MICHIGAN STATE UNIVERSITY

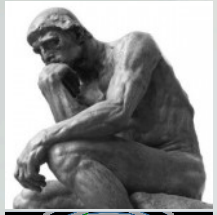
ATLAS EXPERIMENT

ATLAS Searches for Z' and W' Gauge Bosons Decaying to Leptons

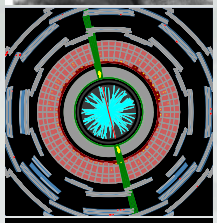
30th of September 2016
Joint Experimental-Theoretical Physics Seminar

Daniel Hayden
daniel.hayden@cern.ch

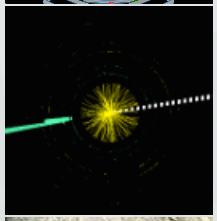
Overview



Theoretical Motivation

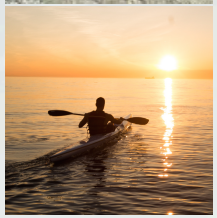


Z' Searches in ATLAS



W' Searches in ATLAS

Other Interesting Searches



What's Next?

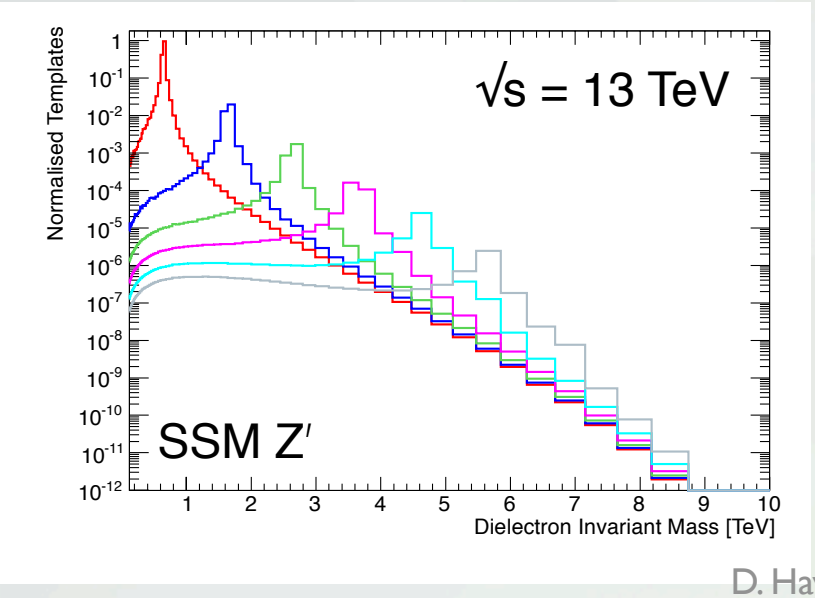
Theoretical Motivation: Z′ Gauge Bosons

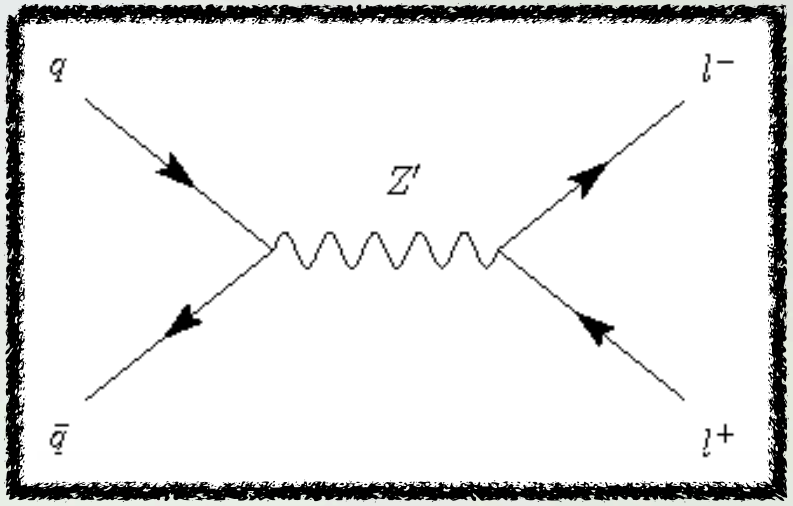
Many theories Beyond the Standard Model (BSM) predict new phenomena which give rise to dilepton final states, such as narrow resonances.

A typical benchmark model used by searches is the Sequential Standard Model.

$$SU(3)_c \text{ x } SU(2)_L \text{ x } U(1)_Y \text{ x } U(1)'$$

- Assumes the same coupling to fermions as the SM Z boson.
- Width / Pole Mass ~ 3%.
- The most sensitive search variable is usually dilepton invariant mass.





Theoretical Motivation: Z′ Gauge Bosons

The E_6 GUT provides a theoretically motivated source of extra gauge bosons:

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$$

GUT Decomposition

SM Forces

The linear combination of these U(1)′ states gives different possible Z′ states depending on the mixing angle θ which sets the coupling the fermions:

$$Z'(\theta) = Z'_\chi cos\theta + Z'_\psi sin\theta$$

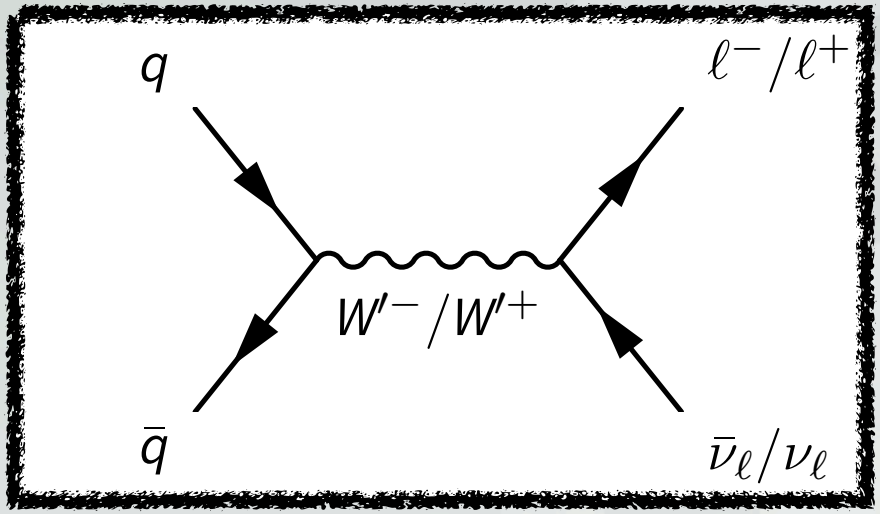
Six commonly motivated values for θ
leads to different models with specific Z′ states named:

$$Z'_\psi \ , \ Z'_N \ , \ Z'_\eta \ , \ Z'_I \ , \ Z'_S \ , \ Z'_\chi$$

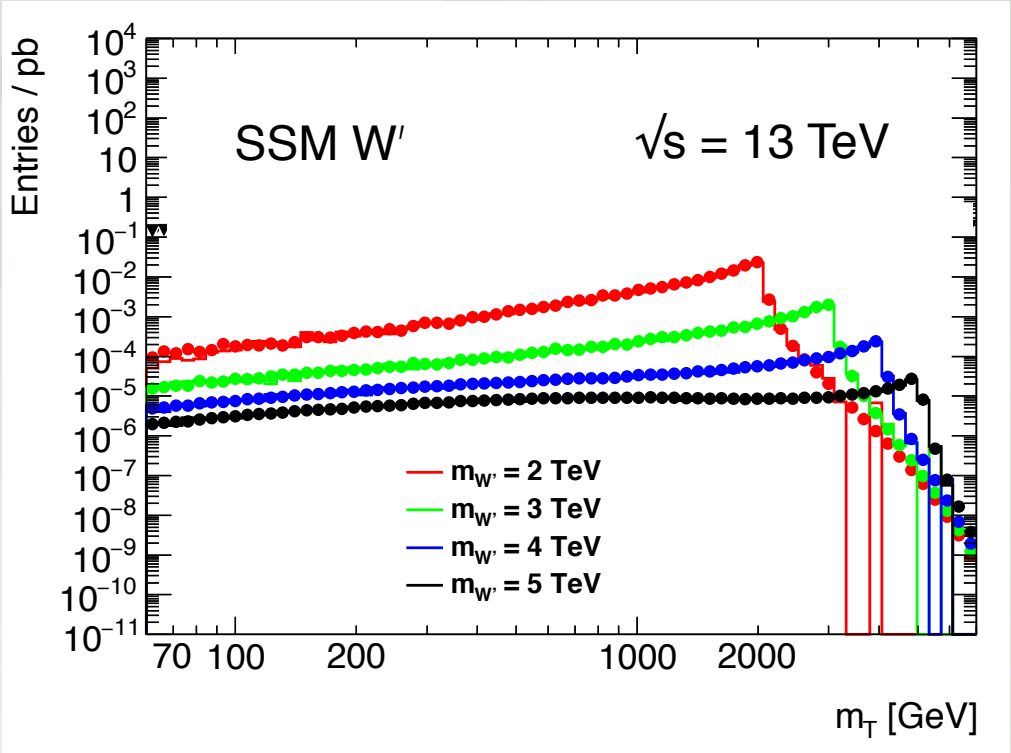
Some other interesting models, not yet quantified in ATLAS searches, predict both a Z′ and W′ gauge boson, such as the left-right symmetric model.

Theoretical Motivation: W′ Gauge Bosons

Similarly to the Z′ case, the benchmark model is the Sequential Standard Model.



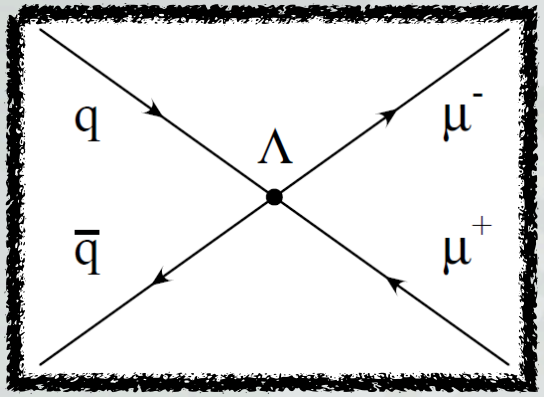
$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \phi_{\ell\nu})},$$



- Assumes the same coupling to fermions as the SM W boson.
- Width / Pole Mass ~3%.
- Of course most realistic models would predict both a Z′ and W′.
- The most sensitive search variable is usually lν transverse mass.

Theoretical Motivation: Other Interesting Models

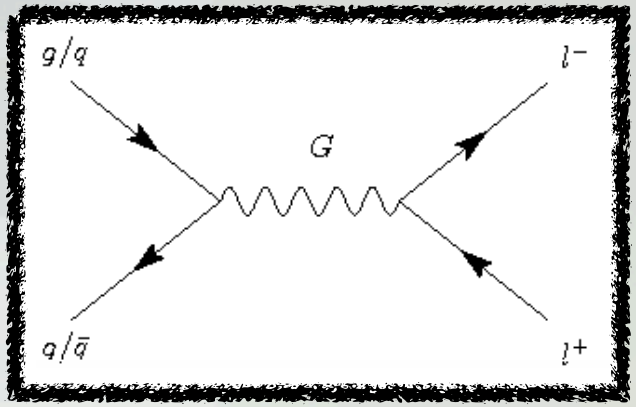
Contact Interactions



$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} - \eta\frac{F_I}{\Lambda^2} + \frac{F_C}{\Lambda^4}$$

- q-ℓ compositeness, with scale, Λ.
- Non-resonant excess over the SM invariant mass spectrum.
- η describes whether the interference is constr./destr. and sets L/R handed couplings.

Randall-Sundrum (RS) Graviton



- Posit warped extra spatial dimensions to explain the hierarchy between the Planck and electro-weak (EW) scale.
- Graviton (G*) has Spin-2, and allowed to decay to SM particles including γγ.
- Parameters of interest: M_{G^*}, k/M_{Pl}.

$$\mathcal{L} = -\left(\frac{G_0^{\mu\nu}}{\overline{M}_{Pl}} + \sum_{n>0}\frac{G_n^{\mu\nu}}{\Lambda_\pi}\right)T_{\mu\nu}\ ,\ \text{where}\ \ \Lambda_\pi = \overline{M}_{Pl}e^{-\pi kR}$$

Ref 1

Z′ Searches in ATLAS

Dielectron Channel	Dimuon Channel
Event-Level Criteria	
Dielectron Trigger	Single Muon Trigger
At least two electrons	At least two muons
Lepton-Level Criteria.	
pT > 30 GeV, within defined η region, and satisfy track quality cuts	
e-identification = Likelihood “Medium”	High pT Muon Working Point
“Loose” isolation criteria (pT dependent, with decreasing threshold)	
-	Opposite sign charge
Select Highest E_T/p_T Pair	
Dielectron Invariant Mass > 80 GeV	Dimuon Invariant Mass > 80 GeV

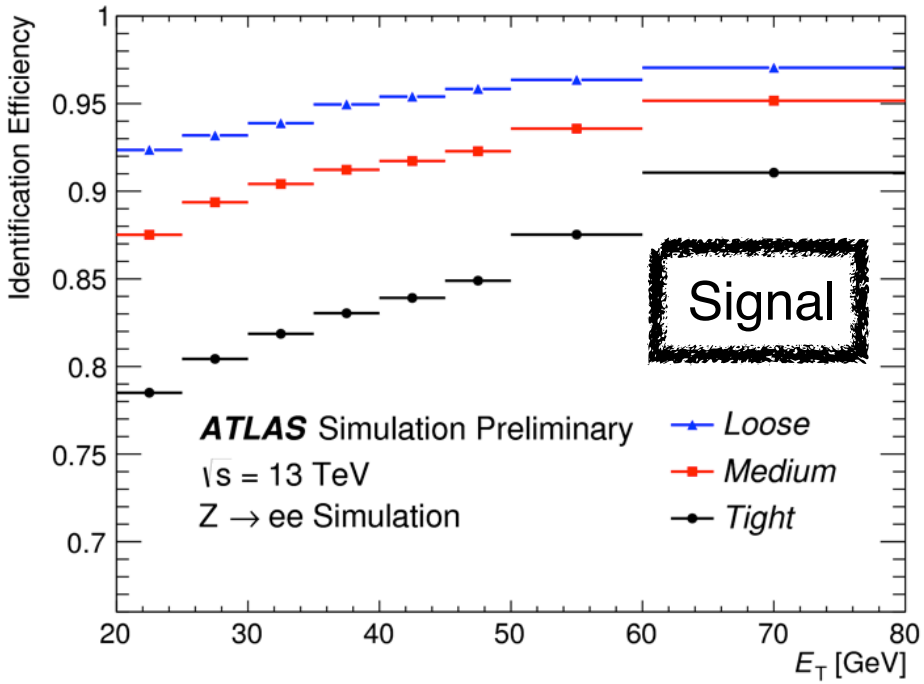
- Very clean search channel, with relatively small and well understood backgrounds.
- High pT muon working point reduces the reconstruction efficiency by 20%, but improves the resolution of muons with pT > 1.5 TeV by 30%.

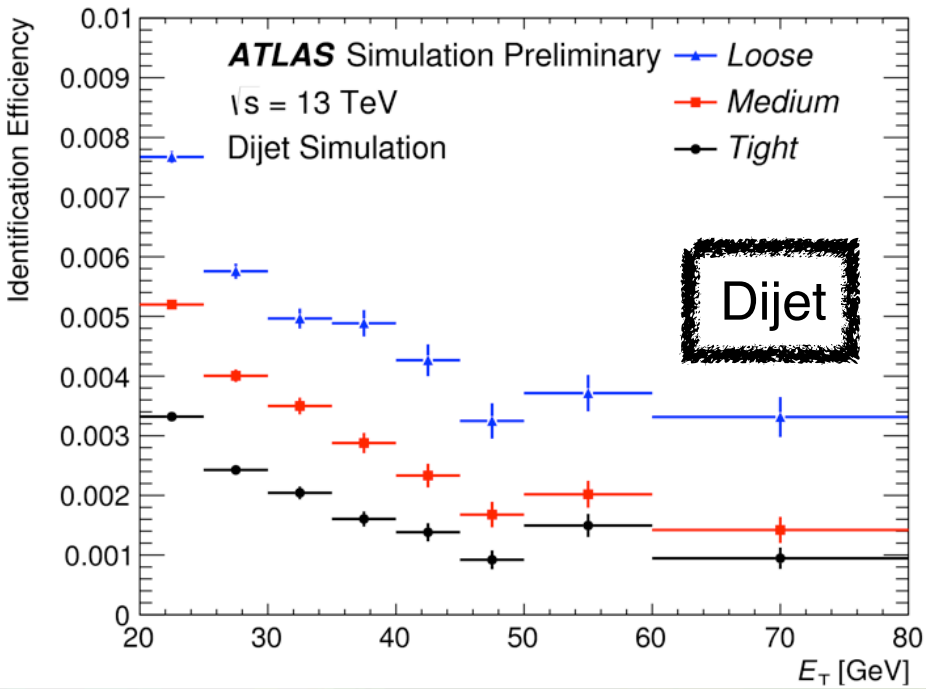
Ref 2

Ref 3

Z′ Searches in ATLAS

Electron Identification





- Numerous shower-shape variables, and inner detector quantities used.
- Well measured quantities are put into a likelihood and 3 working points defined: **Loose**, **Medium**, **Tight**.
- This is an improvement over Run-1 which used a cut-based approach.

Ref 1

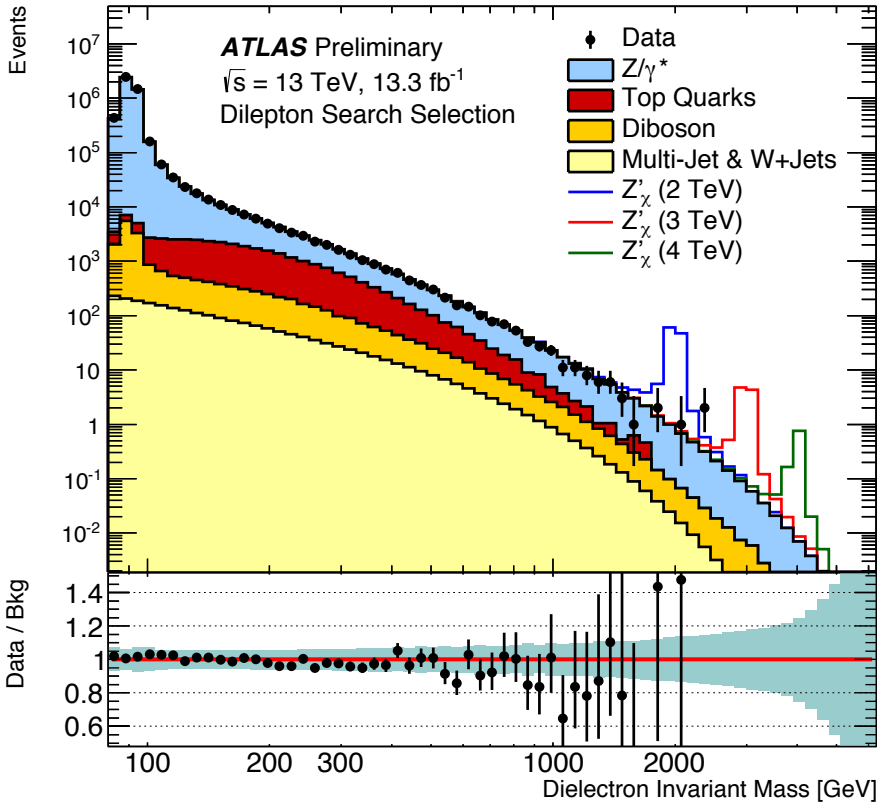
Z′ Searches in ATLAS

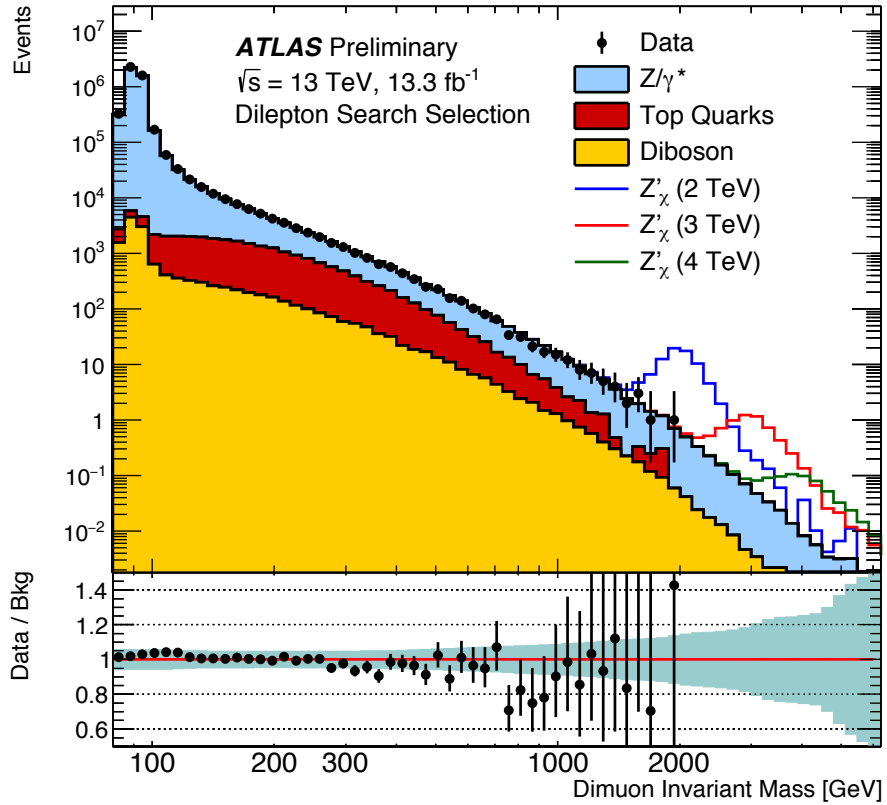
- Backgrounds to this search in order of decreasing contribution:
  - Neutral Current (NC) Drell-Yan (DY),
  - ttbar + single top processes (Top Quarks),
  - Dibosons (WW, WZ, ZZ),
  - QCD Multi-jet & W+jets (negligible in the dimuon channel).
- All backgrounds described with Monte Carlo (MC), except for the Multi-jet & W+jets background which uses a data-driven method.
- Signal templates are created by reweighting at Born level from NC DY.
- Higher-Order cross-sections are used where possible, such as NC DY, where ATLAS calculates NNLO QCD + NLO EW k-factors as a function of truth dilepton invariant mass (PDF: CT14NNLO).
  - NNLO QCD k-factor only, is applied to the signal.

Z′ Searches in ATLAS

Ref 1

Dielectron Channel | **Latest Results!** | Dimuon Channel

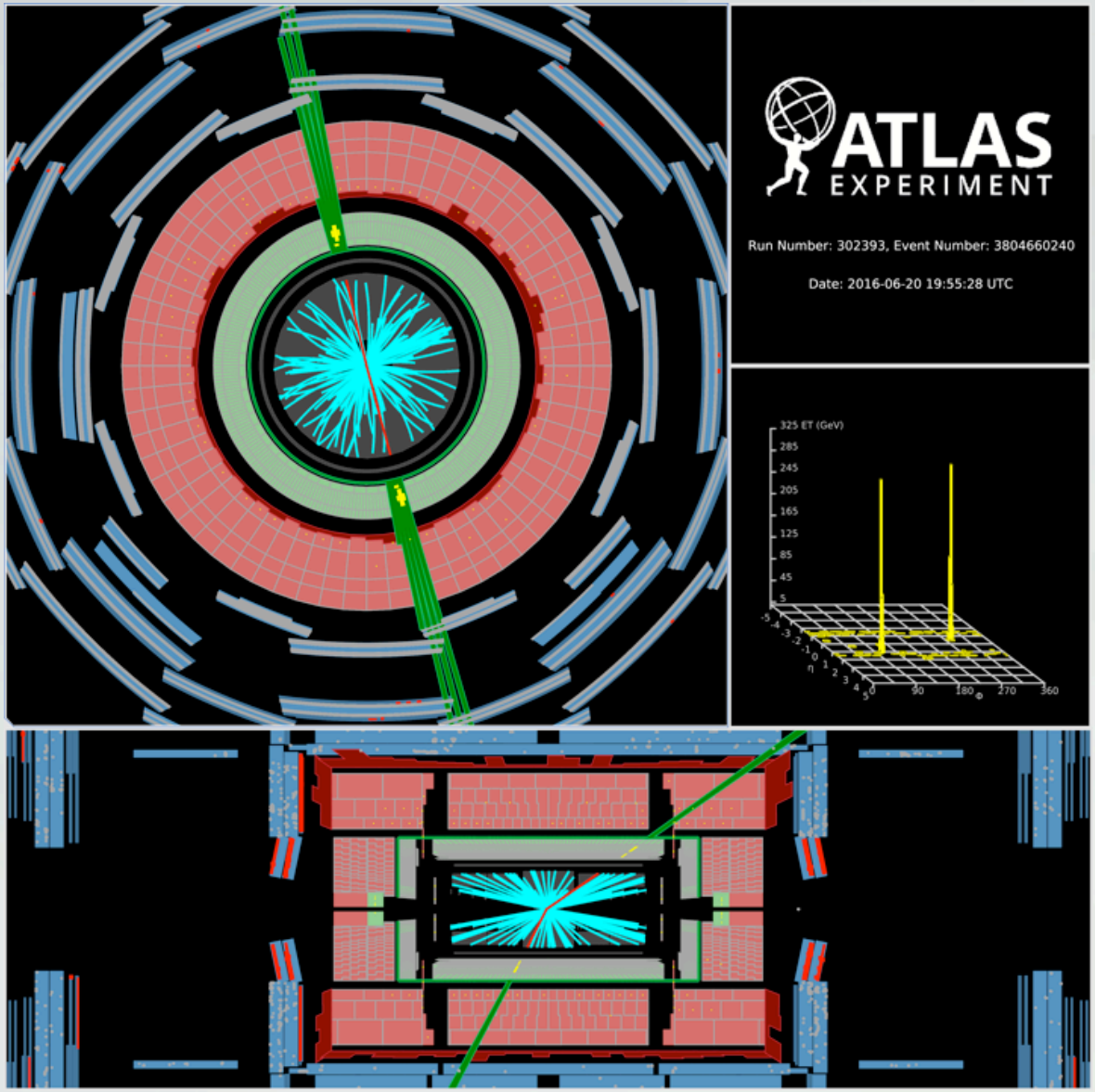




- Using both 2015 and 2016 data at √s = 13 TeV (total: 13.3 /fb).
- Relatively good data/MC agreement (within systematic uncertainties).
- Top Quarks contribution fraction has increased wrt √s = 14/8 TeV.

Ref 1

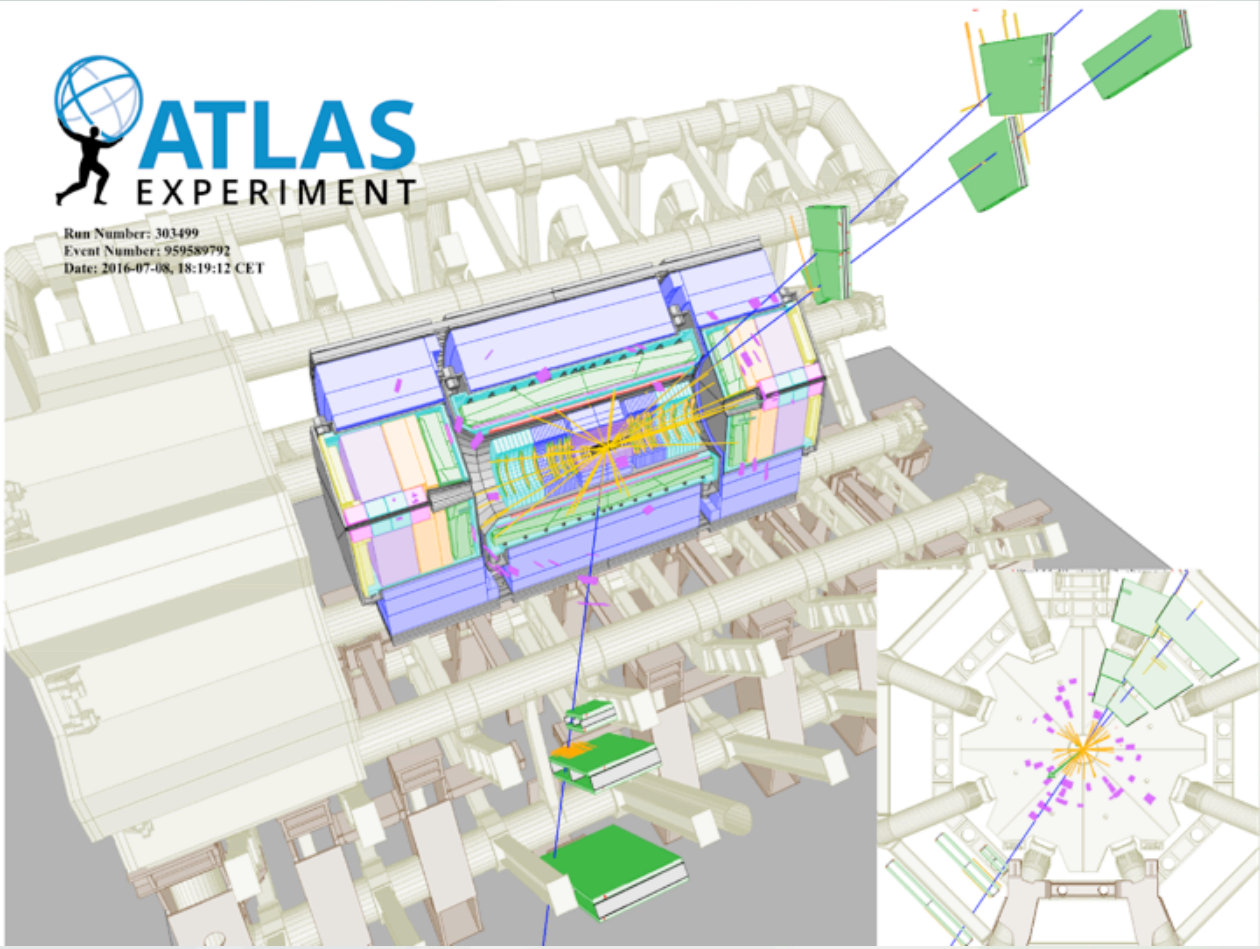
Z′ Searches in ATLAS: Event Displays



- Dielectron mass = 2.38 TeV.
- Very clean Z′ candidate event (NC DY background).
- Electron pT: 889 / 868 GeV.

Z′ Searches in ATLAS: Event Displays

Ref 1



- Dimuon mass = 1.98 TeV.
- Event not a clean Z′/DY candidate. Additional muon, and some missing energy indicates that it is likely a WZ event.
- Muon pT: 604 / 561 GeV.

Ref 1

Z′ Searches in ATLAS

Systematic Uncertainties

- Numbers in the table represent uncertainty at masses of 2 TeV (4 TeV).

Source	Dielectron		Dimuon	
	Signal	Background	Signal	Background
Luminosity	2.9% (2.9%)	2.9% (2.9%)	2.9% (2.9%)	2.9% (2.9%)
MC Statistical	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Beam Energy	2.0% (4.1%)	2.0% (4.1%)	1.9% (3.3%)	1.9% (3.3%)
DY PDF Choice	N/A	<1.0% (8.4%)	N/A	<1.0% (2.0%)
DY PDF Variation	N/A	8.7% (18.5%)	N/A	7.6% (13.2%)
DY PDF Scale	N/A	1.0% (2.0%)	N/A	0.9% (1.5%)
DY α_S	N/A	1.6% (2.7%)	N/A	1.4% (2.3%)
DY EW Corrections	N/A	2.4% (5.5%)	N/A	2.0% (4.0%)
DY Photon-induced Corrections	N/A	3.4% (7.6%)	N/A	3.0% (5.5%)
Top Quarks Theoretical	N/A	<1.0% (<1.0%)	N/A	<1.0% (<1.0%)
Dibosons Theoretical	N/A	<1.0% (<1.0%)	N/A	<1.0% (<1.0%)
Reconstruction Efficiency	<1.0% (<1.0%)	<1.0% (<1.0%)	10.4% (16.7%)	10.4% (16.7%)
Isolation Efficiency	4.0% (4.0%)	4.0% (4.0%)	1.8% (2.0%)	1.8% (2.0%)
Trigger Efficiency	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Identification Efficiency	3.0% (2.9%)	3.0% (2.9%)	N/A	N/A
Lepton Energy Scale	<1.0% (<1.0%)	4.2% (7.3%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Lepton Energy Resolution	<1.0% (<1.0%)	<1.0% (<1.0%)	2.3% (2.1%)	3.6% (9.9%)
Multi-jet & W+jets	N/A	<1.0% (<1.0%)	N/A	N/A
Total	6.2% (7.1%)	12.4% (24.8%)	11.4% (17.5%)	14.6% (25.2%)

Ref 1

Z′ Searches in ATLAS

Systematic Uncertainties

• Num… TeV).

Source					…ckground
Luminosity					% (2.9%)
MC Statist					% (<1.0%)
Beam Ene					% (3.3%)
DY PDF C					% (2.0%)
DY PDF V					% (13.2%)
DY PDF S					% (1.5%)
DY α_S					% (2.3%)
DY EW C					% (4.0%)
DY Photo					% (5.5%)
Top Quark					% (<1.0%)
Dibosons T					% (<1.0%)
Reconstruc					% (16.7%)
Isolation E					% (2.0%)
Trigger Eff					% (<1.0%)
Identificati					N/A
Lepton En					% (<1.0%)
Lepton En					% (9.9%)
Multi-jet &					N/A
Total					% (25.2%)

Dominant Systematic Sources

Both Channels:

• DY PDF Variation: Uncertainty due to eigen-vector (EV) variations of the chosen PDF.

- CT14NNLO has 28 EV.
- These have been re-diagonalised into 7 new EV.
- Quadratic sum of 7 EV matches the 28 EV well.

Dielectron Channel:

• Lepton Energy Scale: Uncertainty in the calibration of the electron energy.

Dimuon Channel:

• Reconstruction Efficiency: Uncertainty in the efficiency to reconstruct muons.

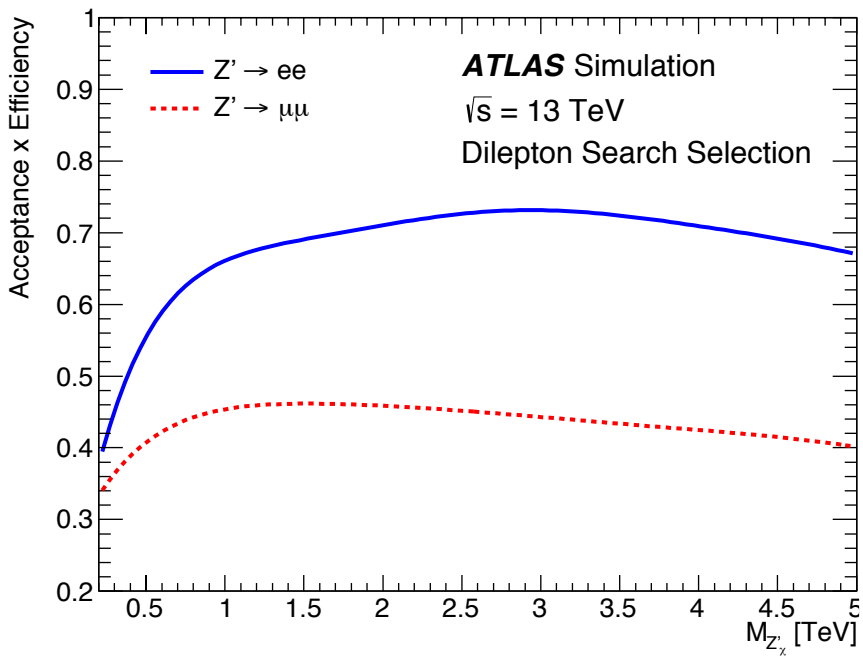
Z′ Searches in ATLAS: Search Phase

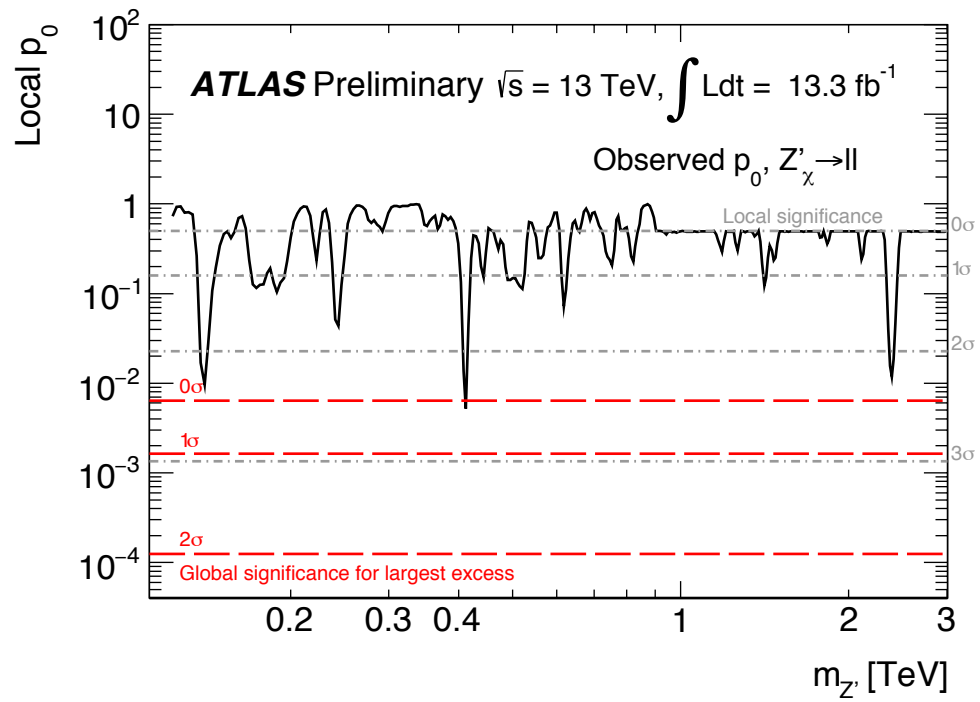
Ref 1

- Use a log-likelihood ratio (LLR) test to quantify significance of any excess. In the absence of significant excess, set exclusion limits.

$$q_0 = -2\ln\left[\frac{\mathcal{L}(\text{data}|0,\hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}\right] \quad \text{for } \hat{\mu} \geqslant 0,$$

$$p_0 = P(q_0 \geqslant q_0^{obs}|\text{background-only}) = \int_{q_0^{obs}}^{\infty} f(q_0|0,\hat{\theta}_0^{obs})dq_0$$

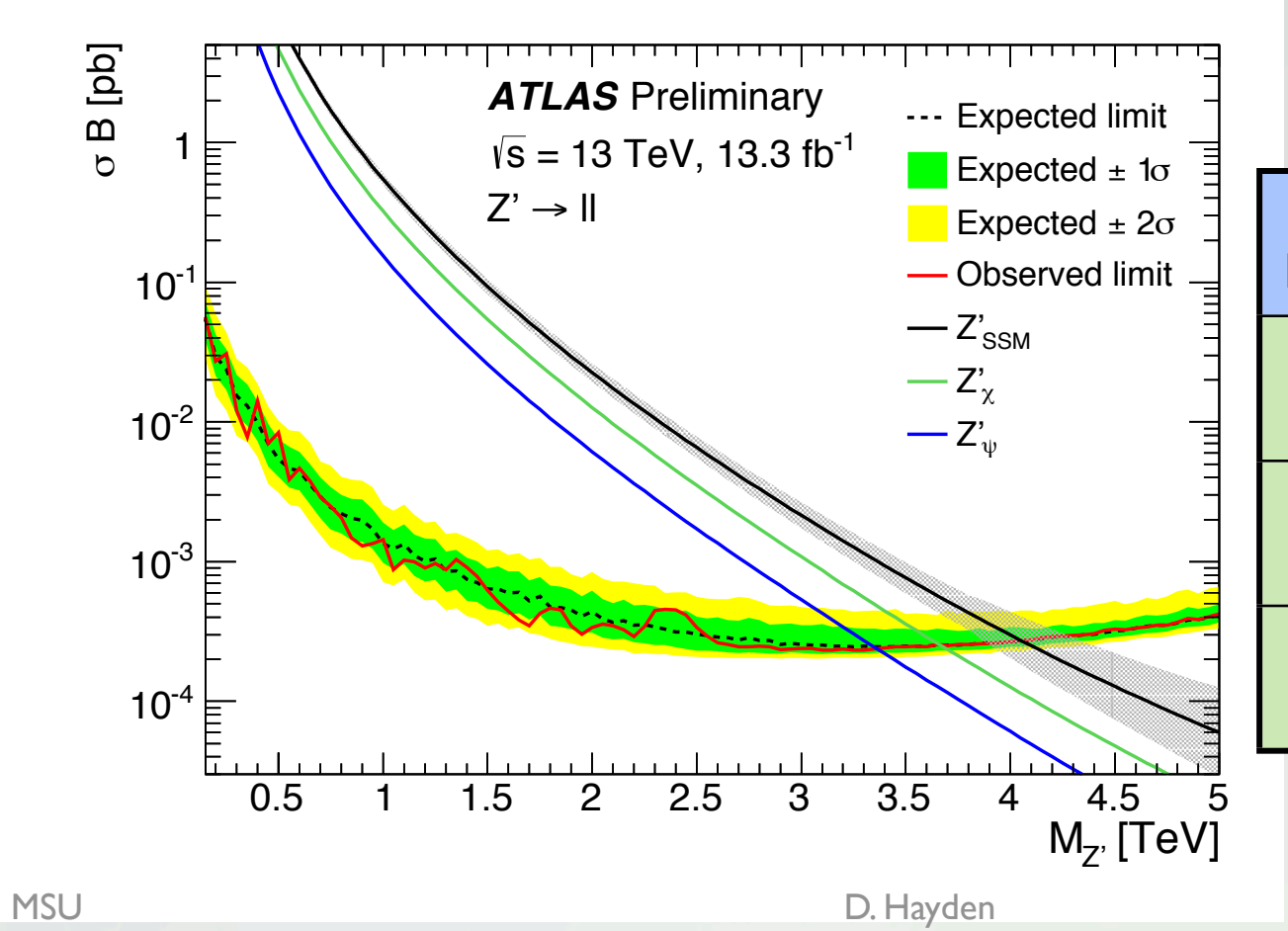




Z′ Searches in ATLAS: Exclusion Limits

Ref 1

- Set exclusion limits on the parameter of interest (σB) at 95% credibility level and convert into limit on the Z′ pole mass.
- Use a Bayesian approach, and Markov Chain Monte Carlo (MCMC) to marginalise the likelihood, integrating out the nuisance parameters.



Z' Model	Lower Obs Mass Limit
SSM	ee, μμ, ℓℓ [TeV]: 3.85, 3.49, 4.05.
χ	ee, μμ, ℓℓ [TeV]: 3.48, 3.18, 3.66.
ψ	ee, μμ, ℓℓ [TeV]: 3.18, 2.90, 3.36.

W′ Searches in ATLAS

Ref 4

eν Channel	μν Channel
Event-Level Criteria	
Single Electron Trigger	Single Muon Trigger
Lepton-Level Criteria.	
pT > 65 GeV	pT > 55 GeV
Within defined η region, and satisfy track quality cuts	
e-identification = Likelihood “Tight”	High pT Muon Working Point
“Loose” isolation criteria (pT dependent, with decreasing threshold)	
ℓν Selection	
Veto Addition electron/muon: LH Medium, pT > 20 GeV / Medium WP, pT > 20 GeV.	
Missing Transverse Energy > 65 GeV	Missing Transverse Energy > 55 GeV
m_T > 130 GeV	m_T > 110 GeV

- Also a very clean search channel, with relatively small and well understood backgrounds. Higher-Order corrections calculated as for Z′.
- In order of decreasing contribution: Charged Current (CC) Drell-Yan (DY), ttbar + single top processes (Top Quarks), dibosons (WW, WZ, ZZ), QCD Multi-jet.

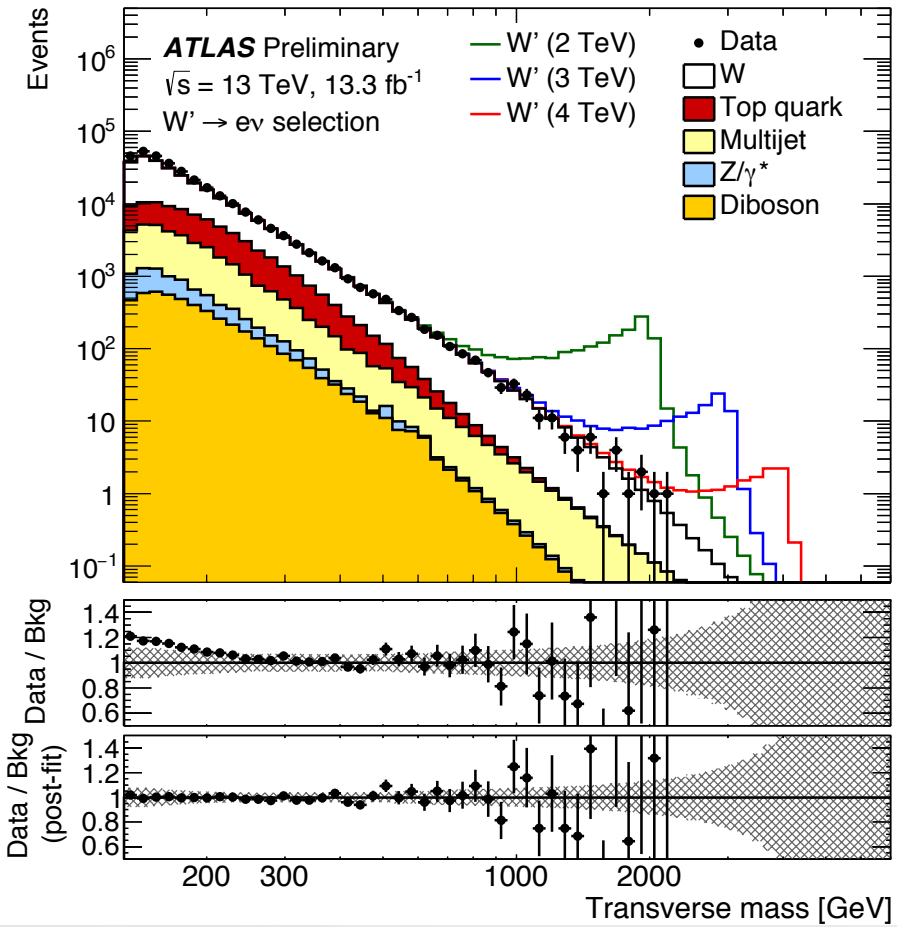
W′ Searches in ATLAS

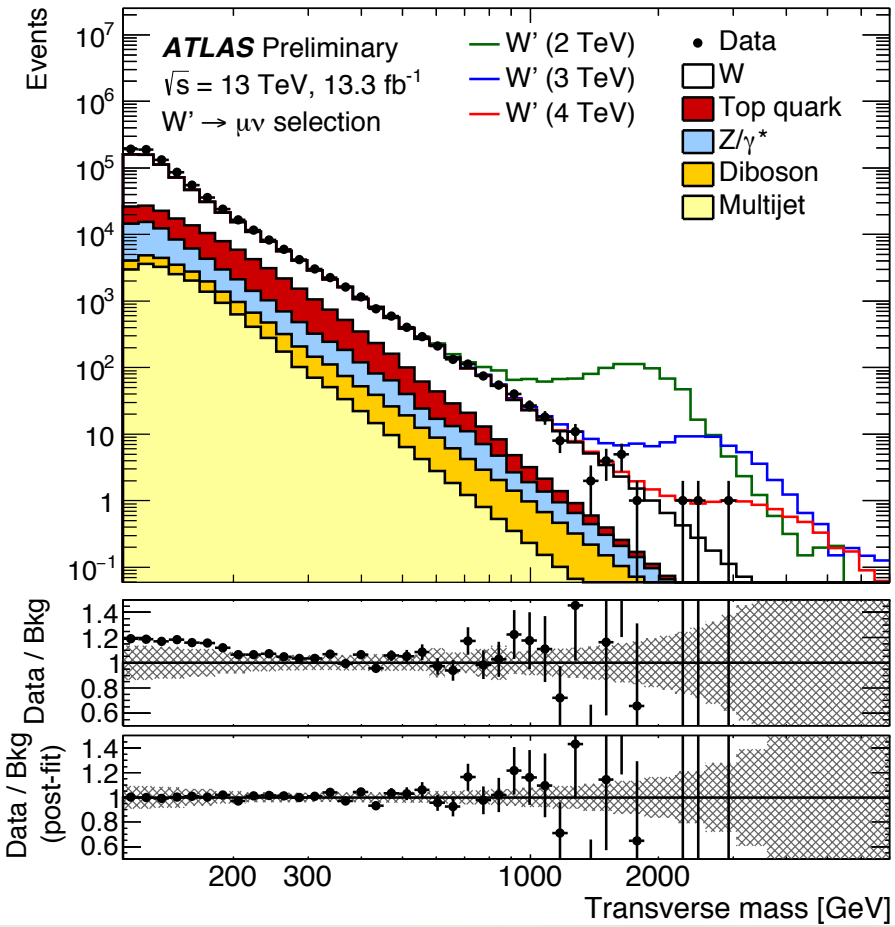
Ref 4

eν Channel

Latest Results!

μν Channel

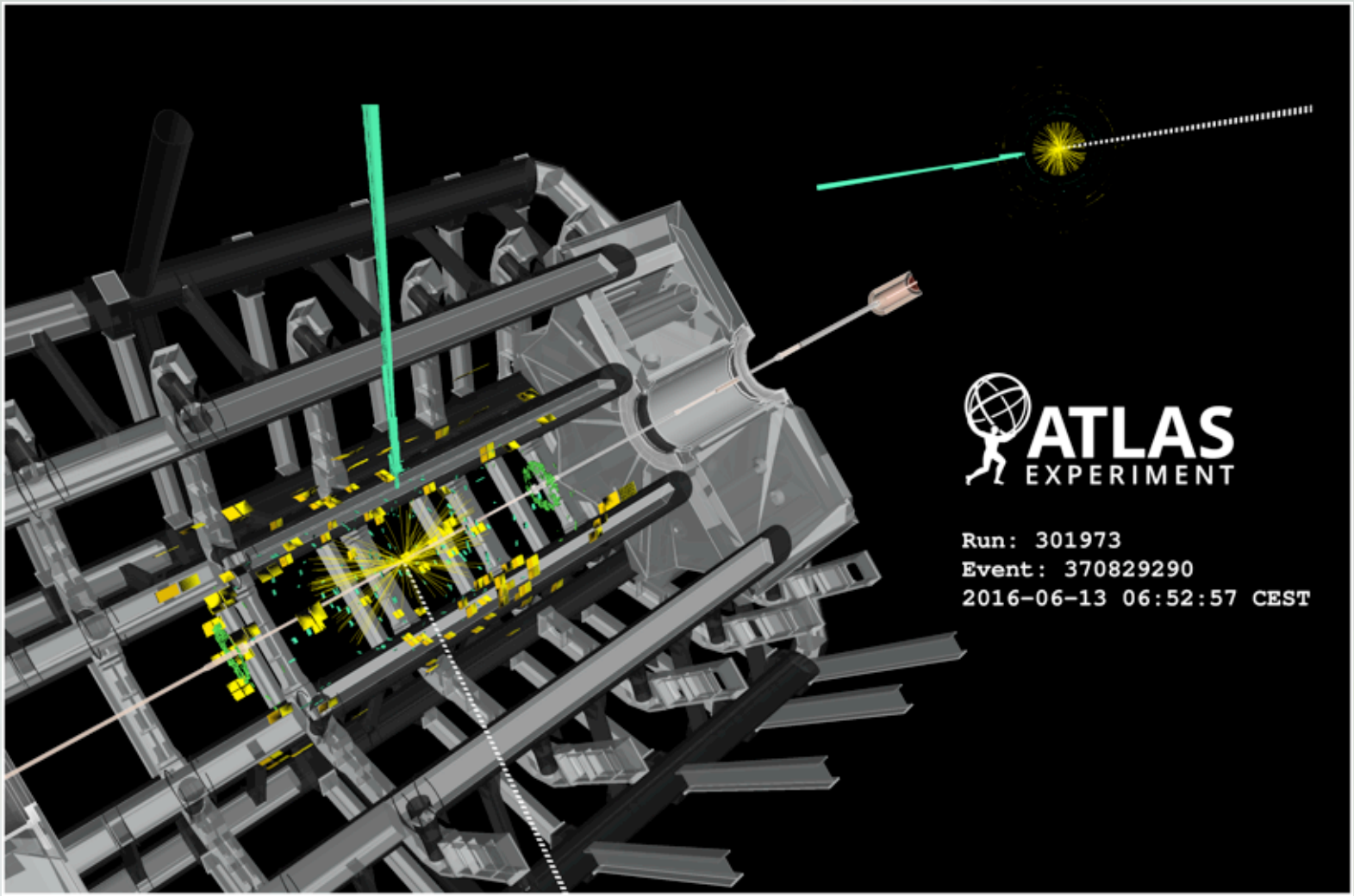




- Relatively good data/MC agreement, especially post-fit.
- Low mT disagreement (pre-fit) due to jet energy scale and low MET.

W′ Searches in ATLAS: Event Displays

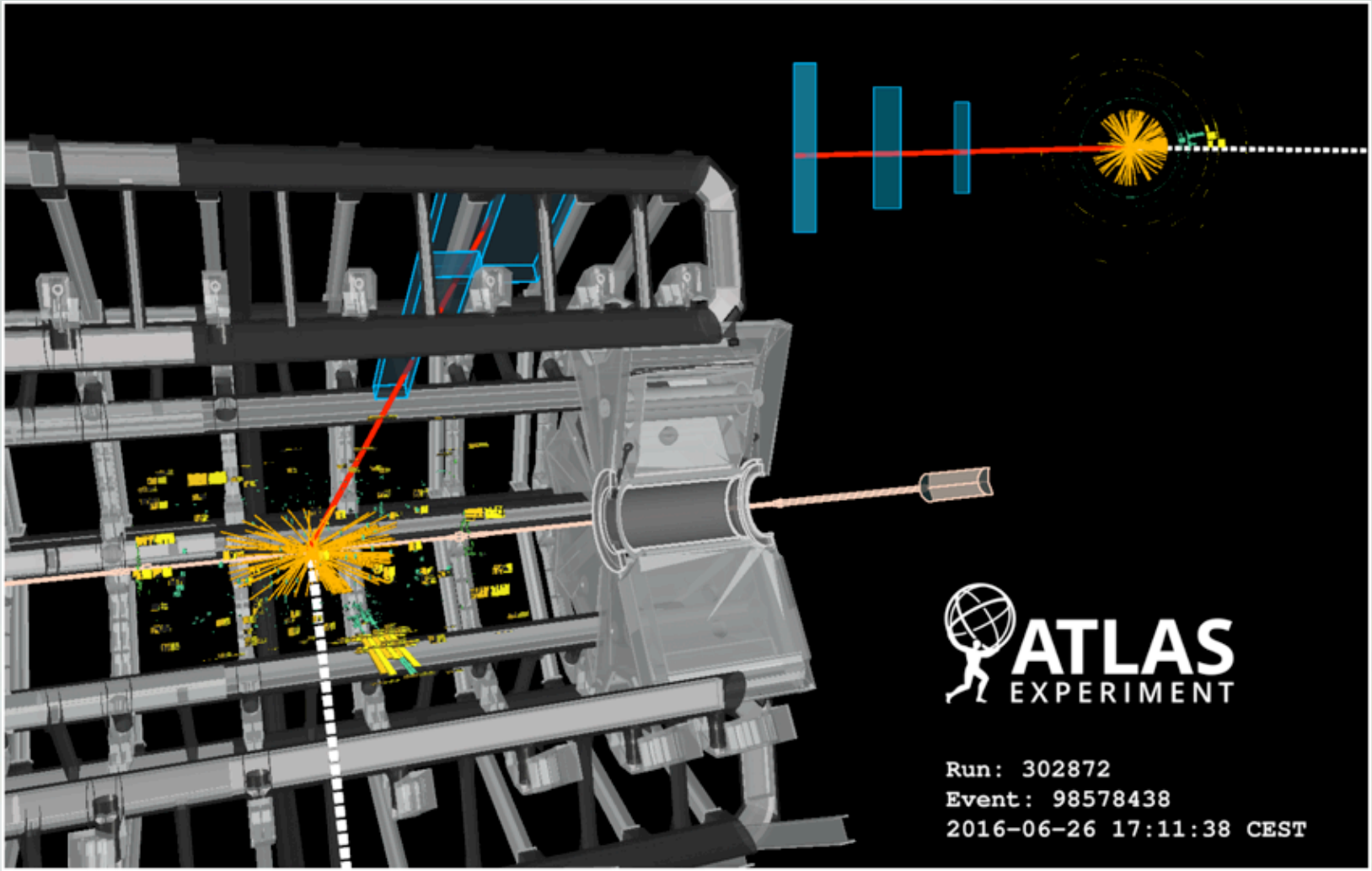
Ref 4



- ev event, mT = 2.19 TeV.
- Electron pT / Event MET: 1.09 TeV / 1.09 TeV.

Ref 4

W′ Searches in ATLAS: Event Displays



- μν event, mT = 2.91 TeV.
- Muon pT / Event MET: 2.01 TeV / 1.05 TeV.

Ref 4

W′ Searches in ATLAS

Systematic Uncertainties

- Numbers in the table represent uncertainty at m_T of 2 TeV (4 TeV).

Source	Electron channel		Muon channel	
	Background	Signal	Background	Signal
Trigger	negl. (negl.)	negl. (negl.)	2% (2%)	2% (2%)
Lepton reconstruction and identification	negl. (negl.)	negl. (negl.)	5% (8%)	4% (7%)
Lepton momentum scale and resolution	4% (6%)	24% (9%)	3% (12%)	2% (3%)
E_T^{miss} resolution and scale	< 0.5% (< 0.5%)	< 0.5% (< 0.5%)	1% (2%)	1% (2%)
Jet energy resolution	< 0.5% (< 0.5%)	3% (< 0.5%)	< 0.5% (1%)	< 0.5% (< 0.5%)
Multijet background	15% (63%)	N/A (N/A)	1% (2%)	N/A (N/A)
Diboson & top background	3% (11%)	N/A (N/A)	17% (70%)	N/A (N/A)
PDF choice for DY	1% (24%)	N/A (N/A)	< 0.5% (< 0.5%)	N/A (N/A)
PDF variation for DY	9% (21%)	N/A (N/A)	7% (11%)	N/A (N/A)
Electroweak corrections	5% (10%)	N/A (N/A)	4% (6%)	N/A (N/A)
Luminosity	3% (1%)	3% (3%)	3% (3%)	3% (3%)
Total	19% (72%)	24% (10%)	20% (73%)	6% (9%)

Ref 4

W′ Searches in ATLAS

Systematic Uncertainties

- Numbers in the table represent uncertainty at m_T of 2 TeV (4 TeV).

Source				nel Signal
Trigger				2% (2%)
Lepton recons and identificat				4% (7%)
Lepton mome scale and reso				2% (3%)
E_T^{miss} resolutio				1% (2%)
Jet energy res				0.5% (< 0.5%)
Multijet backg				N/A (N/A)
Diboson & top				N/A (N/A)
PDF choice fo				N/A (N/A)
PDF variation				N/A (N/A)
Electroweak c				N/A (N/A)
Luminosity				3% (3%)
Total	19% (72%)	24% (10%)	20% (73%)	6% (9%)

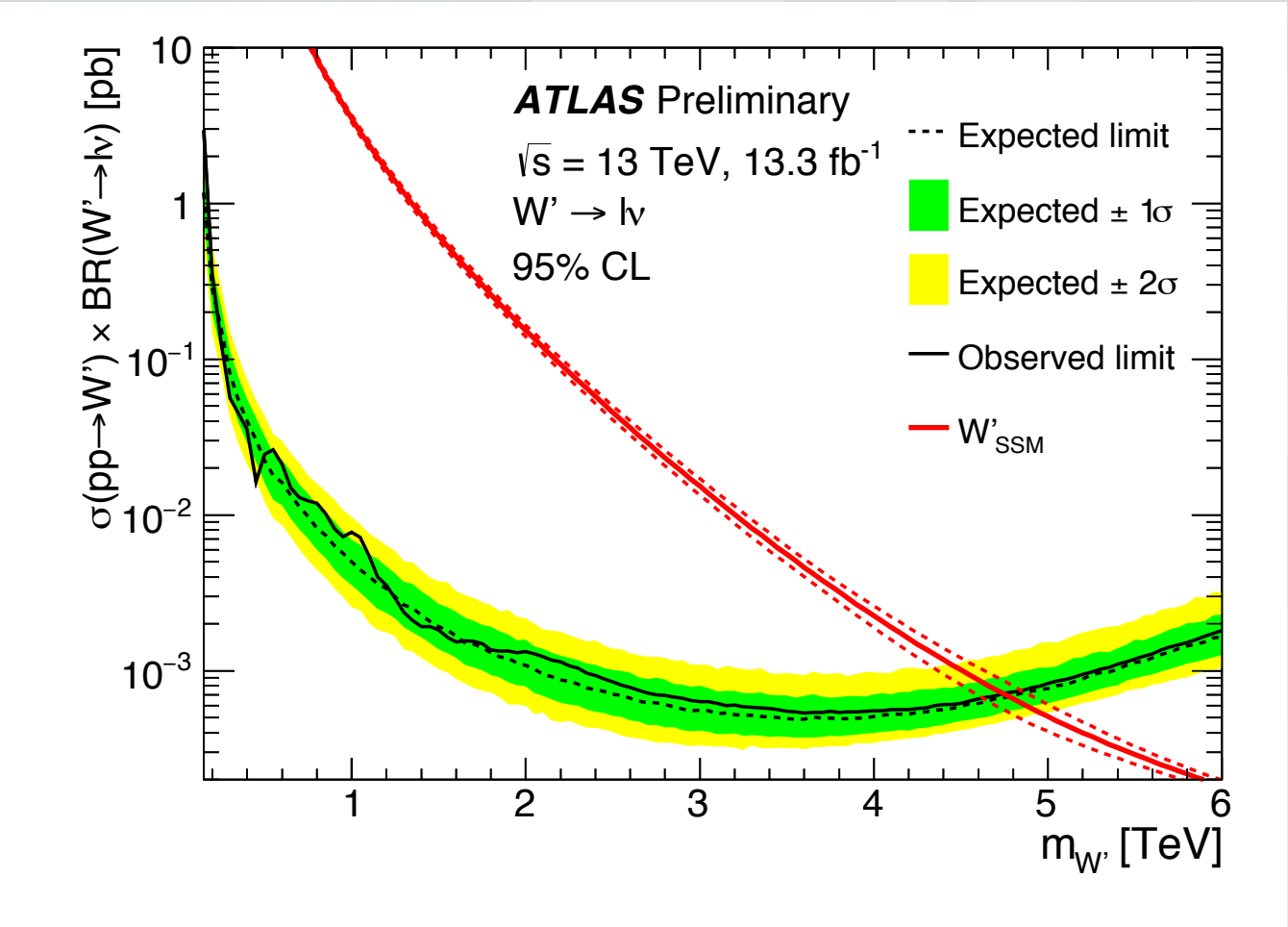
Dominant Systematic Sources

- Similarly to Z′: PDF variation and lepton energy scale are important systematic uncertainties.
- Additionally, for the W′ search:
  - PDF choice is more important for W^+/W^-, with NNPDF30NNLO dominating at high m_T.
  - Background extrapolations for the Top Quarks, Diboson, and Multi-jet backgrounds, cause large systematic uncertainties at high m_T in this search.

Ref 4

W′ Searches in ATLAS: Search and Limit Setting

- Same tools and methodology used as the Z′ search.
- No significant excess observed, so proceed to set exclusion limits.

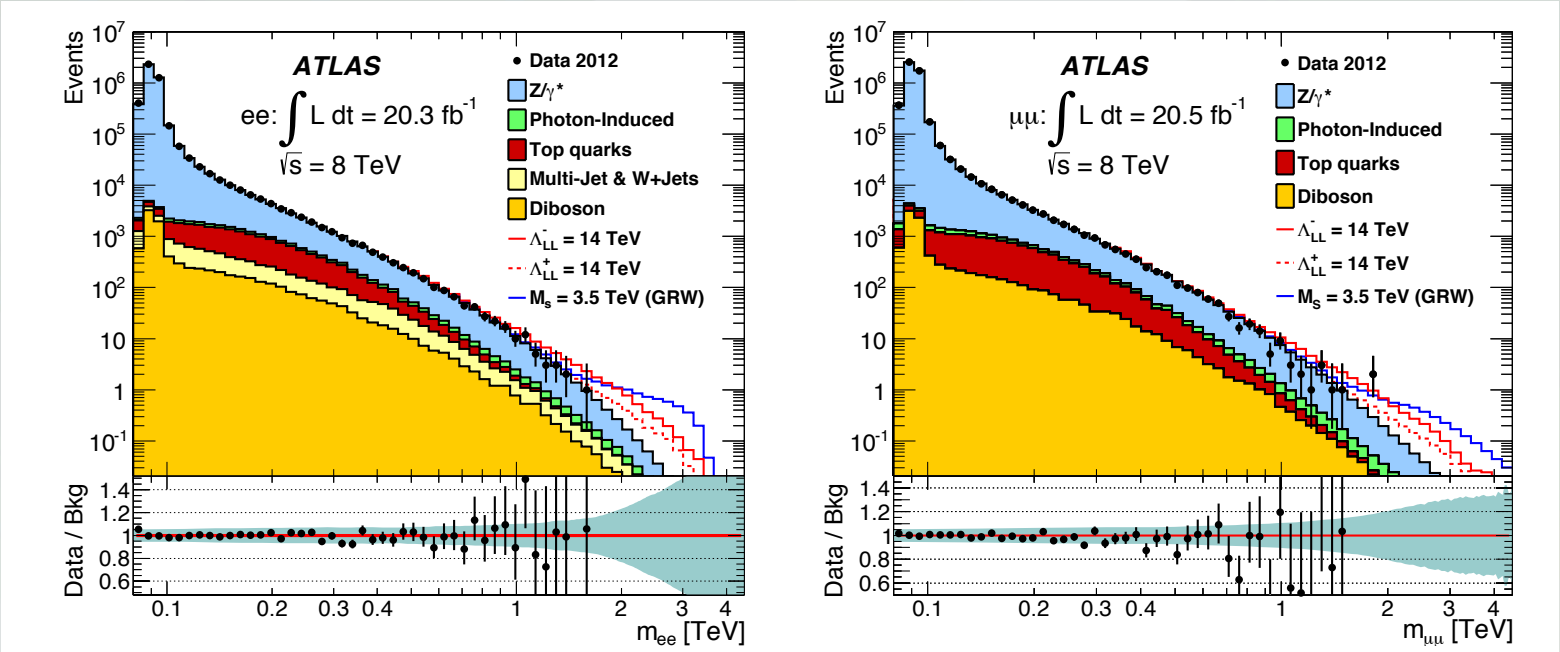


SSM W′ Limits

Decay	$m_{W'}$ lower limit [TeV] Expected	Observed
$W' \to e\nu$	4.59	4.64
$W' \to \mu\nu$	4.33	4.19
$W' \to \ell\nu$	4.77	4.74

Other Interesting Searches: Contact Interactions

Ref 5



- An interesting aspect of this search was that it utilised forward-backward asymmetry as an additional discrimination variable.

$$\cos\theta^* = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m(\ell^+\ell^-)\sqrt{m(\ell^+\ell^-)^2 + p_T(\ell^+\ell^-)^2}},$$

N_F: $\cos\theta^* > 0$,

N_B: $\cos\theta^* < 0$,

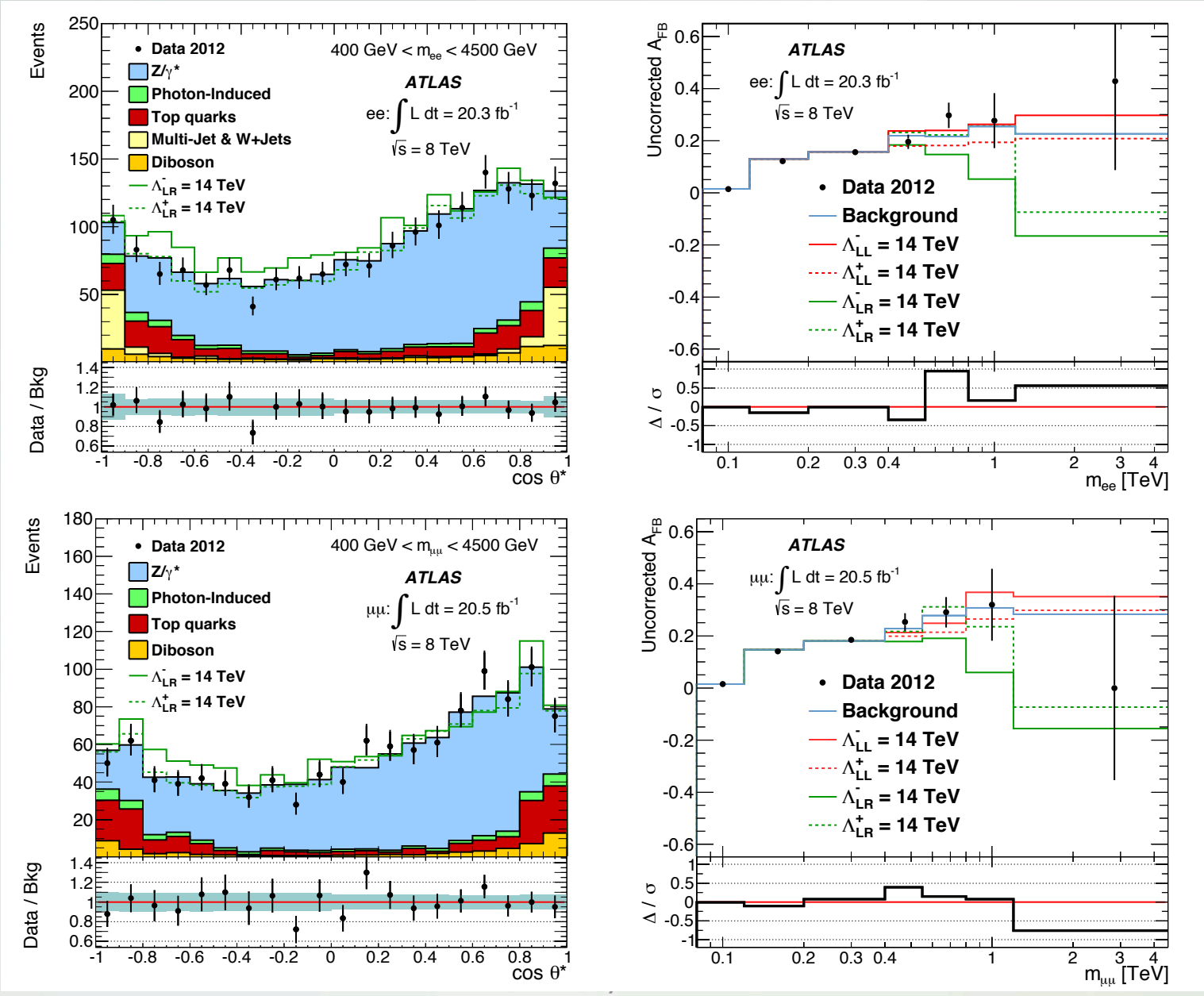
Ref 6

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B},$$

- $\cos\theta^*$ is defined in the Collins-Soper Frame: the angle between incoming partons and outgoing dilepton system.

Other Interesting Searches: Contact Interactions

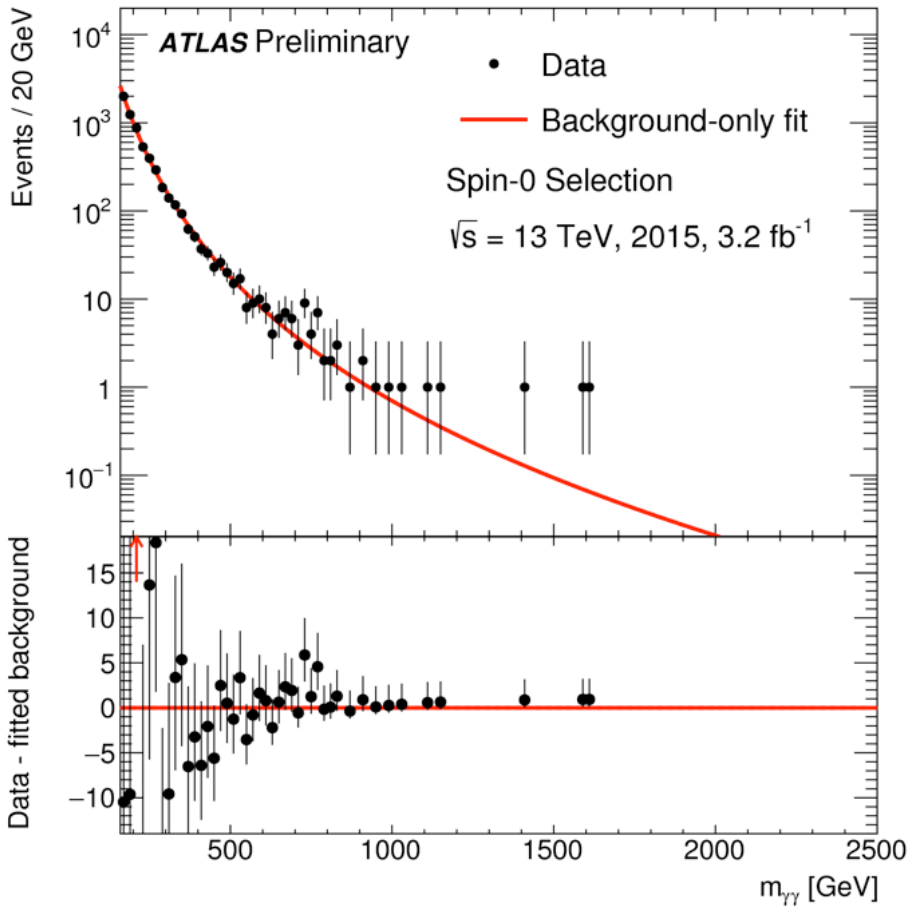
Ref 5

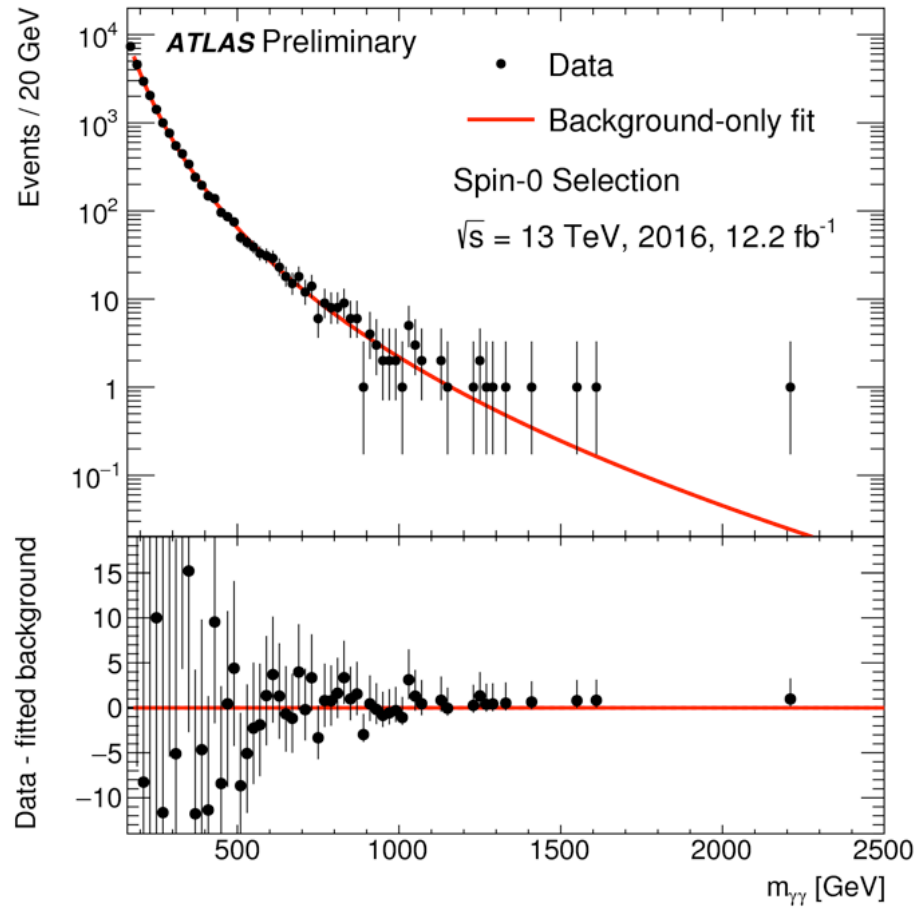


Ref 7

Other Interesting Searches: Diphoton Searches

Latest Results!



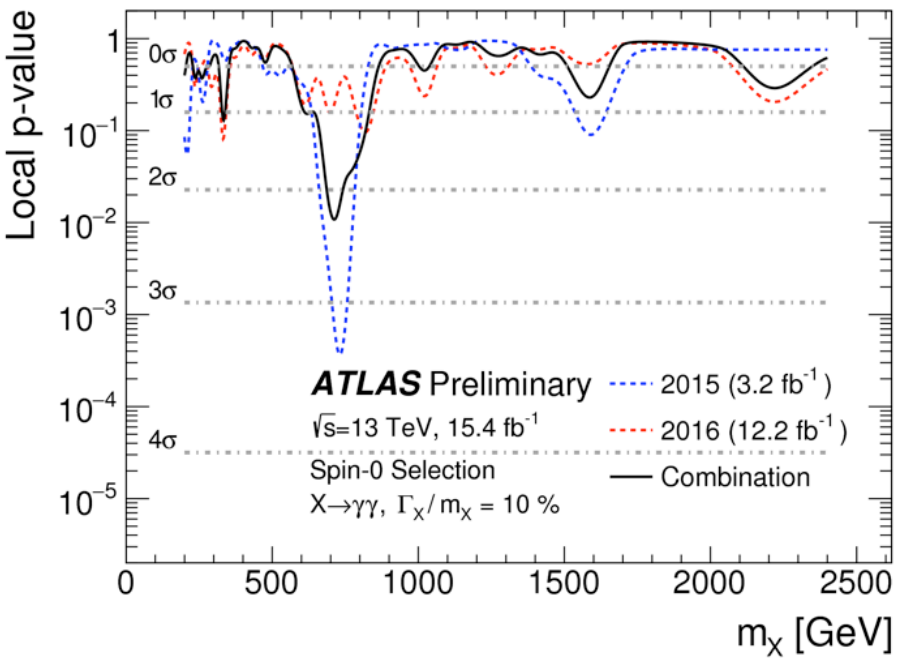


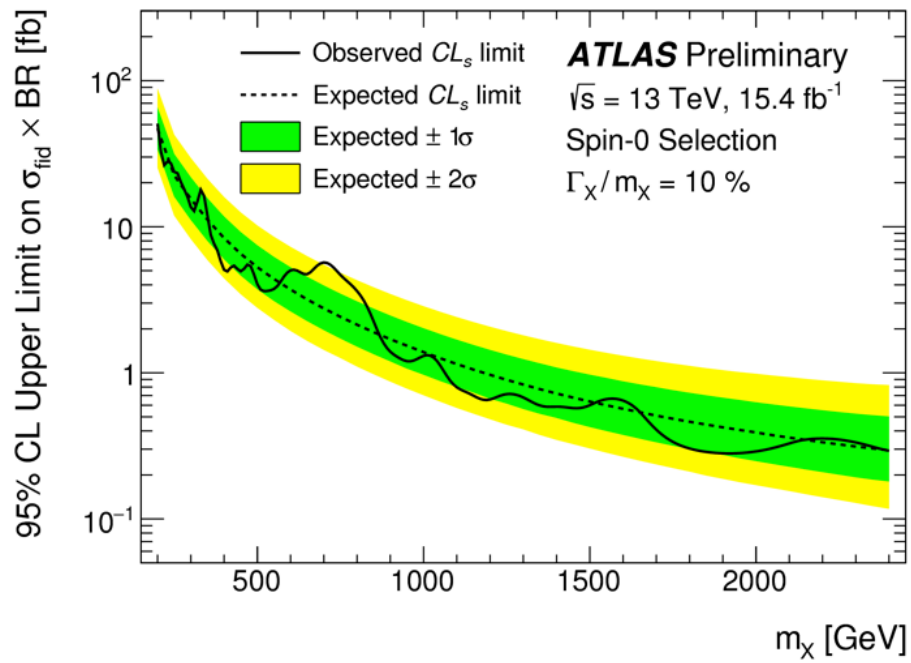
- Similar to dilepton search, looking for either Higgs or Gravitons.
- Significance of 2015 observation is slowly diminishing sadly.

Ref 7

Other Interesting Searches: Diphoton Searches

Latest Results!



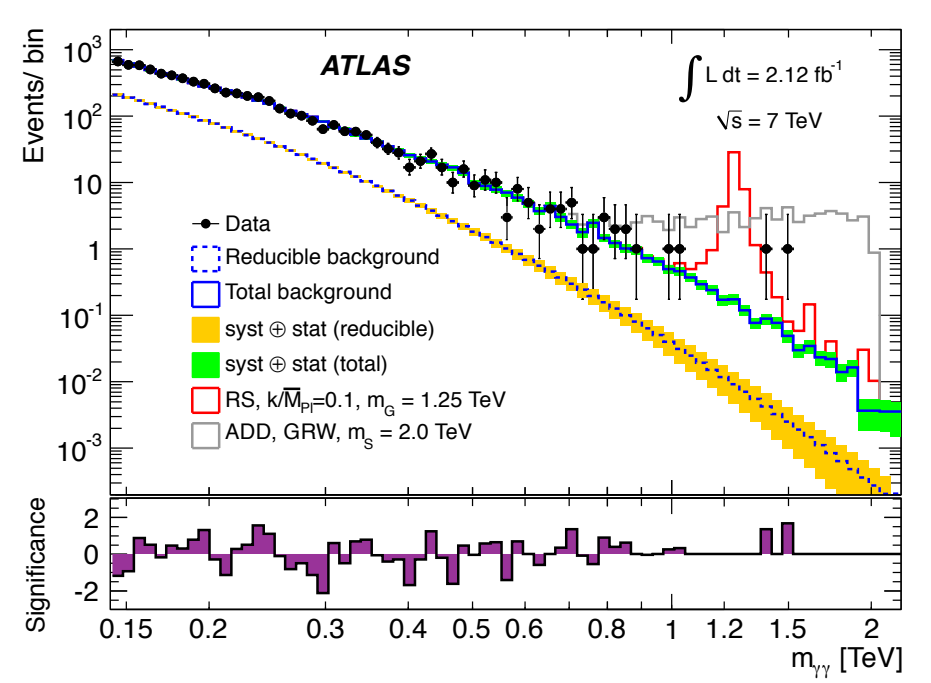


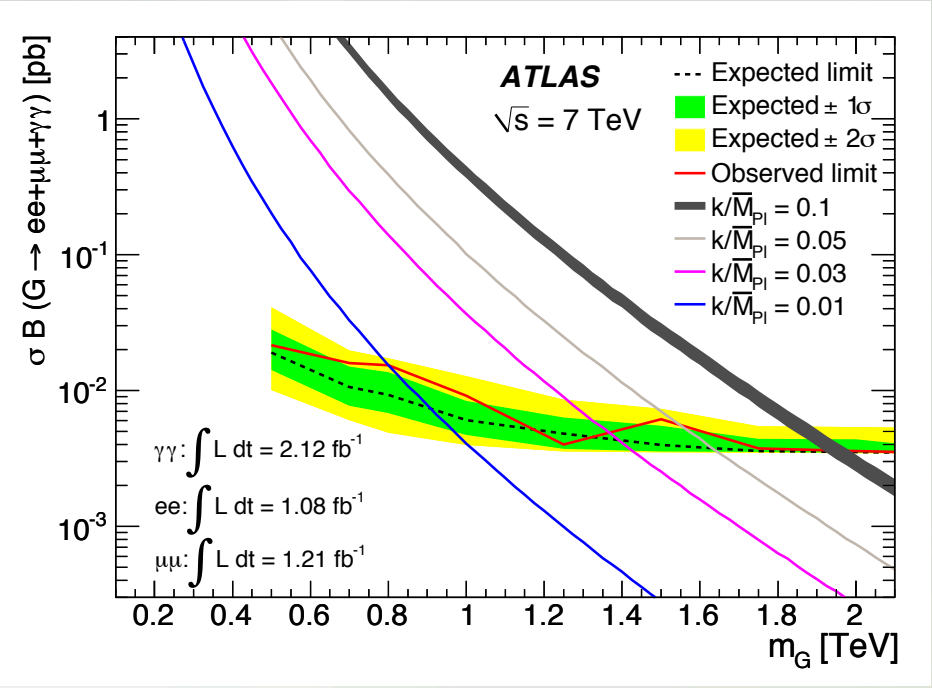
- Similar to dilepton search, looking for either Higgs or Gravitons.
- Shown here for Spin-2 selection, only differs slightly from Spin-2.
- Significance of 2015 observation is slowly diminishing sadly.

Ref 8

Other Interesting Searches: Diphoton Searches

- Previously, dilepton and diphoton channels have been combined for the RS Graviton search! (Also ADD Graviton not described today).





- Cross-checks were also performed in the dilepton channel for the 2016 diphoton search. Dielectron and Dimuon channel are both interesting regions to confirm/deny a Graviton-like signal.
- Important to be ready for a discovery, and able to combined searches.

What's Next?

- The "fast and lightweight" search era of the LHC is coming to an end.
  - Dijet searches have "burnt off" the O(10-100) increase in signal cross-sections by going from $\sqrt{s}$ = 8 TeV to $\sqrt{s}$ = 13 TeV.
  - Clean search channels such as dilepton and diphoton will not get a sizeable increase in sensitivity for at least a year.
  - Predicted 2015+2016 dataset = ~ 35 /fb. Double by end of 2017?

- If new physics does not jump out at us this year, it doesn't mean that it isn't there, we may need to look harder.

- Searches should start to look into exclusive signal regions.
  - Instead of inclusive Z' search, look for Z' + 1 jet, Z' + 2 jets, etc.
  - Start to use missing energy cuts, and jet vetoes, eke out signal.

- One could also turn to a wider combination of search channels.
  - Give the maximum feedback to theorists to help point us forward.
  - Be ready for if/when a signal does appear, to characterise it fast.

Ref 9

What's Next?

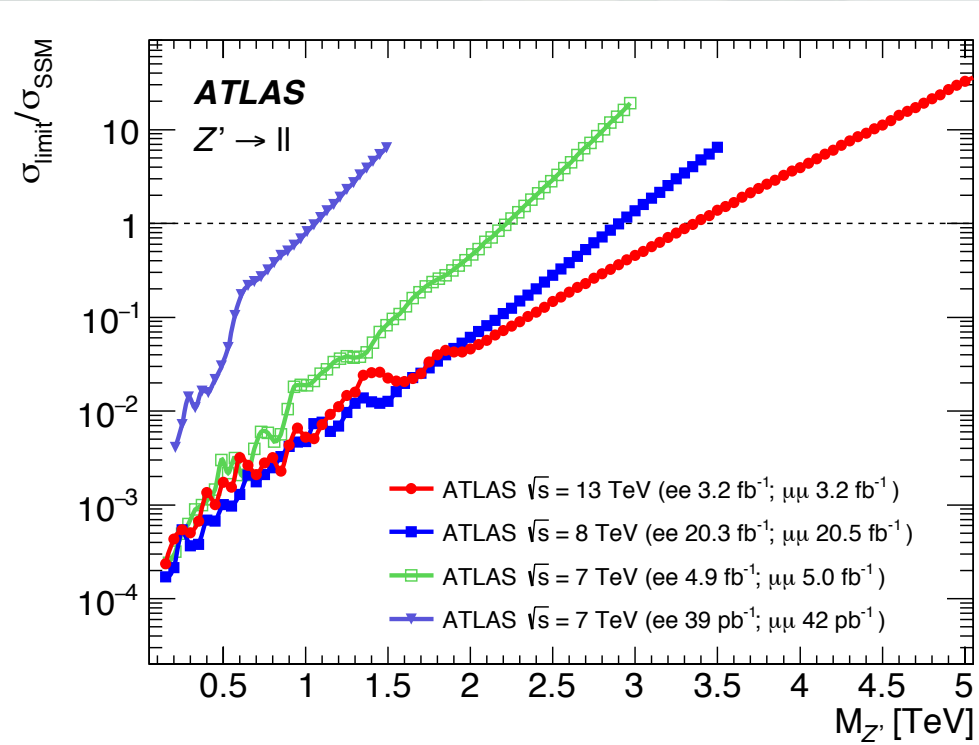
- All of these discussions, and more, are currently happening in ATLAS.
- For example, on the grand combination topic:
  - General heavy vector resonance interpretation in terms in singlet and triplet representations.
  - Parameterise signal in N-dimensional coupling space, and produce results on the multitude of various relationships.

Channel	$V^0 \in (\mathbf{1},\mathbf{3})_\mathbf{1}$	$V^+ \in (\mathbf{1},\mathbf{3})_\mathbf{1}$	$V^0 \in (\mathbf{1},\mathbf{1})_\mathbf{0}$ $\in \mathbf{3}$ of $SU(2)_R$	$V^+ \in (\mathbf{1},\mathbf{1})_\mathbf{1}$ $\in \mathbf{3}$ of $SU(2)_R$
ll	□	×	□□	×
$l\nu$	×	□	×	×
$l\nu_R$	×	×	×	□□
jj	□	□	□□	□□
tb	×	□	×	□□
tt	□	×	□□	×
WW	□	×	□□	×
ZZ	×	×	×	×
Zh	□	×	□□	×
WZ	×	□	×	□□
Wh	×	□	×	□□
$W\gamma$	×	□	×	□□
hh	×	×	×	×

Ref 10

Conclusions

- Some great recent results from the ATLAS collaboration, but unfortunately no sign of new physics so far. Still a chance this year!
- Thoughts are starting to turn to more novel approaches, to eke out any signal that nature could be hiding in the 2015+2016 dataset.
- An exciting time to be doing research in particle physics, hoping that nature still has some surprises for us yet, at the LHC.



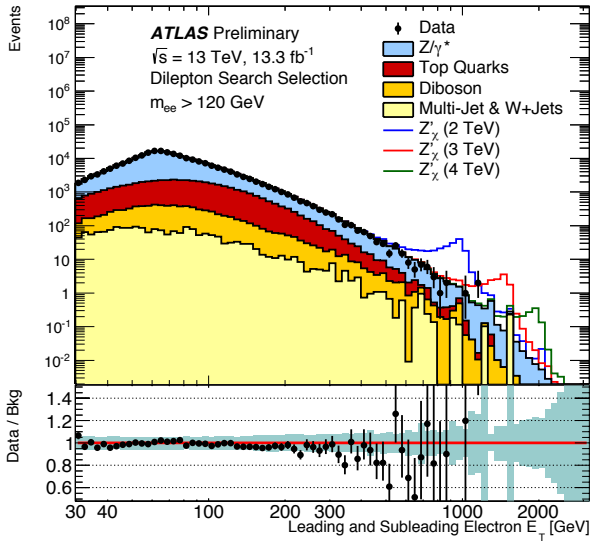
References

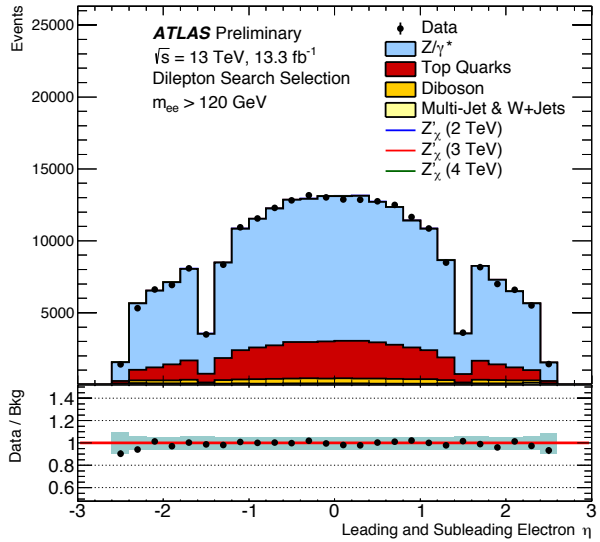
- **Ref 1:** https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-045/ . ICHEP CONF Note 2016.
- **Ref 2:** https://arxiv.org/abs/1603.05598. Accepted by EPJ C (2016).
- **Ref 3:** https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-024/ . Morind CONF Note 2015.
- **Ref 4:** https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-063/ . ICHEP CONF Note 2016.
- **Ref 5:** http://arxiv.org/abs/1407.2410. Accepted by EPJ C (2014).
- **Ref 6:** J.C. Collins, D.E. Soper, Phys. Rev. D 16, 2219 (1977).
- **Ref 7:** https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-059/ . ICHEP CONF Note 2016.
- **Ref 8:** http://arxiv.org/abs/1112.2194. Accepted by PLB (2011).
- **Ref 9:** https://arxiv.org/abs/1402.4431. Accepted by JHEP (2014).
- **Ref 10:** http://arxiv.org/abs/1607.03669. Accepted by PLB (2015).

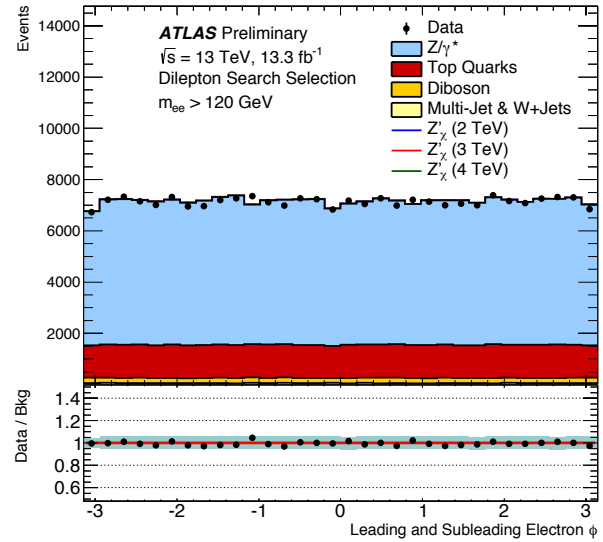
Backup Slides

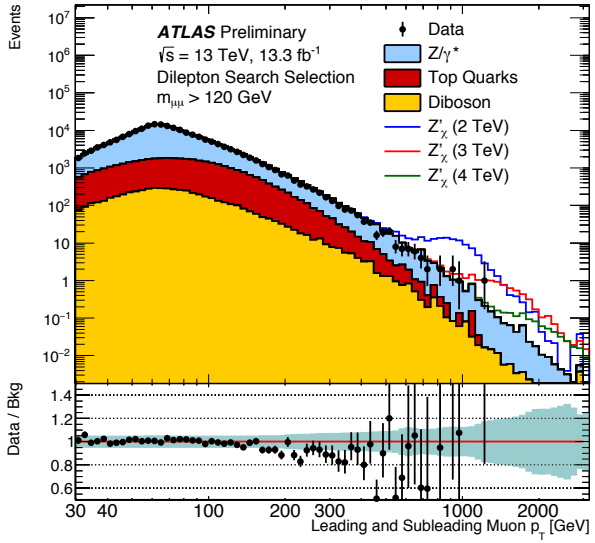
Ref 1

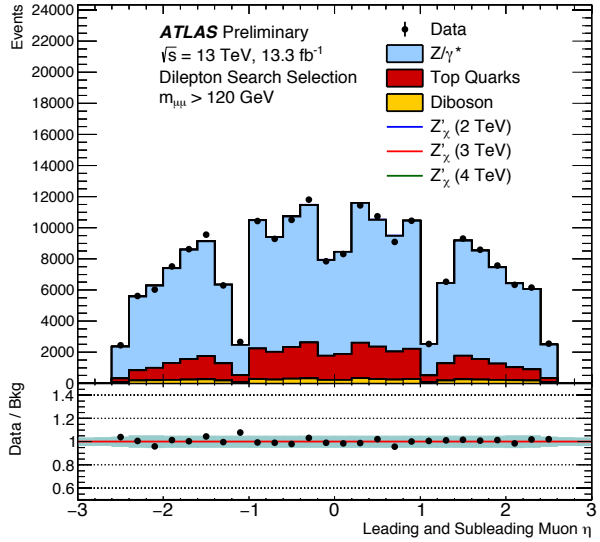
Dilepton Search: Lepton Kinematics

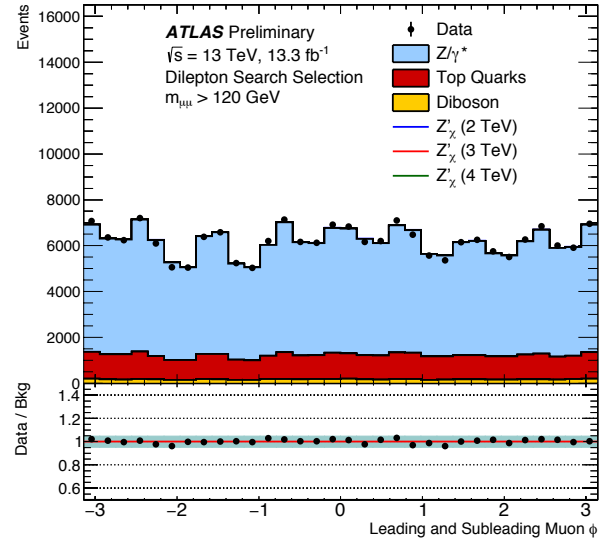






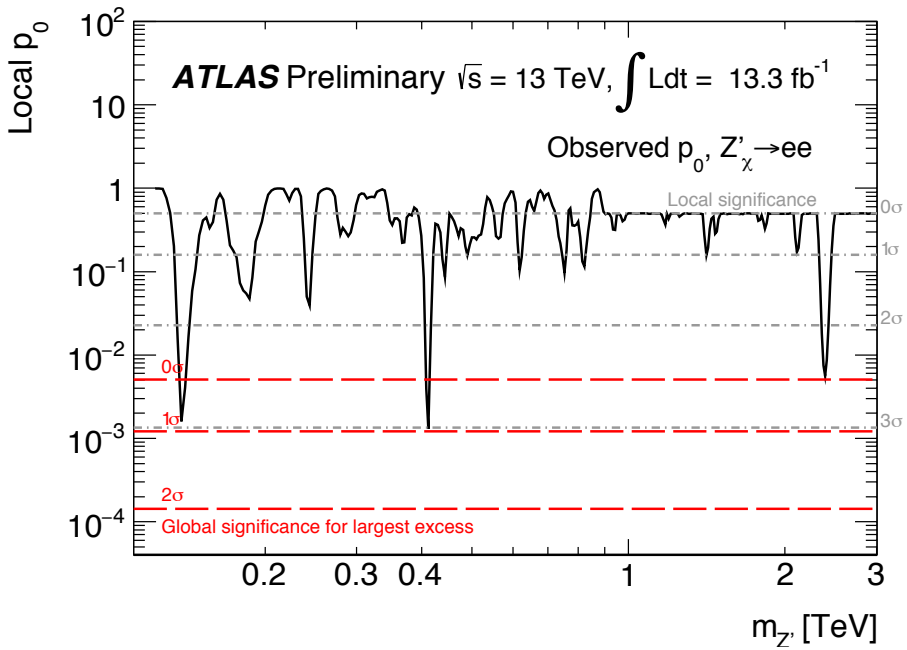


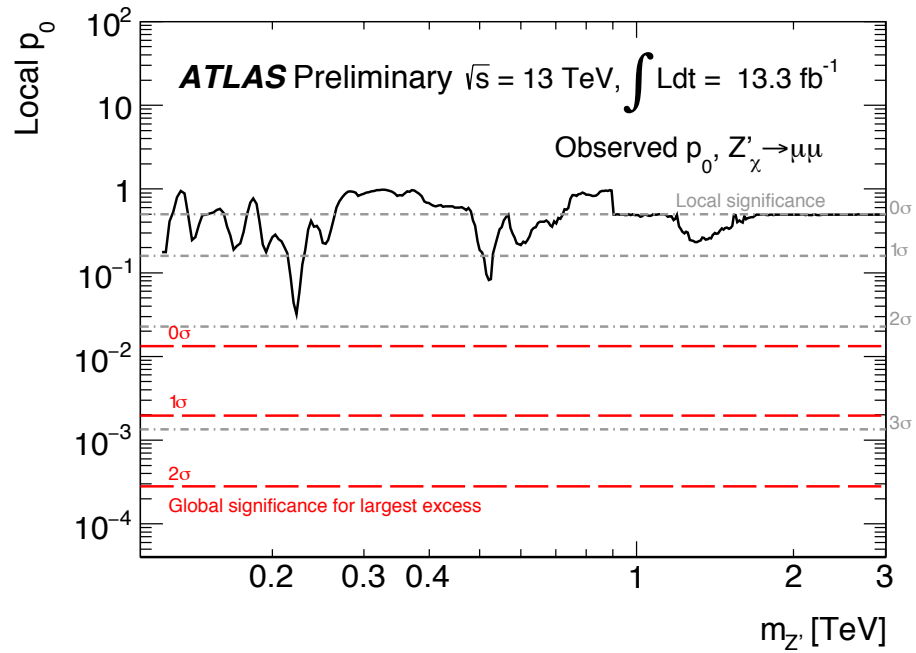


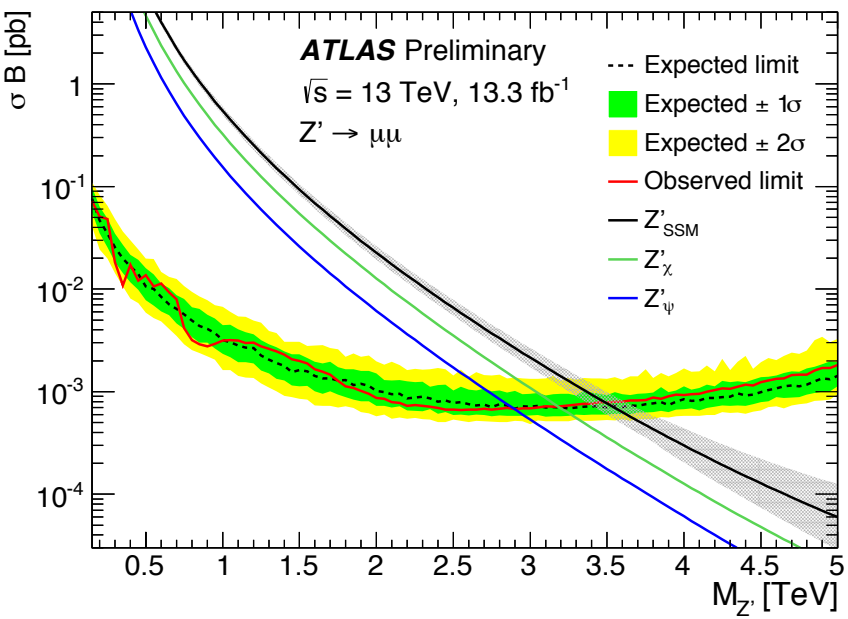


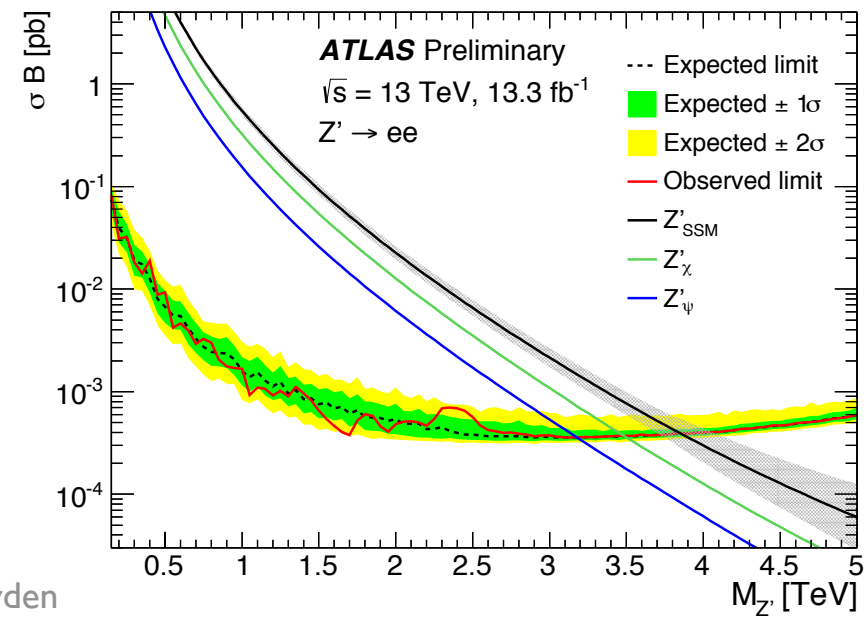
Dilepton Search: Search and Limits

Ref 1









Ref 1

Dilepton Search: Limit Table

Model	Width [%]	θ_{E_6} [Rad]	Lower limits on $m_{Z'}$ [TeV]					
			ee		$\mu\mu$		$\ell\ell$	
			Obs	Exp	Obs	Exp	Obs	Exp
Z'_{SSM}	3.0	-	3.85	3.86	3.49	3.53	4.05	4.06
Z'_{χ}	1.2	0.50	3.48	3.49	3.18	3.19	3.66	3.67
Z'_{S}	1.2	0.63 π	3.43	3.44	3.14	3.14	3.62	3.61
Z'_{I}	1.1	0.71 π	3.37	3.37	3.08	3.08	3.55	3.55
Z'_{η}	0.6	0.21 π	3.25	3.25	2.96	2.94	3.43	3.42
Z'_{N}	0.6	-0.08 π	3.23	3.23	2.95	2.94	3.41	3.41
Z'_{ψ}	0.5	0 π	3.18	3.18	2.90	2.88	3.36	3.35

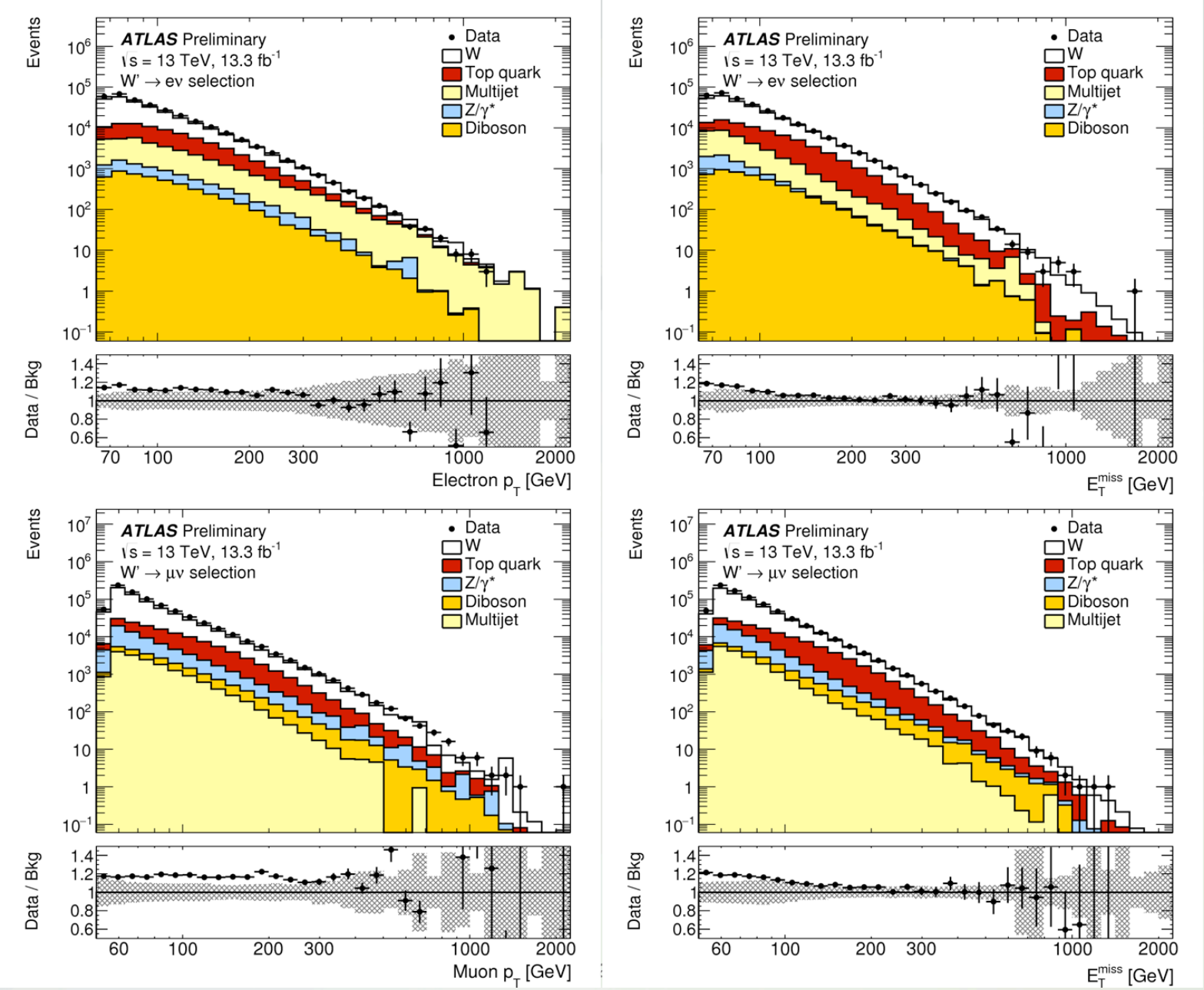
Electron Identification: Likelihood Variables

Ref 3

Type	Description	Name
Hadronic leakage	Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| < 0.8$ or $\|\eta\| > 1.37$)	R_{had1}
	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \|\eta\| < 1.37$)	R_{had}
Back layer of EM calorimeter	Ratio of the energy in the back layer to the total energy in the EM accordion calorimeter. This variable is only used below 100 GeV because it is known to be inefficient at high energies.	f_3
Middle layer of EM calorimeter	Lateral shower width, $\sqrt{(\Sigma E_i \eta_i^2)/(\Sigma E_i) - ((\Sigma E_i \eta_i)/(\Sigma E_i))^2}$, where E_i is the energy and η_i is the pseudorapidity of cell i and the sum is calculated within a window of 3×5 cells	$w_{\eta 2}$
	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centered at the electron cluster position	R_ϕ
	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centered at the electron cluster position	R_η
Strip layer of EM calorimeter	Shower width, $\sqrt{(\Sigma E_i (i - i_{\max})^2)/(\Sigma E_i)}$, where i runs over all strips in a window of $\Delta\eta \times \Delta\phi \approx 0.0625 \times 0.2$, corresponding typically to 20 strips in η, and $i_{\max}$ is the index of the highest-energy strip	w_{stot}
	Ratio of the energy difference between the largest and second largest energy deposits in the cluster over the sum of these energies	E_{ratio}
	Ratio of the energy in the strip layer to the total energy in the EM accordion calorimeter	f_1
Track conditions	Number of hits in the innermost pixel layer; discriminates against photon conversions	n_{Blayer}
	Number of hits in the pixel detector	n_{Pixel}
	Number of total hits in the pixel and SCT detectors	n_{Si}
	Transverse impact parameter with respect to the beam-line	d_0
	Significance of transverse impact parameter defined as the ratio of d_0 and its uncertainty	d_0/σ_{d_0}
	Momentum lost by the track between the perigee and the last measurement point divided by the original momentum	$\Delta p/p$
TRT	Likelihood probability based on transition radiation in the TRT	eProbabilityHT
Track-cluster matching	$\Delta\eta$ between the cluster position in the strip layer and the extrapolated track	$\Delta\eta_1$
	$\Delta\phi$ between the cluster position in the middle layer and the track extrapolated from the perigee	$\Delta\phi_2$
	Defined as $\Delta\phi_2$, but the track momentum is rescaled to the cluster energy before extrapolating the track from the perigee to the middle layer of the calorimeter	$\Delta\phi_{\mathrm{res}}$
	Ratio of the cluster energy to the track momentum	E/p

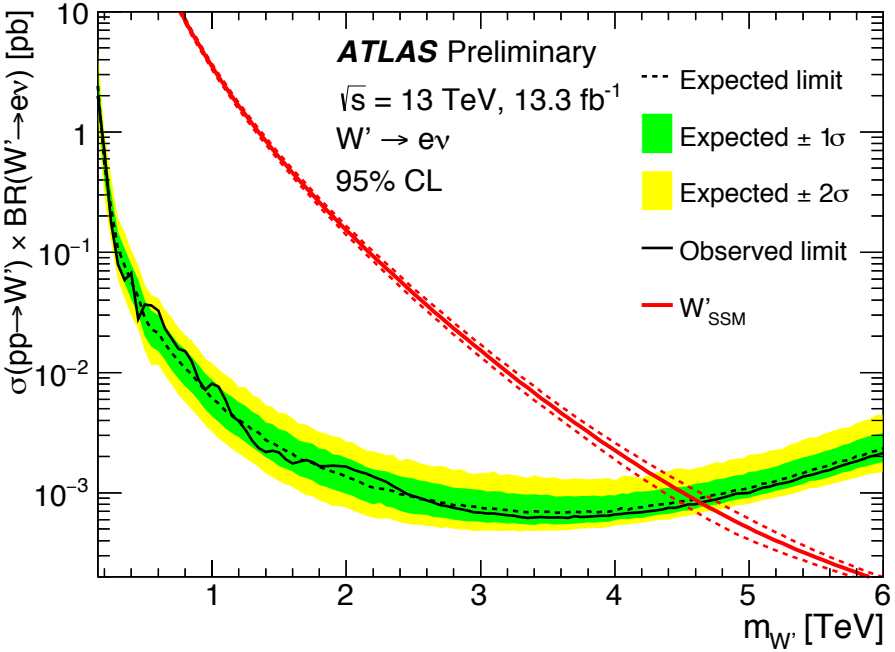
Lepton+MET Search: Lepton Kinematics

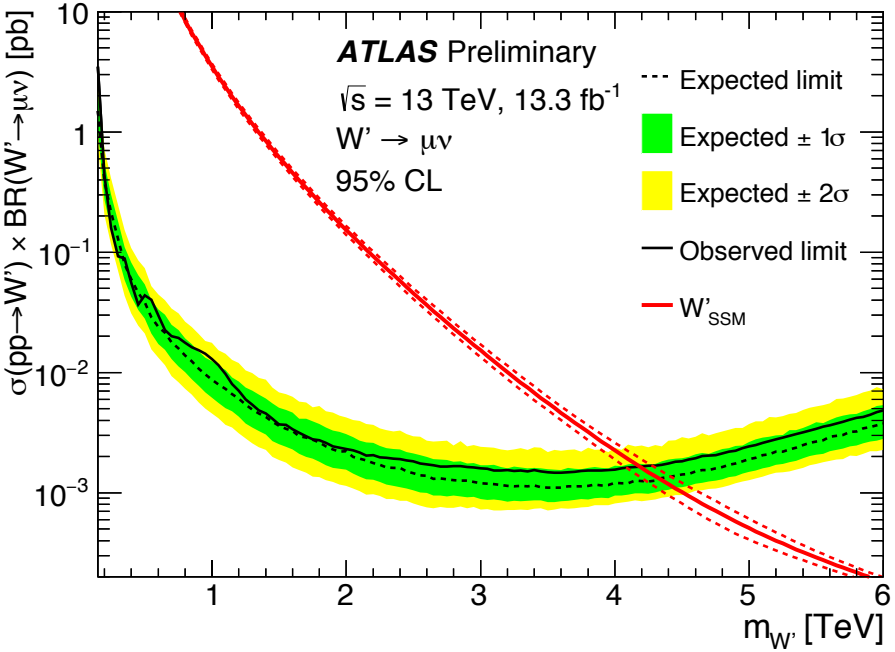
Ref 4

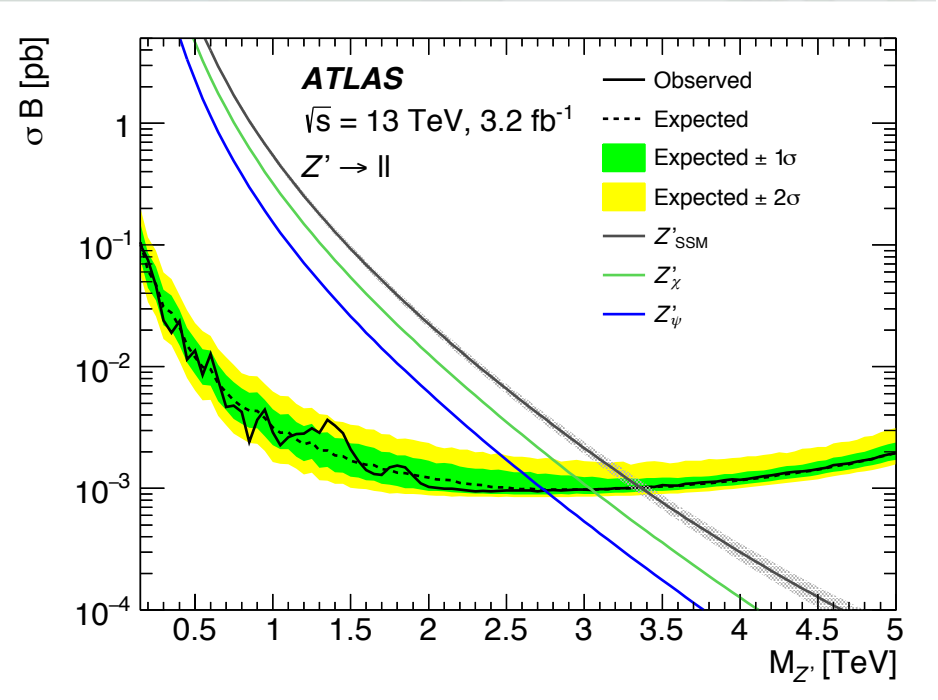
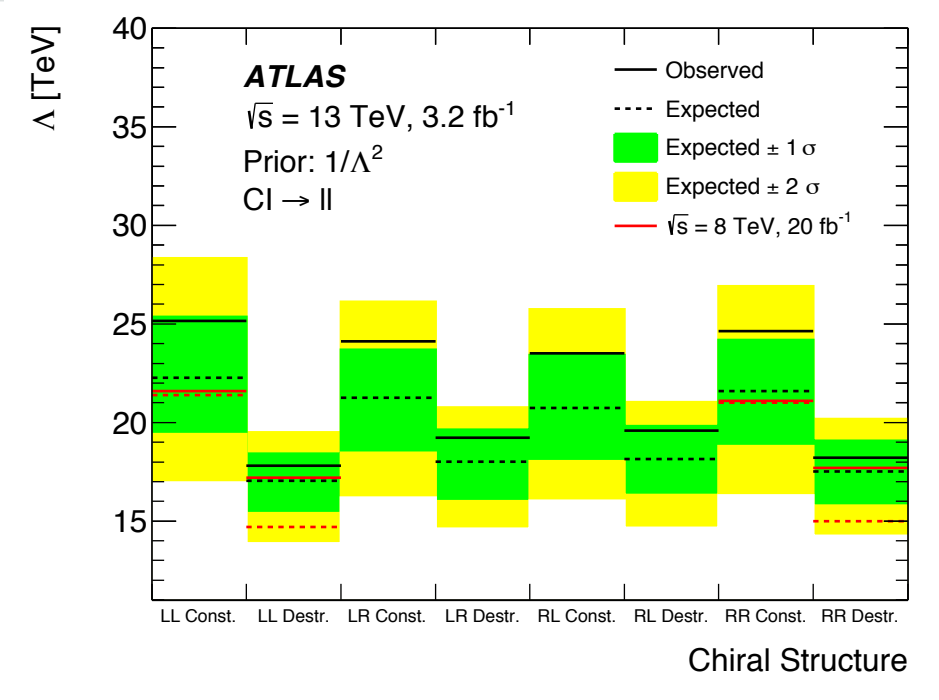


Ref 4

Lepton+MET Search: Limits





Ref 10

Z′ and Contact Interactions: 2015 Limits