Searches for high mass dilepton resonances in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS Experiment

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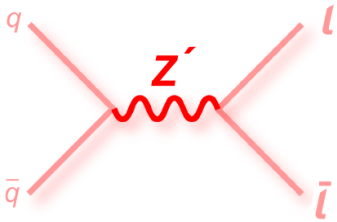
Theoretical Motivations

- New high mass resonances are predicted in several extensions of the Standard Model
  - Set limits on spin 1 and spin 2 resonances

- Spin 1: benchmark is Sequential Standard Model (SSM)
  - Z' has same leptonic couplings as SM Z
  - Width scales linearly with mass

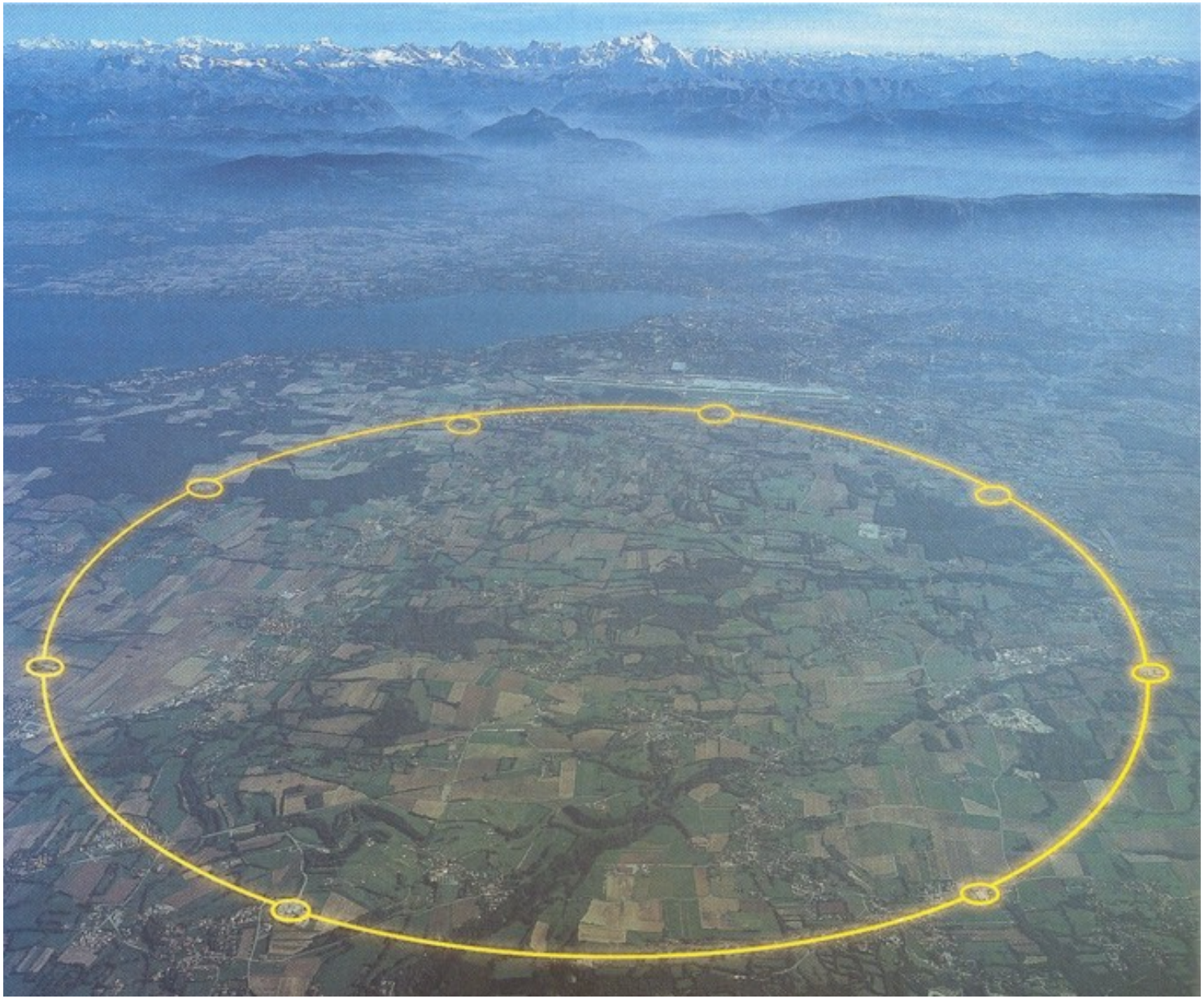


- Also consider Grand Unification E_6-inspired models
  - E_6 broken to $SU(5) \times U(1)_\chi \times U(1)_\psi$
  - Z' candidate is linear combination of U(1) gauge bosons:

$$Z'(\theta_{E_6}) = Z'_\psi \cos\theta_{E_6} + Z'_\chi \sin\theta_{E_6}$$

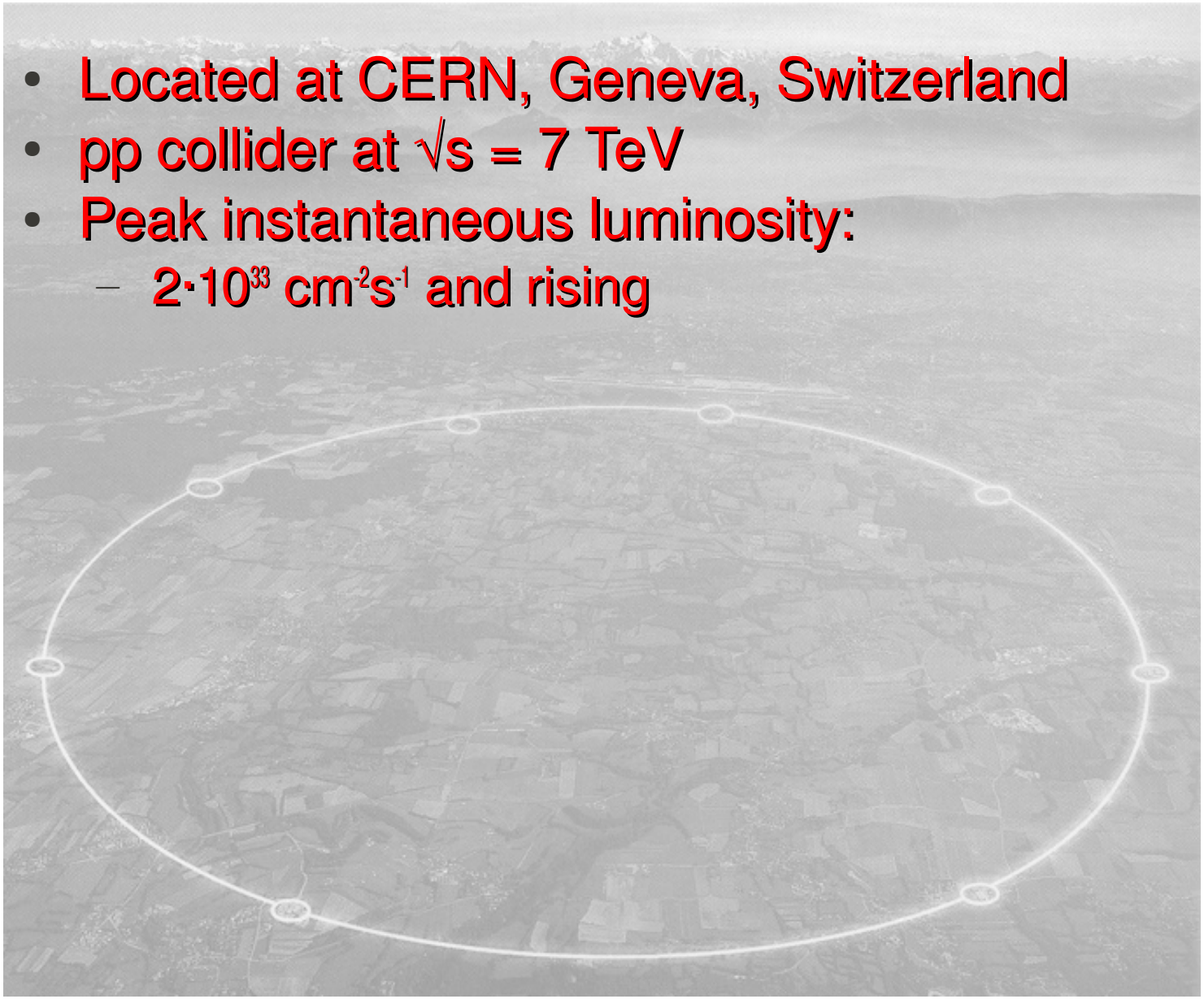
- Spin 2: benchmark is Randall-Sundrum (RS) Graviton
  - *See talk by **Evan Wulf** for more info*

Large Hadron Collider



Large Hadron Collider

- Located at CERN, Geneva, Switzerland
- pp collider at $\sqrt{s}$ = 7 TeV
- Peak instantaneous luminosity:
  - $2 \cdot 10^{33}$ $cm^{-2}s^{-1}$ and rising



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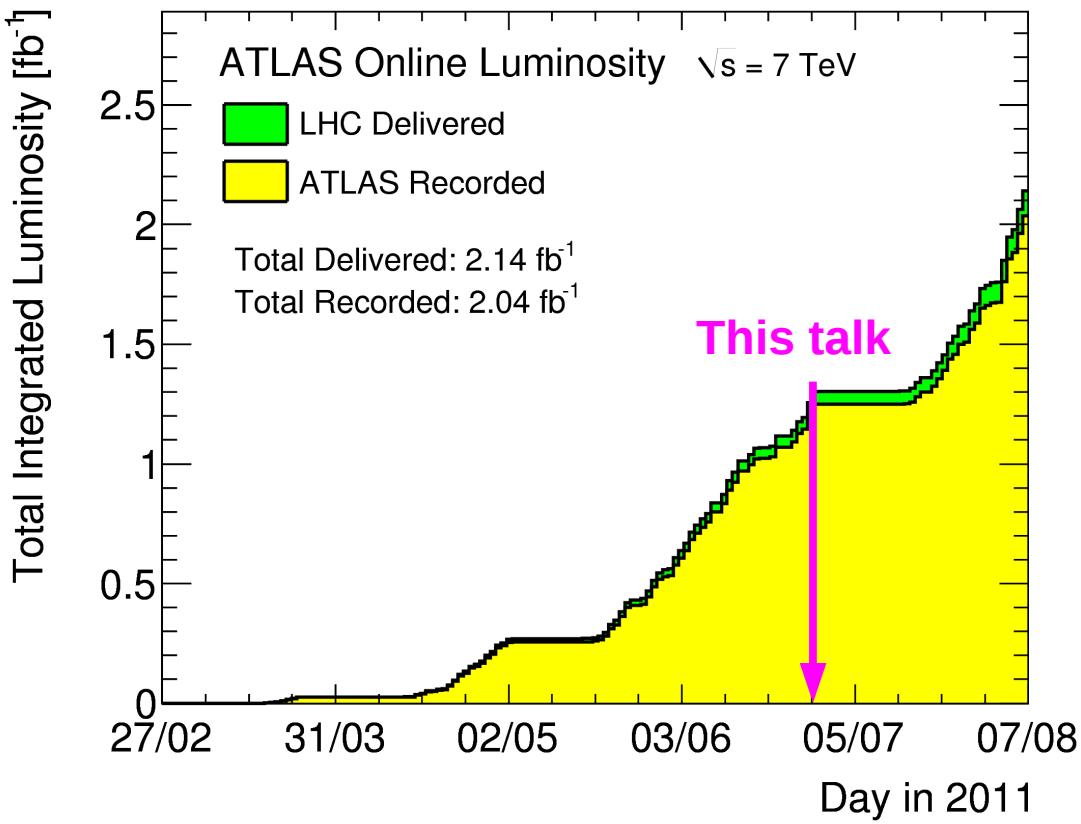
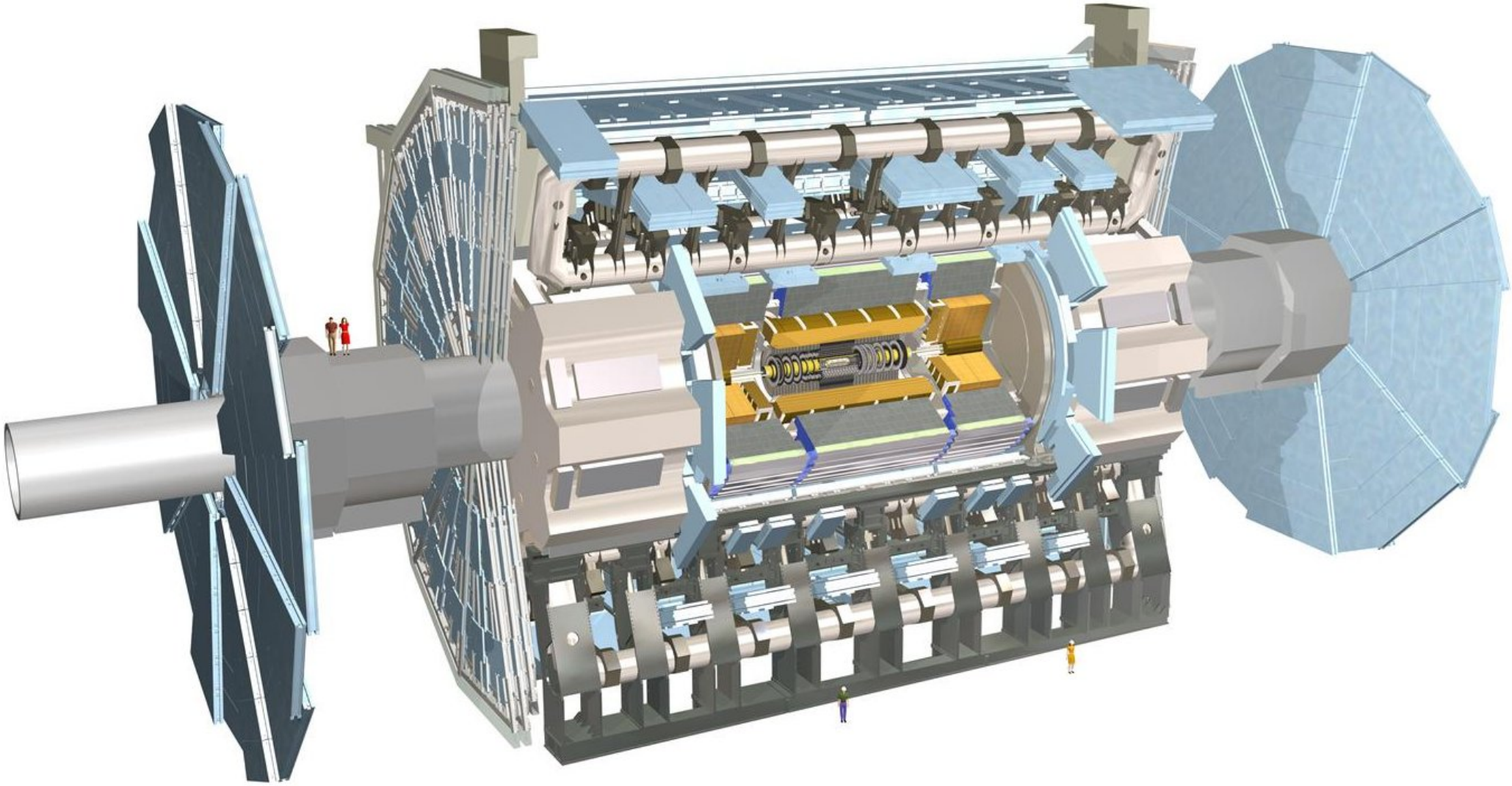


ATLAS Detector



ATLAS Detector

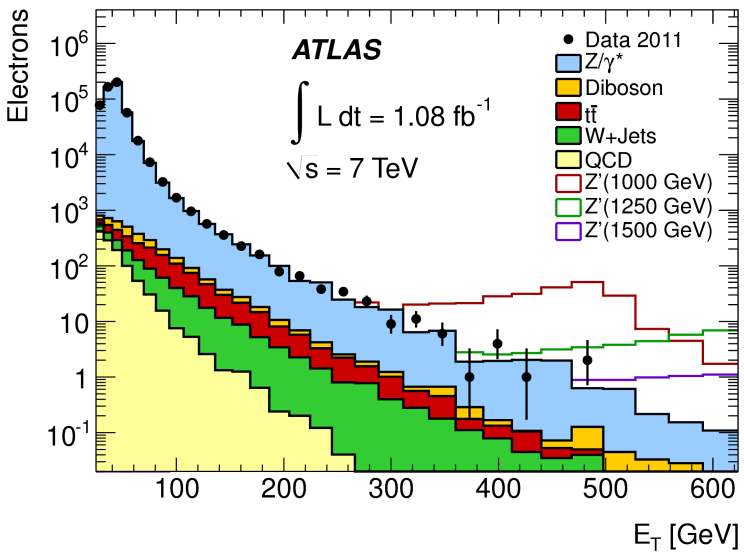
- **Inner Detector**
  - Coverage for $|\eta| < 2.5$
- **Electromagnetic Calorimeter**
  - Central region coverage for $|\eta| < 2.47$
  - Energy resolution (in barrel): 1.1% at 1 TeV
- **Muon Spectrometer**
  - Coverage for $|\eta| < 2.5$
  - Momentum resolution (in barrel): 15% at 1 TeV

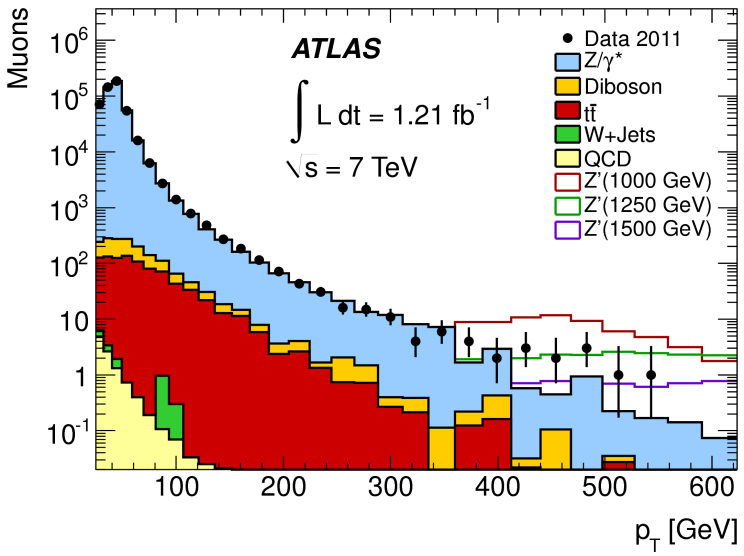
Signal and Backgrounds

- Select events with two leptons of same flavor (ee, μμ)
- Search for excess above Standard Model expectations in high invariant mass region

Main backgrounds
Drell Yan (irreducible)
Dibosons (WW,WZ,ZZ)
Top quark pair production
SM W+jets
QCD dijets

Non-prompt muons (including cosmic rays) found to be negligible for muon channel





Electron Selection

- Electrons reconstructed as cluster in EM calorimeter matched with track from Inner Detector

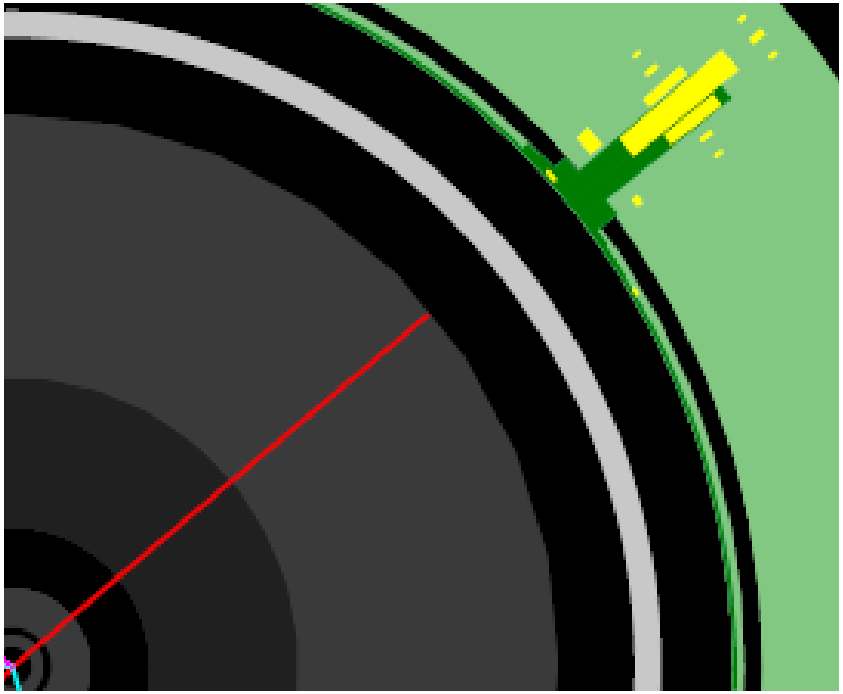
Detailed selection:

- Trigger requiring single "Medium" electron with $E_T > 20$ GeV
- 2 electrons with:
  - $E_T > 25$ GeV
  - $|\eta| < 2.47$, exclude calorimeter crack region $1.37 < |\eta| < 1.52$
  - "Medium" Electron ID
    - Transverse shower shapes
    - Hadronic calorimeter leakage
    - Track quality
    - Track-cluster matching
  - Hit in first pixel layer ("B-layer")
- Leading electron isolated:
  - $\sum E_T < 7\,GeV$ within a cone of $\Delta R < 0.2$

Total acceptance*efficiency:

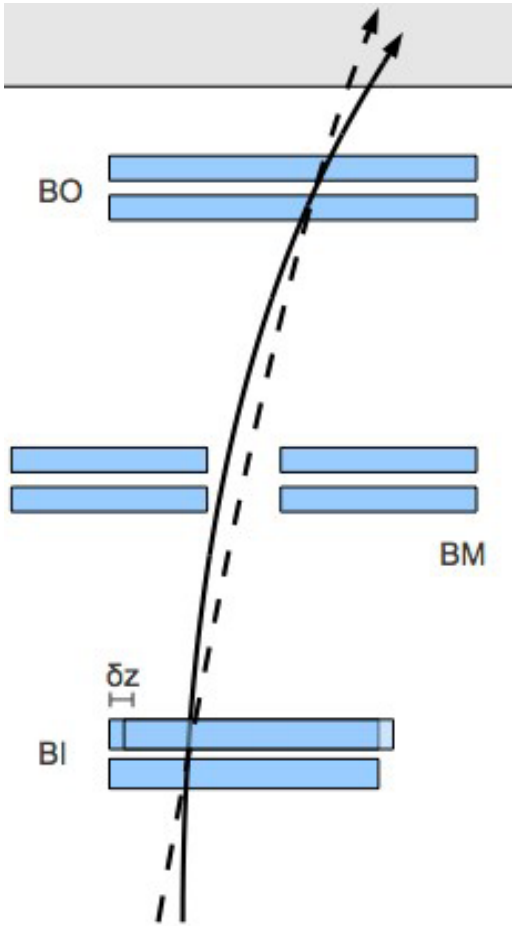
- ~67% for Z' masses above 1 TeV

Robust selection to suppress instrumental background and ensure well-understood leptons



Muon Selection

Robust selection to suppress instrumental background and ensure <u>well-understood leptons</u>



- Muons reconstructed from combination of tracks in Inner Detector and Muon Spectrometer

<u>Detailed selection:</u>

- Trigger requiring single Muon with $p_T > 22$ GeV
- Primary vertex with $|z| < 200$ mm
- 2 muons with:
  - $p_T > 25$ GeV
  - $|\eta| < 2.4$
  - Track quality in Inner Detector
  - Precision hits in all 3 muon stations
  - Hit in non-bending plane
  - Veto on overlapping hits in barrel and endcaps
  - $|d_0| < 0.2$ mm, $|z_0| < 1$ mm
  - Isolation: $\sum p_T^{trk} < 0.05\, p_T$ within a cone of $\Delta R < 0.3$
  - Opposite charge

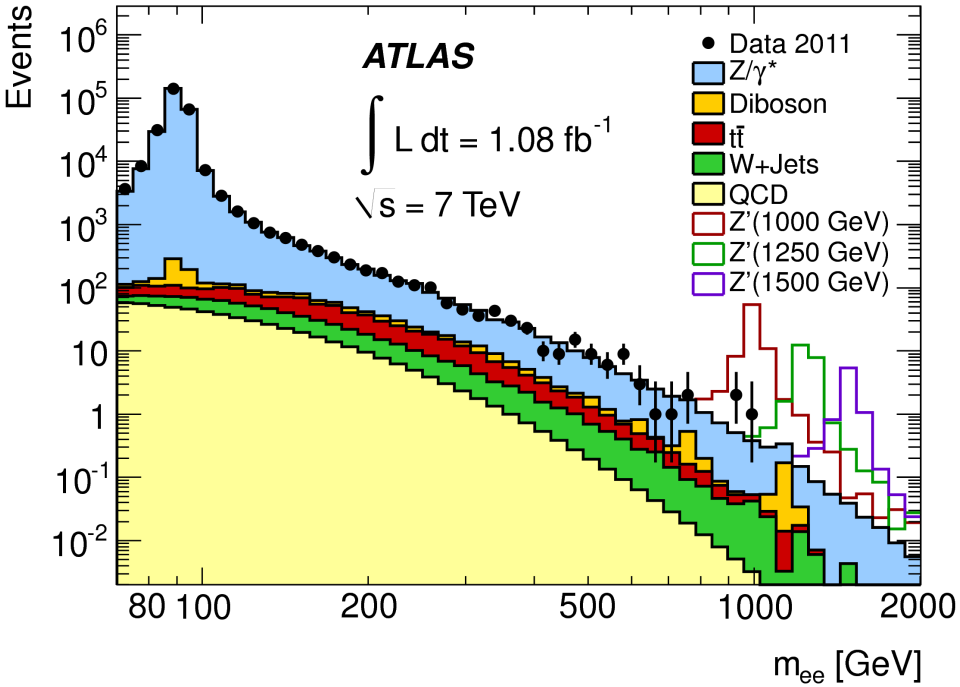
<u>Total acceptance*efficiency</u>:

- ~42% for Z' masses above 1 TeV

Electron QCD Dijet Background

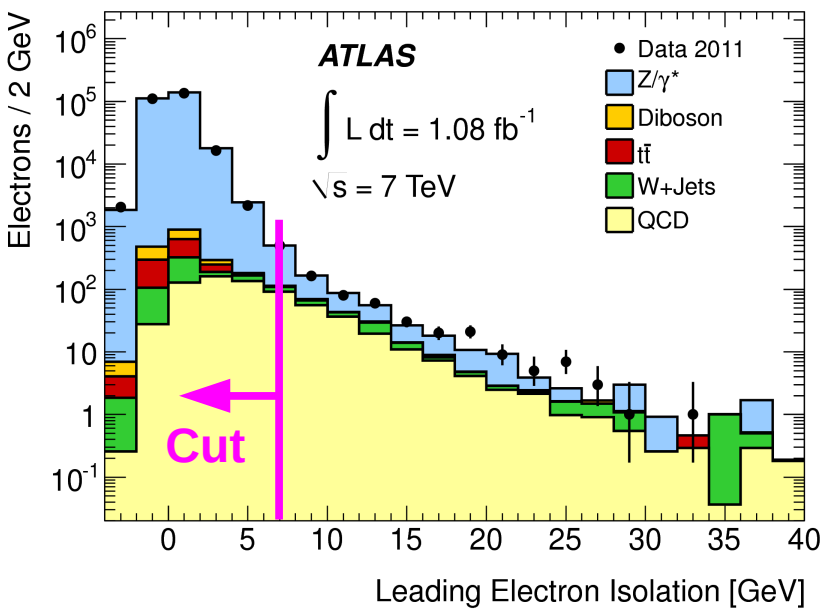
- All backgrounds taken from MC except QCD dijets
- Baseline method is inverted identification:
  - Require two electrons passing looser cuts but failing Medium Electron ID cuts to derive shapes for QCD dijet background
  - QCD dijet invariant mass shape is fit with an empirical function to allow extrapolation to high mass: $f(x) = p_0 x^{p_1} x^{p_2 * Log x}$
  - Normalization is determined using a binned likelihood fit in invariant mass, in the range 70 < m_{ee} < 200 GeV

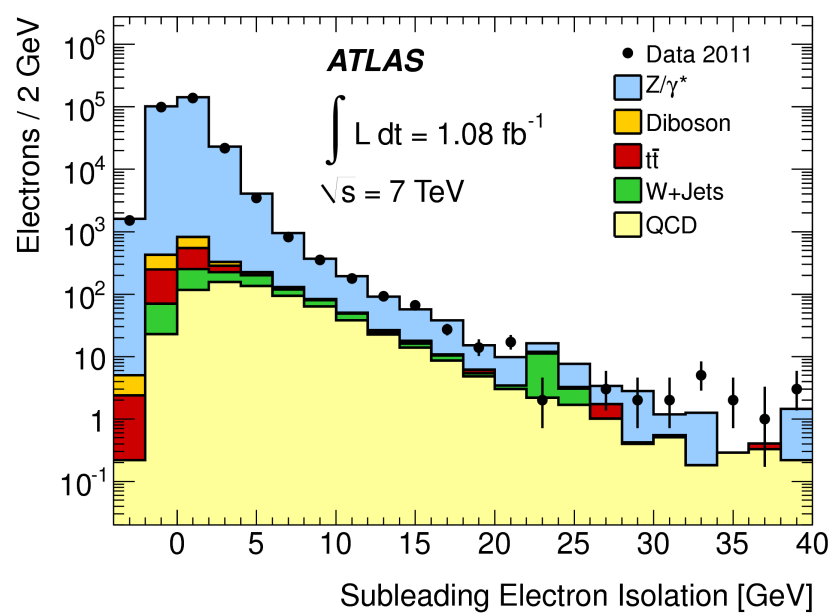
m_{ee} [GeV]	QCD Events
70 – 110	332 +/- 59
110 – 200	191 +/- 75
200 – 400	36 +/- 29
400 – 800	1.8 +/- 1.4
800 – 3000	< 0.05



Electron QCD Dijet Background

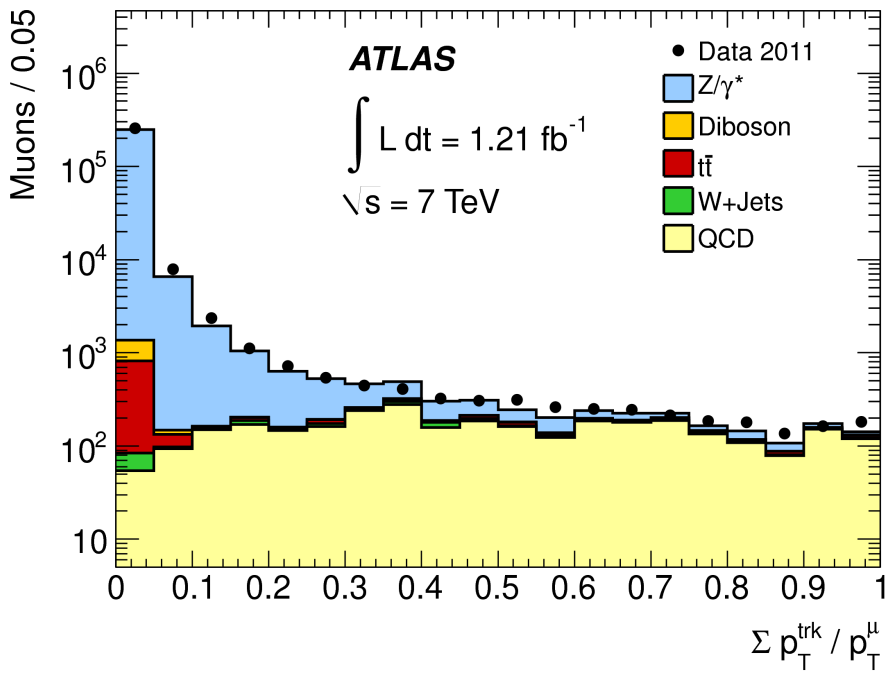
- Cross checks and systematics from two other methods:
  - Fake rates method derives fake rate for jets to pass Z' selection in dijet data, applies fake rate to dielectron events where one electron passes jet-like cuts
  - Isolation fit uses binned likelihood fits in calorimeter isolation
    - Signal templates taken from W electrons in data
    - Background templates taken from reversing ID cuts in data
    - Leading and subleading electrons are fit separately in bins of invariant mass
    - Results of fits are combined using a system of equations to obtain event level background predictions





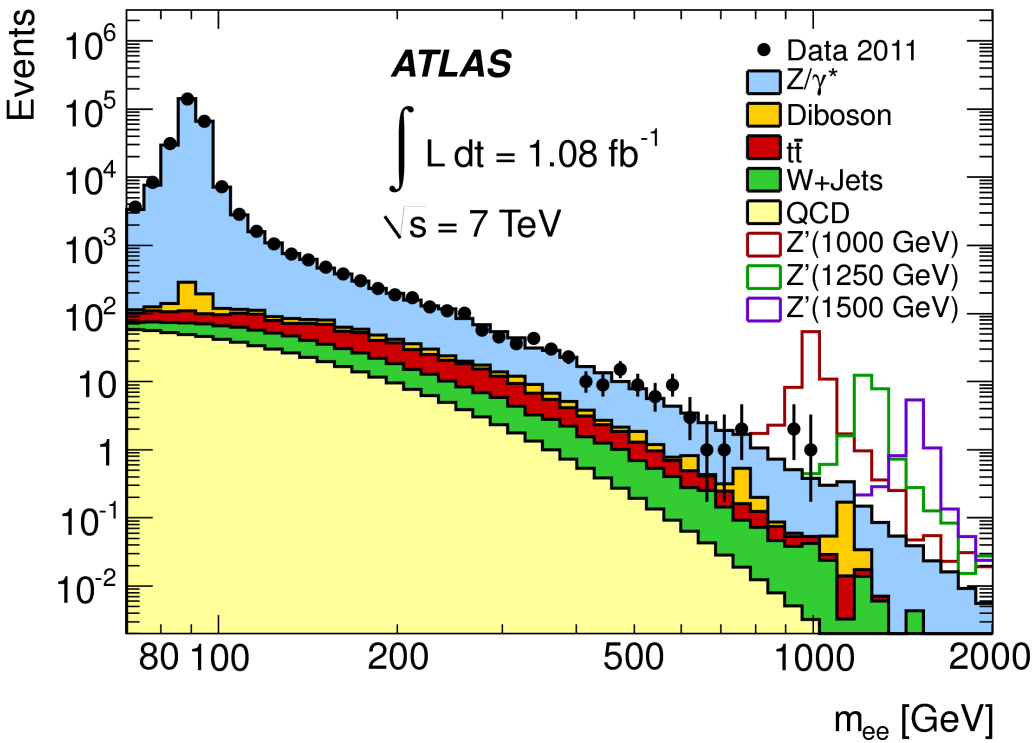
Muon QCD Dijet Background

- All backgrounds also taken from MC except QCD dijets
- Use a reversed isolation method:
  - QCD shapes from data events with both muons non-isolated:
    - $0.1 < (\sum p_T^{trk}) / p_T^{muon} < 1.0$ for tracks within a cone of $\Delta R < 0.3$
  - Normalization taken from the ratio of isolated to non-isolated dimuon events in QCD (bbar/ccbar) MC

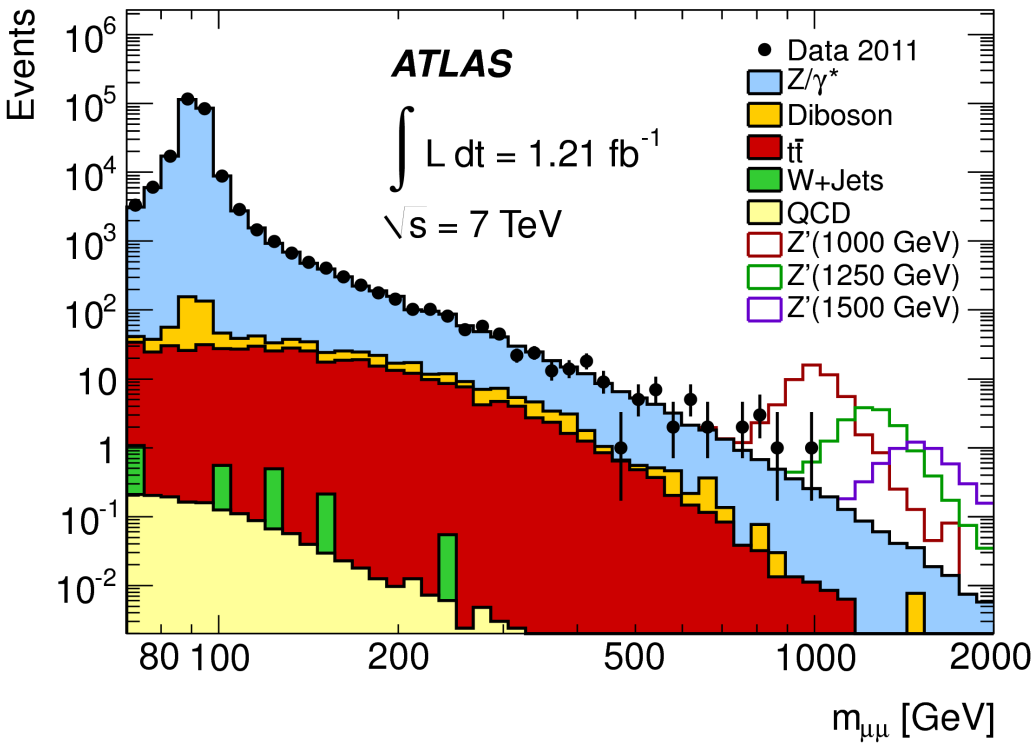


Results: Invariant Mass

Electrons



Muons

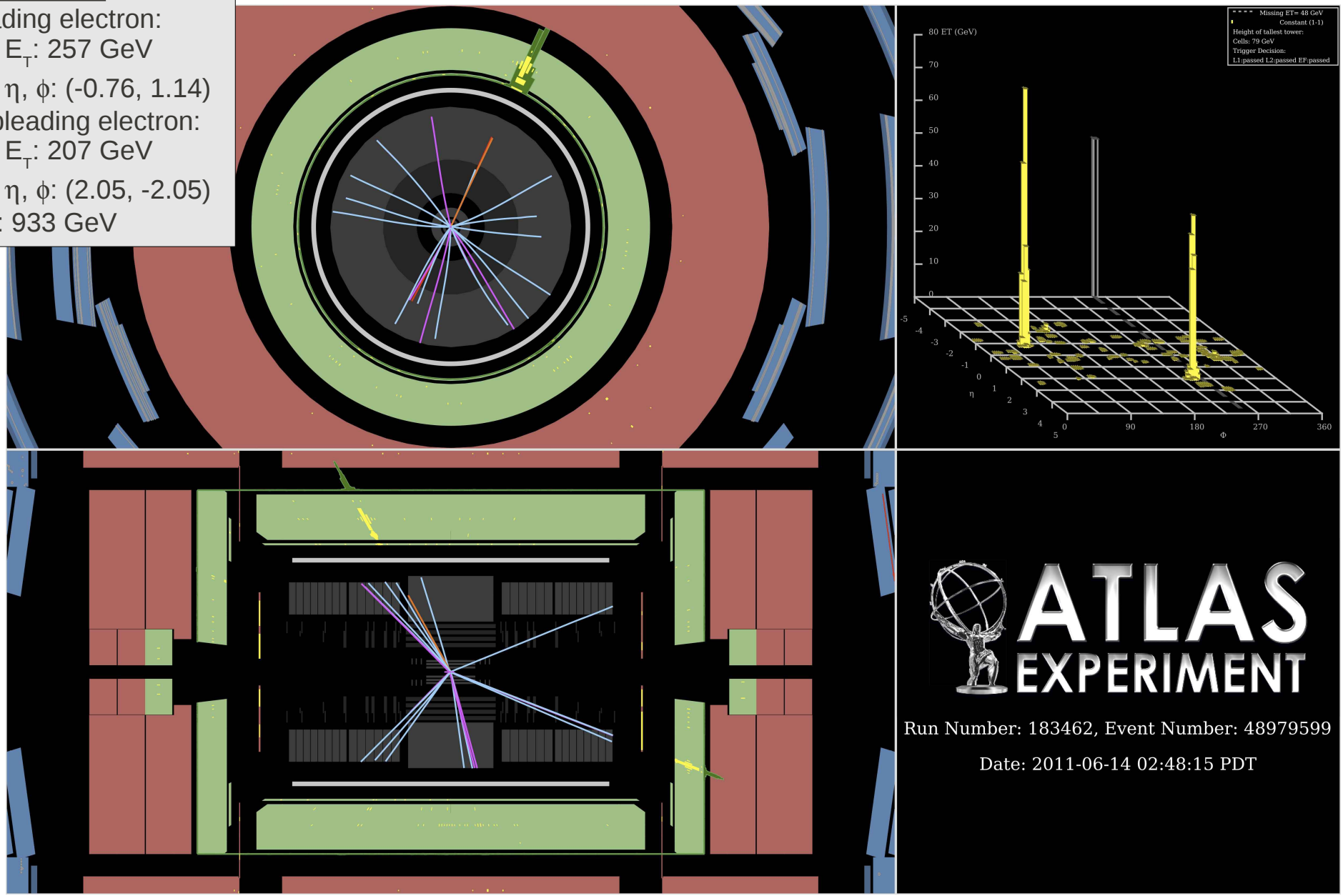


MC normalized to data in Z peak region
($70 < m_{\ell\ell} < 110$ GeV)

No excess observed over SM expectations:
set limits on σB

Highest m_{ee} Event

Event Details:
- Leading electron:
  - E_T: 257 GeV
  - η, ϕ: (-0.76, 1.14)
- Subleading electron:
  - E_T: 207 GeV
  - η, ϕ: (2.05, -2.05)
- m_{ee}: 933 GeV



Systematic Uncertainties

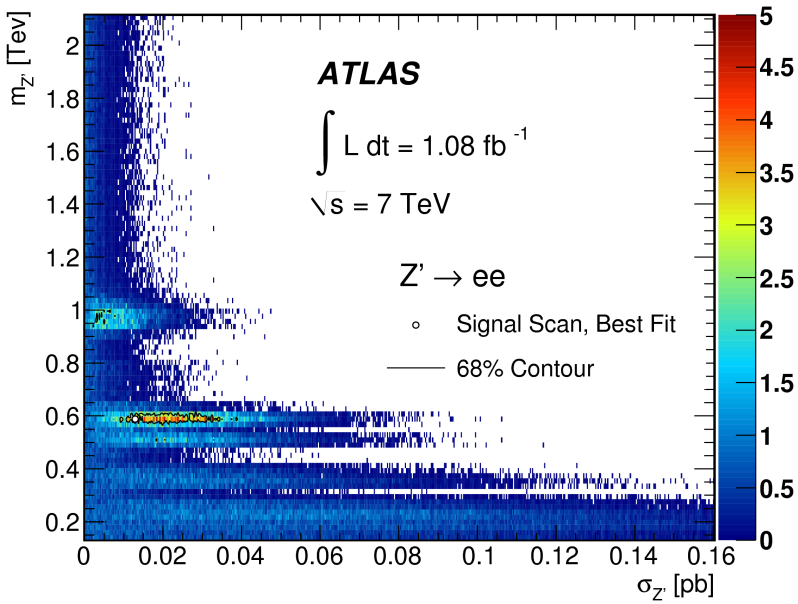
- Reduce background systematics by normalizing MC to data in Z peak region (70 < $m_{\ell\ell}$ < 110 GeV)
  - Luminosity and other mass-independent systematics cancel
  - Normalization factor: 0.99
- Uncertainties treated as correlated across all mass bins

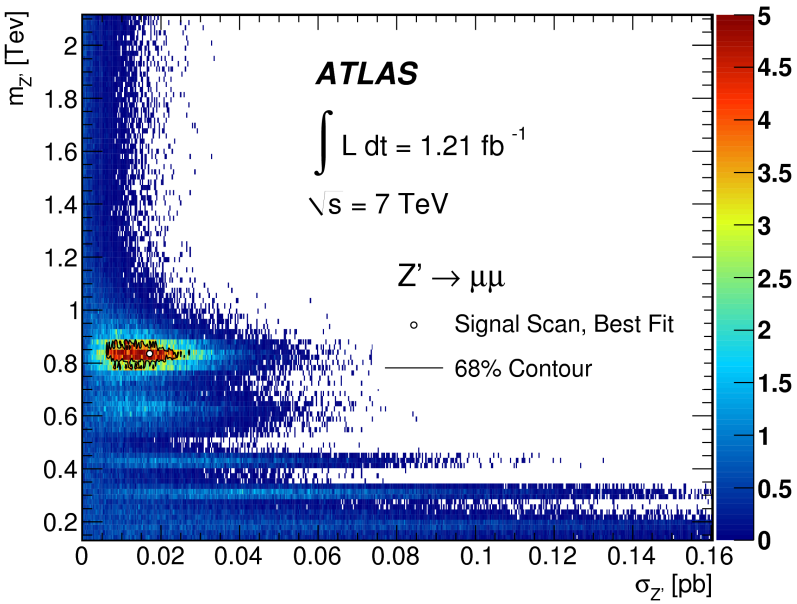
Source	dielectrons		dimuons	
	signal	background	signal	background
Normalization	5%	NA	5%	NA
PDFs/α_S	NA	10%	NA	10%
QCD K-factor	NA	3%	NA	3%
Weak K-factor	NA	4.5%	NA	4.5%
Trigger/Reconstruction	negligible	negligible	4.5%	4.5%
Total	5%	11%	7%	12%

Systematic uncertainties on numbers of expected events at $m_{\ell\ell}$ = 1.5 TeV

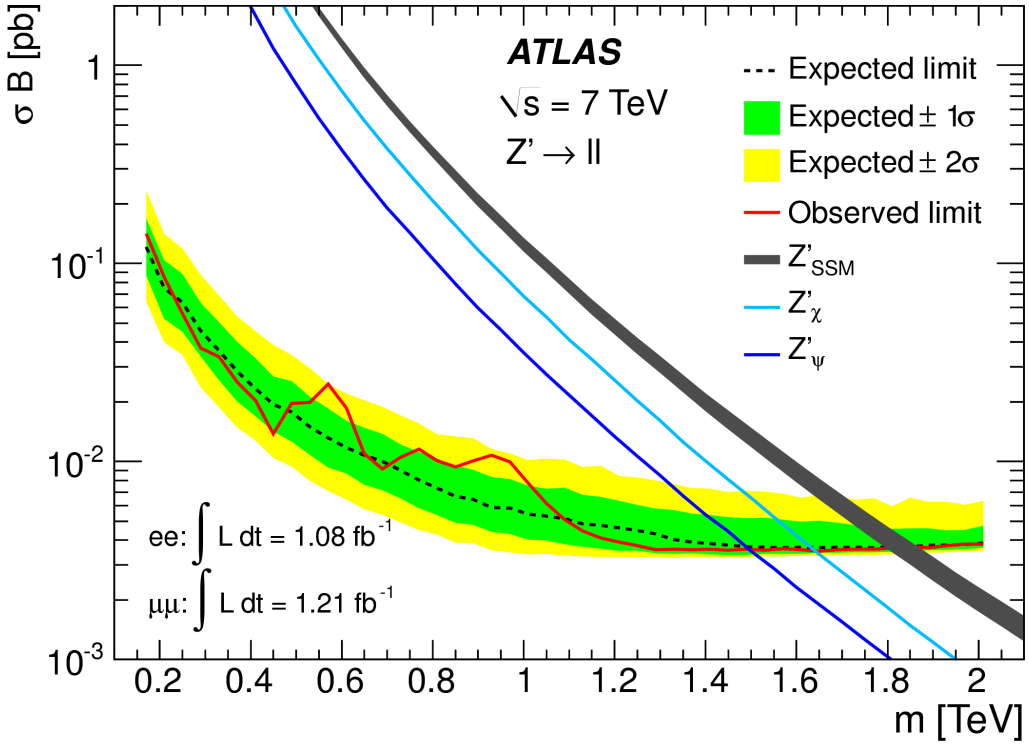
Statistical Method

- Use template shape fitting and Bayesian statistics
- Log likelihood ratio for discovery statistics: $LLR = -2 ln \frac{L(S+B)}{L(B)}$
  - Systematics: nuisance parameters, marginalized
  - 2D likelihood fit in bins of $\sigma_{Z'}$ and $M_{Z'}$
  - Marginalized posterior probability density shown on z-axis below
- P-values: electrons: 24%, muons: 54%
  - No excess: set limits





Spin 1 Combined Limits

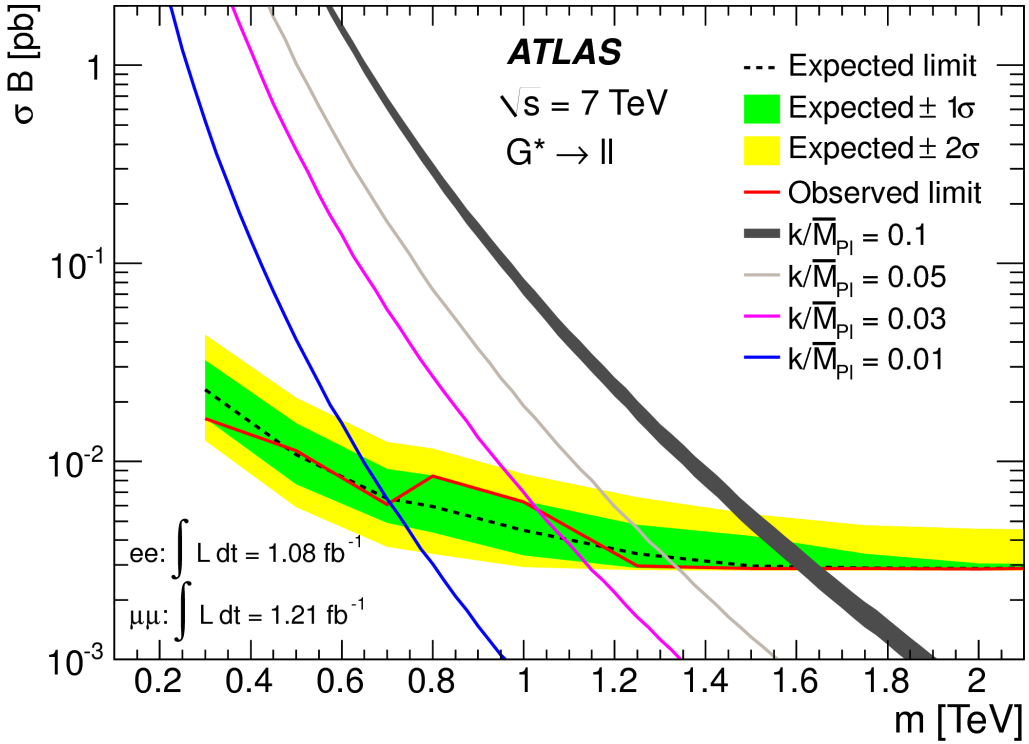


	Observed limit mass [TeV]	Expected limit mass [TeV]
$Z'_{SSM} \to e^+e^-$	1.70	1.70
$Z'_{SSM} \to \mu^+\mu^-$	1.61	1.61
$Z'_{SSM} \to \ell^+\ell^-$	1.83	1.83

Model	Z'_ψ	Z'_N	Z'_η	Z'_I	Z'_S	Z'_χ
Mass limit [TeV]	1.49	1.52	1.54	1.56	1.60	1.64

95% CL limits set with Bayesian method, flat prior in $\sigma_{Z'}$

Spin 2 Combined Limits



Limits for a coupling of $k/M_{pl} = 0.1$

	Observed limit mass [TeV]	Expected limit mass [TeV]
$G^* \to e^+e^-$	1.51	1.50
$G^* \to \mu^+\mu^-$	1.45	1.44
$G^* \to \ell^+\ell^-$	1.63	1.63

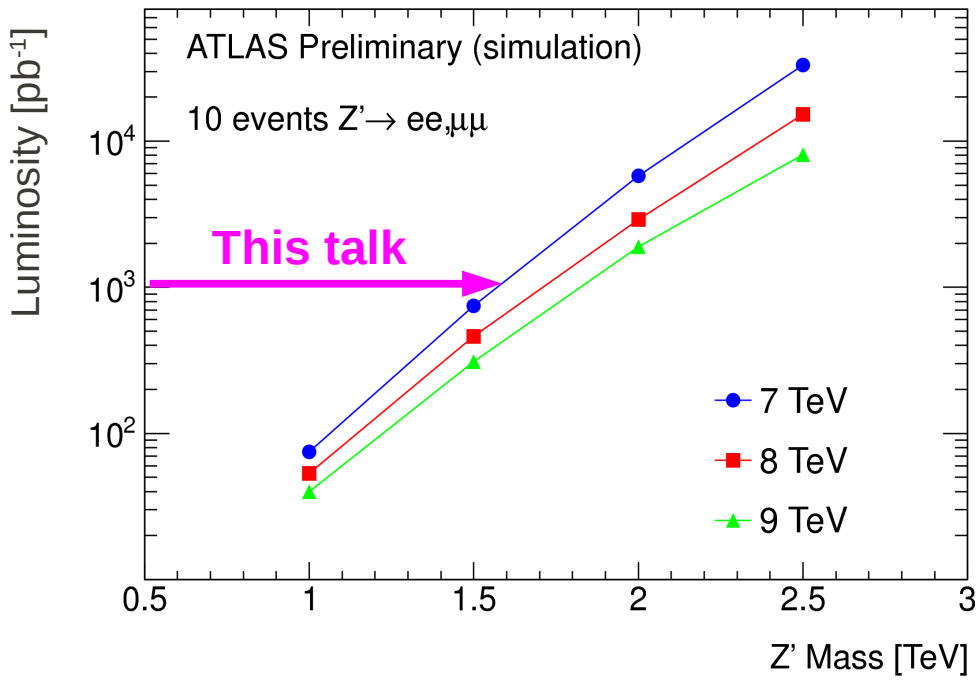
Limits for varying coupling k/M_{pl}

	RS Graviton			
Coupling	0.01	0.03	0.05	0.1
Mass limit [TeV]	0.71	1.03	1.33	1.63

95% CL limits set with Bayesian method, flat prior in σ_{G^*}

Conclusions

- No excess above Standard Model expectations seen in high mass dilepton events
  - Set limits on spin 1 and spin 2 models
- With much more data to be collected this year, discoveries may still be lurking...



Required luminosity to see 10 signal events

Bonus Slides

More details on MC processes

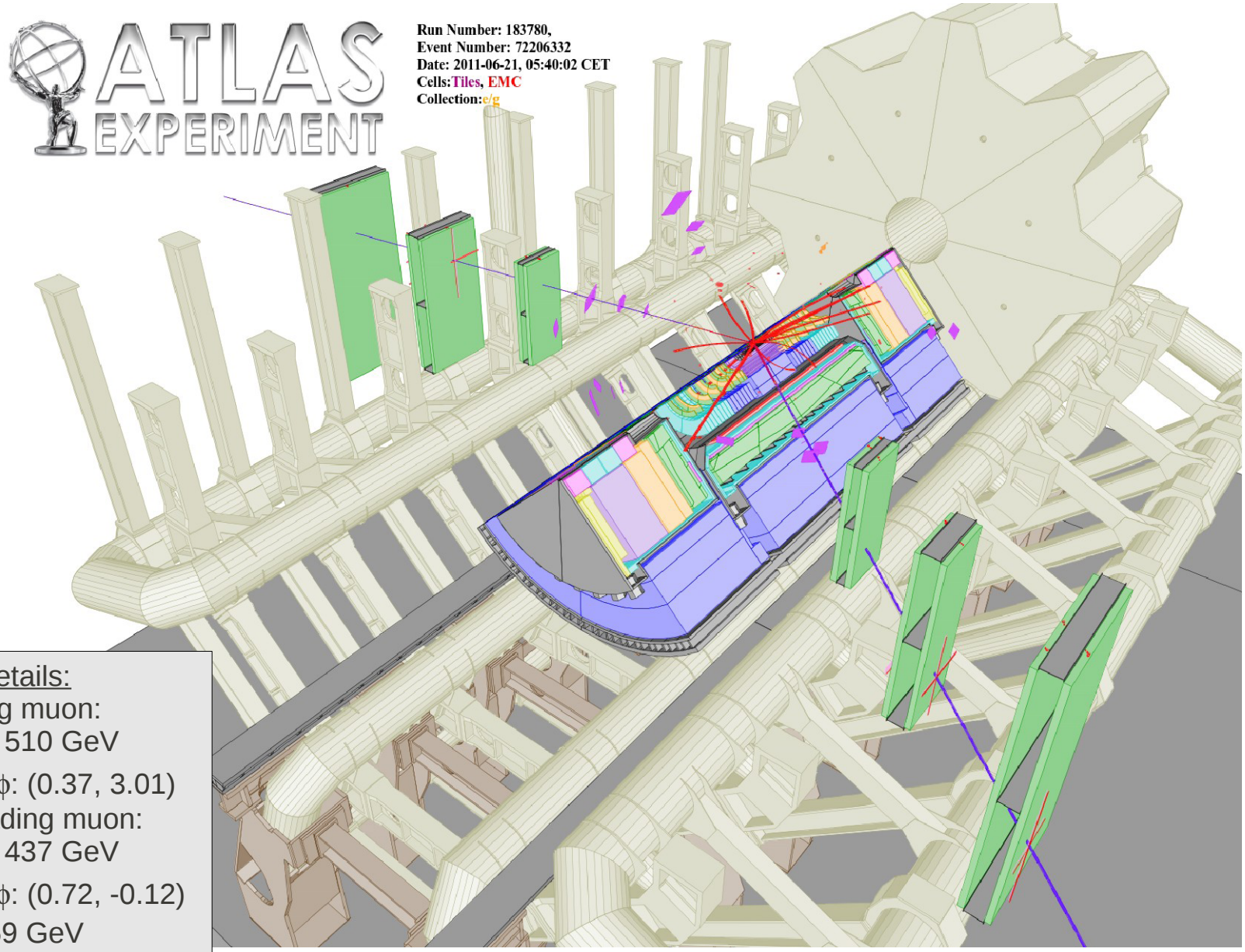
Process	Generator	Order
SSM Z'	PYTHIA	LO*, mass dependent k-factors for NNLO QCD corrections
RS Graviton	PYTHIA	LO*
Drell Yan	PYTHIA	LO*, mass dependent k-factors for NNLO QCD and higher order EW corrections
Dibosons	HERWIG	LO*, scaled to NLO cross section
W+jets	ALPGEN	LO*, scaled to NNLO cross section
Top quark pairs	MC@NLO	NLO, scaled to NNLO cross section

Expected/Observed Events

$m_{e^+e^-}$ [GeV]	70-110	110-200	200-400	400-800	800-3000
DY	258482 ± 410	5449 ± 180	613 ± 26	53.8 ± 3.1	2.8 ± 0.1
$t\bar{t}$	218 ± 36	253 ± 10	82 ± 3	5.4 ± 0.3	0.1 ± 0.0
Diboson	368 ± 19	85 ± 5	29 ± 2	3.1 ± 0.5	0.3 ± 0.1
W+jets	150 ± 100	150 ± 26	43 ± 10	4.6 ± 1.8	0.2 ± 0.4
QCD	332 ± 59	191 ± 75	36 ± 29	1.8 ± 1.4	< 0.05
Total	259550 ± 510	6128 ± 200	803 ± 40	68.8 ± 3.9	3.4 ± 0.4
Data	259550	6117	808	65	3

$m_{\mu^+\mu^-}$ [GeV]	70-110	110-200	200-400	400-800	800-3000
DY	236319 ± 320	5171 ± 150	483 ± 22	40.3 ± 2.5	2.0 ± 0.3
$t\bar{t}$	193 ± 21	193 ± 20	63 ± 6	4.2 ± 0.4	0.1 ± 0.0
Diboson	307 ± 16	69 ± 5	25 ± 2	1.7 ± 0.5	< 0.05
W+jets	1 ± 1	1 ± 1	< 0.5	< 0.05	< 0.05
QCD	1 ± 1	< 0.5	< 0.5	< 0.05	< 0.05
Total	236821 ± 487	5434 ± 150	571 ± 23	46.1 ± 2.6	2.1 ± 0.3
Data	236821	5406	557	51	5

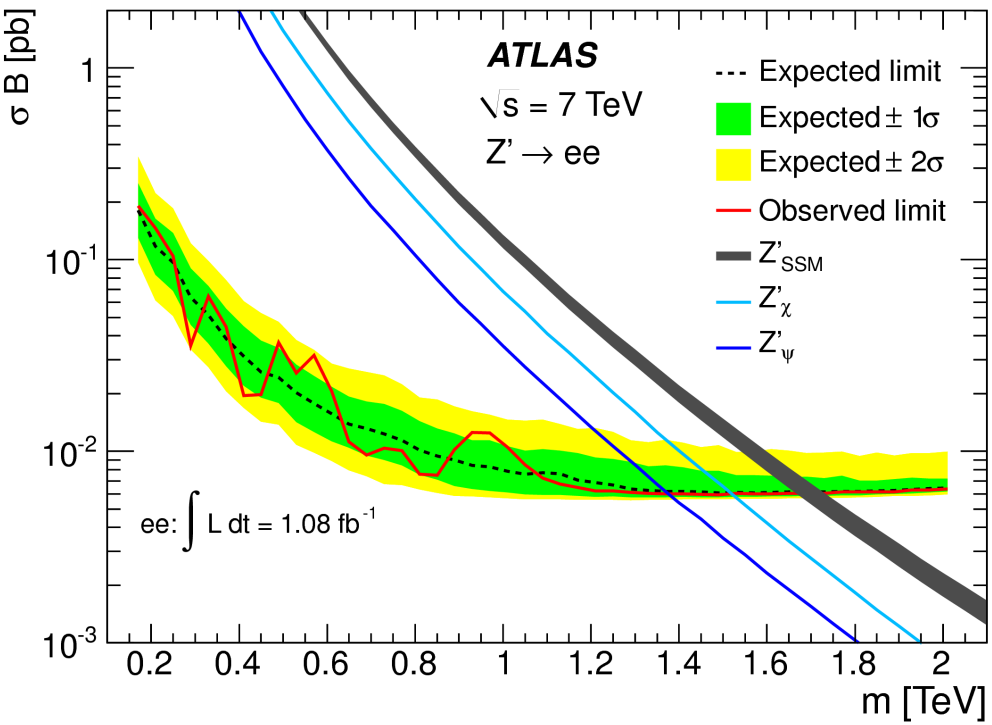
Highest $m_{\mu\mu}$ Event

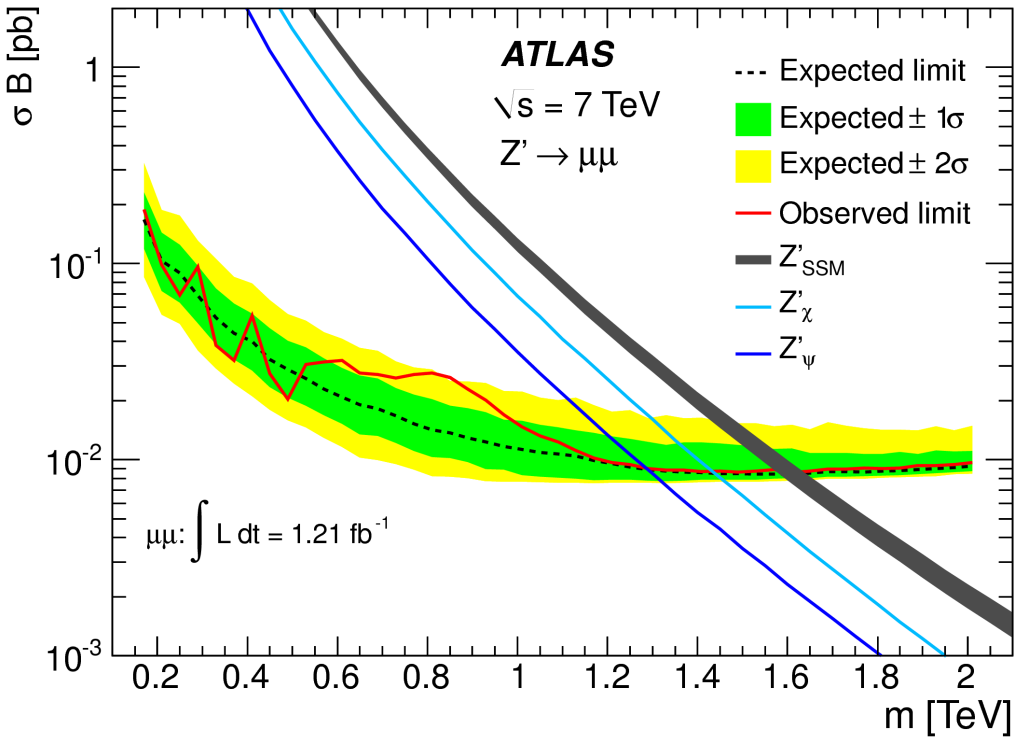


Event Details:

- Leading muon:
  - p_T: 510 GeV
  - η, ϕ: (0.37, 3.01)
- Subleading muon:
  - p_T: 437 GeV
  - η, ϕ: (0.72, -0.12)
- $m_{\mu\mu}$: 959 GeV

Spin 1 Individual Channel Limits





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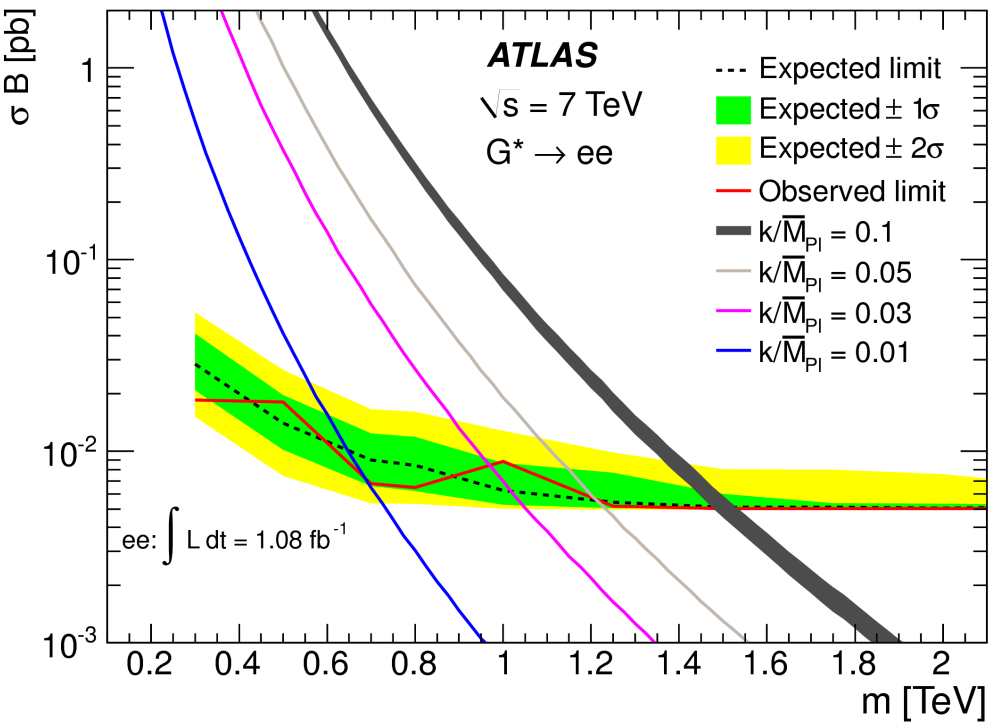
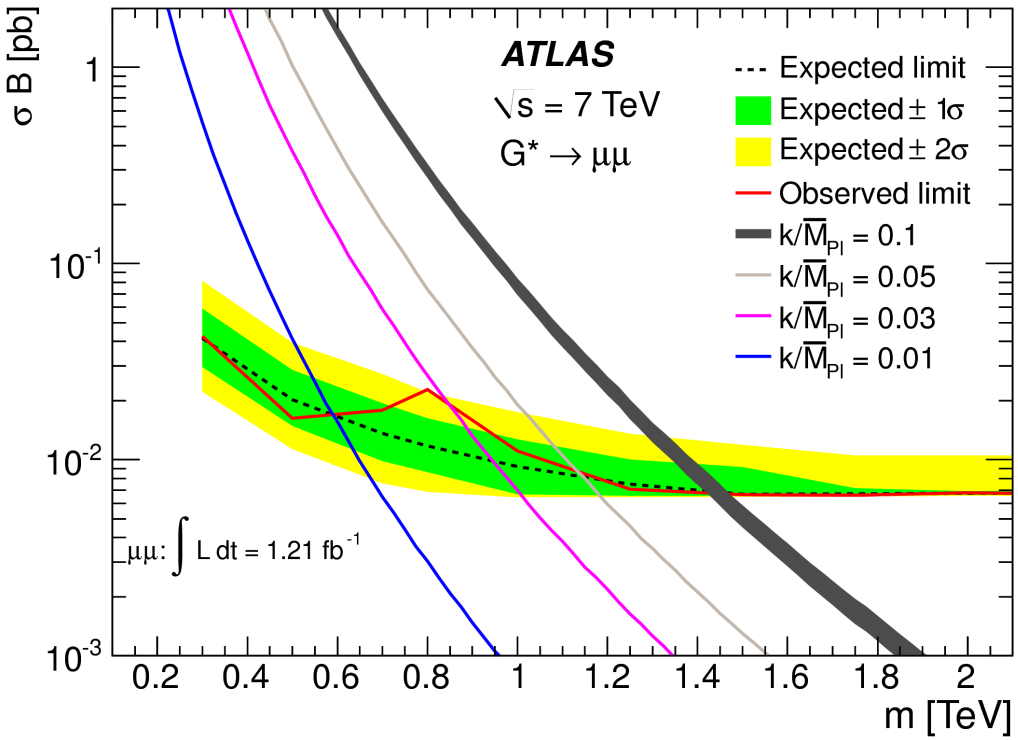
Spin 2 Individual Channel Limits





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Sensitivity: Limit Setting