Searches for Exotics:

Heavy resonances with the ATLAS detector

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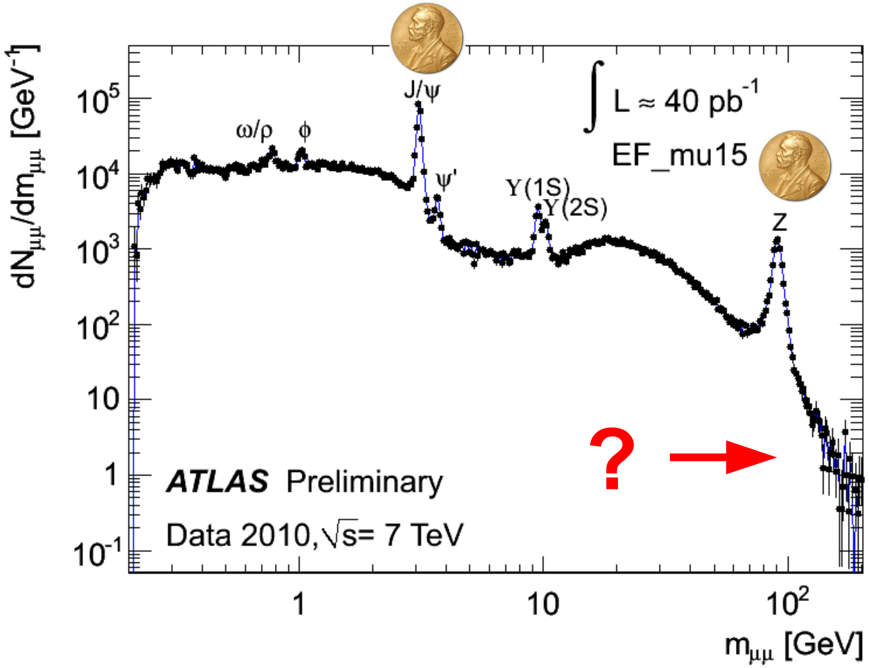
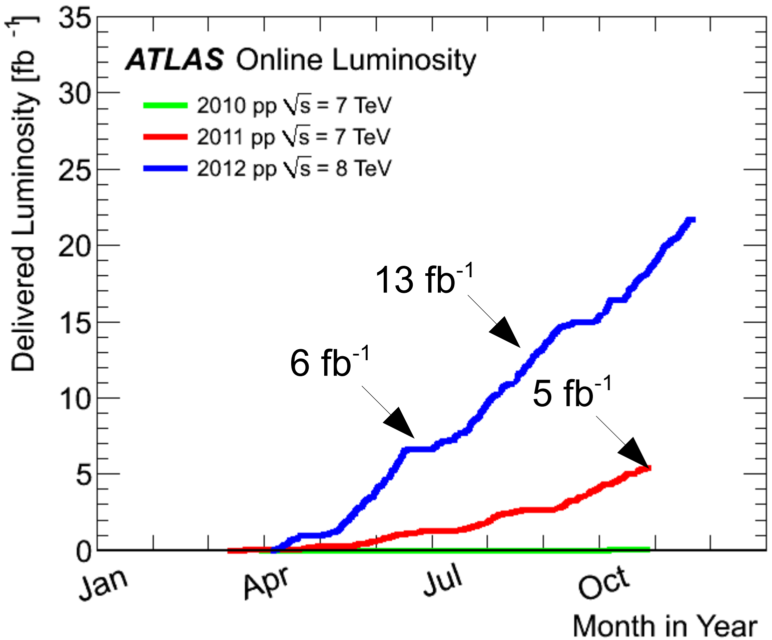
Introduction

- Heavy resonance discoveries have played a very significant role in the development of particle physics
- Examples: J/ψ, Upsilon, W, Z
- Most theories beyond the SM predict such new resonances
- We look for heavy resonances at the Large Hadron Collider!
- This talk:
  - *jj*
  - *ℓ+ℓ-*
  - *γγ*
  - *ℓν*
  - *WW → ℓνℓν*
  - *ZW, ZZ → ℓℓqq*
  - *ττ*
  - *tt, tj*

References shown on the conclusion slide

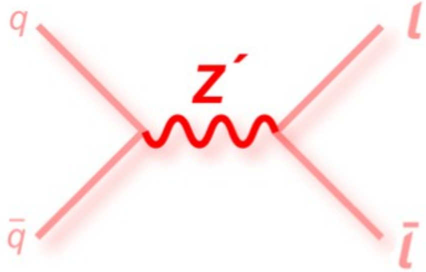




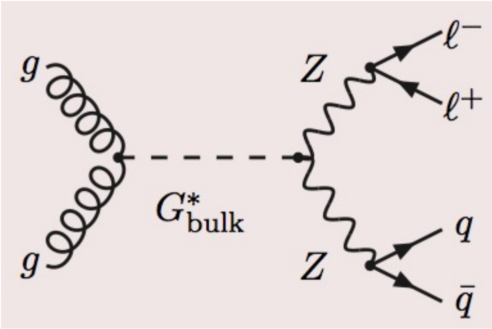
Introduction

- Searches are signature-based, but interpreted in terms of theories beyond the Standard Model, used as benchmarks

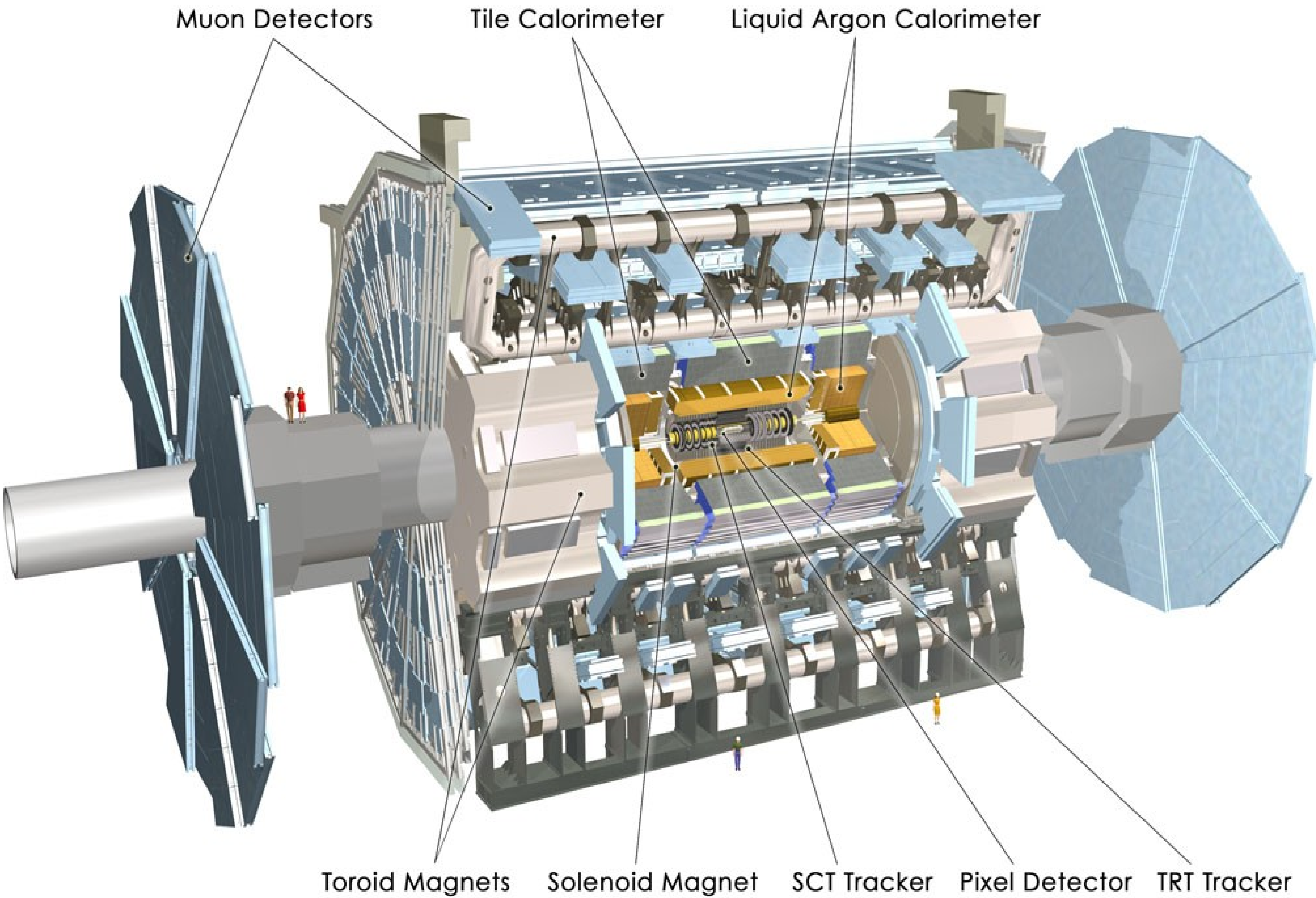
- W' and Z': Additional gauge bosons
  - Sequential Standard Model (SSM)
    - Not well-motivated, but simplest
  - Grand Unified Theories
    - E.g. $E_6 \rightarrow SU(5) \times U(1)_\psi \times U(1)_\chi$



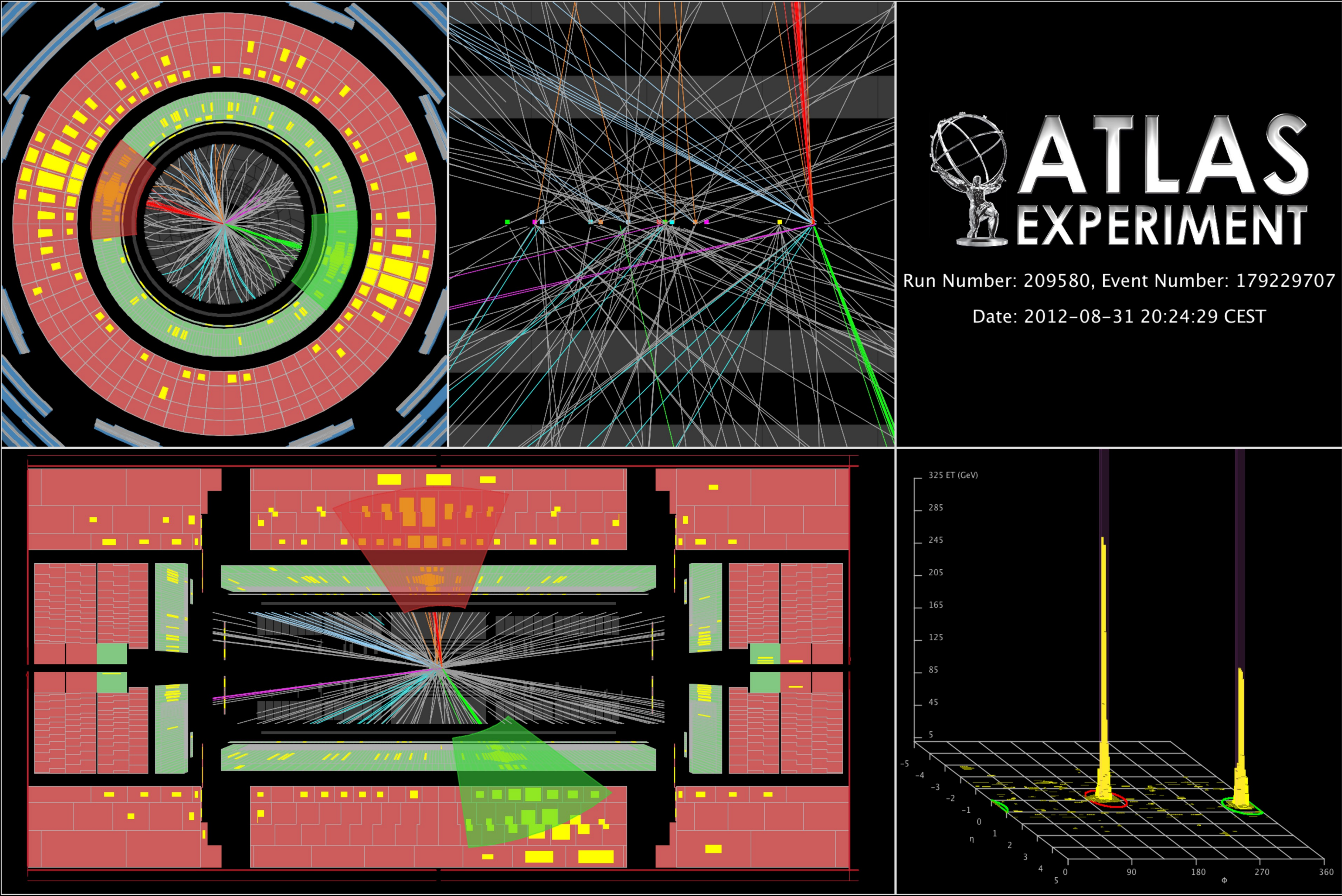
- Extra dimensions
  - Randall-Sundrum models: G*, G^*_{bulk}
  - TeV^{-1} Kaluza-Klein models: g_{KK}, Z_{KK} ...
  - ADD models



- Other solutions to the hierarchy problem: Technicolour, chiral bosons (W*, Z*)
- Excited fermions, Colour-octet scalars, String resonances, Quantum black holes...
- Effective four-fermion contact interactions with scale Λ


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

$$\chi \rightarrow jj$$


ATLAS
EXPERIMENT
Run Number: 209580, Event Number: 179229707
Date: 2012-08-31 20:24:29 CEST
325 ET (GeV)
285
245
205
165
125
85
45
5
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ

m_{jj} = 4.69 TeV

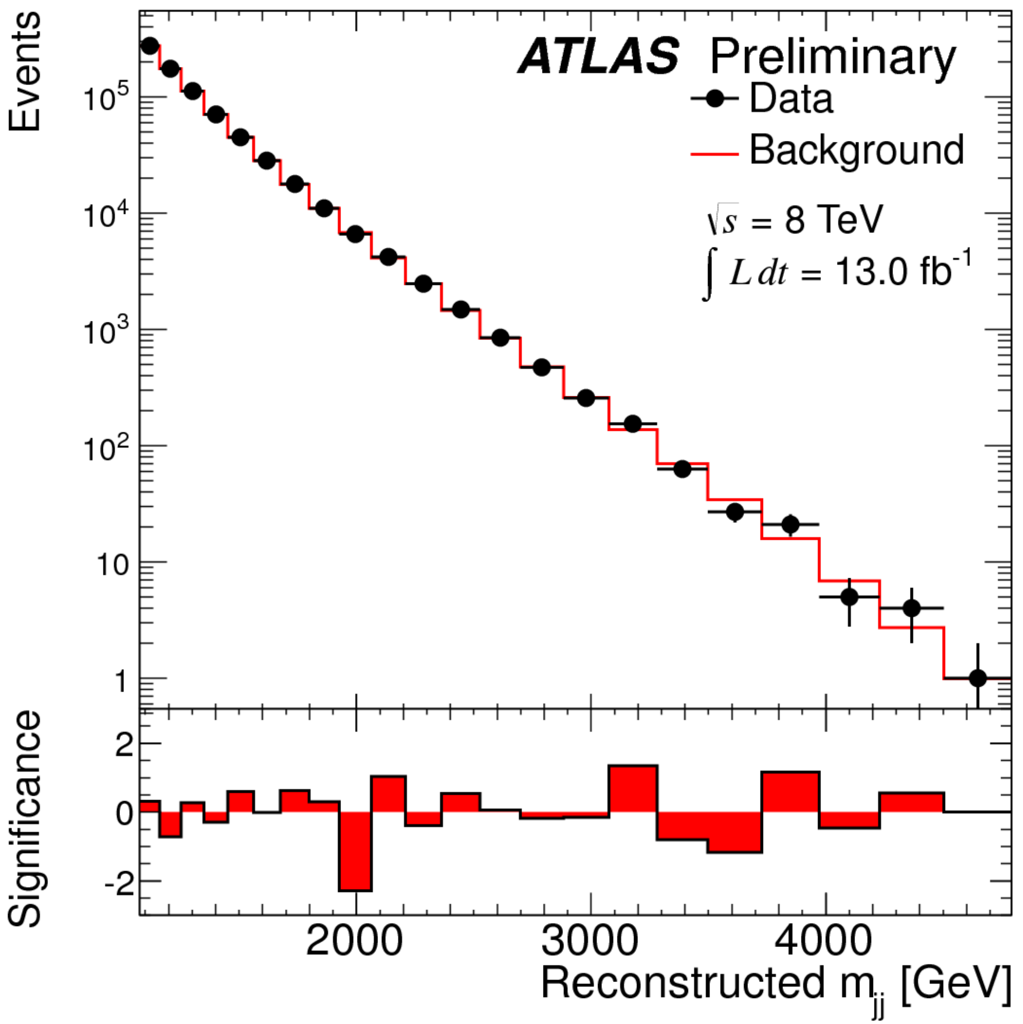
Dijet resonances – √s = 8 TeV

- Invariant mass spectrum from the two highest-p_T central jets
- Data-driven background estimate: spectrum fit using

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x},$$

$$x \equiv m_{jj}/\sqrt{s}.$$

- No significant excess
  - Bin-by-bin significance
  - Global *p* > 0.5



Dijet resonances – $\sqrt{s}$ = 8 TeV

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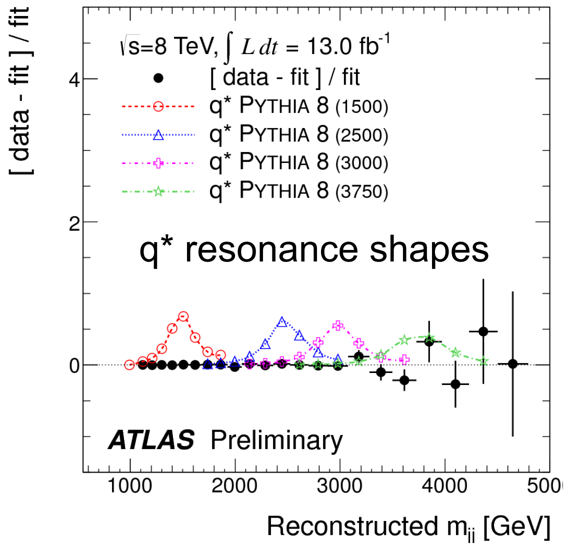
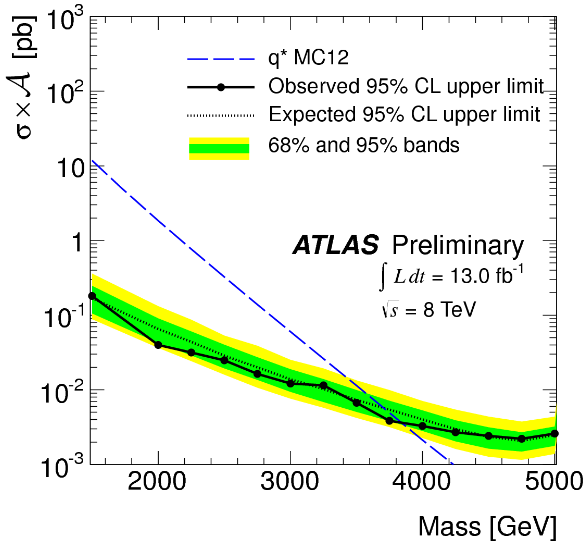
- Data-driven background estimate: spectrum fit using

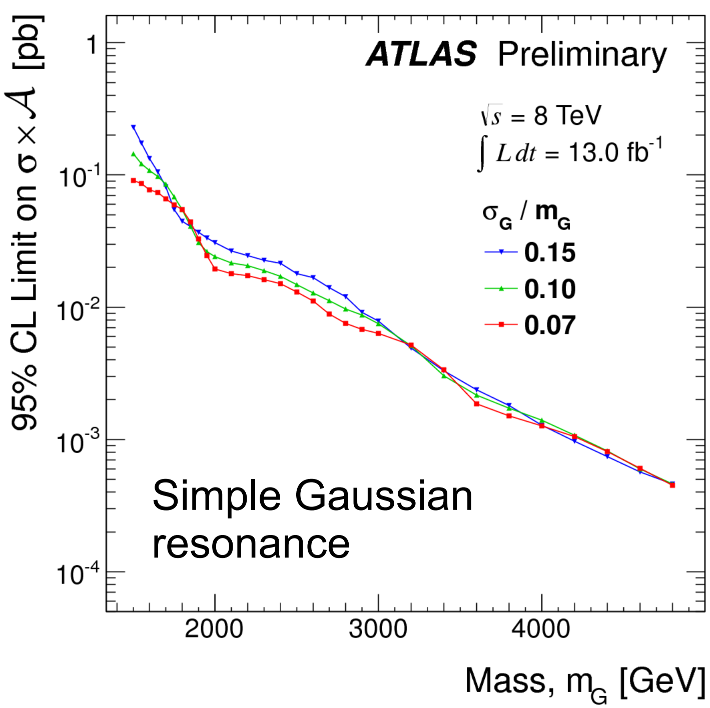
$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x},$$

$$x \equiv m_{jj}/\sqrt{s}$$

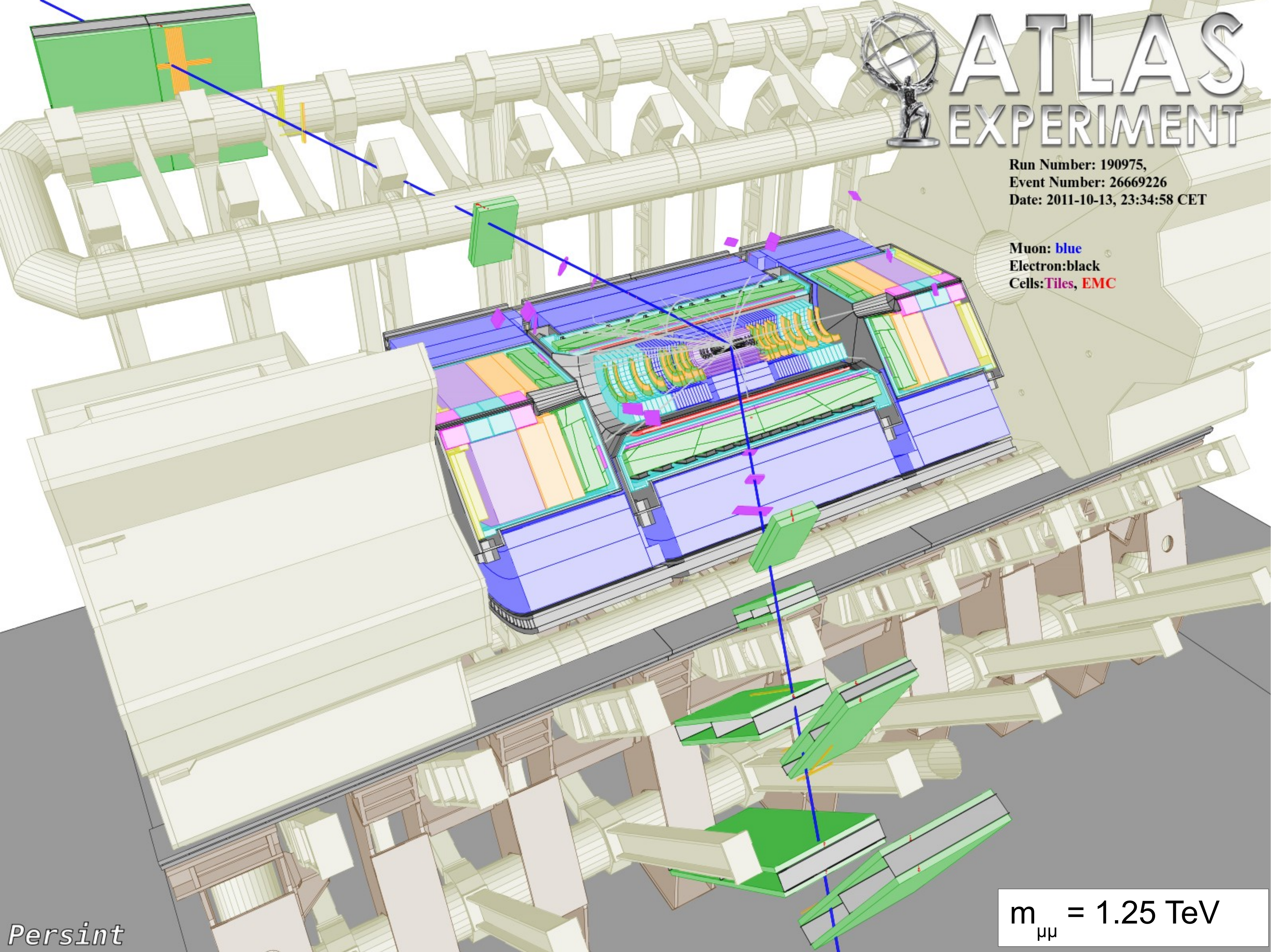
- No significant excess, global *p* > 0.5
- Limits on q*: M > 3.84 TeV
- Model-independent limits
- Angular analysis and limits on further models using data taken in 2011 at $\sqrt{s}$ = 7 TeV [see appendix]

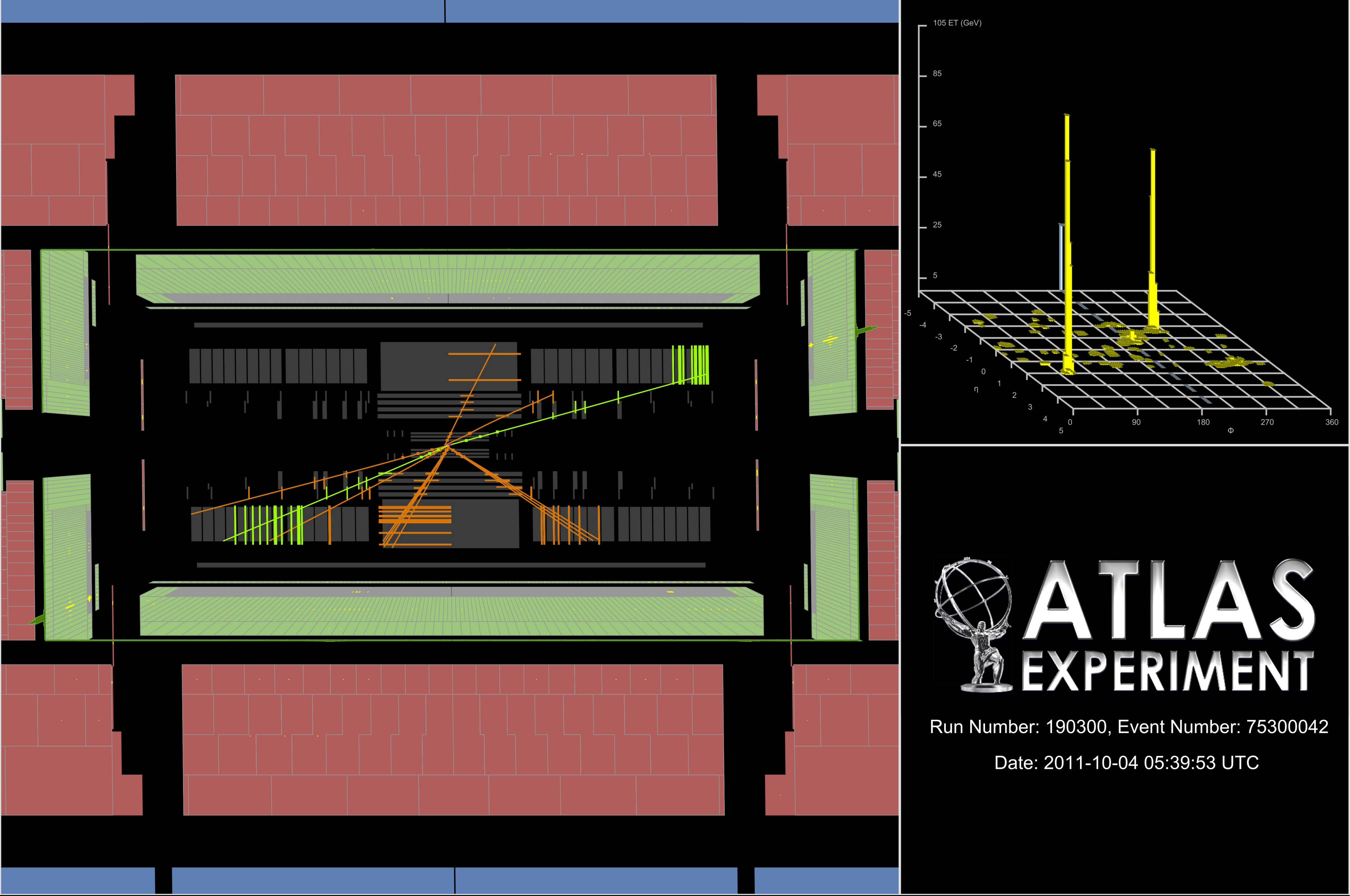






$$X \rightarrow \ell^{+}\ell^{-}$$


ATLAS
EXPERIMENT
Run Number: 190975,
Event Number: 26669226
Date: 2011-10-13, 23:34:58 CET
Muon: blue
Electron:black
Cells:Tiles, EMC
Persint
$m_{\mu\mu}$ = 1.25 TeV


105 ET (GeV)
85
65
45
25
5
η
Φ
0
90
180
270
360
ATLAS EXPERIMENT
Run Number: 190300, Event Number: 75300042
Date: 2011-10-04 05:39:53 UTC

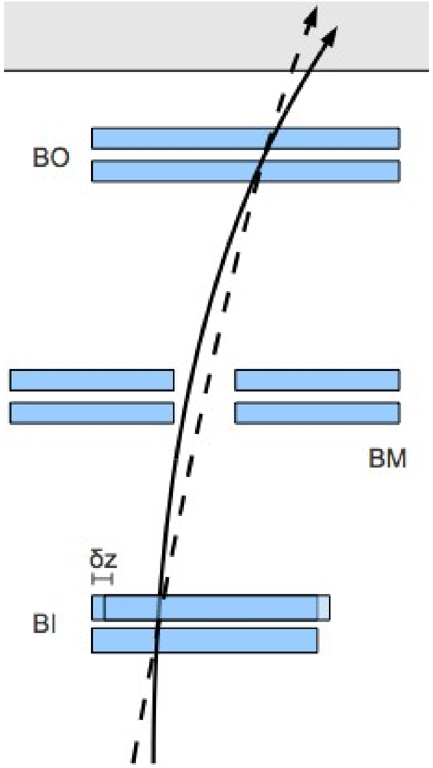
m_{ee} = 1.66 TeV

Dilepton resonances

- Main experimental challenges
  - Muon channel

$$\frac{\sigma(p_T)}{p_T} = S_1 + S_2 \cdot p_T$$

    - Momentum measured as track curvature
    - Very-high momentum → Very straight tracks!
    - Use only the best-aligned chambers: $S_2 < 0.25/\text{TeV}$

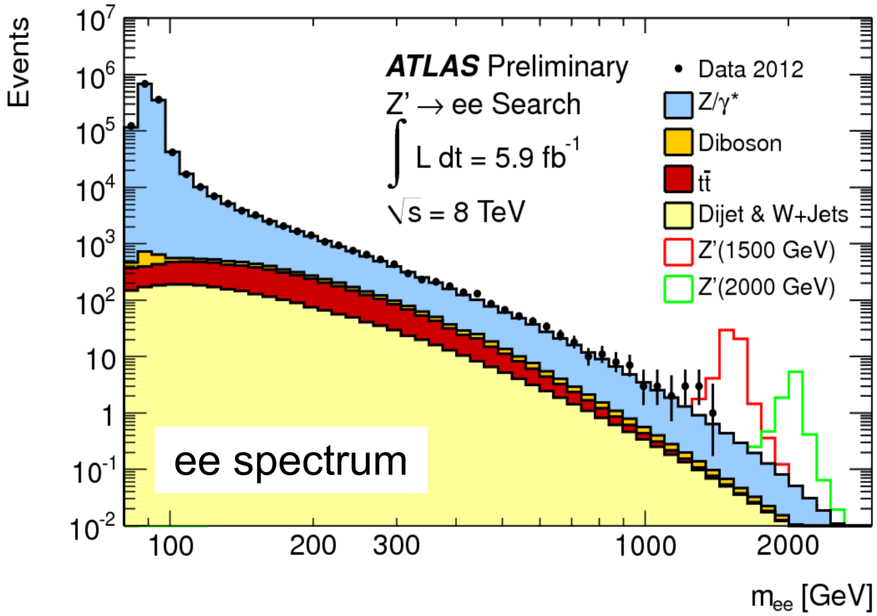


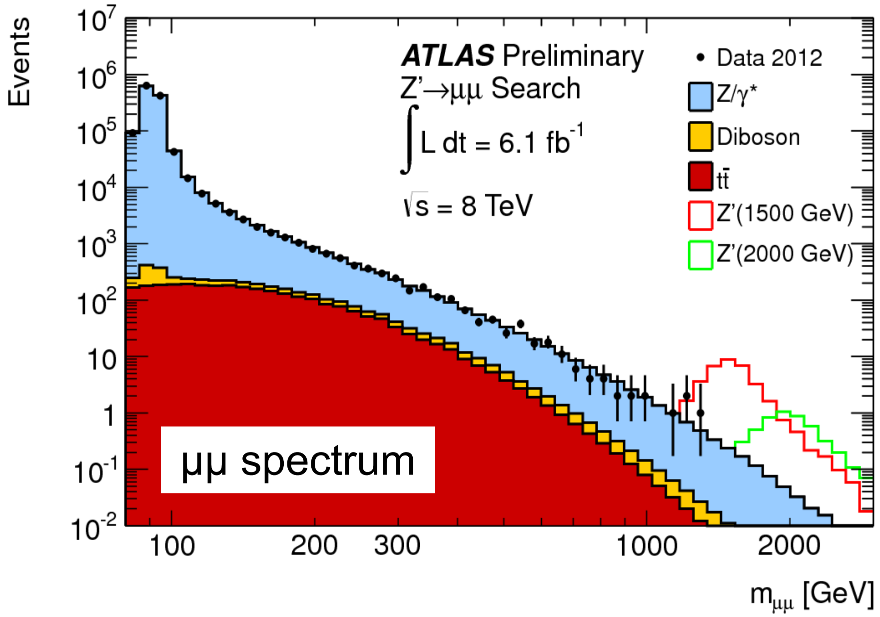
  - Electron channel

$$\frac{\sigma(E)}{E} = \frac{k_1}{\sqrt{E}} + k_2$$

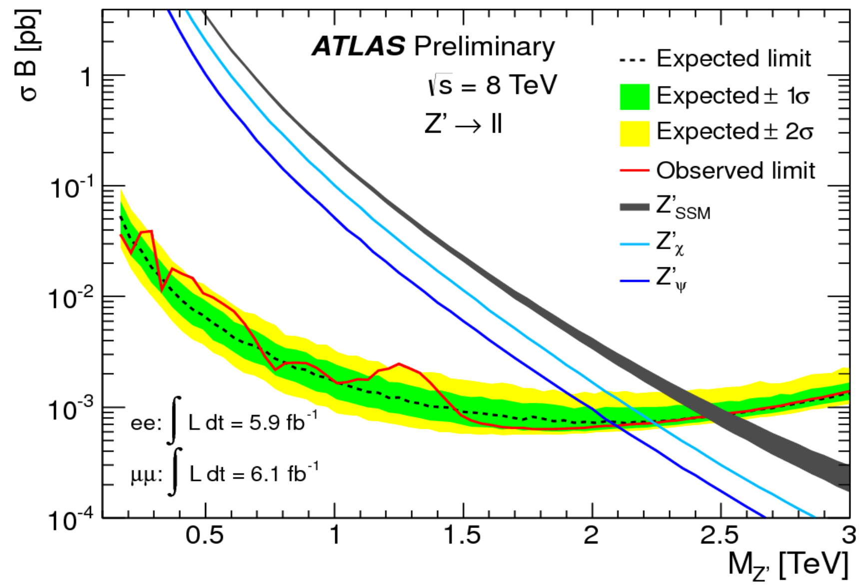
    - The EM calorimeter provides a good energy measurement: $k_2 < 2\%$
    - Main challenge is particle identification:
      need stringent cuts to distinguish high-energy electrons from
      QCD jets and converted photons
    - Data-driven strategies to estimate what remains after these cuts

Dilepton resonances – $\sqrt{s}$ = 8 TeV



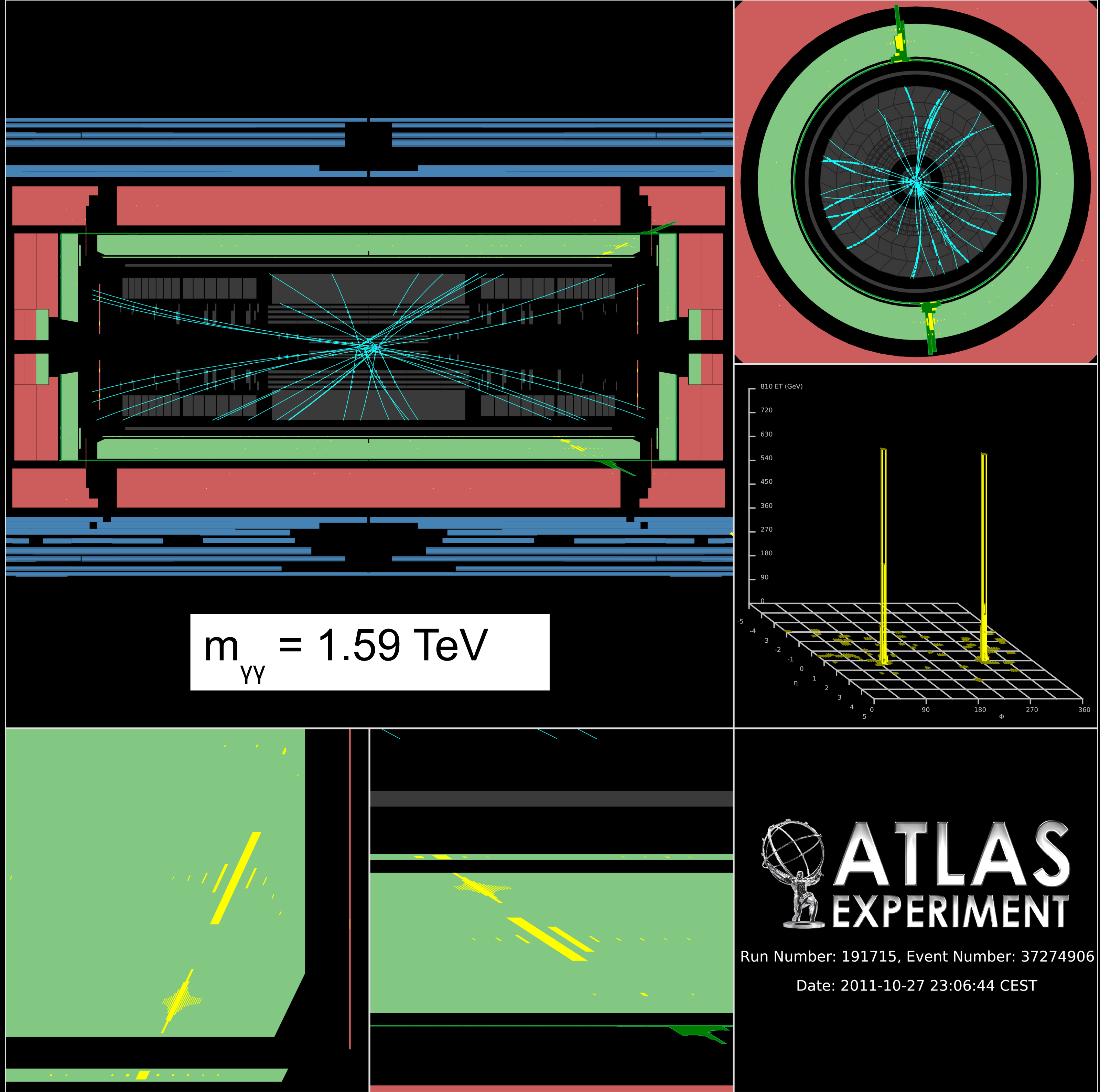


Z'_{SSM}: M > 2.49 TeV



- Backgrounds:
  - Z/γ*, dibosons, ttbar, W+jets (simulated)
  - QCD multijets (data-driven)
- Normalization to the Z peak: 80-110 GeV
- Good agreement with the Standard Model with *p*-values: 9% (ee) and 69% (μμ)
- Limits on further models using data taken in 2011 at $\sqrt{s}$ = 7 TeV [see appendix]

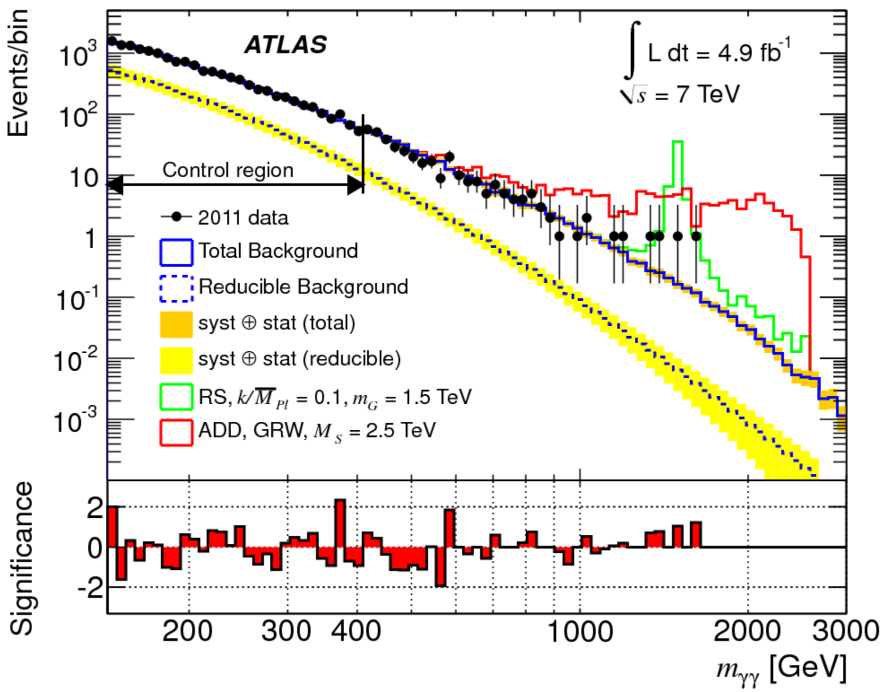
$$\chi \rightarrow \gamma\gamma$$

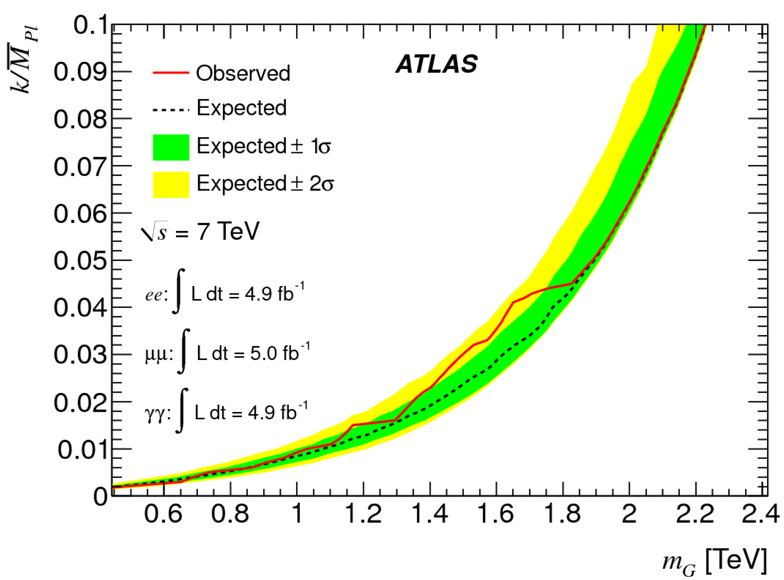


$m_{\gamma\gamma}$ = 1.59 TeV
810 ET (GeV)
720
630
540
450
360
270
180
90
0
η
Φ
ATLAS
EXPERIMENT
Run Number: 191715, Event Number: 37274906
Date: 2011-10-27 23:06:44 CEST

Diphoton resonances – √s = 7 TeV

- Tight photon selection:
  - Shower width and energy distribution in the EM Calorimeter
  - Isolation requirement
- Ambient energy correction
  - Removes contributions from the underlying event and pile-up
- Backgrounds: SM γγ (simulated);
  γj, jγ and jj (data-driven)
- Good agreement with the SM,
  with *p*-value 86%
- Combined with the dilepton analysis
  results at √s = 7 TeV
- G* → ee/μμ/γγ: M > 2.23 TeV, for $k/\overline{M}_{Pl}$ = 0.1



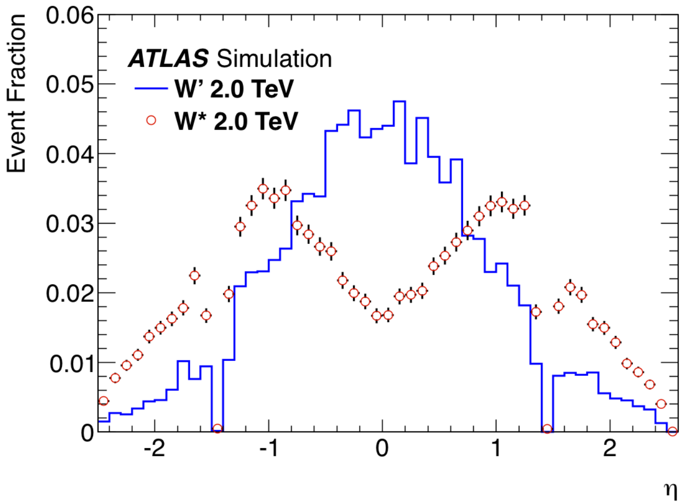


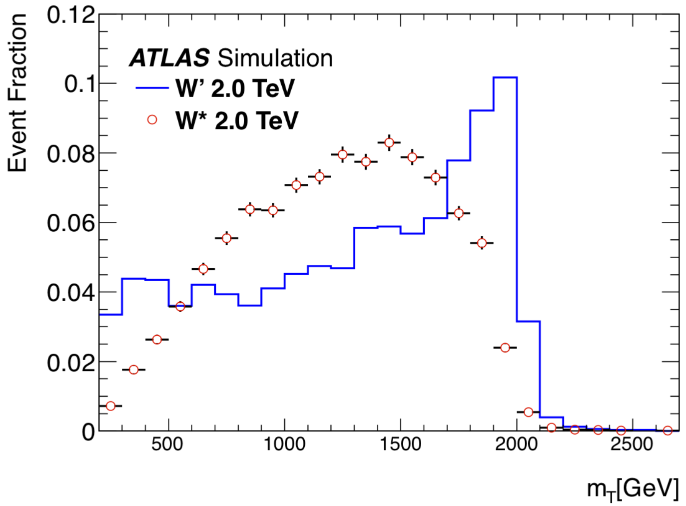
$$\chi \rightarrow \ell \nu$$

Lepton + neutrino resonances – $\sqrt{s}$ = 7 TeV

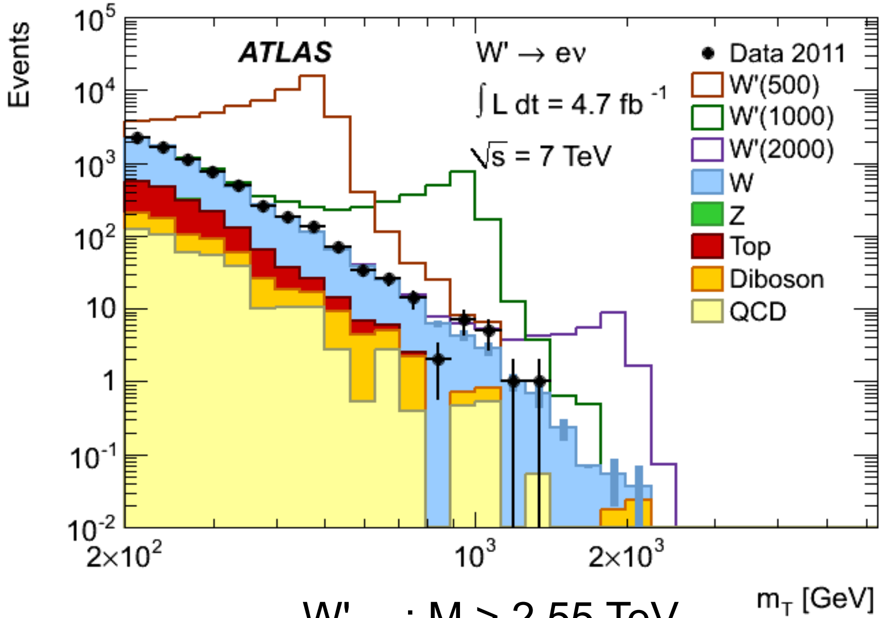
- Exactly one very-high-energy electron or muon, with high missing transverse momentum (E_T^{miss})
- Same lepton selection as in the dilepton analysis
- Looking for an excess in the m_T distribution: $m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos \varphi_{\ell\nu})}$
- Backgrounds:
  - Mainly W, but also Z/γ* where one lepton is not reconstructed, dibosons, ttbar, single top (all simulated); QCD mulitjets (from data)
- Benchmark signals:

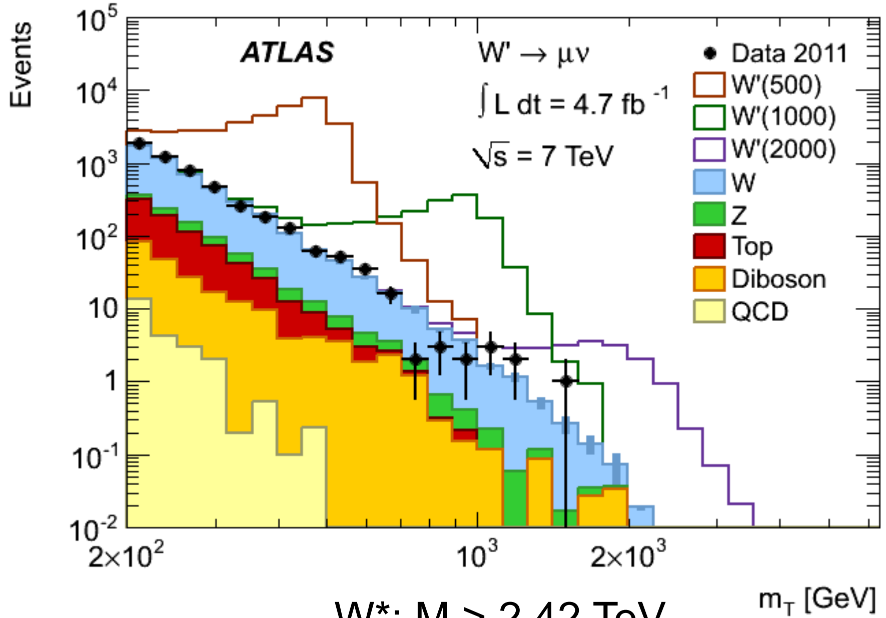
  W' and W*





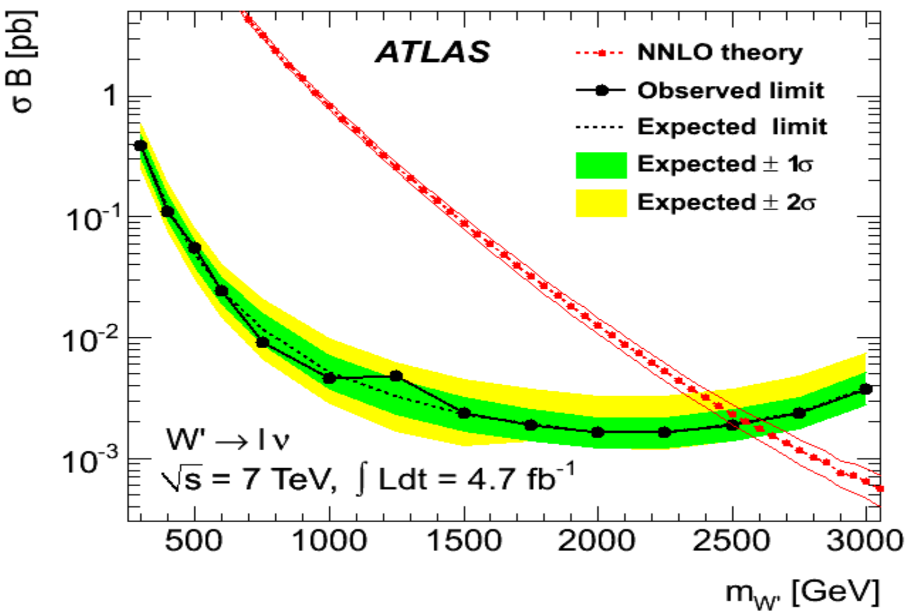
Lepton + neutrino resonances – $\sqrt{s}$ = 7 TeV

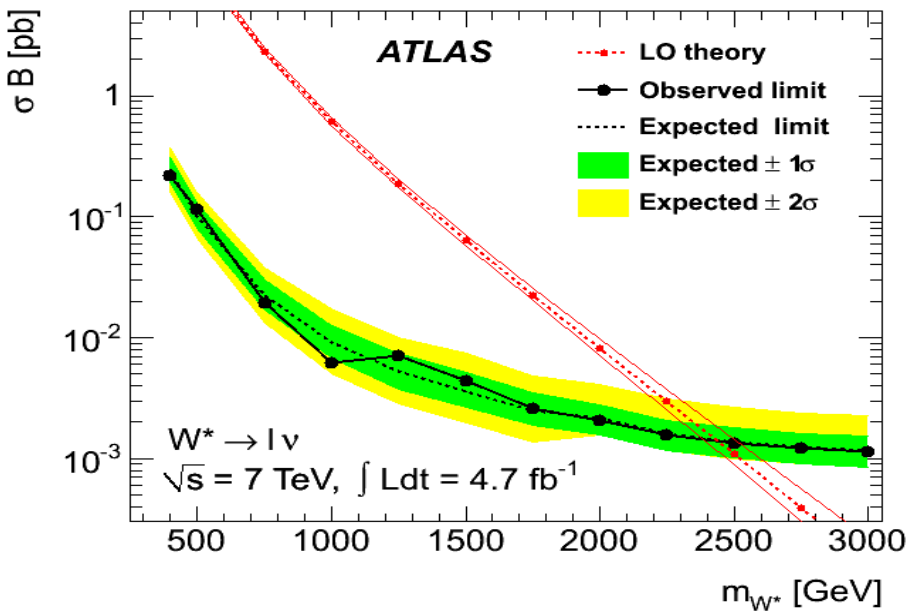




W'_{SSM}: M > 2.55 TeV

W*: M > 2.42 TeV

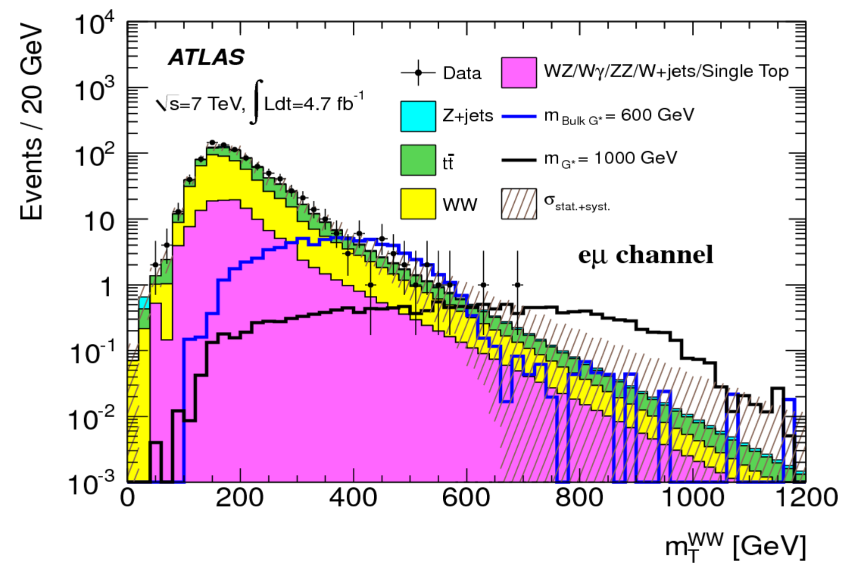




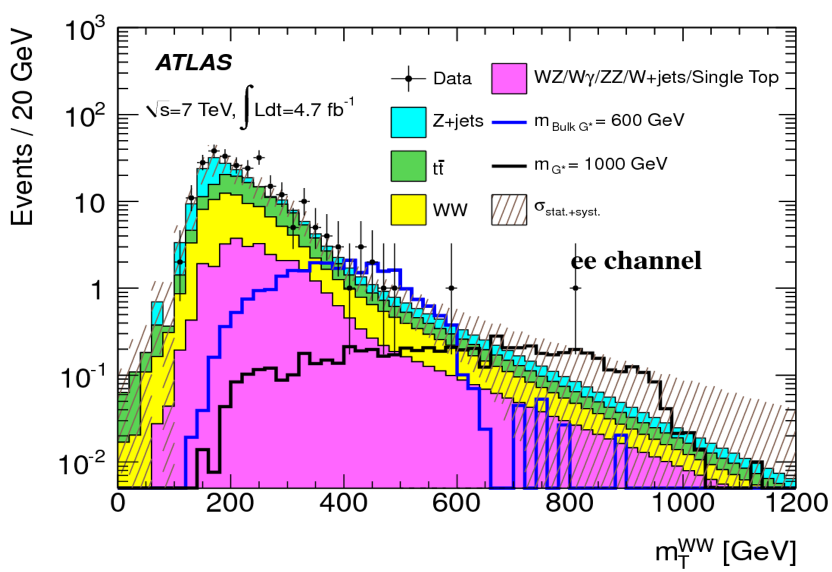
$$\chi \rightarrow \nu \nu$$

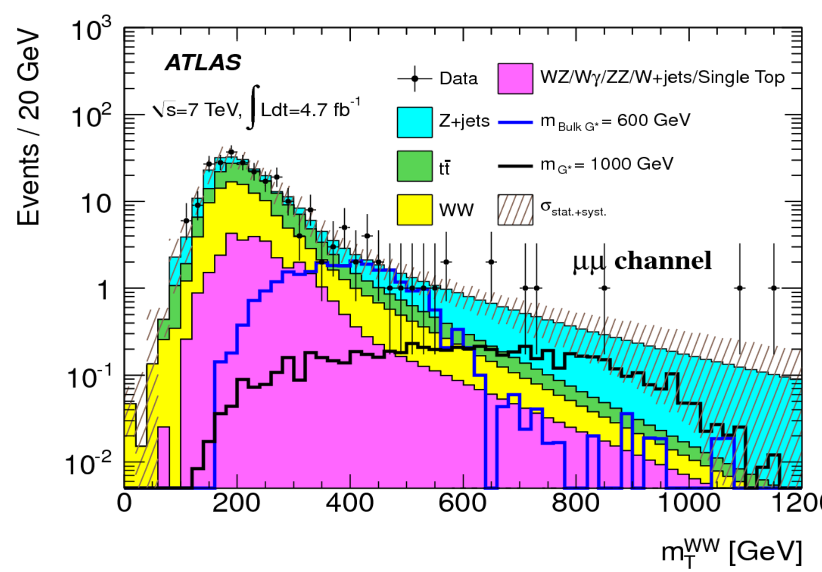
Resonances → WW → lνlν – $\sqrt{s}$ = 7 TeV

- Exactly two oppositely-charged high-p_T leptons, and large E_T^{miss}
- Suppress Z/γ*: m_{ll} > 106 GeV
- b-tag veto to reject ttbar events
- Cross-check Z/γ* and ttbar background estimates using control regions
- Background fits for m_T^{WW} > 300 GeV



$$m_{\mathrm{T}}^{WW} = \sqrt{(\sum_{i=1}^{2} p_{\mathrm{T}}^{\ell i} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\sum_{i=1}^{2} p_{x}^{\ell i} + E_{x}^{\mathrm{miss}})^2 - (\sum_{i=1}^{2} p_{y}^{\ell i} + E_{y}^{\mathrm{miss}})^2}$$



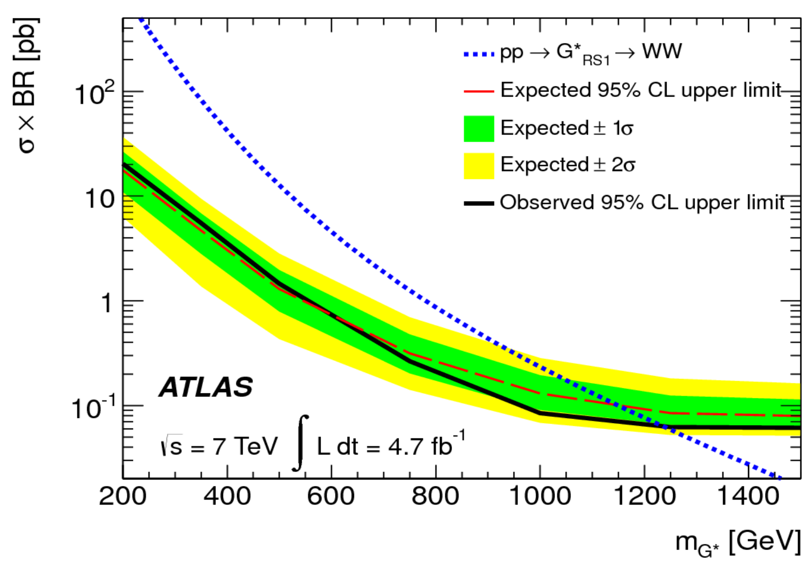


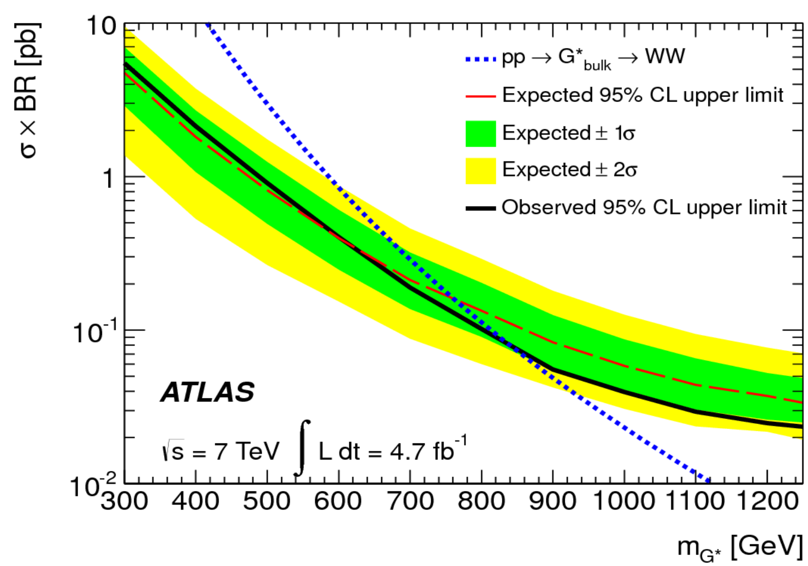
Resonances → WW → lνlν – $\sqrt{s}$ = 7 TeV

- Exactly two oppositely-charged high-p_T leptons, and large E_T^{miss}
- Suppress Z/γ*: m_{ll} > 106 GeV
- b-tag veto to reject ttbar events
- Cross-check Z/γ* and ttbar background estimates using control regions
- Background fits for m_T^{WW} > 300 GeV

- Sensitive to high-mass resonances
- No significant excess
- Looking for RS G* and G^*_{bulk}
- G*: M > 1.23 TeV, for $k/\overline{M}_{Pl}$ = 0.1
- G^*_{bulk}: M > 0.84 TeV, for $k/\overline{M}_{Pl}$ = 0.1

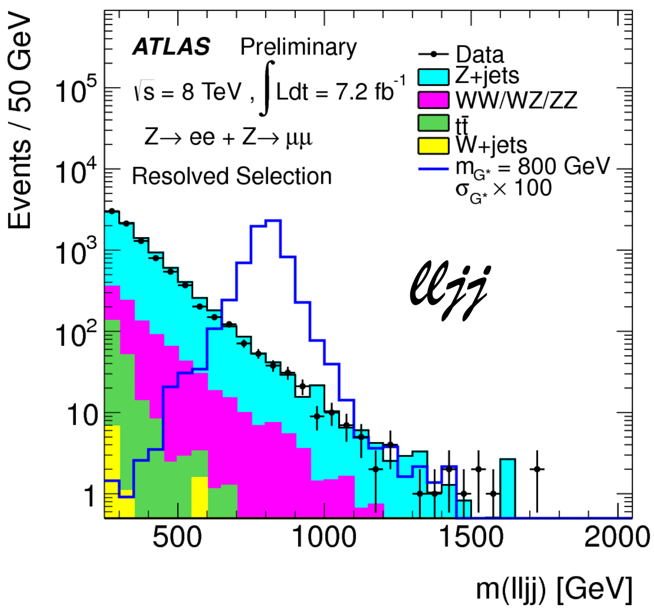
$$m_T^{WW} = \sqrt{\left(\sum_{i=1}^{2} p_T^{\ell i} + E_T^{miss}\right)^2 - \left(\sum_{i=1}^{2} p_x^{\ell i} + E_x^{miss}\right)^2 - \left(\sum_{i=1}^{2} p_y^{\ell i} + E_y^{miss}\right)^2}$$

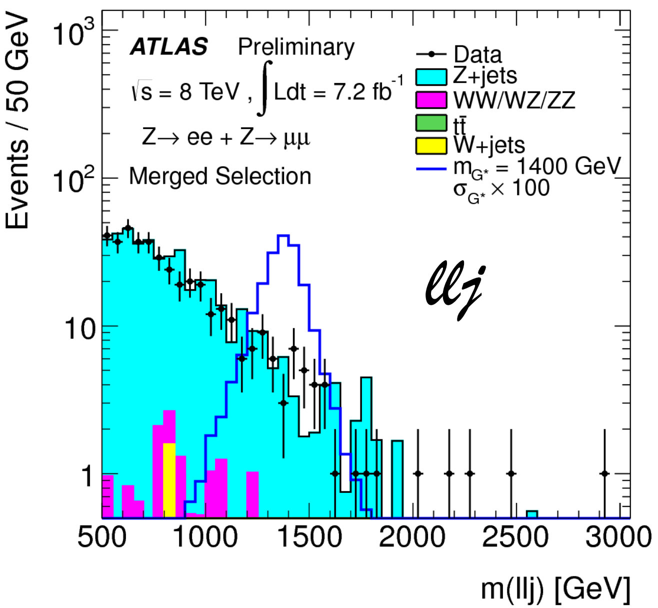


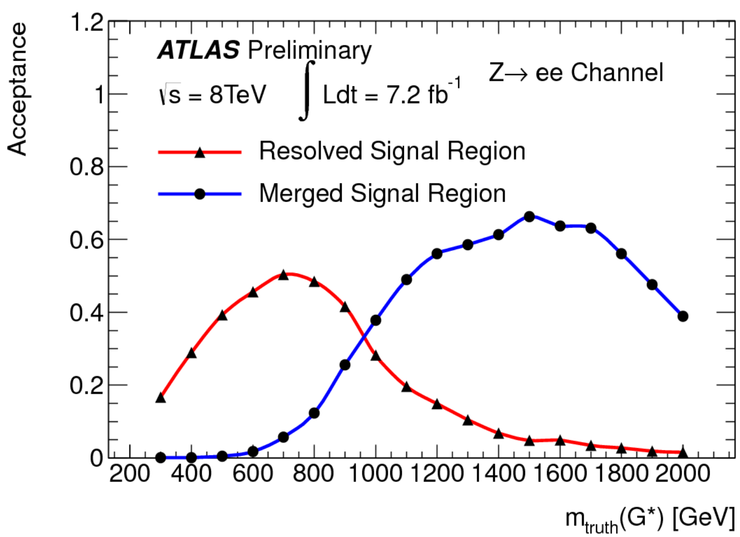


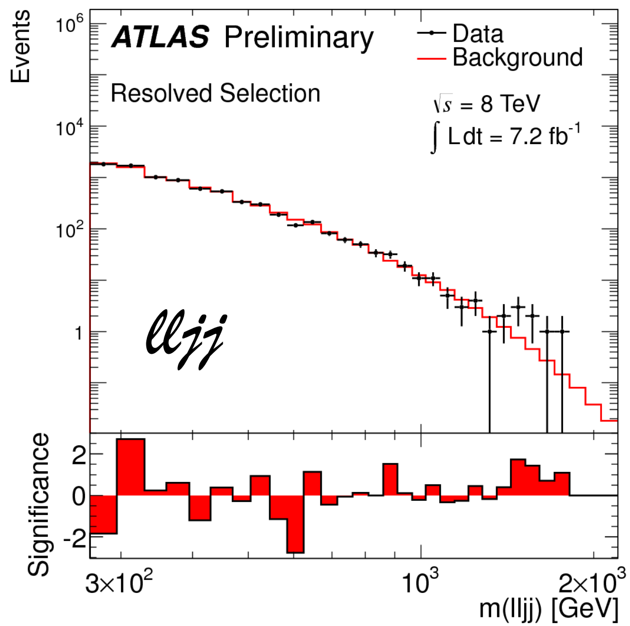
Resonances → ZW or ZZ → llqq, $\sqrt{s}$ = 8 TeV

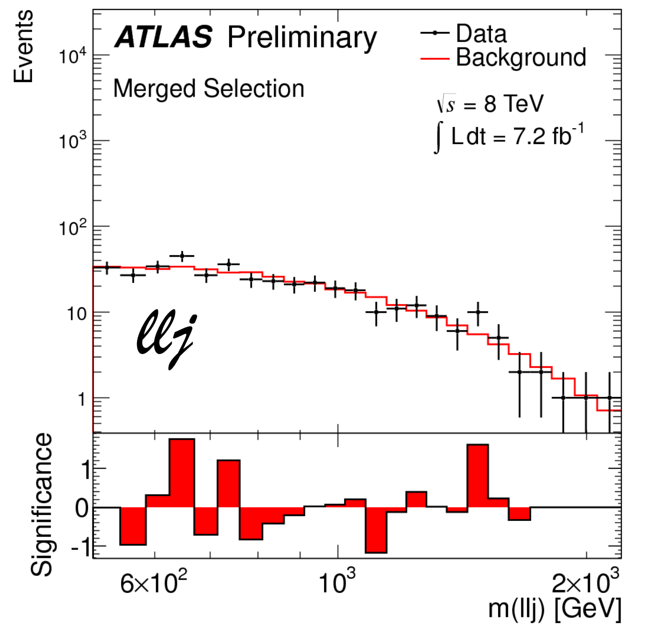
- Looking for an excess in the mass spectrum
- For very high-mass resonances, the W/Z are very boosted and hadronic decays merge into a single large jet
- Leptons from Z decay: $66 < m_{ll} < 116$ GeV











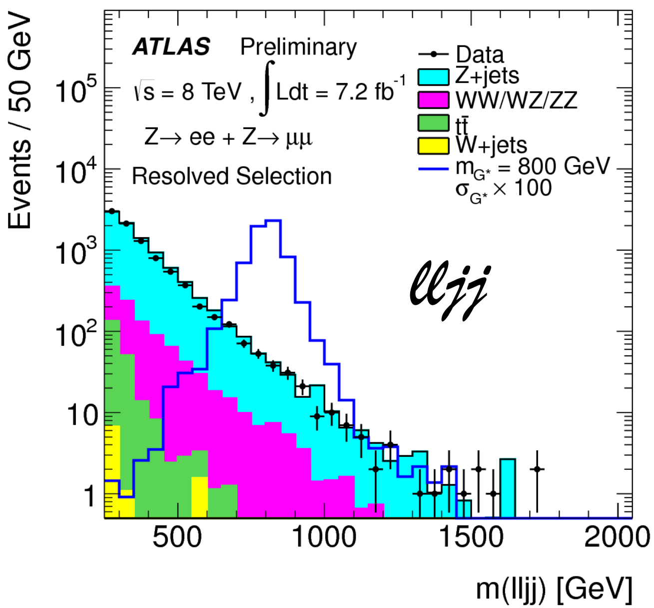
Resonances → ZW or ZZ → llqq, $\sqrt{s}$ = 8 TeV

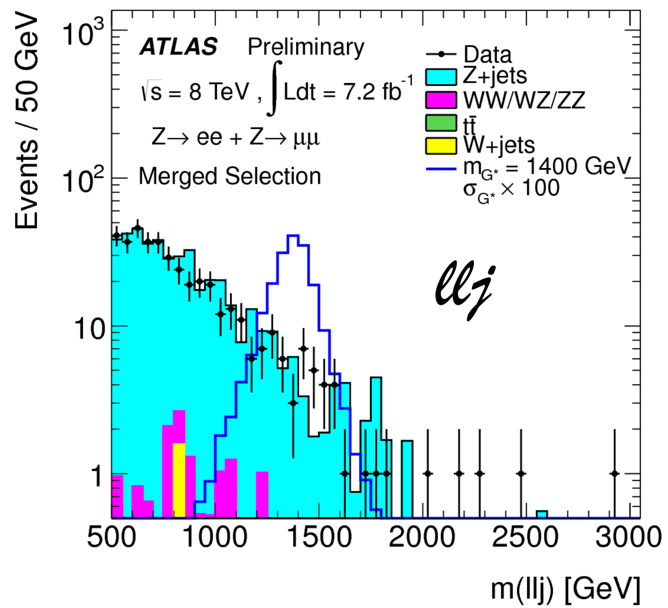
- Background fit function:

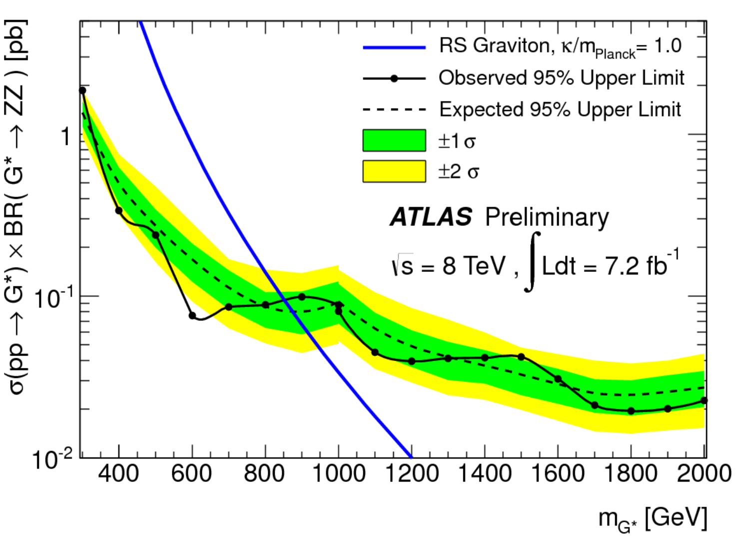
$$p_0 \cdot \frac{(1-x)^{p_1}}{x^{p_2+p_3\cdot\ln(x)}},$$

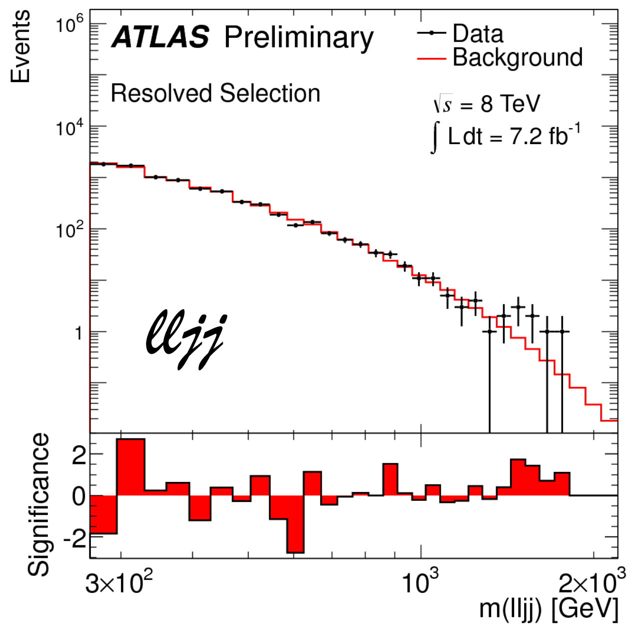
$$x = m_{\ell\ell jj}/\sqrt{s} \quad \text{or}\; m_{\ell\ell j}/\sqrt{s}$$

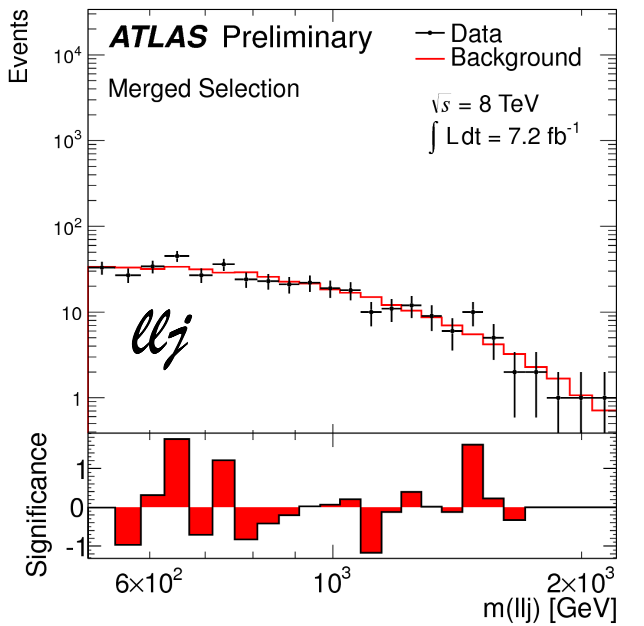
- No significant excess
- G^*_{bulk}: M > 0.88 TeV, for $k/\overline{M}_{Pl}$ = 1.0







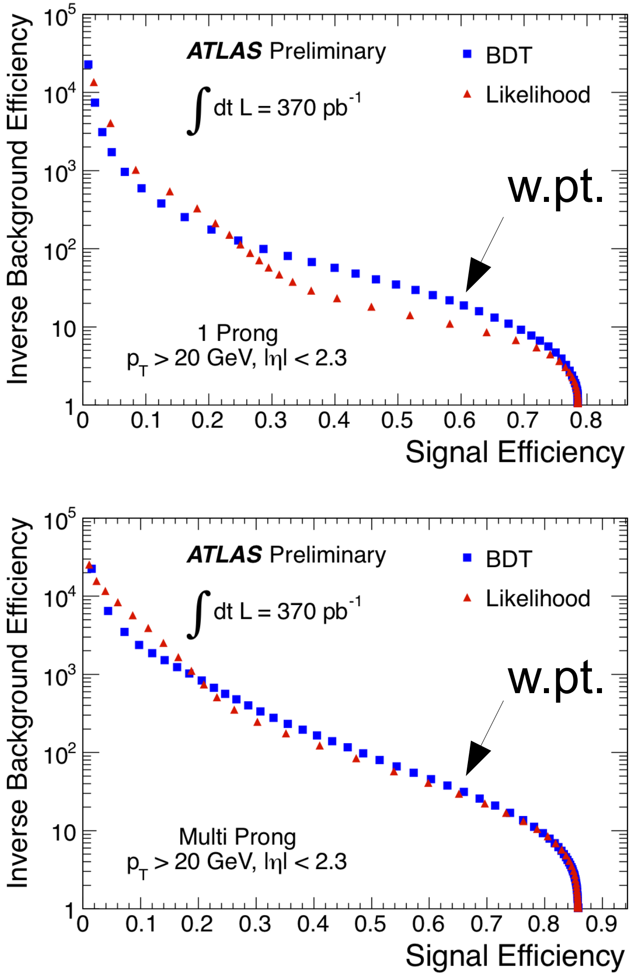




3rd generation searches

Ditau resonances – $\sqrt{s}$ = 7 TeV

- New gauge bosons in theories beyond the SM may couple preferentially to 3rd generation fermions
- Hadronic tau decay identification
  - Boosted Decision Trees to discriminate against QCD jets
  - Using shower shape and tracking identification
- Backgrounds:
  - Z/γ*, Dibosons, ttbar, single top (simulated)
  - W+jets & QCD multijets (data-driven)
- Search performed by counting events above threshold in m_T^{tot}

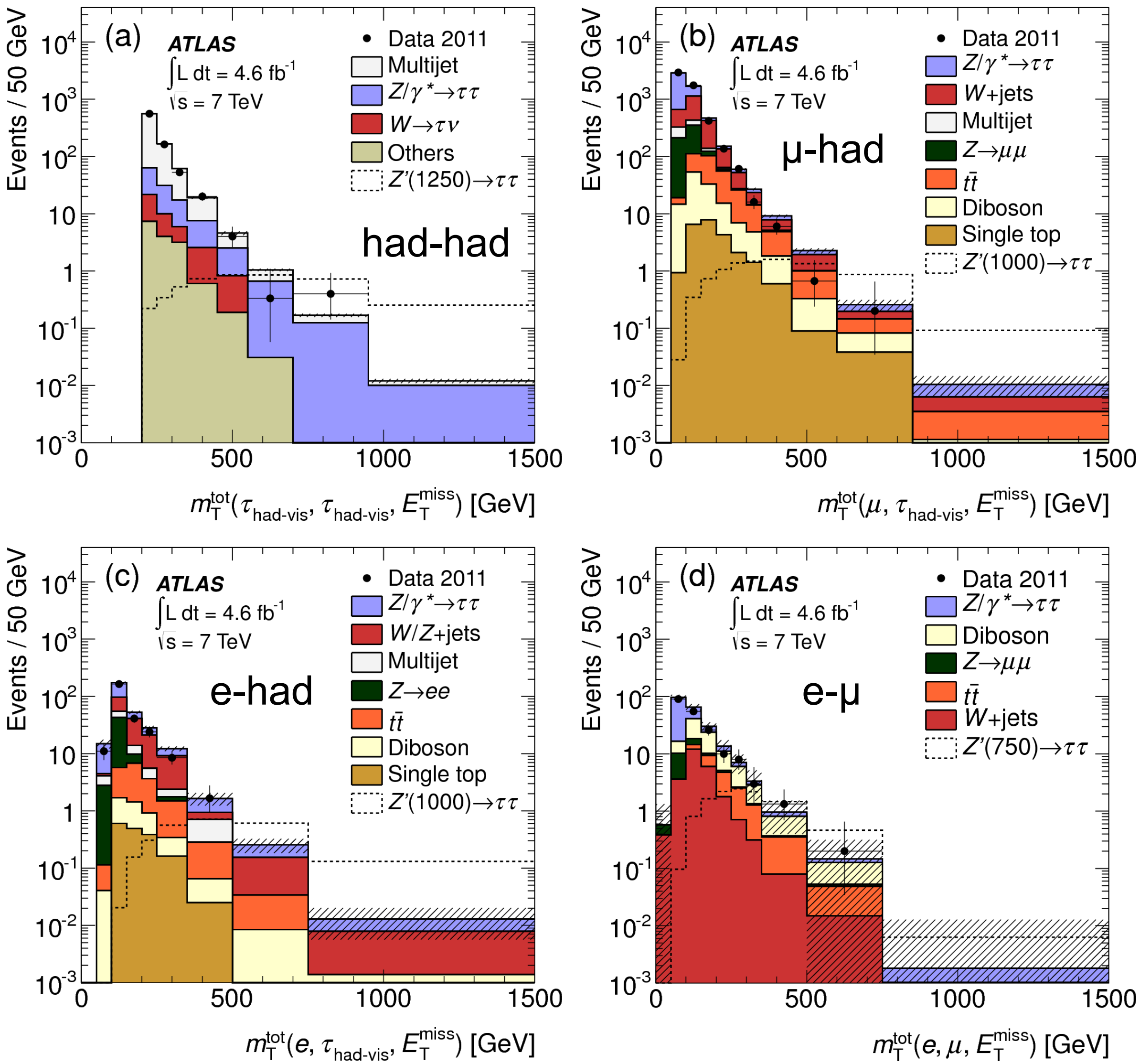


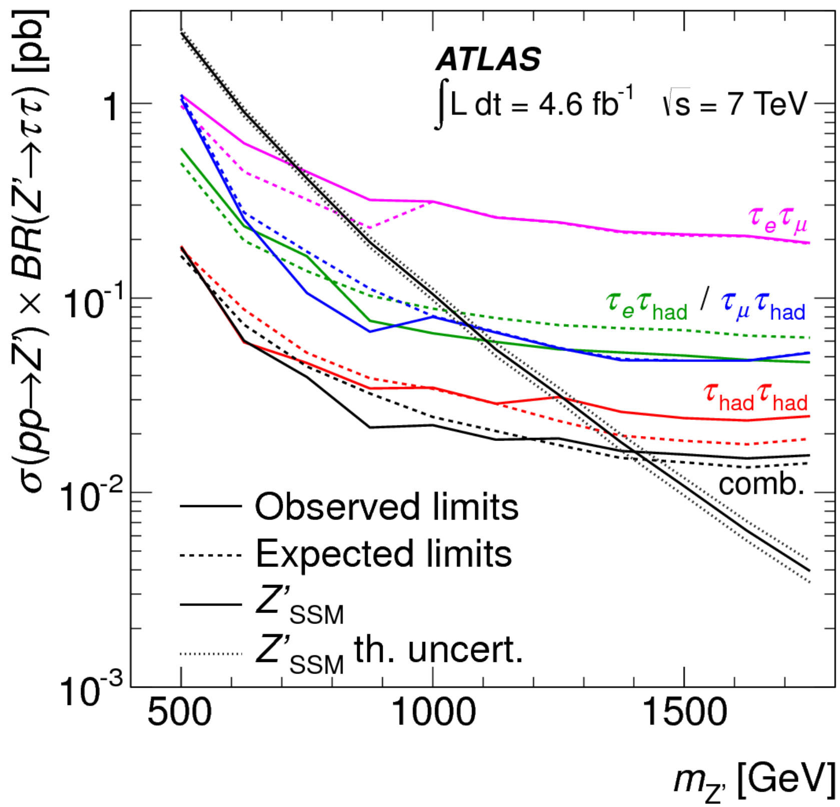
$$m_T^{tot} = \sqrt{2p_{T1}p_{T2}C + 2E_T^{miss}p_{T1}C_1 + 2E_T^{miss}p_{T2}C_2}$$

where C = 1 – cos Δφ, with Δφ taken between the respective momenta or E_T^{miss}

Ditau resonances – √s = 7 TeV

- Results with 2011 data at √s = 7 TeV, from 4 search channels



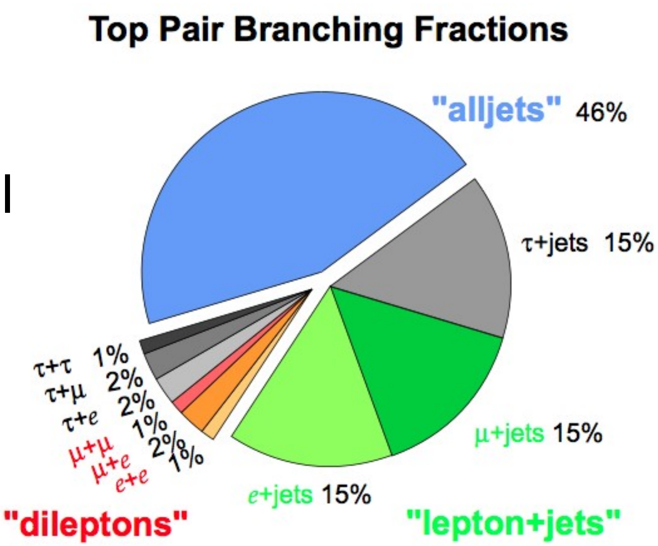


Z'$_{SSM}$: M > 1.4 TeV

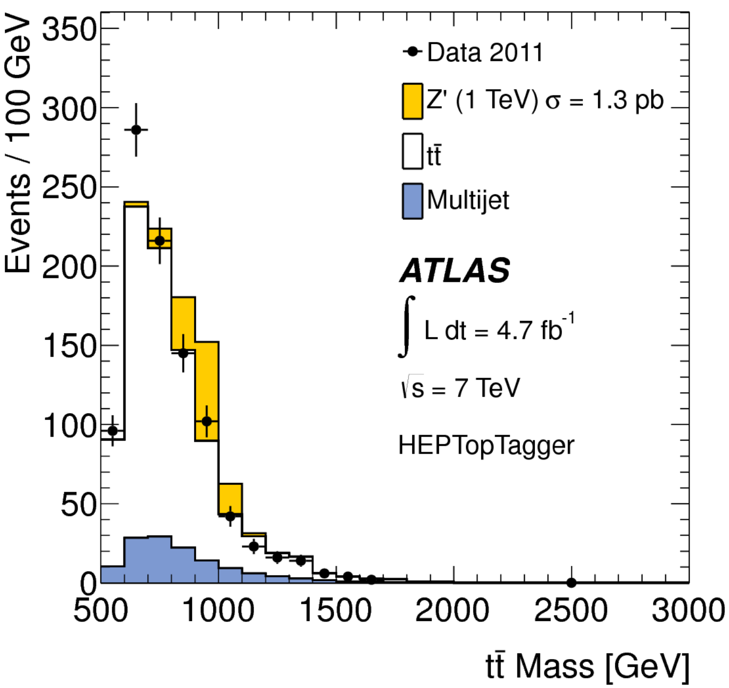
$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{2p_{\mathrm{T}1}p_{\mathrm{T}2}C + 2E_{\mathrm{T}}^{\mathrm{miss}}p_{\mathrm{T}1}C_1 + 2E_{\mathrm{T}}^{\mathrm{miss}}p_{\mathrm{T}2}C_2}$$

Ditop resonances – Fully hadronic – $\sqrt{s}$ = 7 TeV

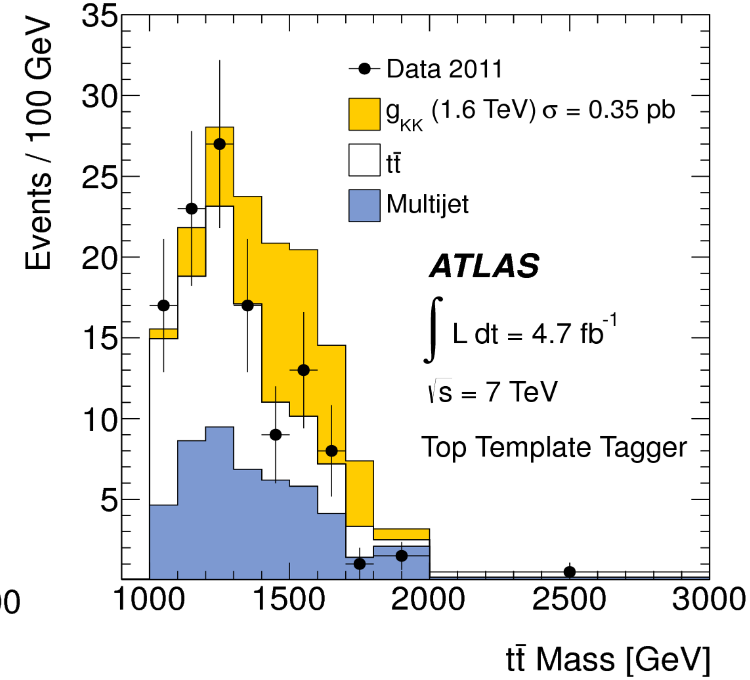
- New physics may be related to the heavy top mass
- Hadronic top-tagging allows a search for resonances decaying to top quark pairs in the fully hadronic channel
- Two top-tagging algorithms with complementary results
- Data-driven QCD multijet background estimate



HEPTopTagger

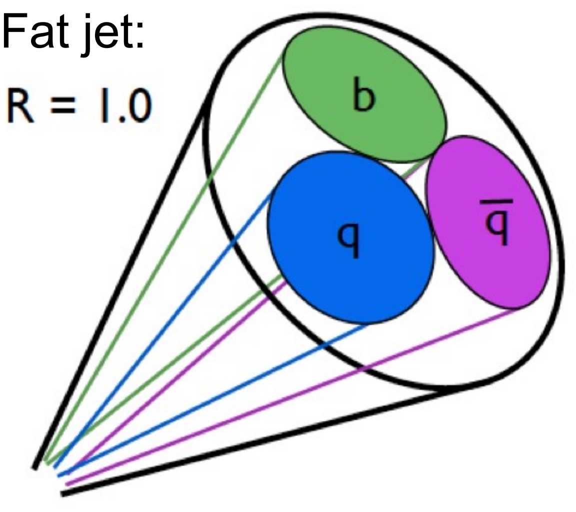


TopTemplateTagger



Fat jet:

R = 1.0



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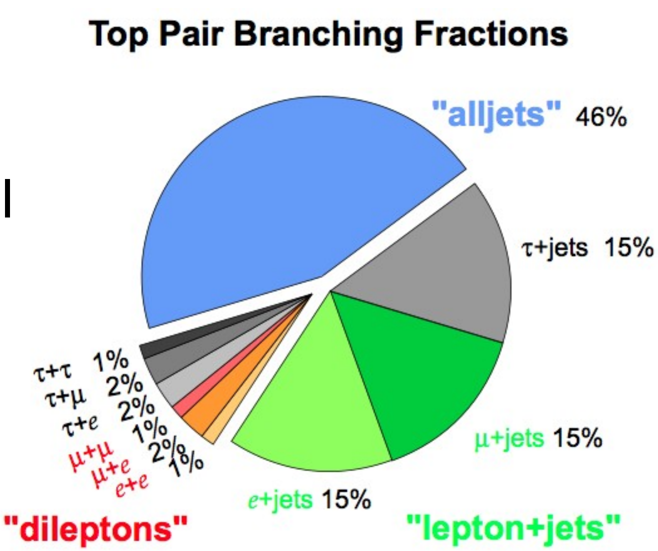
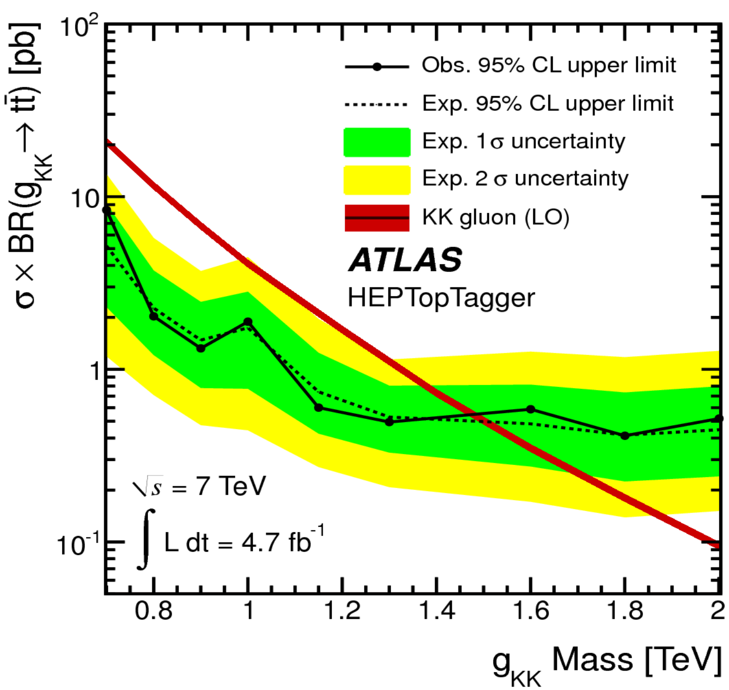
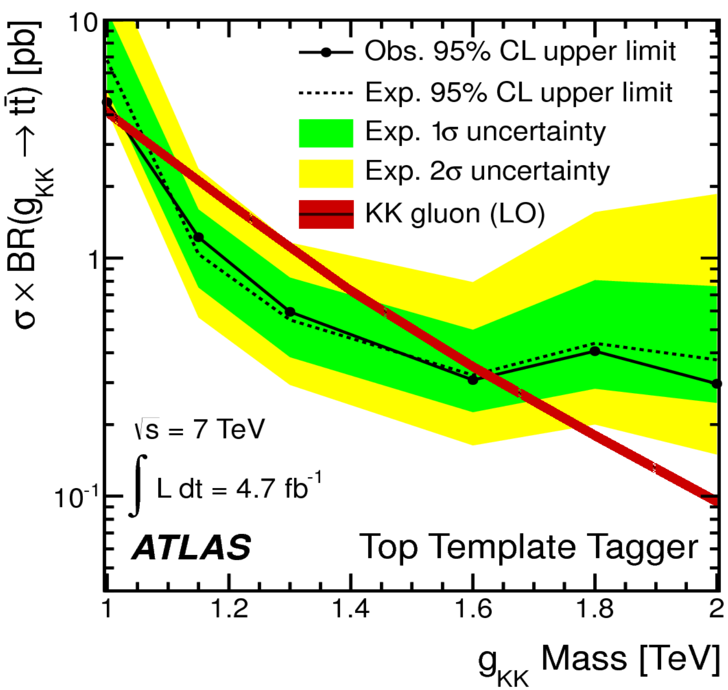


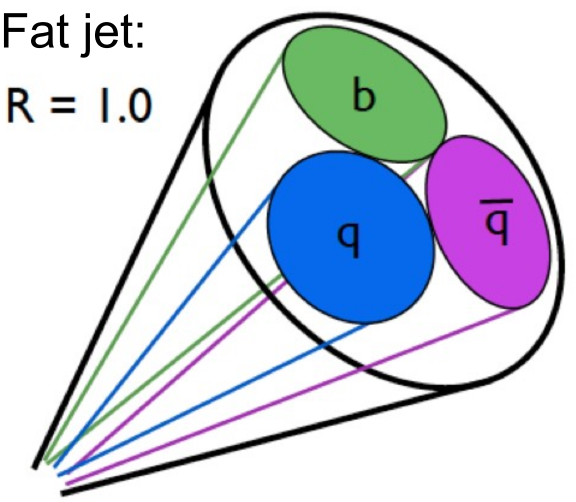
g_{KK} excluded for [0.70, 1.62] TeV; Z' in appendix





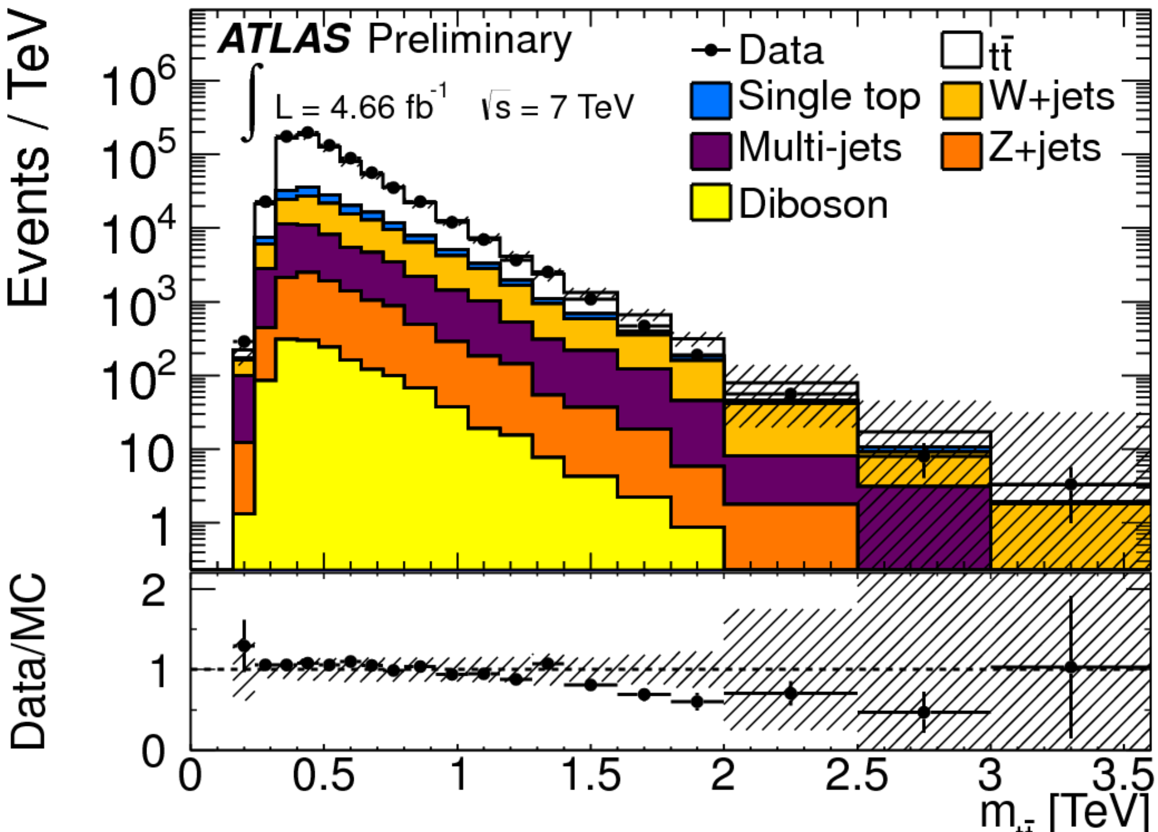
Fat jet:

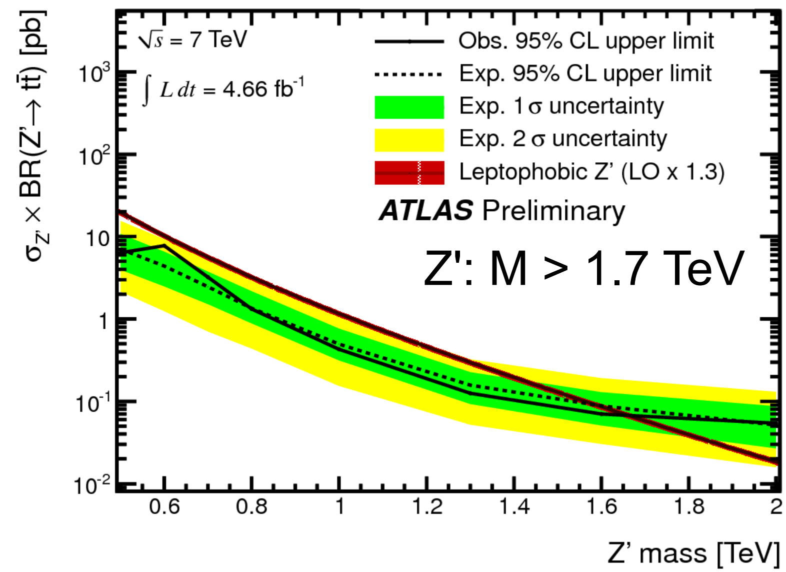
R = 1.0

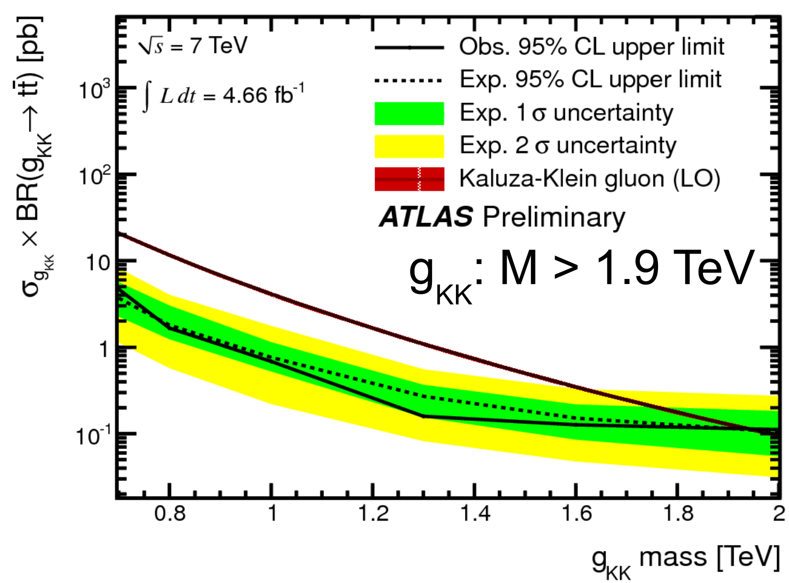


Ditop resonances – Semi-leptonic – $\sqrt{s}$ = 7 TeV

- Semi-leptonic channel: eνb+jjb or μνb+jjb
- Resolved selection: assign jets to either top quark using a χ^2 algorithm
- Boosted selection: one b-tag and one fat jet

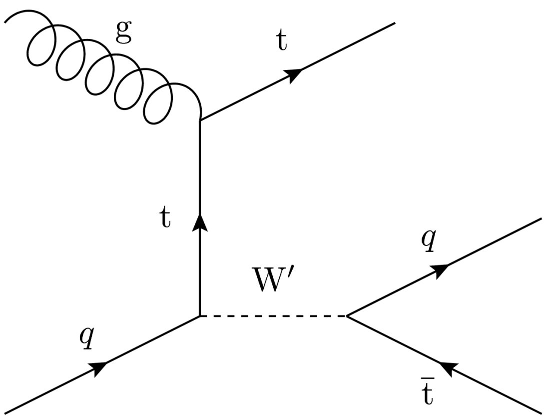




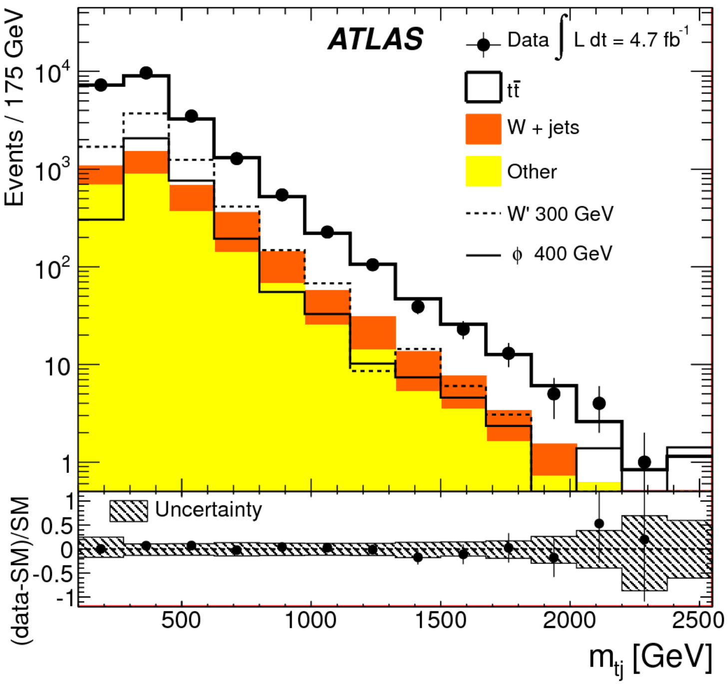


Top + jet resonances – $\sqrt{s}$ = 7 TeV

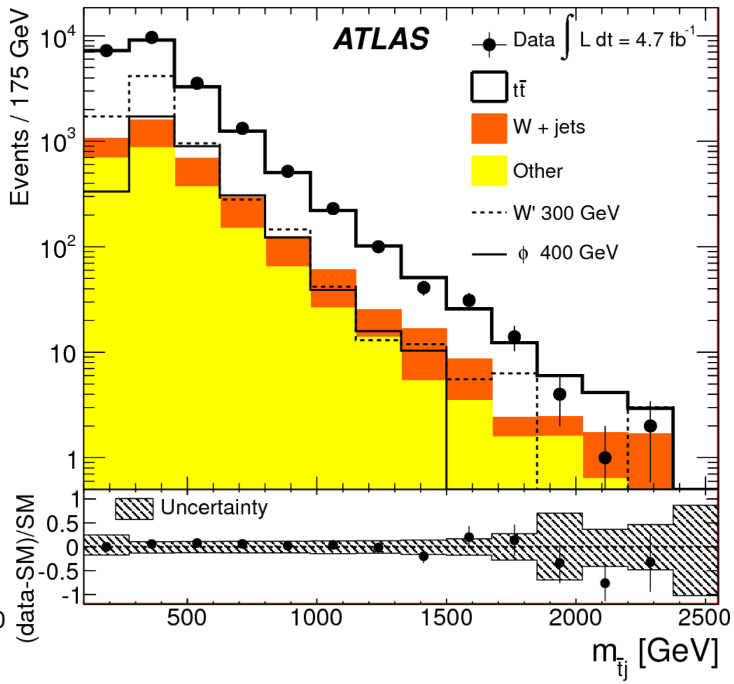
- Semi-leptonic ttbar selection,
  with at least one additional jet (at least 5 jets in total)
- Likelihood test to assign jets to either top quark
- The additional jets forming the highest top-jet and
  highest antitop-jet invariant mass are considered

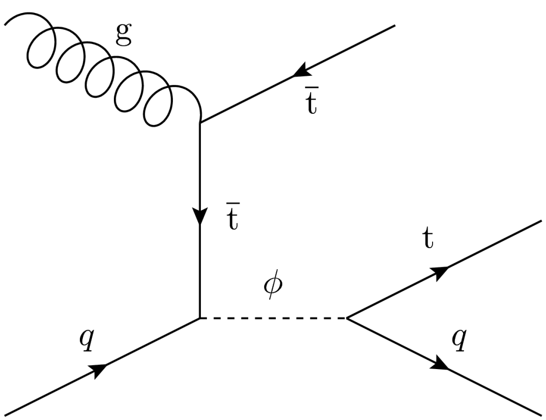


Top-jet invariant mass



Antitop-jet invariant mass





Top + jet resonances – $\sqrt{s}$ = 7 TeV

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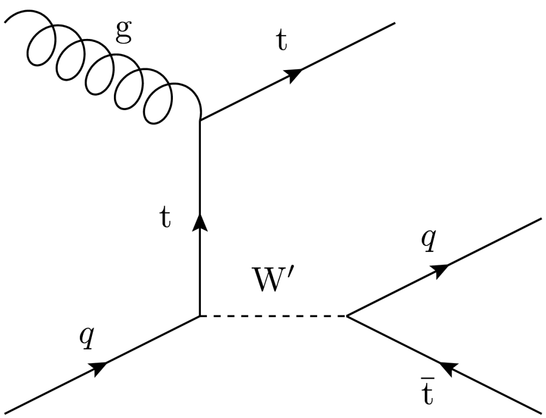
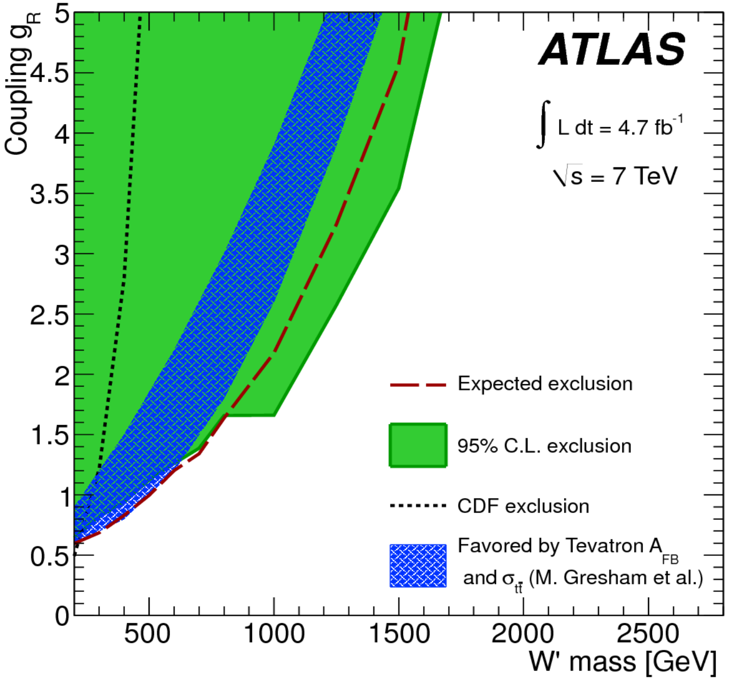
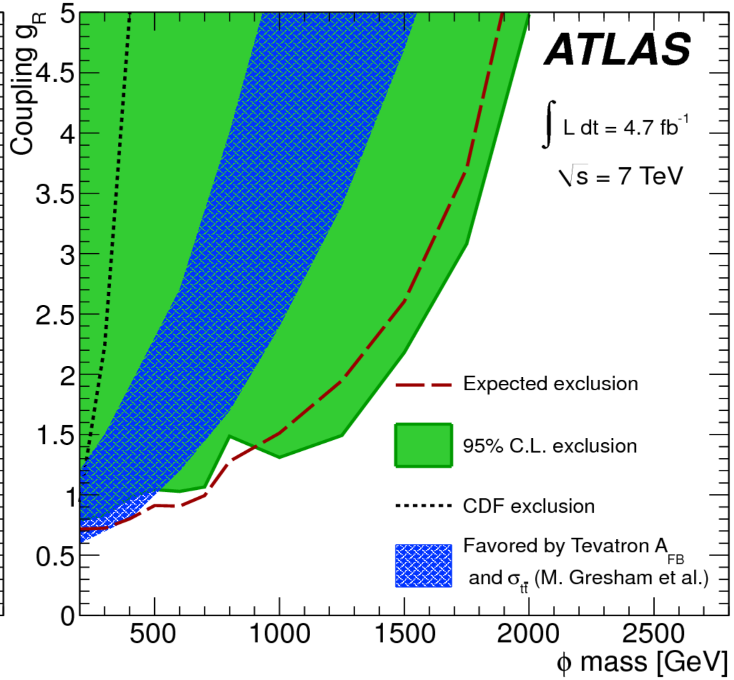
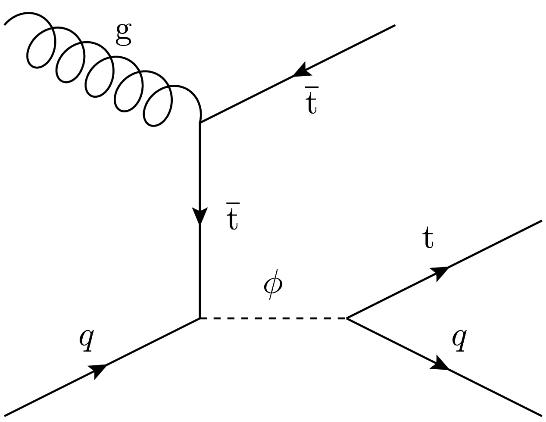


Colour-singlet limits



Colour-triplet limits



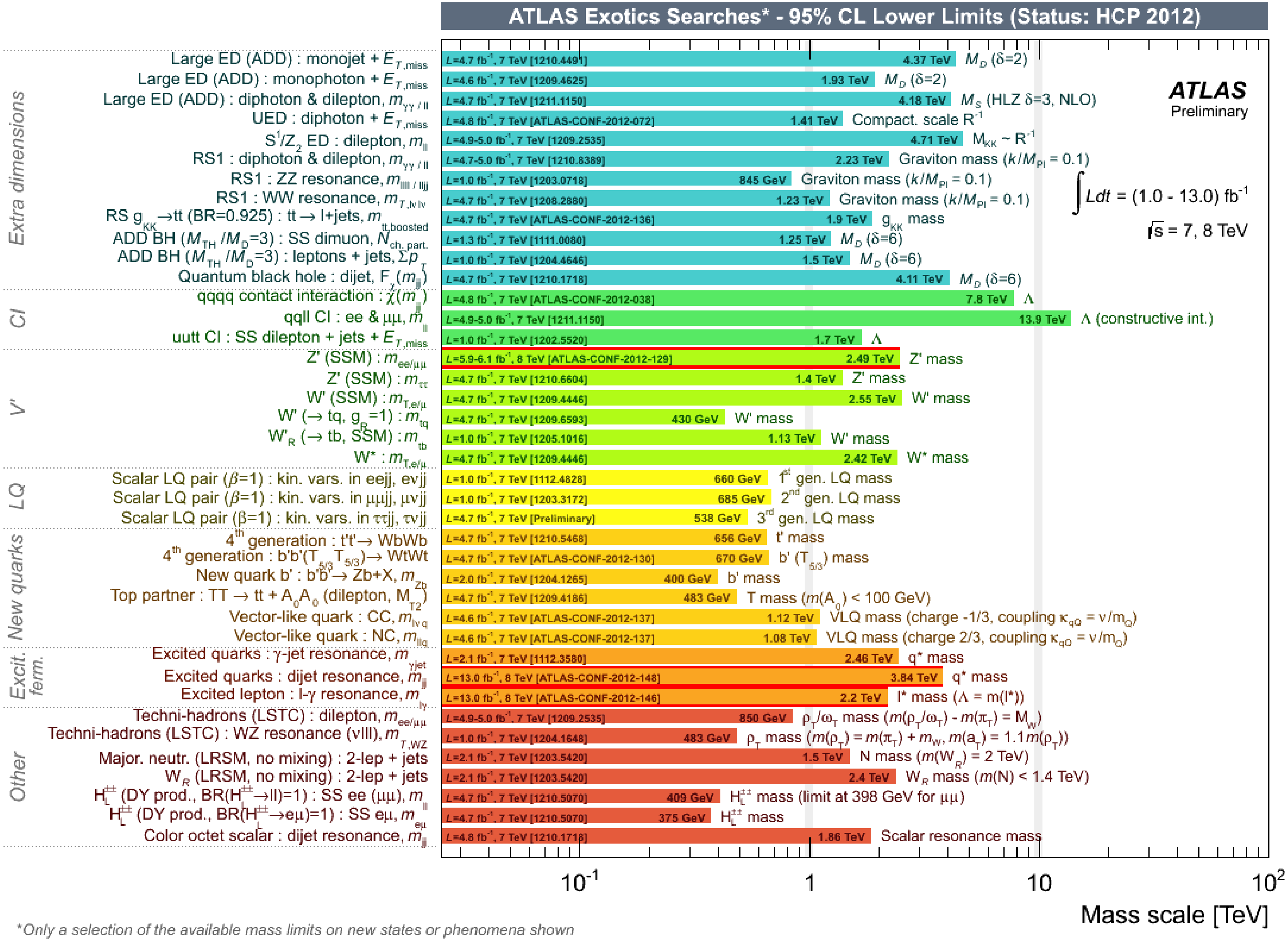


Exclusion of the phase space favoured by the Tevatron A_{FB} and σ_{tt}

Conclusion

- We have searched for heavy resonances in the ATLAS experiment
- Looking forward to analyze the full 2012 dataset: > 20 fb^{-1} !
- For more information:

8 TeV	Dijet	ATLAS-CONF-2012-148	
	Dilepton	ATLAS-CONF-2012-129	
	ZW or ZZ → llqq	ATLAS-CONF-2012-150	
$\sqrt{s}$ = 7 TeV	Dijet	1210.1718	Submitted to JHEP
	Dilepton (resonant)	1209.2535	Accepted by JHEP
	Dilepton (non-resonant)	1211.1150	Submitted to Phys. Rev. D
	Diphoton	1210.8389	Submitted to Phys. Lett. B
	Lepton + Neutrino	1209.4446	Submitted to EPJC
	Ditau	1210.6604	Submitted to Phys. Lett. B
	WW → lνlν	1208.2880	Submitted to Phys. Lett. B
	Ditop, semi-leptonic	ATLAS-CONF-2012-136	
	Ditop, fully hadronic	1211.2202	Submitted to JHEP
	Top + Jet	1209.6593	Submitted to PRD Rapid C.



- There are a lot more results from the ATLAS Exotics group!
- Other talks here by Andrée Robichaud-Véronneau and John Leslie Almond

Acknowledgements

UBC

TRIUMF

ATLAS EXPERIMENT

CERN

Gouvernement du Canada

Government of Canada

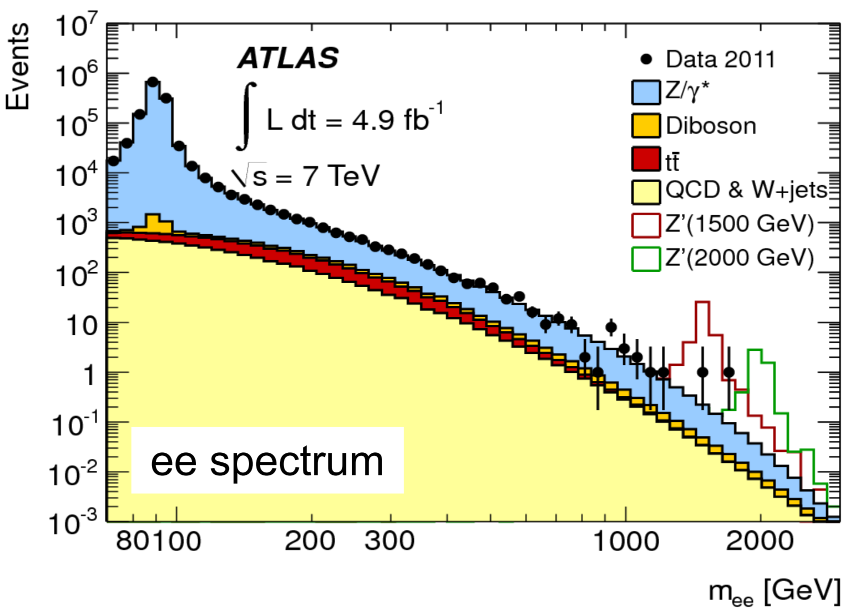
Bourses d'études supérieures du Canada Vanier

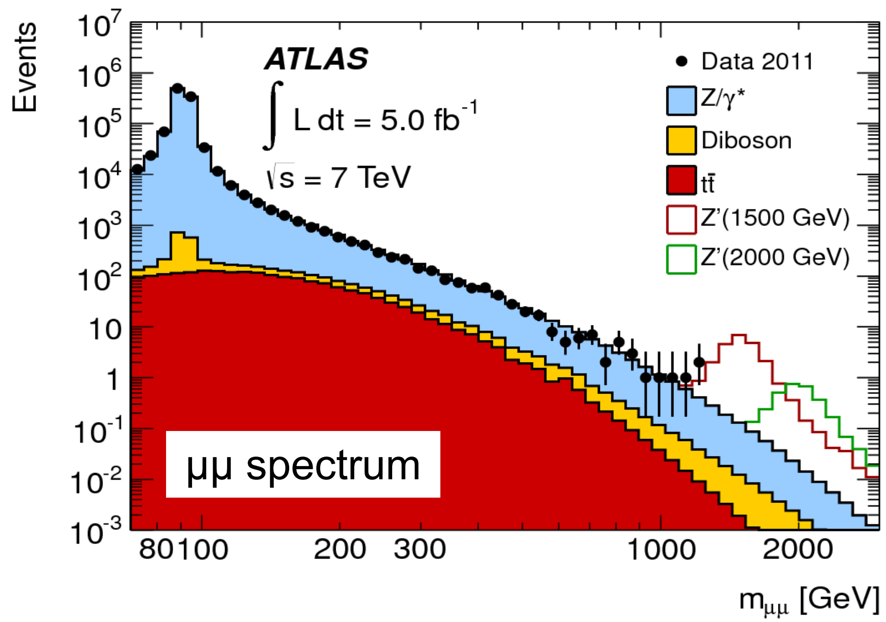
Vanier Canada Graduate Scholarships

Canada

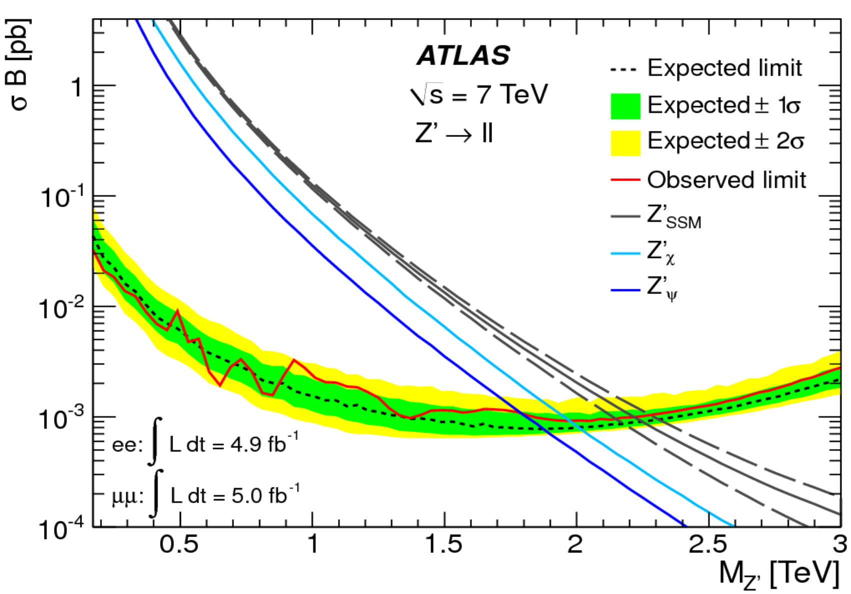
BONUS SLIDES

Dilepton resonances – $\sqrt{s}$ = 7 TeV





Z'_{SSM}: M > 2.22 TeV



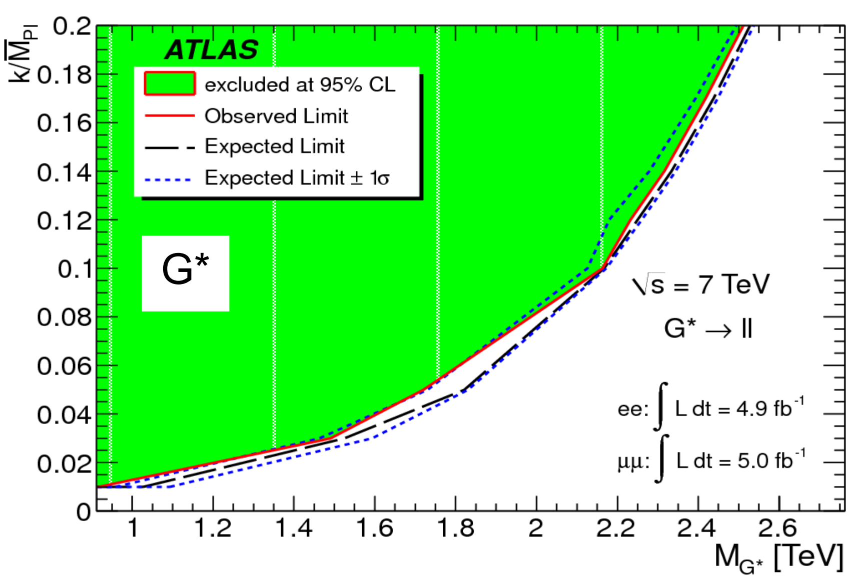
- Backgrounds:

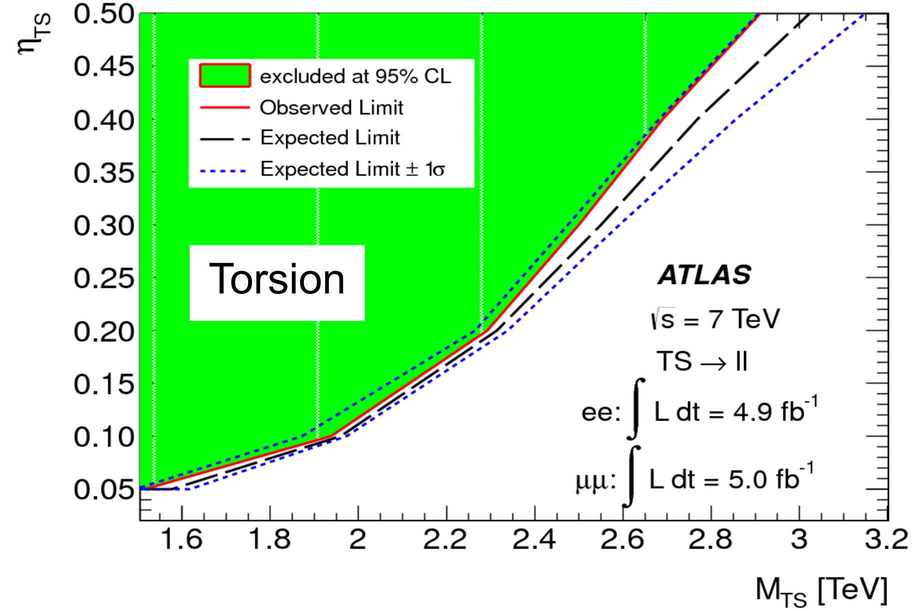
  Z/γ*, dibosons, ttbar (simulated)

  W+jets & QCD multijets (data-driven)
- Normalization to the Z peak: 70-110 GeV
- Good agreement with the Standard Model with *p*-values: 36% (ee) and 68% (μμ)

Model	Z'_ψ	Z'_N	Z'_η	Z'_I	Z'_S	Z'_χ
Observed limit [TeV]	1.79	1.79	1.87	1.86	1.91	1.97
Expected limit [TeV]	1.87	1.87	1.92	1.91	1.95	2.00

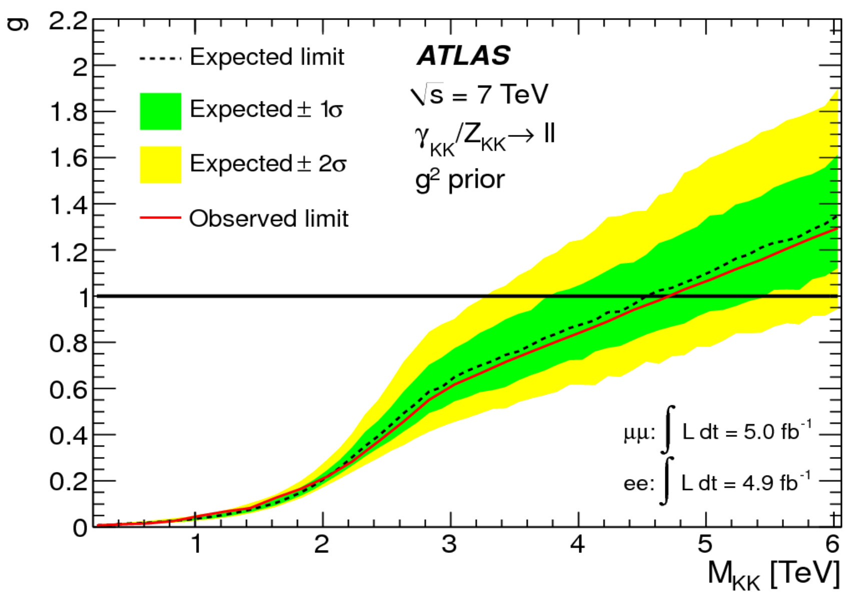
Dilepton resonances – $\sqrt{s}$ = 7 TeV

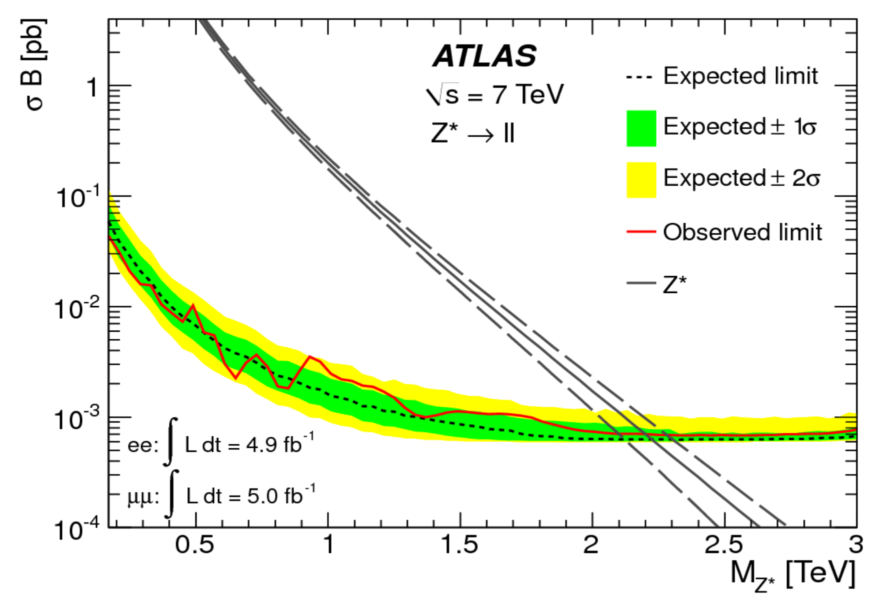




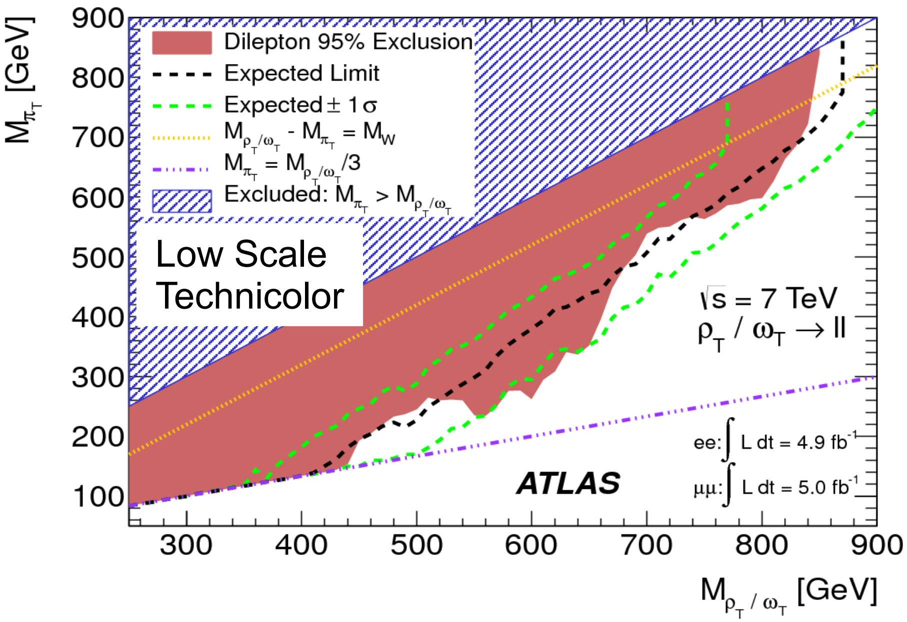
γ_{KK}/Z_{KK}: M > 4.17 TeV

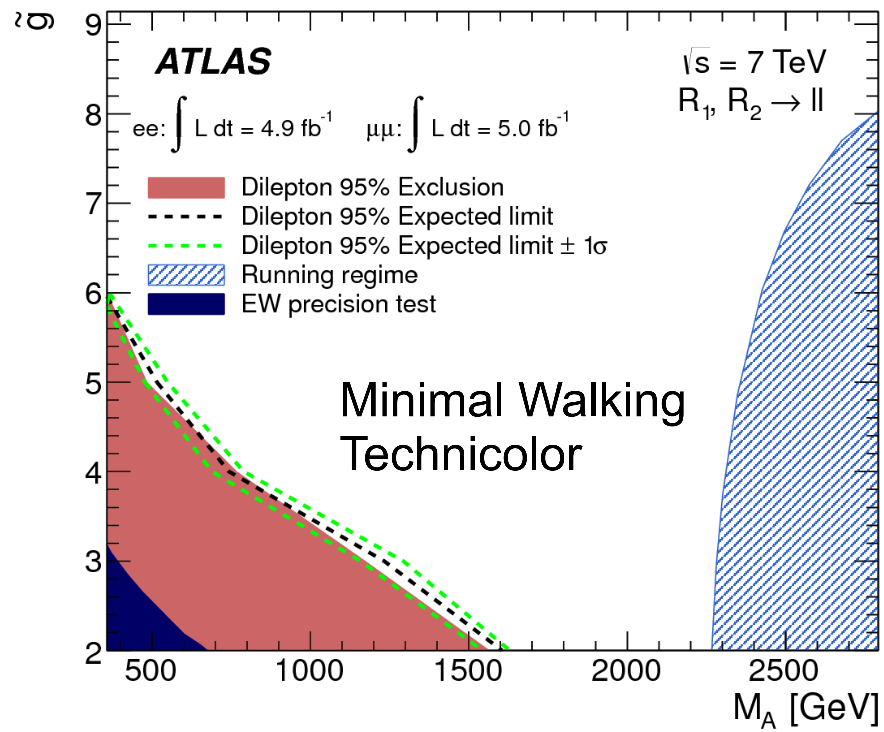
Z*: M > 2.20 TeV



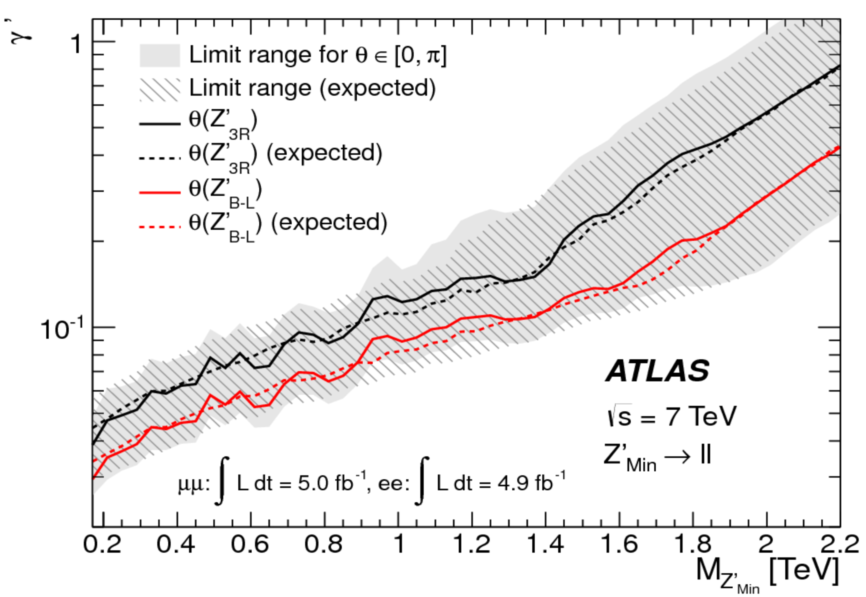


Dilepton resonances – $\sqrt{s}$ = 7 TeV





Minimal Z' models



- Low Scale Technicolor:
  - ρ_T/ω_T: M > 850 GeV, for $M_{\rho T/\omega T}$ - $M_{\pi T}$ = M_W
- Minimal Walking Technicolor:
  - M_A > 1.56 TeV, for g = 2
- Minimal Z' models: M > [1.1, 2.1] TeV, for γ' = 0.2

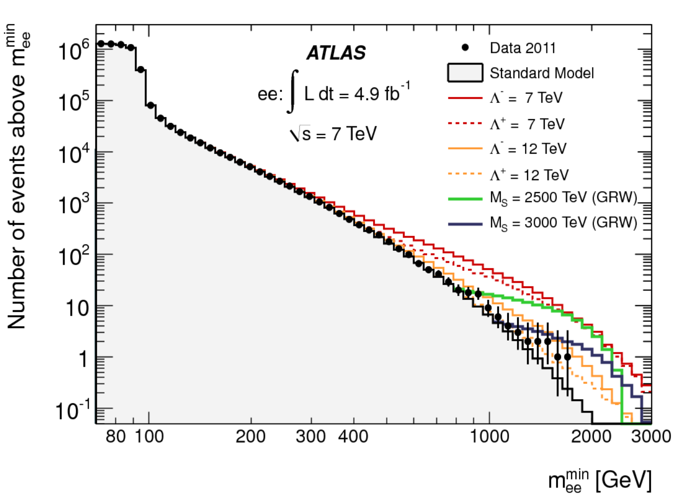
Non-resonant dilepton and diphoton searches – $\sqrt{s}$ = 7 TeV

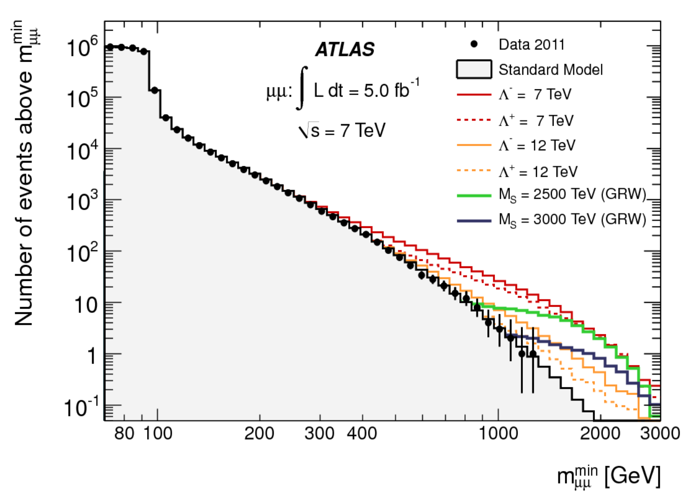
- Searches looking for an excess of events in the high-invariant-mass tail
- Contact interactions (llqq): Λ > 13.9 TeV for constructive interference, $1/\Lambda^2$ prior
- ADD M_S > [2.8, 4.2] TeV, depending on n_{ED} and the choice of model and prior

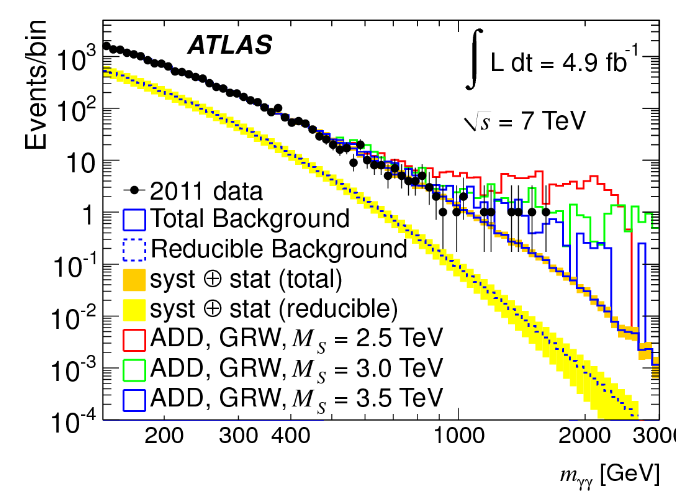
Channel	Prior	Expected limit [TeV] Constr.	Expected limit [TeV] Destr.	Observed limit [TeV] Constr.	Observed limit [TeV] Destr.
ee	$1/\Lambda^2$	13.8	10.4	12.1	9.5
	$1/\Lambda^4$	12.5	9.8	11.4	9.1
$\mu\mu$	$1/\Lambda^2$	12.7	9.9	12.9	9.6
	$1/\Lambda^4$	11.6	9.1	11.7	9.0
$ee+\mu\mu$	$1/\Lambda^2$	15.0	11.3	13.9	10.2
	$1/\Lambda^4$	13.8	10.5	12.9	9.8

Channel	Prior	GRW	Hewett	HLZ $n=3$	HLZ $n=4$	HLZ $n=5$	HLZ $n=6$	HLZ $n=7$
ee	$1/M_S^4$	2.95	2.63	3.51	2.95	2.66	2.48	2.34
	$1/M_S^8$	2.82	2.67	3.08	2.82	2.68	2.59	2.52
$\mu\mu$	$1/M_S^4$	3.07	2.74	3.65	3.07	2.77	2.58	2.44
	$1/M_S^8$	2.82	2.67	3.08	2.82	2.68	2.59	2.52
$ee+\mu\mu$	$1/M_S^4$	3.27	2.92	3.88	3.27	2.95	2.75	2.60
	$1/M_S^8$	3.09	2.92	3.37	3.09	2.94	2.84	2.76
$ee+\mu\mu$ $+\gamma\gamma$	$1/M_S^4$	3.51	3.14	4.18	3.51	3.17	2.95	2.79
	$1/M_S^8$	3.39	3.20	3.69	3.39	3.22	3.11	3.02

Dilepton distributions: number of events above m_{ll}^{min}

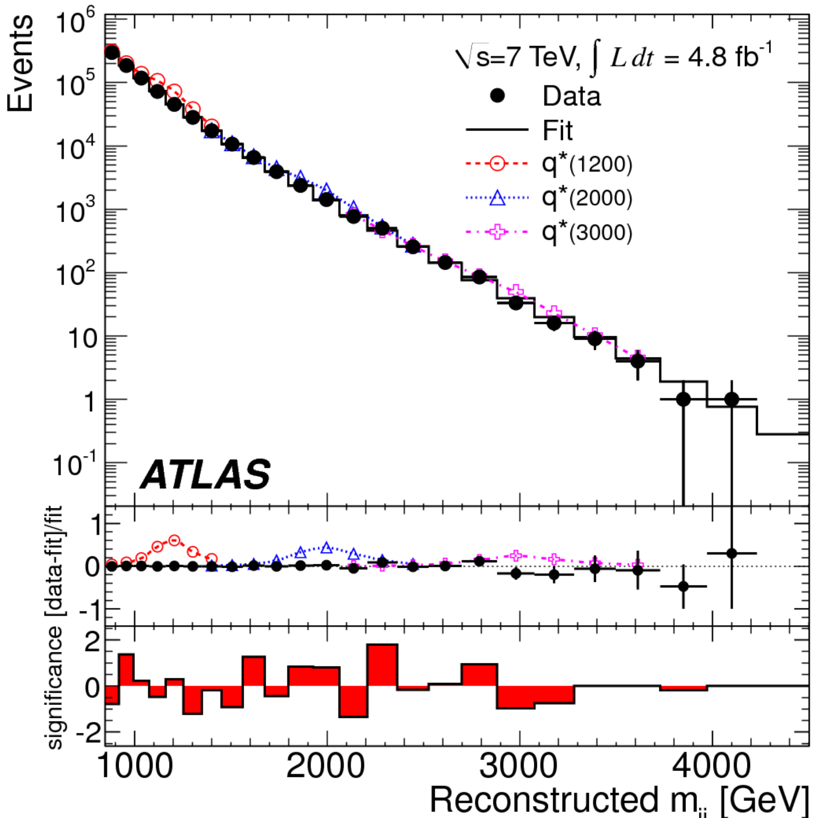


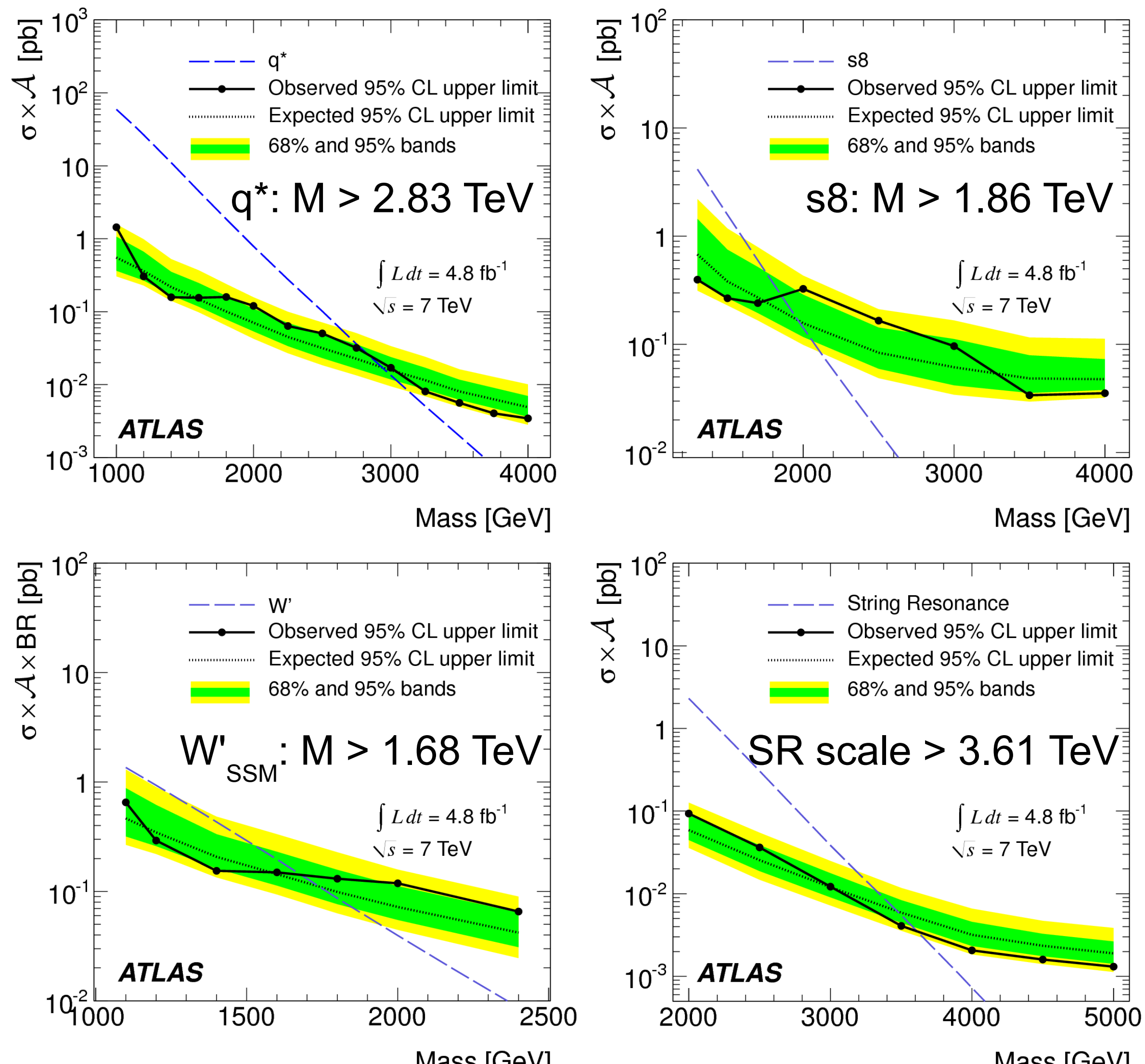




Dijet resonances – $\sqrt{s}$ = 7 TeV

- Limits on further models, with 2011 data taken at $\sqrt{s}$ = 7 TeV
- From the invariant mass spectrum





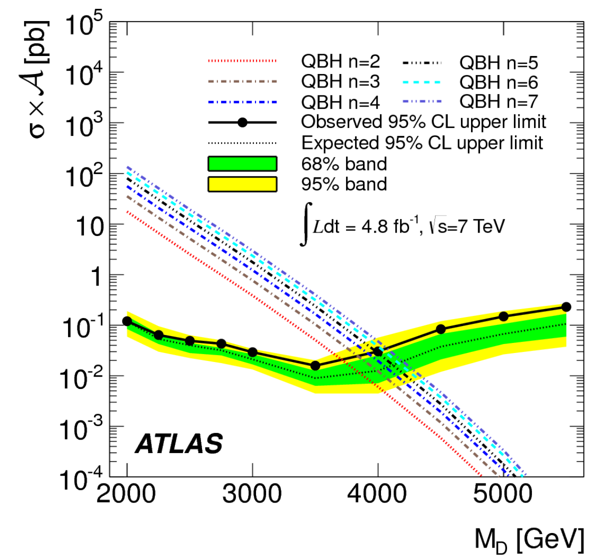
Dijet angular analysis – $\sqrt{s}$ = 7 TeV

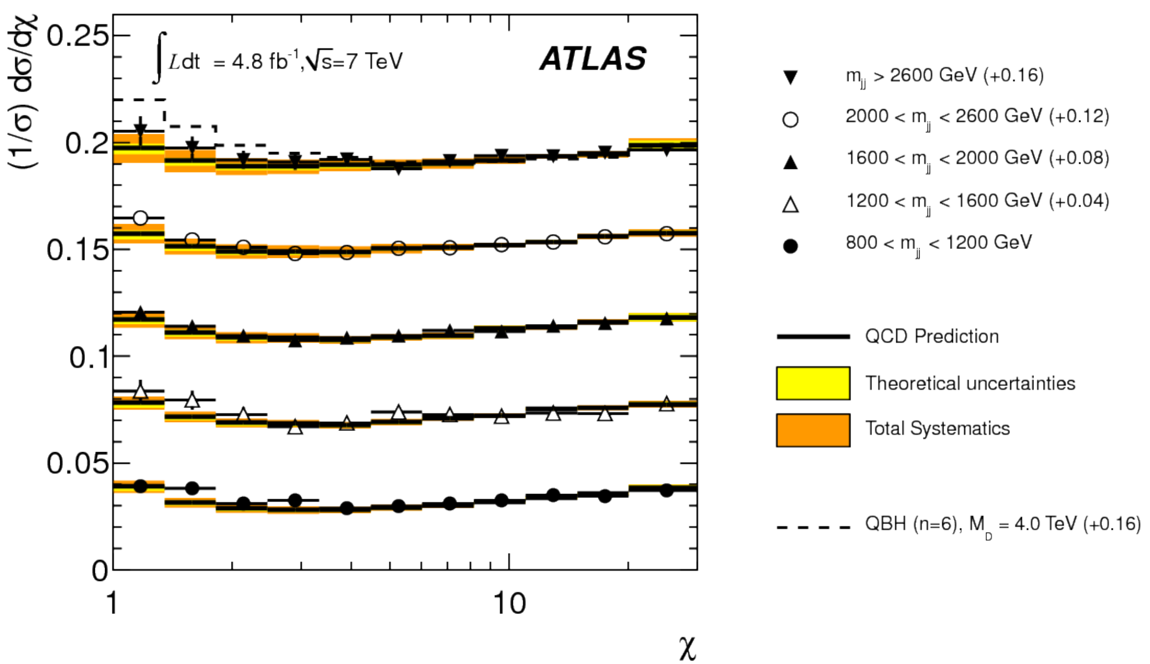
- Angular analysis, with 2011 data at $\sqrt{s}$ = 7 TeV

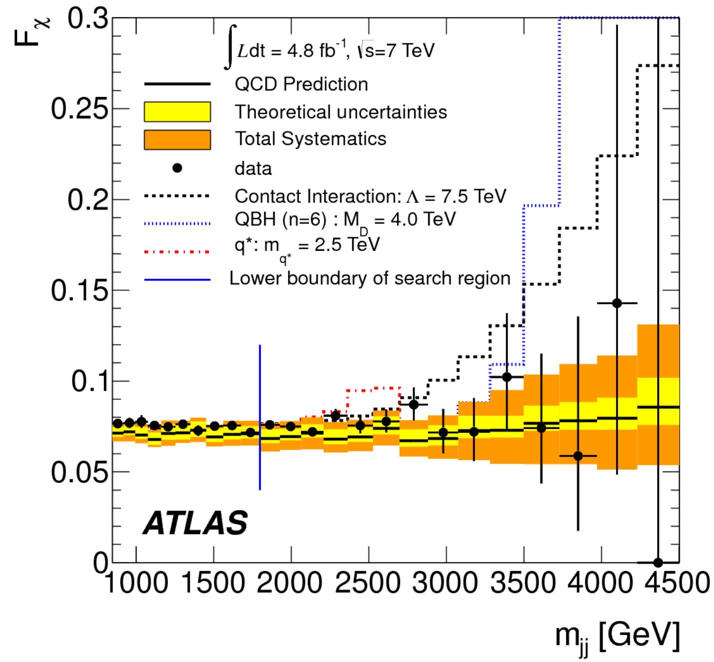
$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right),\ y^* = \frac{1}{2}(y_1 - y_2)$$: Jet rapidity difference

$$\chi \equiv \exp(|y_1 - y_2|) = \exp(2|y^*|)$$

$$F_\chi(m_{jj}) \equiv \frac{\mathrm{d}N_{\mathrm{central}}/\mathrm{d}m_{jj}}{\mathrm{d}N_{\mathrm{total}}/\mathrm{d}m_{jj}},\ N_{\mathrm{central}} : |y^*| < 0.6$$

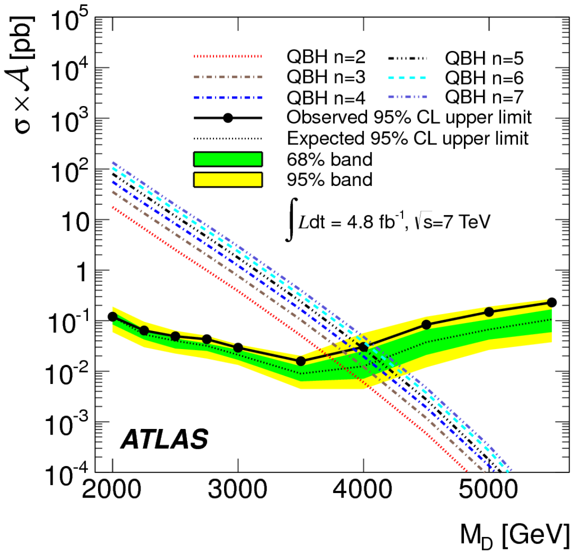


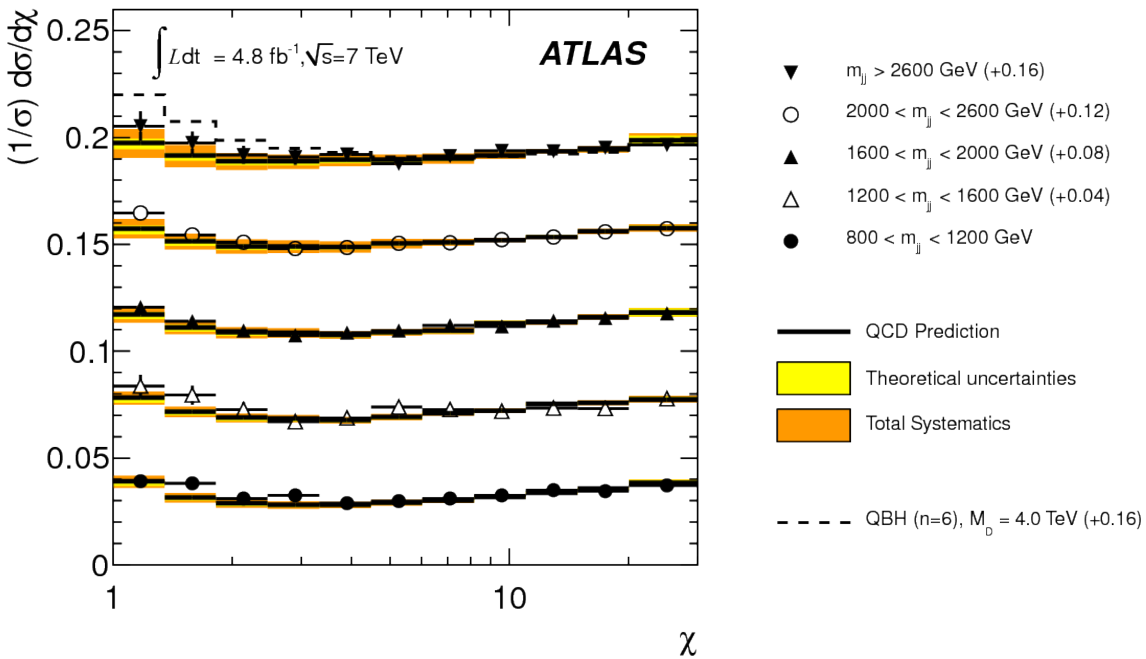


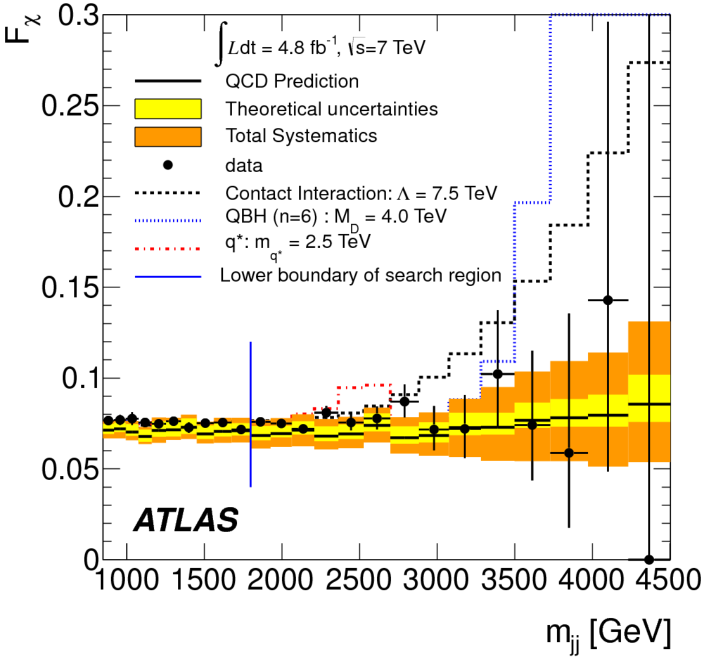


Dijet angular analysis – $\sqrt{s}$ = 7 TeV

- Angular analysis, with 2011 data at $\sqrt{s}$ = 7 TeV
  - Data are consistent with QCD NLO simulation
  - Quantum black holes:
    M_D > 4.11 TeV, for n_{ED} = 6
  - Contact interactions: Λ > 7.6 TeV

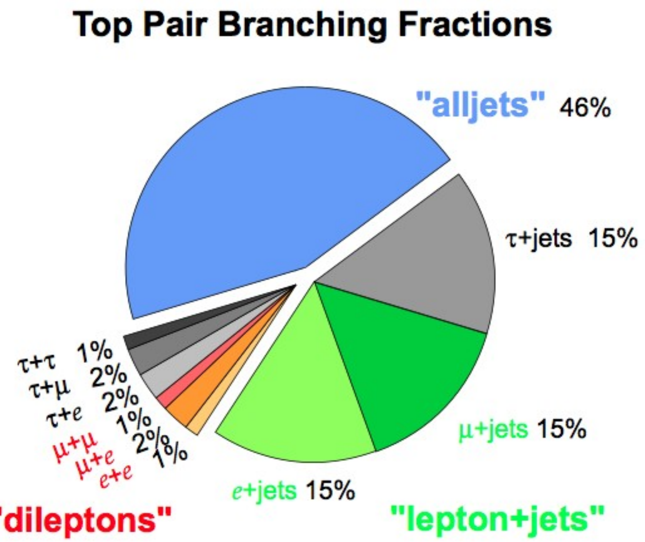




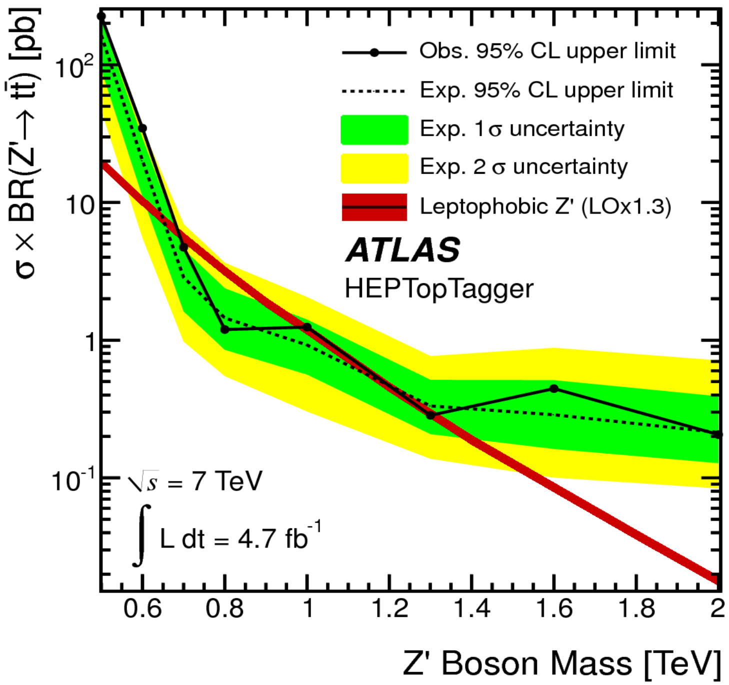


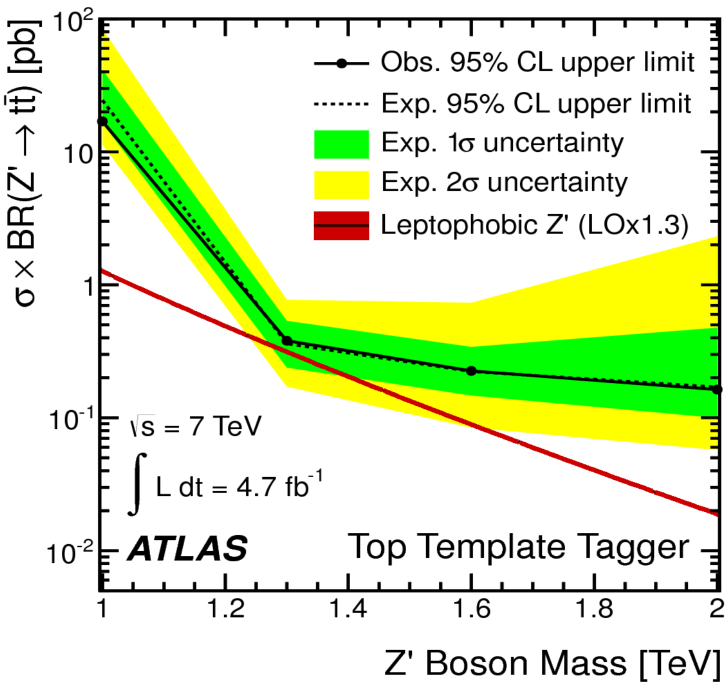
Ditop resonances – Fully hadronic – $\sqrt{s}$ = 7 TeV

- New physics may be related to the heavy top mass
- Hadronic top-tagging allows a search for resonances decaying to top quark pairs in the fully hadronic channel
- Two top-tagging algorithms with complementary results
- Data-driven QCD multijet background estimate



Leptophobic Z' excluded for [0.70, 1.00] TeV and [1.28, 1.32] TeV





Fat jet:

R = 1.0