Status of the search for Z' bosons decaying to leptons in ATLAS

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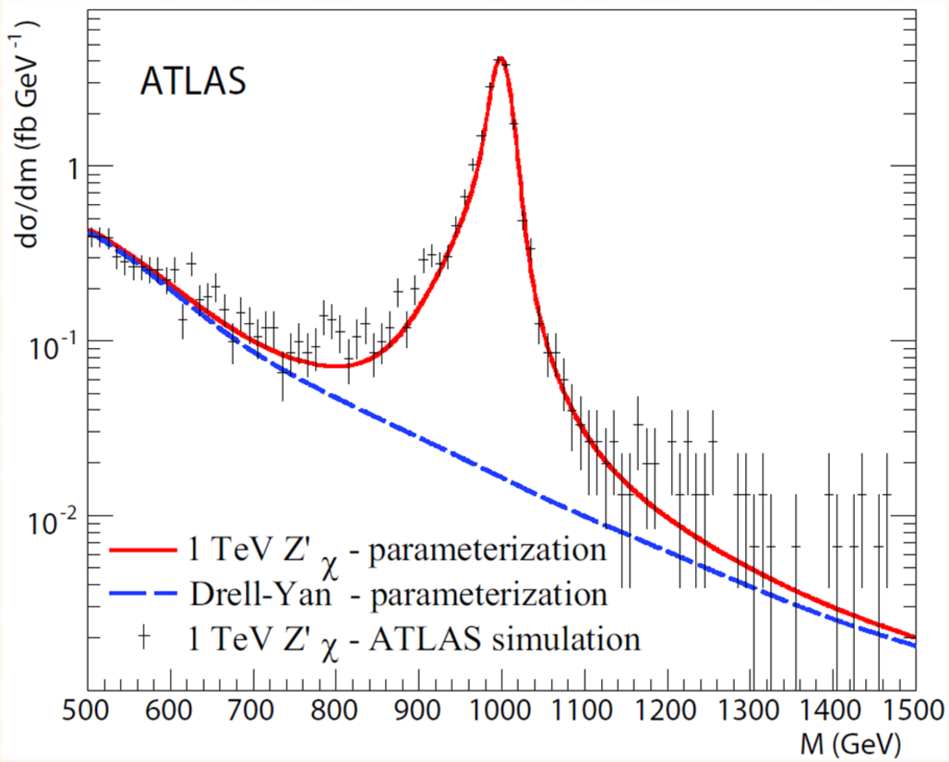
What is a *Z'*?

From our perspective, a *Z'* is any massive particle (heavier than the *Z*) that decays to two leptons—anything that would produce a bump in the Drell-Yan mass spectrum

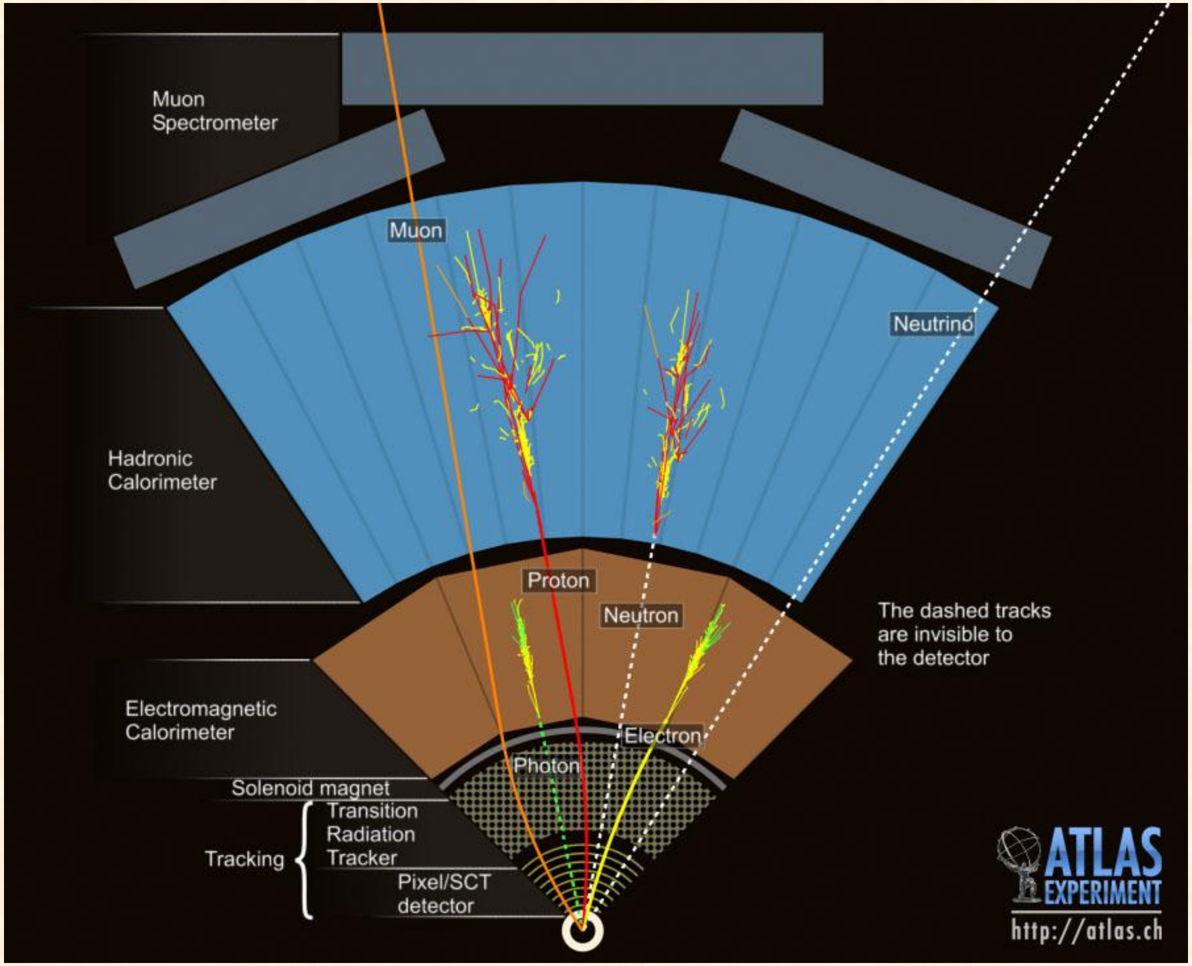


Plot from "CSC book" [CERN-OPEN-2008-020]

This classification allows us to be sensitive to a range of models of physics beyond the SM!

Analysis strategy

Look for deviations from the Standard Model expectation in dielectron and dimuon events, from 130-3000 GeV in invariant mass



Full detail available in ATLAS-CONF-2012-129

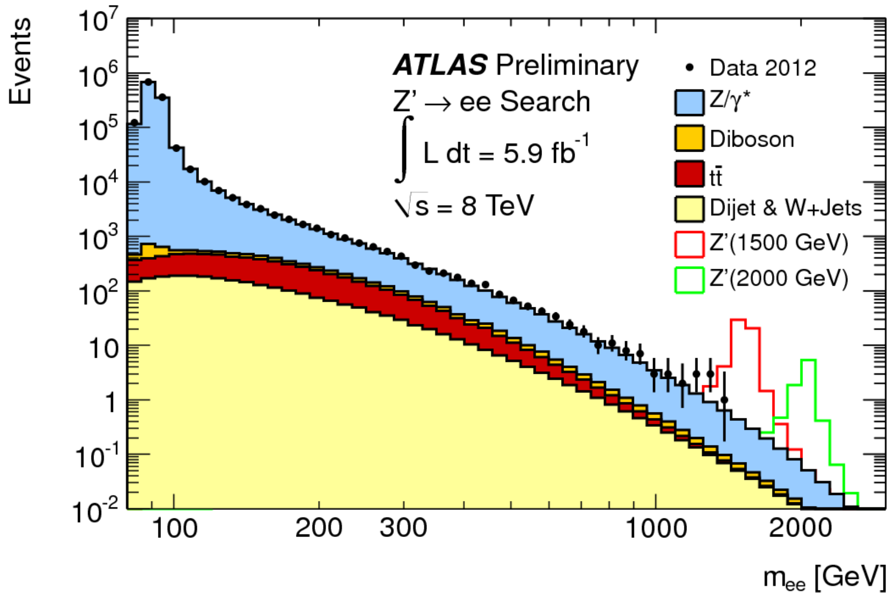
Dielectron acceptance ~70% in signal region
Dimuon acceptance ~40% in signal region

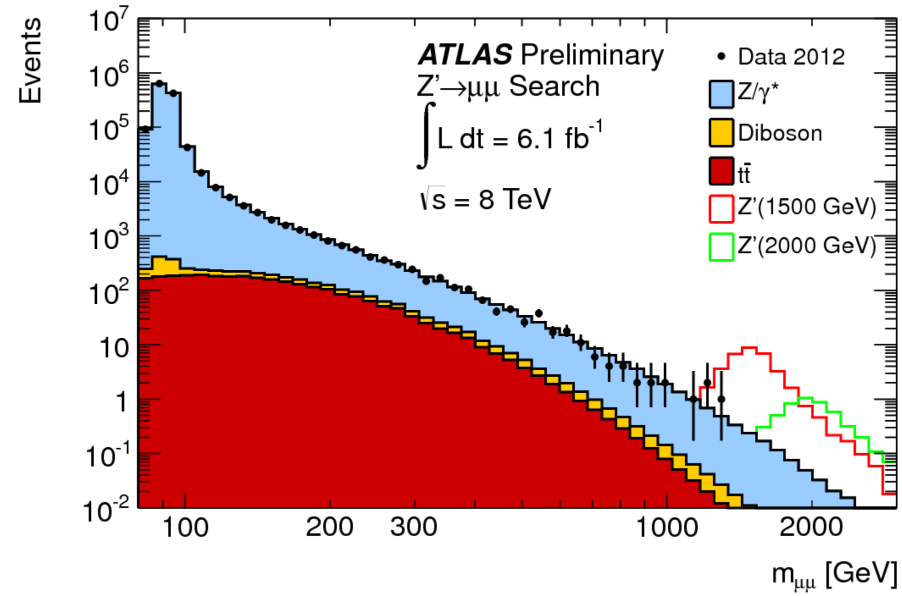
Backgrounds

Background	Electrons	Muons
Drell-Yan, $t\bar{t}$, and Dibosons	Estimated from simulation	Estimated from simulation
W+jets	Estimated from simulation	Negligible
Dijets and γ+jet	Data-driven estimate	Negligible

- For both electrons and muons, the Drell-Yan process is dominant and irreducible
- For muons, an inverted isolation selection is performed to measure contribution from W+jets, $c\bar{c}$, and $b\bar{b}$; found to be negligible

Dilepton invariant mass



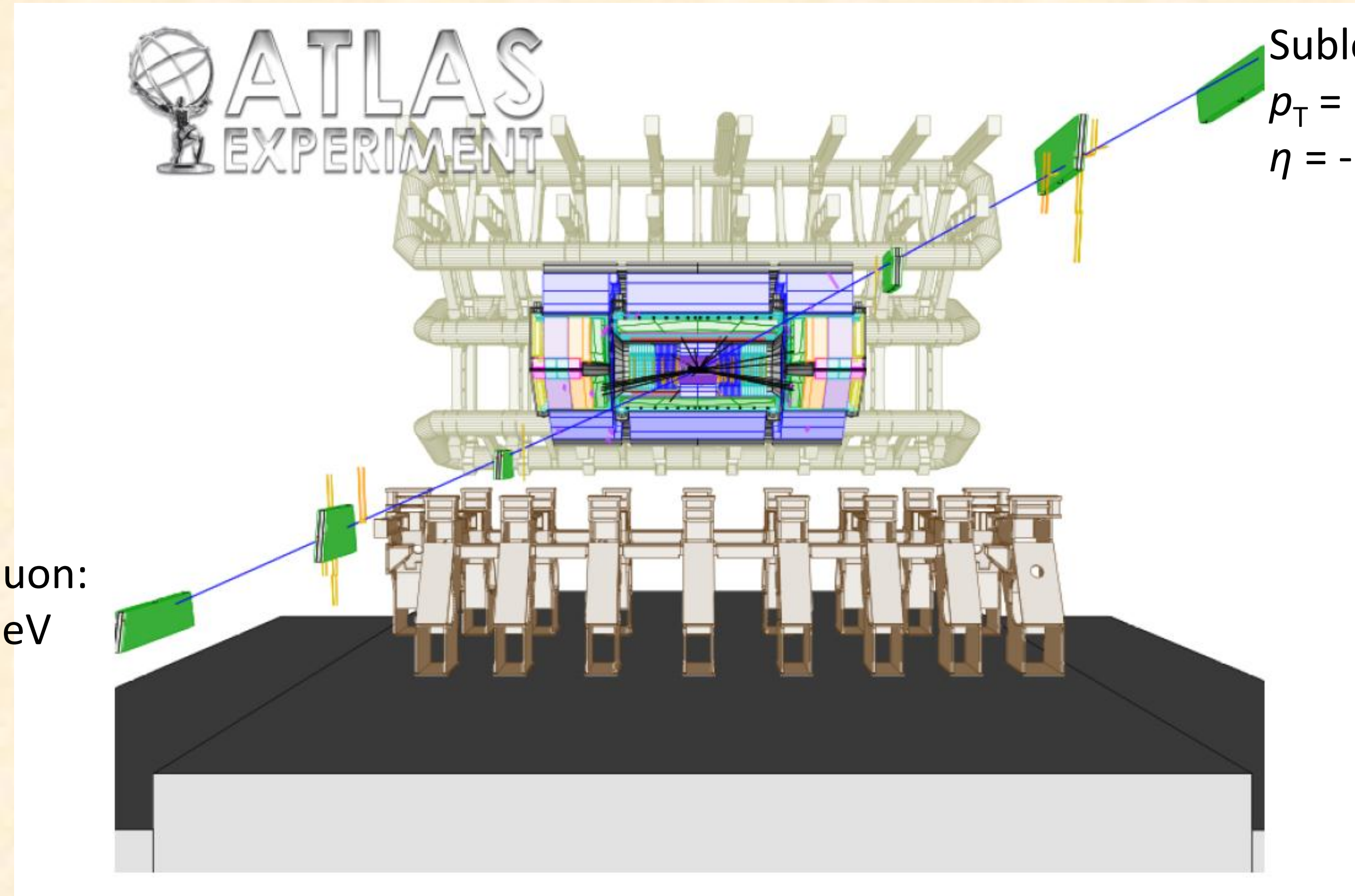


m_{ee} [GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000
Z/γ^*	36200 ± 1500	4330 ± 180	412 ± 20	21.6 ± 1.5	3.03 ± 0.35
$t\bar{t}$	2190 ± 250	750 ± 130	53 ± 19	0.86 ± 0.18	0.041 ± 0.017
W + jets	470 ± 130	130 ± 40	10.6 ± 3.0	0.30 ± 0.09	0.026 ± 0.009
Diboson	482 ± 34	172 ± 22	21 ± 8	0.91 ± 0.05	0.117 ± 0.014
Dijet	720 ± 240	250 ± 120	34 ± 23	2.1 ± 2.0	0.4 ± 0.5
Total	40100 ± 1600	5620 ± 260	530 ± 40	25.8 ± 2.5	3.6 ± 0.6
Data	39875	5760	615	31	5

$m_{\mu\mu}$[GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000
Z/γ^*	27800 ± 1800	2800 ± 250	247 ± 27	12.4 ± 1.6	1.8 ± 0.3
$t\bar{t}$	1390 ± 170	470 ± 100	33 ± 15	0.68 ± 0.30	0.04 ± 0.04
Diboson	306 ± 25	107 ± 17	12 ± 6	0.47 ± 0.09	0.050 ± 0.020
Total	29500 ± 1800	3370 ± 270	293 ± 31	13.6 ± 1.6	1.9 ± 0.3
Data	28516	3341	276	10	3

All backgrounds are normalized to the *Z* peak (80-110 GeV) in order to cancel mass-independent systematics

Highest-mass dimuon event



Subleading muon:
p_T = 274 GeV
η = -1.35

Leading muon:
p_T = 289 GeV
η = 1.54

Invariant mass $m_{\mu\mu}$ = 1258 GeV

Systematic uncertainties

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	5%	NA	5%	NA
PDF / α_s / α_{em} / scale	NA	20%	NA	20%
Electroweak corrections	NA	4.5%	NA	4.5%
Efficiency	$< 3\%$	$< 3\%$	6%	6%
Dijet and W + jets background	NA	21%	NA	$< 3\%$
Total	5%	30%	8%	21%

- Only mass-dependent sources of uncertainty are considered
  - Normalization uncertainty reflects the uncertainty on the *Z* cross section in the normalization region
- All uncertainties are correlated across all bins in the search region

Limit calculation

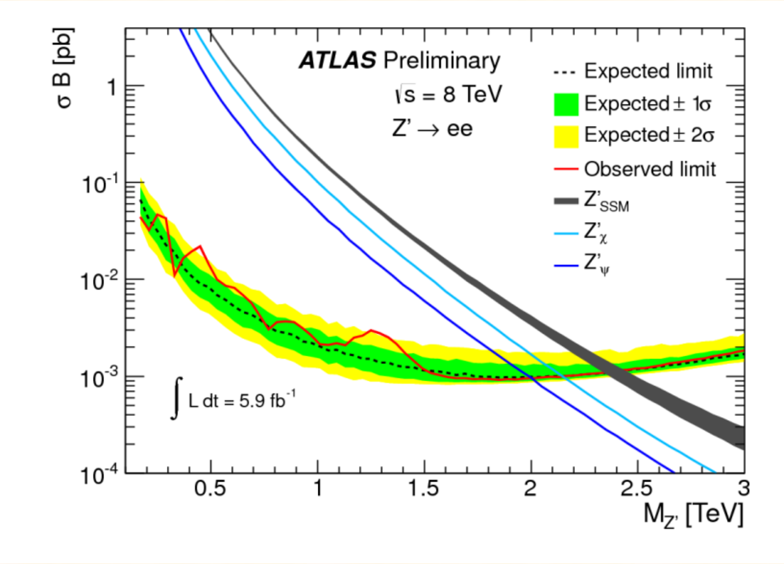
- We don't observe an excess, so we set 95% CL upper limits on the number of signal events
- Limit is set using a Bayesian technique in which the systematic uncertainties are incorporated as nuisance parameters
  - A likelihood function is constructed for each prospective signal mass
  - Converted into a posterior probability density using Bayes' Theorem; limit found via

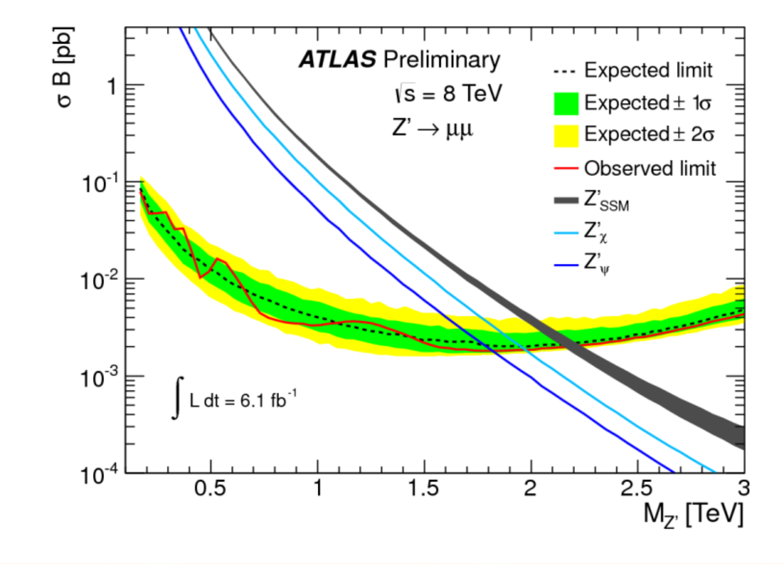
$$0.95 = \frac{\int_0^{N_{Z'}^{95}} \mathcal{L}'(N_{Z'})\pi(N_{Z'})d(N_{Z'})}{\int_0^{\infty} \mathcal{L}'(N_{Z'})\pi(N_{Z'})d(N_{Z'})}$$

- Limit on the number of events observed is converted into a limit on signal cross section times branching ratio via

$$\sigma B(Z') = \sigma B(Z)\frac{N_{Z'}A_Z}{N_Z A_{Z'}}$$

Limits





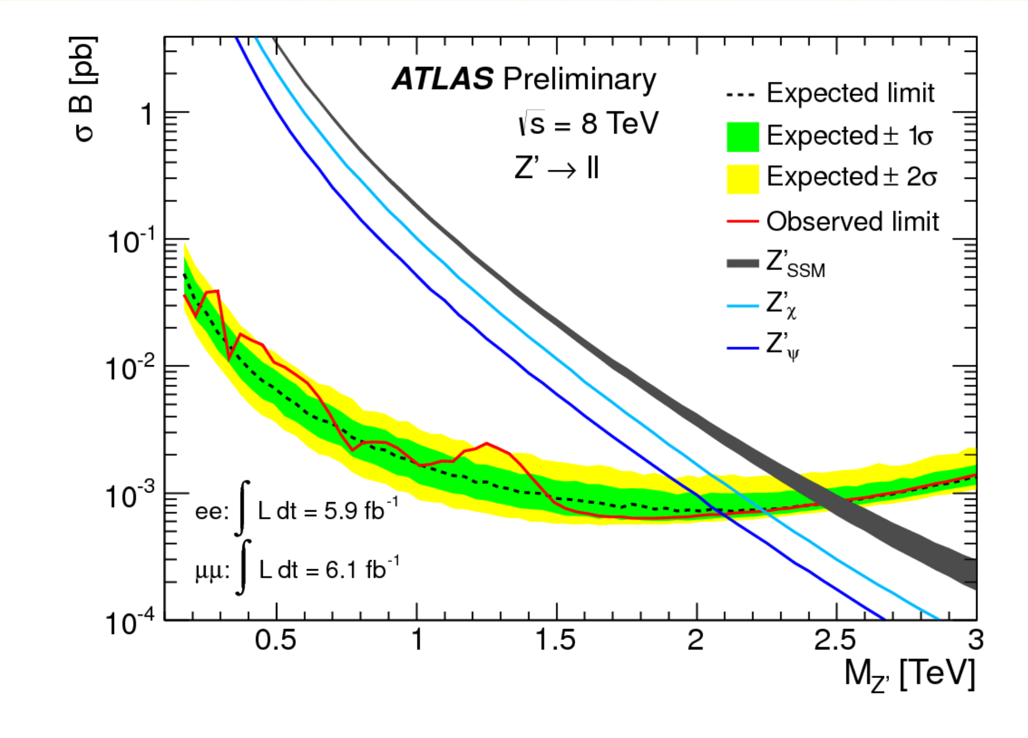


Table 4: e^+e^-, $\mu^+\mu^-$ and combined 95% C.L. mass limits on $Z'_{\rm SSM}$.

	$Z'_{\rm SSM} \to e^+e^-$	$Z'_{\rm SSM} \to \mu^+\mu^-$	$Z'_{\rm SSM} \to \ell^+\ell^-$
Observed mass limit [TeV]	2.39	2.19	2.49
Expected mass limit [TeV]	2.39	2.17	2.49

Table 5: Combined mass limits at 95% C.L. on the E_6-motivated Z' models.

Model	Z'_ψ	$Z'_{\rm N}$	Z'_η	Z'_I	$Z'_{\rm S}$	Z'_χ
Observed mass limit [TeV]	2.09	2.10	2.15	2.14	2.18	2.24
Expected mass limit [TeV]	2.07	2.08	2.14	2.13	2.17	2.23

Conclusions

- A search for dilepton resonances in 6 fb^{-1} of data at $\sqrt{s}$ = 8 TeV has been performed
- No statistically significant excess has been observed
- A lower limit on the mass of an SSM *Z'* has been set at 2.49 TeV
  - Most recent CMS limit uses statistical combination with 7 TeV data; set at 2.59 TeV
- We have by now collected more than twice this amount of data—stay tuned!

Backup

Dielectron event selection

- Good Runs List (ATLAS data quality—stable beam, all subdetectors functioning correctly, etc.)
- At least one primary vertex with which more than two tracks are associated
- Diphoton trigger with thresholds $E_T > 35$ GeV and $E_T > 25$ GeV for leading and subleading objects, respectively
- Reject events with LAr errors, to protect against noise bursts and data corruption
- $|\eta| < 2.47$, with a fiducial cut of $1.37 < |\eta| < 1.52$ to exclude the calorimeter crack region
- Leading electron $p_T > 40$ GeV; subleading $p_T > 30$ GeV
- Both electrons must have a well-reconstructed track in the inner detector, including a minimum requirement on the amount of transition radiation
- Inner detector tracks for both electrons must be matched with clusters in the calorimeter whose shower shapes are consistent with those expected for electromagnetic showers
- Cluster must pass calorimeter quality requirements
- Both electrons must be isolated, such that $\Sigma E_T(\Delta R < 0.2) < 7$ GeV

Dielectron acceptance ~70% in signal region

Dimuon event selection

- Good Runs List (ATLAS data quality—stable beam, all subdetectors functioning correctly, etc.)
- At least one primary vertex with which more than two tracks are associated, and $|z_{PV}| < 200$ mm
- Single-muon trigger with threshold $p_{\mathrm{T}} > 24$ GeV
- $|d_0| < 0.2$ mm, $|z_0 - z_{PV}| < 1$ mm
- $p_{\mathrm{T}} > 25$ GeV
- Both muons must be isolated, such that $\Sigma p_{\mathrm{T}}(\Delta R < 0.2)/p_{\mathrm{T}} < 0.05$
- Both muons must be combined muons with a high-quality inner-detector track and a muon spectrometer track with at least three hits each in the inner, middle, and outer stations of the precision tracking chambers, and at least one hit in the non-bending plane
- Muons must have opposite charge

Dimuon acceptance ~40% in signal region

Reverse-ID method for dielectron QCD background

- Accounts for fake electrons coming from hadrons, semileptonic heavy flavor decays, and photon conversions
- Template fit in m_{ee} between 80-200 GeV
- Two templates:
  - MC backgrounds (Drell-Yan, W+jets, $t\bar{t}$, and dibosons) after full event selection
  - "QCD template"—data with reversed electron ID cuts—same selection performed on MC and the MC is subtracted from the data, leading to a QCD-enriched data sample
  - The two are summed and normalized to data (using standard selection)—the normalization factor is 1.004
- The QCD template is scaled by this factor; to extrapolate to high m_{ee}, the distribution is fitted
  - Many different fit ranges, using two functions:

$$f_1(x) = p_0 x^{p_1} x^{p_2 \log(x)}$$

$$f_2(x) = p_0(1 - (x/\sqrt{s}))^{p_1} \cdot (x/\sqrt{s})^{-p_2 - p_3 \log(x/\sqrt{s})}$$

  - Systematic uncertainty obtained by measuring fluctuations among fits

Theoretical systematic uncertainties

- PDF/coupling uncertainty
  - 7% at 1 TeV; 20% at 2 TeV
  - Obtained by varying the parameter set of MSTW2008, NNPDF2.1, CT10, CT10W PDFs and evaluating the individual uncertainty bands
  - Includes uncertainties due to α_s variations
  - Largest difference among all variations in obtained *K*-factors is added in quadrature to the overall uncertainty
- Electroweak corrections
  - 4.5% at 2 TeV
  - Accounts for neglecting real boson emission, higher order electroweak and O($\alpha\alpha_s$) corrections

Experimental systematic uncertainties

- Electrons:
  - Identification+reconstruction efficiency uncertainty—2% at 2 TeV
    - Evaluated by studying the mass dependence of the calorimeter isolation cut
  - QCD multijet background uncertainty—21% at 2 TeV
    - Evaluated by comparing the background with the QCD contribution increased by 1σ with the nominal background
- Muons:
  - Trigger and identification+reconstruction efficiency uncertainty—6% at 2 TeV
    - Dominated by the effect of large energy loss due to bremsstrahlung in the calorimeter
  - Resolution uncertainty—$<$ 3 % at 2 TeV
    - Muon resolution is dominated by the constant intrinsic resolution+misalignment term having only to do with detector geometry
    - Has been found to be negligible due to strict muon reconstruction quality requirements

Details on limit calculation

- A likelihood function is constructed for each prospective signal mass by multiplying all Poisson probabilities for each bin in the search range

$$\mathcal{L}(data|N_j,\theta_i) = \prod_{k=1}^{N_{bin}} \frac{\mu_k^{n_k} e^{-\mu_k}}{n_k!} \prod_{i=1}^{N_{sys}} G(\theta_i, 0, 1)$$

Expected number of events in bin *k*, from backgrounds + signal

Observed number of events in bin *k*

Unit-width Gaussian prior for systematic *i*

  – Converted into a posterior probability density using Bayes' Theorem; limit found via

$$0.95 = \frac{\int_0^{N_{Z'}^{95}} \mathcal{L}'(N_{Z'})\pi(N_{Z'})d(N_{Z'})}{\int_0^{\infty} \mathcal{L}'(N_{Z'})\pi(N_{Z'})d(N_{Z'})}$$

- Limit on the number of events observed is converted into a limit on signal cross section times branching ratio via

$$\sigma B(Z') = \sigma B(Z)\frac{N_{Z'}A_Z}{N_Z A_{Z'}}$$

More details on limit calculation—combination of channels

- Likelihood function defined as the product of Poisson probabilities for the observed data given the expectation from the signal + background template in each mass bin over the search region:

$$\mathcal{L}(data|\sigma B, \theta_i) = \prod_{l=1}^{N_{channel}} \prod_{k=1}^{N_{bin}} \frac{\mu_{lk}^{n_{lk}} e^{-\mu_{lk}}}{n_{lk}!} \prod_{i=1}^{N_{sys}} G(\theta_i, 0, 1)$$

- First product represents the combination of the dielectron and dimuon channels
- Reduced likelihood function is calculated by integrating out the nuisance parameters:

$$\mathcal{L}'(data|\sigma B) = \int \mathcal{L}(\sigma B, \theta_1, ..., \theta_N) d\theta_1, ..., d\theta_N$$