ | 2 e, $\mu$, 1 $\gamma$ | – | – | 13.0 | $\ell^*$ mass 2.2 TeV | $\Lambda = 2.2$ TeV | 1308.1364 |
| | Excited lepton $\nu^* \to \ell W, \nu Z$ | 3 e, $\mu$, $\tau$ | – | – | 20.3 | $\nu^*$ mass 1.6 TeV | $\Lambda = 1.6$ TeV | 1411.2921 |
| Other | LSTC $a_T \to W\gamma$ | 1 e, $\mu$, 1 $\gamma$ | – | Yes | 20.3 | $a_T$ mass 960 GeV | | 1407.8150 |
| | LRSM Majorana $\nu$ | 2 e, $\mu$ | 2 j | – | 20.3 | $N^0$ mass 2.0 TeV | $m(W_R) = 2.4$ TeV, no mixing | 1506.06020 |
| | Higgs triplet $H^{\pm\pm} \to \ell\ell$ | 2 e, $\mu$ (SS) | – | – | 20.3 | $H^{\pm\pm}$ mass 551 GeV | DY production, BR($H_L^{\pm\pm} \to \ell\ell$)=1 | 1412.0237 |
| | Higgs triplet $H^{\pm\pm} \to \ell\tau$ | 3 e, $\mu$, $\tau$ | – | – | 20.3 | $H^{\pm\pm}$ mass 400 GeV | DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1 | 1411.2921 |
| | Monotop (non-res prod) | 1 e, $\mu$ | 1 b | Yes | 20.3 | spin-1 invisible particle mass 657 GeV | $a_{\text{non-res}} = 0.2$ | 1410.5404 |
| | Multi-charged particles | – | – | – | 20.3 | multi-charged particle mass 785 GeV | DY production, $\lvert q\rvert = 5e$ | 1504.04188 |
| | Magnetic monopoles | – | – | – | 7.0 | monopole mass 1.34 TeV | DY production, $\lvert g\rvert = 1 g_D$, spin 1/2 | Preliminary |

$\sqrt{s} = 7$ TeV $\sqrt{s} = 8$ TeV

$10^{-1}$ 1 10 Mass scale [TeV]

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

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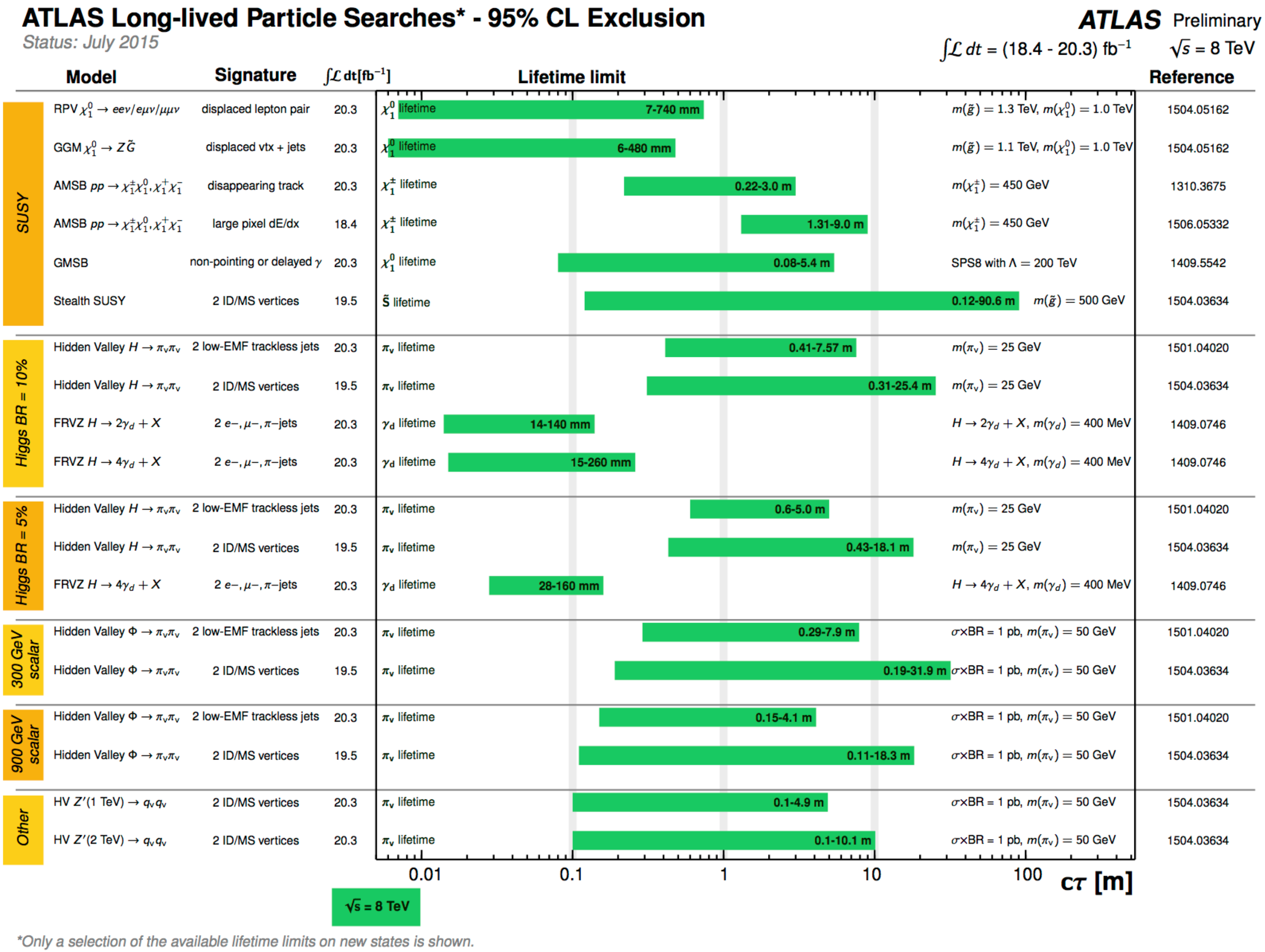
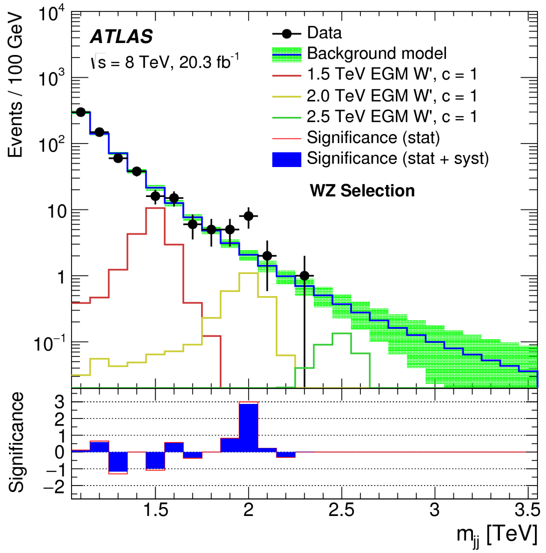
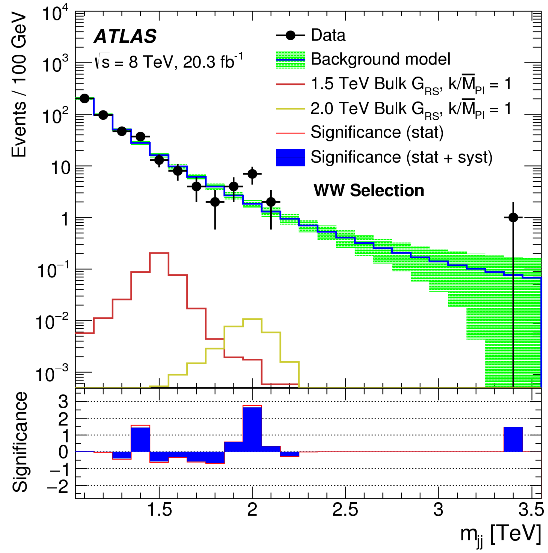
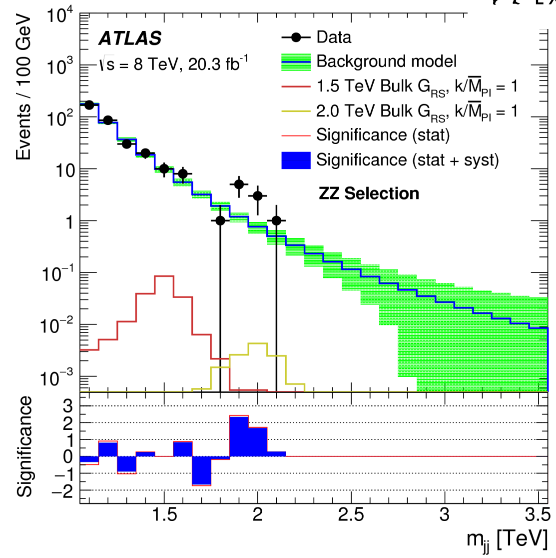
# Long-lived particle searches: Run1 summary

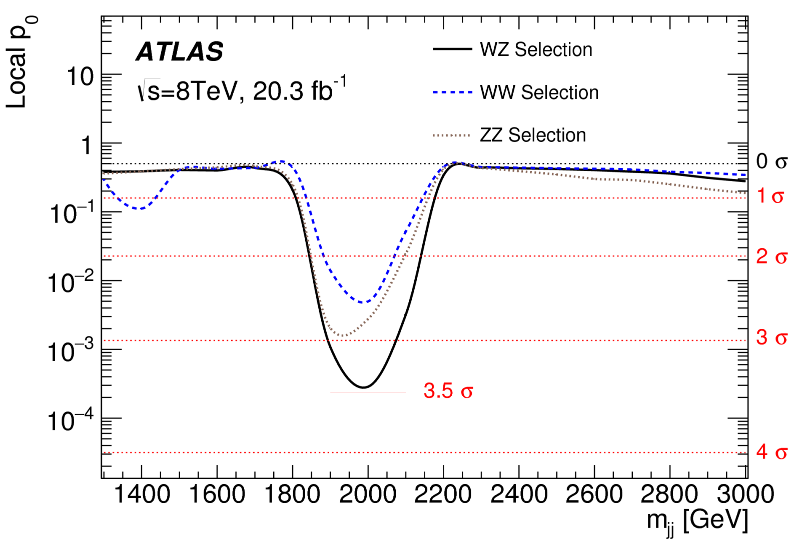


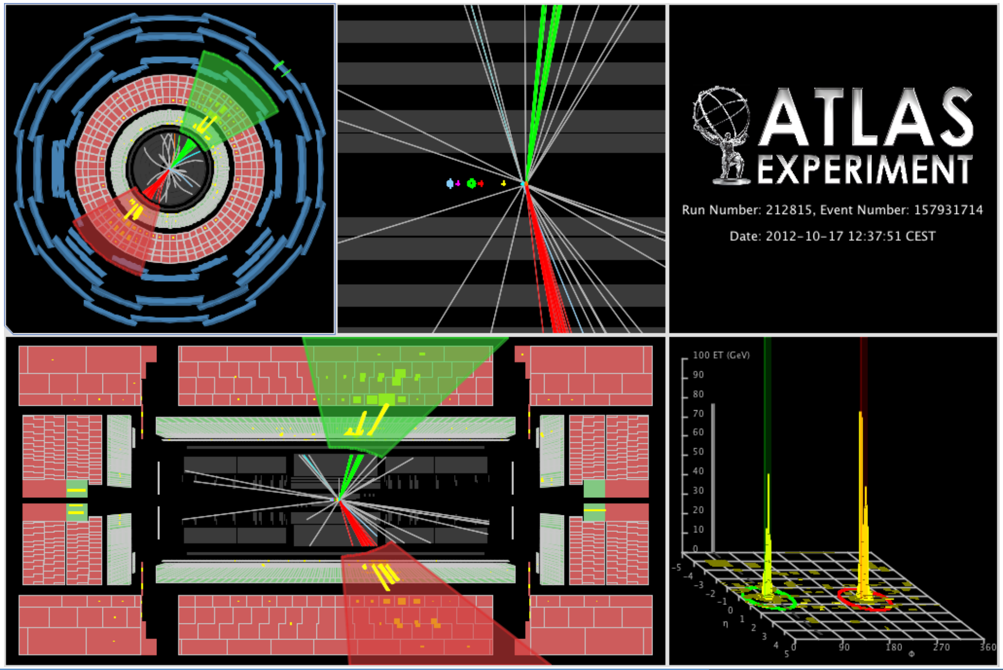
# Exotics: Run1 - diboson resonances with boson-tagged jets

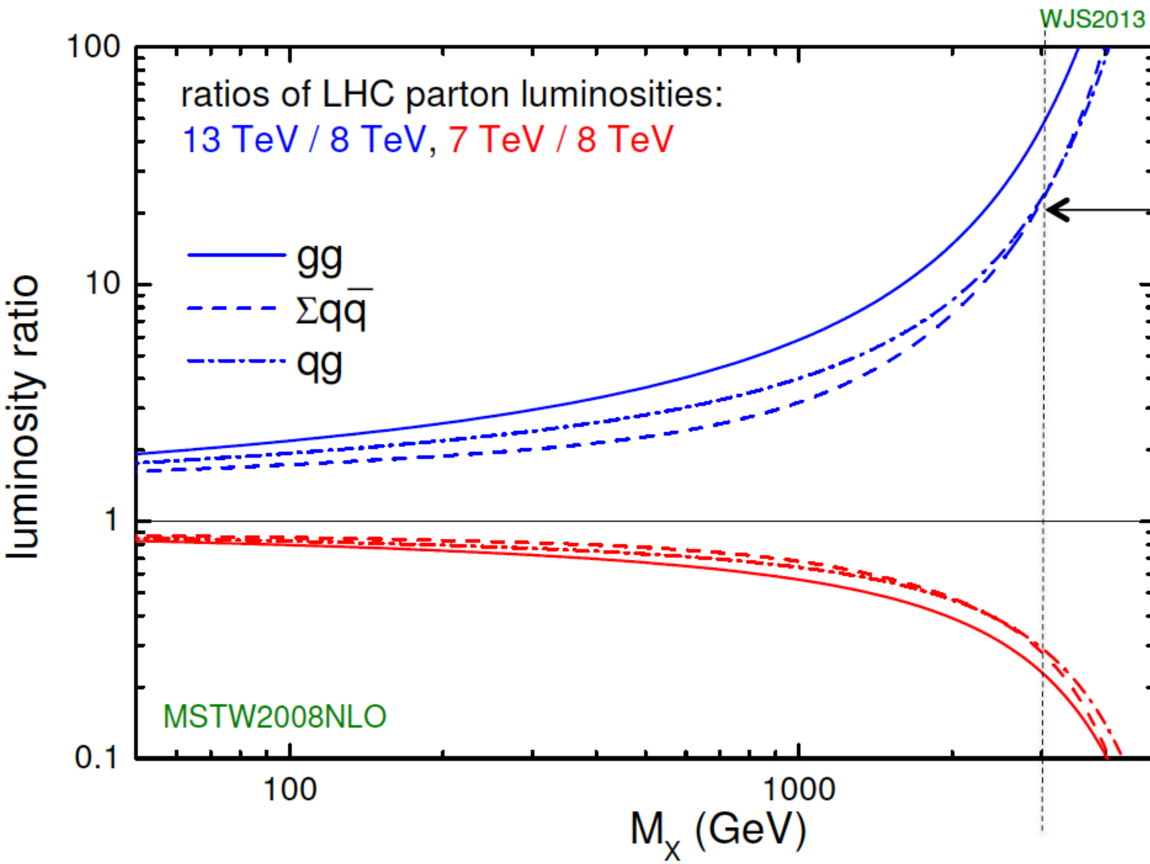





Ratio of 13 TeV / 8 TeV Cross sections:

- Z' at 3 TeV: **20**
- q* at 4 TeV: **56**
- QBH at 5 TeV: **370**
- QBH at 6 TeV: **9000**

ATLAS EXPERIMENT

## ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

**ATLAS** Preliminary

$\int \mathcal{L}\,dt = (3.2 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

| | Model | $\ell, \gamma$ | Jets† | $E_T^{miss}$ | $\int \mathcal{L}\,dt[\mathrm{fb}^{-1}]$ | Limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Extra dimensions | ADD $G_{KK} + g/q$ | – | ≥ 1 j | Yes | 3.2 | $M_D$ 6.58 TeV | $n = 2$ | 1604.07773 |
| | ADD non-resonant $\ell\ell$ | 2 $e, \mu$ | – | – | 20.3 | $M_S$ 4.7 TeV | $n = 3$ HLZ | 1407.2410 |
| | ADD QBH $\rightarrow \ell q$ | 1 $e, \mu$ | 1 j | – | 20.3 | $M_{th}$ 5.2 TeV | $n = 6$ | 1311.2006 |
| | ADD QBH | – | 2 j | – | 15.7 | $M_{th}$ 8.7 TeV | $n = 6$ | ATLAS-CONF-2016-069 |
| | ADD BH high $\sum p_T$ | ≥ 1 $e, \mu$ | ≥ 2 j | – | 3.2 | $M_{th}$ 8.2 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1606.02265 |
| | ADD BH multijet | – | ≥ 3 j | – | 3.6 | $M_{th}$ 9.55 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1512.02586 |
| | RS1 $G_{KK} \rightarrow \ell\ell$ | 2 $e, \mu$ | – | – | 20.3 | $G_{KK}$ mass 2.68 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1405.4123 |
| | RS1 $G_{KK} \rightarrow \gamma\gamma$ | 2 $\gamma$ | – | – | 3.2 | $G_{KK}$ mass 3.2 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1606.03833 |
| | Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$ | 1 $e, \mu$ | 1 J | Yes | 13.2 | $G_{KK}$ mass 1.24 TeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2016-062 |
| | Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$ | – | 4 b | – | 13.3 | $G_{KK}$ mass 360-860 GeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2016-049 |
| | Bulk RS $g_{KK} \rightarrow tt$ | 1 $e, \mu$ | ≥ 1 b, ≥ 1J/2j | Yes | 20.3 | $g_{KK}$ mass 2.2 TeV | BR = 0.925 | 1505.07018 |
| | 2UED / RPP | 1 $e, \mu$ | ≥ 2 b, ≥ 4 j | Yes | 3.2 | KK mass 1.46 TeV | Tier (1,1), BR($A^{(1,1)} \rightarrow tt$) = 1 | ATLAS-CONF-2016-013 |
| Gauge bosons | SSM $Z' \rightarrow \ell\ell$ | 2 $e, \mu$ | – | – | 13.3 | $Z'$ mass 4.05 TeV | | ATLAS-CONF-2016-045 |
| | SSM $Z' \rightarrow \tau\tau$ | 2 $\tau$ | – | – | 19.5 | $Z'$ mass 2.02 TeV | | 1502.07177 |
| | Leptophobic $Z' \rightarrow bb$ | – | 2 b | – | 3.2 | $Z'$ mass 1.5 TeV | | 1603.08791 |
| | SSM $W' \rightarrow \ell\nu$ | 1 $e, \mu$ | – | Yes | 13.3 | $W'$ mass 4.74 TeV | | ATLAS-CONF-2016-061 |
| | HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A | 0 $e, \mu$ | 1 J | Yes | 13.2 | $W'$ mass 2.4 TeV | $g_V = 1$ | ATLAS-CONF-2016-082 |
| | HVT $W' \rightarrow WZ \rightarrow qqqq$ model B | – | 2 J | – | 15.5 | $W'$ mass 3.0 TeV | $g_V = 3$ | ATLAS-CONF-2016-055 |
| | HVT $V' \rightarrow WH/ZH$ model B | multi-channel | | | 3.2 | $V'$ mass 2.31 TeV | $g_V = 3$ | 1607.05621 |
| | LRSM $W'_R \rightarrow tb$ | 1 $e, \mu$ | 2 b, 0-1 j | Yes | 20.3 | $W'$ mass 1.92 TeV | | 1410.4103 |
| | LRSM $W'_R \rightarrow tb$ | 0 $e, \mu$ | ≥ 1 b, 1 J | – | 20.3 | $W'$ mass 1.76 TeV | | 1408.0886 |
| CI | CI $qqqq$ | – | 2 j | – | 15.7 | $\Lambda$ 19.9 TeV | $\eta_{LL} = -1$ | ATLAS-CONF-2016-069 |
| | CI $\ell\ell qq$ | 2 $e, \mu$ | – | – | 3.2 | $\Lambda$ 25.2 TeV | $\eta_{LL} = -1$ | 1607.03669 |
| | CI $uutt$ | 2(SS)/≥3 $e,\mu$ | ≥1 b, ≥1 j | Yes | 20.3 | $\Lambda$ 4.9 TeV | $\lvert C_{RR}\rvert = 1$ | 1504.04605 |
| DM | Axial-vector mediator (Dirac DM) | 0 $e, \mu$ | ≥ 1 j | Yes | 3.2 | $m_A$ 1.0 TeV | $g_q$=0.25, $g_\chi$=1.0, $m(\chi) < 250$ GeV | 1604.07773 |
| | Axial-vector mediator (Dirac DM) | 0 $e, \mu$, 1 $\gamma$ | 1 j | Yes | 3.2 | $m_A$ 710 GeV | $g_q$=0.25, $g_\chi$=1.0, $m(\chi) < 150$ GeV | 1604.01306 |
| | $ZZ\chi\chi$ EFT (Dirac DM) | 0 $e, \mu$ | 1 J, ≤ 1 j | Yes | 3.2 | $M_*$ 550 GeV | $m(\chi) < 150$ GeV | ATLAS-CONF-2015-080 |
| LQ | Scalar LQ 1st gen | 2 $e$ | ≥ 2 j | – | 3.2 | LQ mass 1.1 TeV | $\beta = 1$ | 1605.06035 |
| | Scalar LQ 2nd gen | 2 $\mu$ | ≥ 2 j | – | 3.2 | LQ mass 1.05 TeV | $\beta = 1$ | 1605.06035 |
| | Scalar LQ 3rd gen | 1 $e, \mu$ | ≥1 b, ≥3 j | Yes | 20.3 | LQ mass 640 GeV | $\beta = 0$ | 1508.04735 |
| Heavy quarks | VLQ $TT \rightarrow Ht + X$ | 1 $e, \mu$ | ≥ 2 b, ≥ 3 j | Yes | 20.3 | T mass 855 GeV | T in (T,B) doublet | 1505.04306 |
| | VLQ $YY \rightarrow Wb + X$ | 1 $e, \mu$ | ≥ 1 b, ≥ 3 j | Yes | 20.3 | Y mass 770 GeV | Y in (B,Y) doublet | 1505.04306 |
| | VLQ $BB \rightarrow Hb + X$ | 1 $e, \mu$ | ≥ 2 b, ≥ 3 j | Yes | 20.3 | B mass 735 GeV | isospin singlet | 1505.04306 |
| | VLQ $BB \rightarrow Zb + X$ | 2/≥3 $e, \mu$ | ≥2/≥1 b | – | 20.3 | B mass 755 GeV | B in (B,Y) doublet | 1409.5500 |
| | VLQ $QQ \rightarrow WqWq$ | 1 $e, \mu$ | ≥ 4 j | Yes | 20.3 | Q mass 690 GeV | | 1509.04261 |
| | VLQ $T_{5/3}T_{5/3} \rightarrow WtWt$ | 2(SS)/≥3 $e,\mu$ | ≥1 b, ≥1 j | Yes | 3.2 | $T_{5/3}$ mass 990 GeV | | ATLAS-CONF-2016-032 |
| Excited fermions | Excited quark $q^* \rightarrow q\gamma$ | 1 $\gamma$ | 1 j | – | 3.2 | $q^*$ mass 4.4 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1512.05910 |
| | Excited quark $q^* \rightarrow qg$ | – | 2 j | – | 15.7 | $q^*$ mass 5.6 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | ATLAS-CONF-2016-069 |
| | Excited quark $b^* \rightarrow bg$ | – | 1 b, 1 j | – | 8.8 | $b^*$ mass 2.3 TeV | | ATLAS-CONF-2016-060 |
| | Excited quark $b^* \rightarrow Wt$ | 1 or 2 $e, \mu$ | 1 b, 2-0 j | Yes | 20.3 | $b^*$ mass 1.5 TeV | $f_g = f_L = f_R = 1$ | 1510.02664 |
| | Excited lepton $\ell^*$ | 3 $e, \mu$ | – | – | 20.3 | $\ell^*$ mass 3.0 TeV | $\Lambda = 3.0$ TeV | 1411.2921 |
| | Excited lepton $\nu^*$ | 3 $e, \mu, \tau$ | – | – | 20.3 | $\nu^*$ mass 1.6 TeV | $\Lambda = 1.6$ TeV | 1411.2921 |
| Other | LSTC $a_T \rightarrow W\gamma$ | 1 $e, \mu$, 1 $\gamma$ | – | Yes | 20.3 | $a_T$ mass 960 GeV | | 1407.8150 |
| | LRSM Majorana $\nu$ | 2 $e, \mu$ | 2 j | – | 20.3 | $N^0$ mass 2.0 TeV | $m(W_R) = 2.4$ TeV, no mixing | 1506.06020 |
| | Higgs triplet $H^{\pm\pm} \rightarrow ee$ | 2 $e$ (SS) | – | – | 13.9 | $H^{\pm\pm}$ mass 570 GeV | DY production, BR($H_L^{\pm\pm} \rightarrow ee$)=1 | ATLAS-CONF-2016-051 |
| | Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$ | 3 $e, \mu, \tau$ | – | – | 20.3 | $H^{\pm\pm}$ mass 400 GeV | DY production, BR($H_L^{\pm\pm} \rightarrow \ell\tau$)=1 | 1411.2921 |
| | Monotop (non-res prod) | 1 $e, \mu$ | 1 b | Yes | 20.3 | spin-1 invisible particle mass 657 GeV | $a_{non-res} = 0.2$ | 1410.5404 |
| | Multi-charged particles | – | – | – | 20.3 | multi-charged particle mass 785 GeV | DY production, $\lvert q\rvert = 5e$ | 1504.04188 |
| | Magnetic monopoles | – | – | – | 7.0 | monopole mass 1.34 TeV | DY production, $\lvert g\rvert = 1g_D$, spin 1/2 | 1509.08059 |

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

$10^{-1}$ 1 10 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

# CONCLUSION/SUMMARY

# Summary

- Remember that the LHC design energy was/is 14TeV!
- So we are just getting started!! We'll be taking data for the next 10-20 years (depending on other machines)

- A search is successful if it improves the previous constraints on some new physics model….or, of course, if it leads to a discovery.

- It is **very unlikely** that we will discover what we search for.
- But we **may** discover a significant deviation from the SM expectation
  - That's when the real fun (and hard work) begins!

Thanks! Some backup slides may follow

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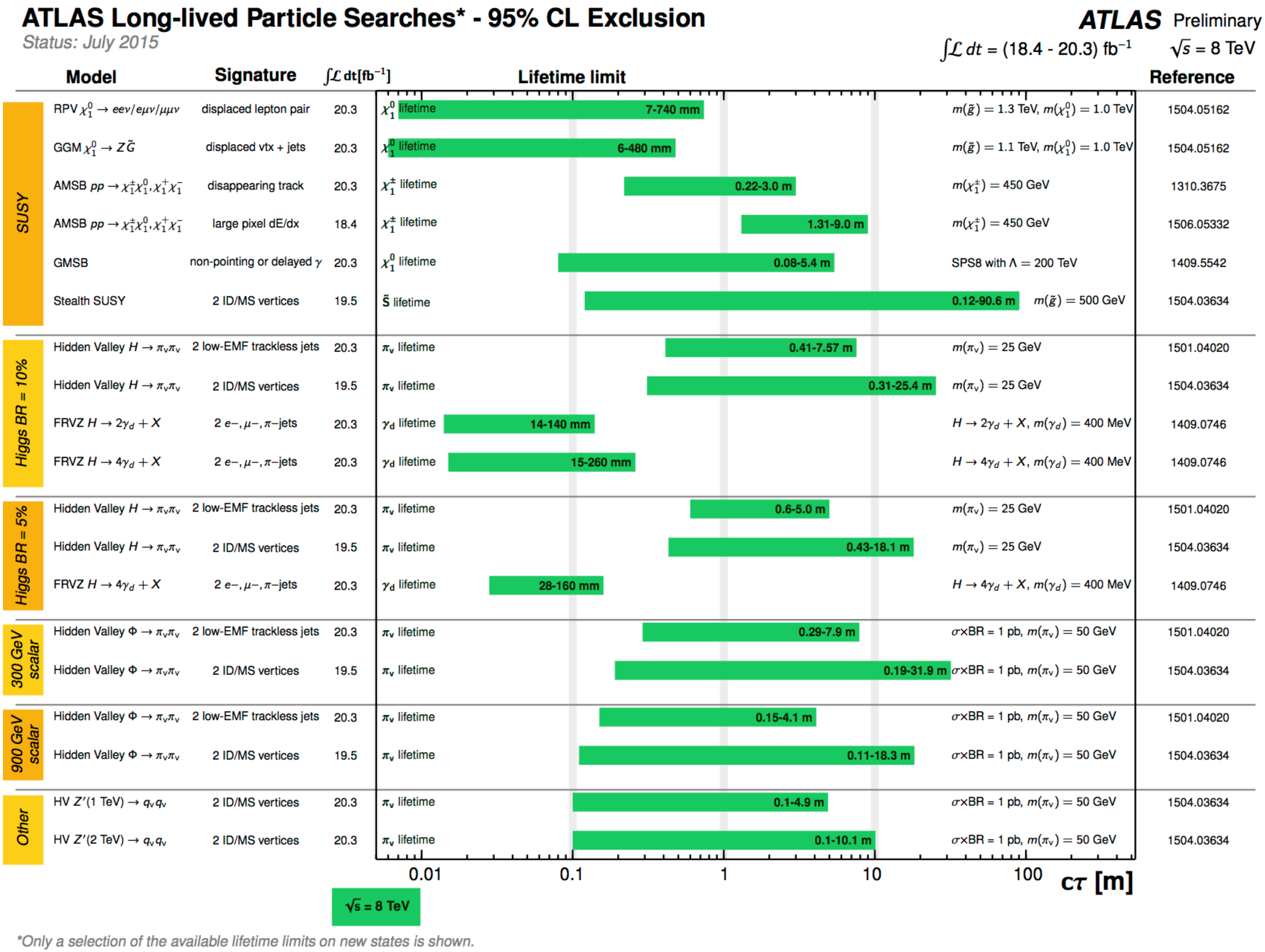
# Run 1 Searches for Exotic long-lived New Phenomena



## Variable definitions

- Missing transverse momentum (or energy):

$$E_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2}$$

where $E_{x(y)}^{\mathrm{miss}} = -\sum E_{x(y)}$ summed over all calibrated $e, \gamma, \mu, \tau$, jets...

- Scalar transverse-energy sum:

$$H_{\mathrm{T}} = \sum_{\mathrm{jets},\ell} p_{\mathrm{T}}$$

- Effective mass:

$$m_{\mathrm{eff}}^{(\mathrm{incl})} = \sum_{\mathrm{jets},\ell} p_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$$

- Transverse mass ($1\ell$):

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos[\Delta\phi(\vec{\ell}, E_{\mathrm{T}}^{\mathrm{miss}})])}$$

- Contransverse mass (measures the masses of pair-prod. semi-invisibly decaying heavy particles, e.g. $\tilde{b} \to b\chi^0$):

$$m_{\mathrm{CT}}^2(v_1, v_2) = [E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)]^2 - [\boldsymbol{p}_{\mathrm{T}}(v_1) - \boldsymbol{p}_{\mathrm{T}}(v_2)]^2$$