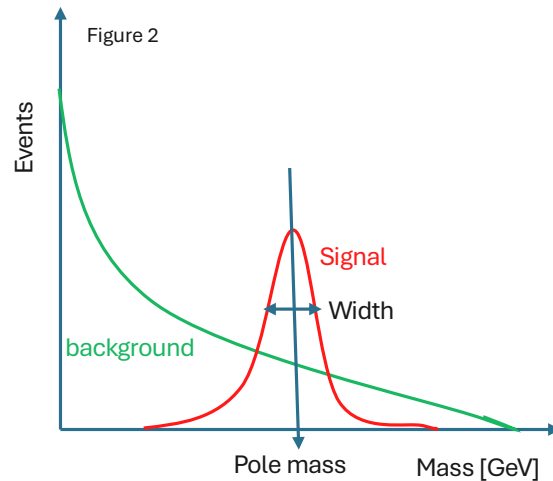
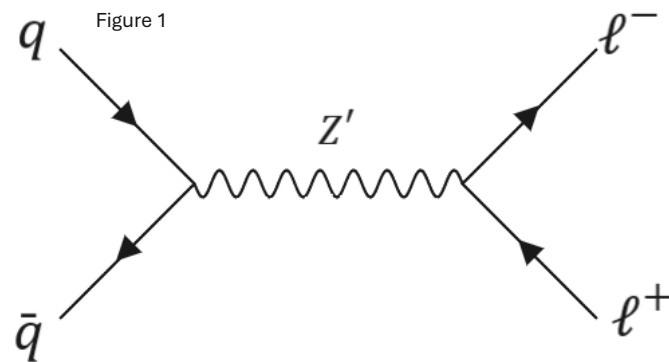


A Search for Z' Dilepton Resonances with *ATLAS* in Run 3 at the LHC

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Supervisor: Professor Tracey Berry

- Massive neutral spin-1 particles, consequence of additional Beyond Standard Model (BSM) $U(1)'$ symmetry
- Proposed by number of BSM theory models, search focuses on benchmark models [1]:
 - ‘Sequential Standard Model’ Z'_{SSM} - artificial model with same couplings to leptons as Standard Model Z
 - E6 motivated GUTs (Z'_χ and Z'_ψ)
- Can have TeV-scale masses – search for them with the LHC!
- ‘Minimal models’; fully specified by pole mass and width (measurable properties of potential resonance)



The Dilepton Channel

- Z'_χ , Z'_ψ , and Z'_{SSM} can all decay to pairs of stable oppositely charged leptons (electrons or muons):
 - Relatively small, well-understood backgrounds
 - Fully reconstructed final state
 - High signal selection efficiency
 - Rich history of discovery! (J/ψ (1974) , Υ (1977), Z (1983))
- Clear experimental signature in general purpose detector like ATLAS:
 - $\mu^+ \mu^-$:
 - Tracks in Inner Detector
 - Some showering in EM Calorimeter
 - Hits in Muon System
 - $e^+ e^-$:
 - Tracks in Inner Detector
 - Showers in EM Calorimeter

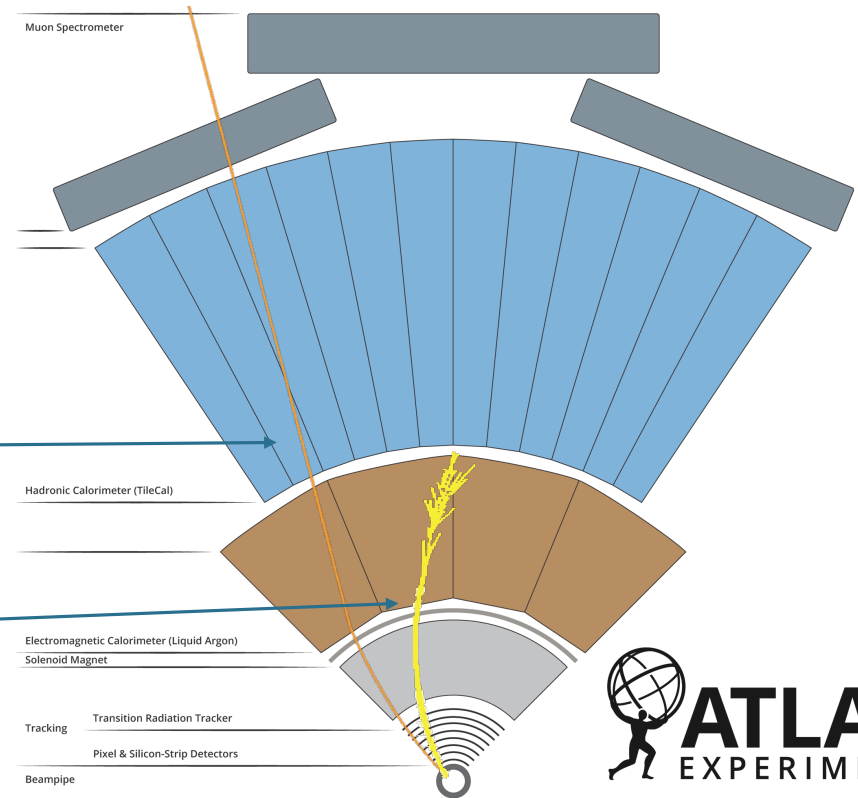


Figure 3

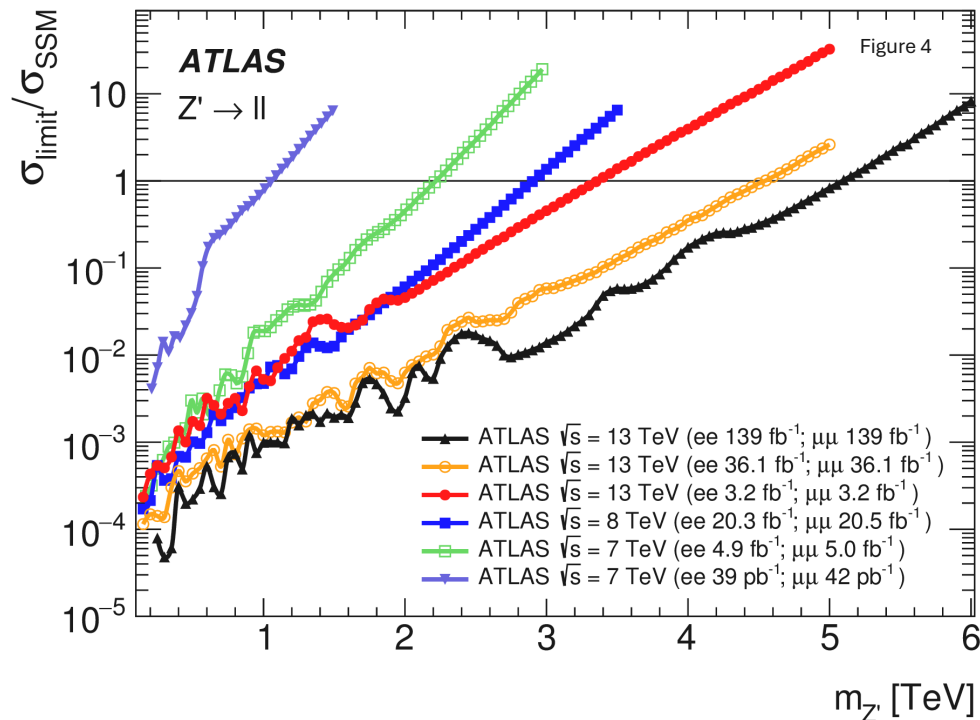
- Searches in Run 1 and Run 2 by ATLAS and CMS
- Observed no deviation from Standard Model background-only hypothesis, set limits at 95% Confidence Level

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		ll	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

Table 1: ATLAS limits on Z' mass

Model	Lower Limit on $M_{Z'}$ (TeV)					
	ee		$\mu\mu$		ll	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.11	4.13	4.29	4.30	4.56	4.55
Z'_{SSM}	4.72	4.72	4.89	4.90	5.15	5.14

Table 2: CMS limits on Z' mass

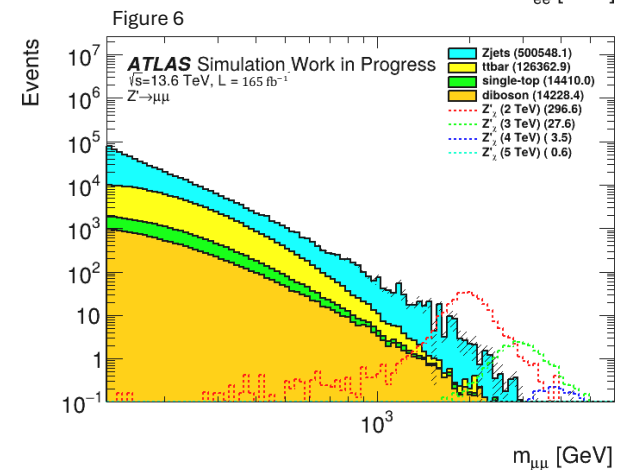
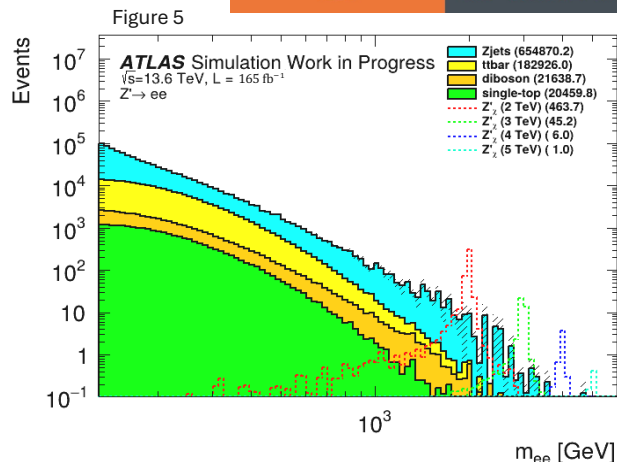


[Figure 4] Froidevaux, D. (2020). Integration of Detectors into a Large Experiment: Examples from ATLAS and CMS. In: Fabjan, C., Schopper, H. (eds) Particle Physics Reference Library. Springer, Cham. https://doi.org/10.1007/978-3-030-35318-6_16

[Table 1] The ATLAS collaboration., Aad, G., Abbott, B. et al. Search for new non-resonant phenomena in high-mass dilepton final states with the ATLAS detector. *J. High Energy Phys.* 2020, 5 (2020). [https://doi.org/10.1007/JHEP11\(2020\)005](https://doi.org/10.1007/JHEP11(2020)005)

[Table 2] CMS Collaboration. "Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $s = 13$ TeV". In: CERN-EP 026(2021)

- Search uses a partial Run 3 dataset (from 2022-2024 data taking runs – 165 fb^{-1}) and a statistical combination with Run 2 (139 fb^{-1}):
 - Discovery prospects enhanced by higher center-of-mass energy and improved statistics from larger dataset
- Select on ee and $\mu\mu$ channels, also consider their combination $\ell\ell$
- Observable: invariant mass of dilepton system
- Backgrounds (modelled with single analytic function):
 - Drell-Yan (irreducible)
 - $t\bar{t}$
 - Single- t
 - Diboson
 - Fakes (in electron channel only)
- Look for excesses over smoothly falling Standard Model background



Electron Fake Background Estimation

- Contribution to electron channel background from fakes – non-electrons reconstructed as electrons
 - Mostly from multijet processes (not well-modelled by Monte Carlo)
 - Negligible for muon channel
- Estimate using data-driven ‘matrix method’:
 - Use two tiers of selection criteria, selecting on lepton pairs ($N_{leading, subleading}$):
 - Tight T*: contains signal selection; tight ID
 - Baseline*: contains signal selection and other objects; loose ID
 - Loose L* = *baseline* minus *tight*

Tight selection

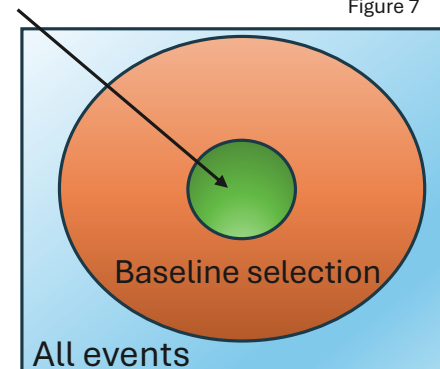


Figure 7

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f & f r_2 & f^2 \\ r_1(1-r_2) & r_1(1-f) & f(1-r_2) & f(1-f) \\ (1-r_1)r_2 & (1-r_1)f & (1-f)r_2 & (1-f)f \\ (1-r_1)(1-r_2) & (1-r_1)(1-f) & (1-f)(1-r_2) & (1-f)(1-f) \end{pmatrix} \cdot \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

Reconstruction
(measurable in data)

Truth (inaccessible in data)

- Invert to give number of fakes in signal selection in terms of measurable quantities!

$$\begin{aligned} N_{TT}^{fake} = & \alpha [r_1 f (f-1)(1-r_2) + f r_2 (r_1-1)(1-f) + f^2 (1-r_1)(1-r_2)] N_{TT} \\ & + \alpha f r_2 [r_1(1-f) + f(1-r_1) + f(r_1-1)] N_{TL} \\ & + \alpha f r_1 [f(1-r_2) + r_2(1-f) + f(r_2-1)] N_{LT} \\ & - \alpha f^2 r_1 r_2 N_{LL} \end{aligned}$$

$$\alpha \equiv \frac{1}{(r_1 - f)(r_2 - f)}$$

Electron Real & Fake Efficiency Estimation

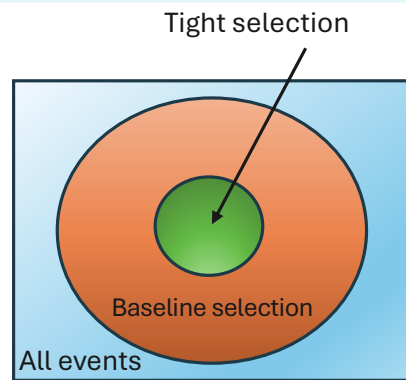


Figure 1

- Need to estimate dilepton real efficiencies r_1, r_2 and single lepton fake efficiency f :

$$r_{1,2} = \frac{N_{tight}^{real}}{N_{baseline}^{real}} \Rightarrow \text{Obtained in high-statistics (Drell-Yan) MC samples}$$

$$f = \frac{N_{tight}^{fake}}{N_{baseline}^{fake}} = \frac{N_{tight}^{data} - N_{tight}^{MC}}{N_{baseline}^{data} - N_{baseline}^{MC}} \Rightarrow \text{Obtained from fake-enriched data samples (invert isolation criteria wrt. to signal selection)}$$

- Create *tight* and *loose* selections, compute ratio of tight to *loose*, bin results in p_T and $|\eta|$

Leading lepton Real Efficiency r_1

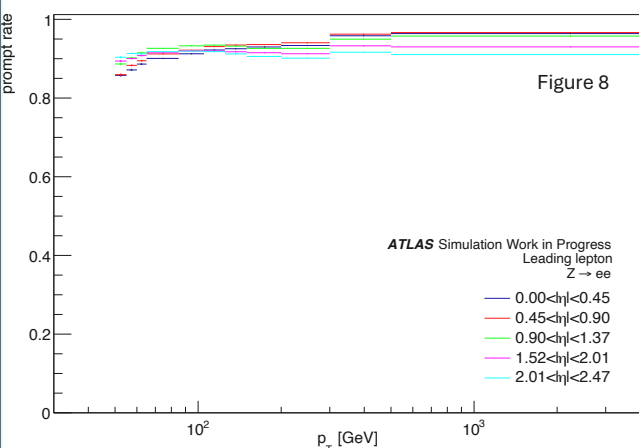


Figure 8

Subleading lepton real efficiency r_2

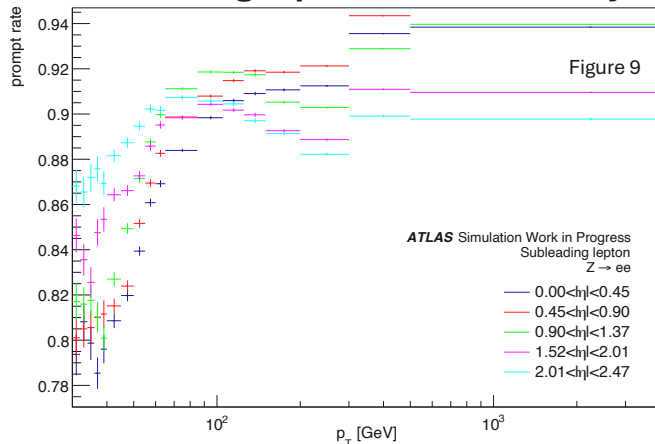


Figure 9

Single-lepton fake efficiency f

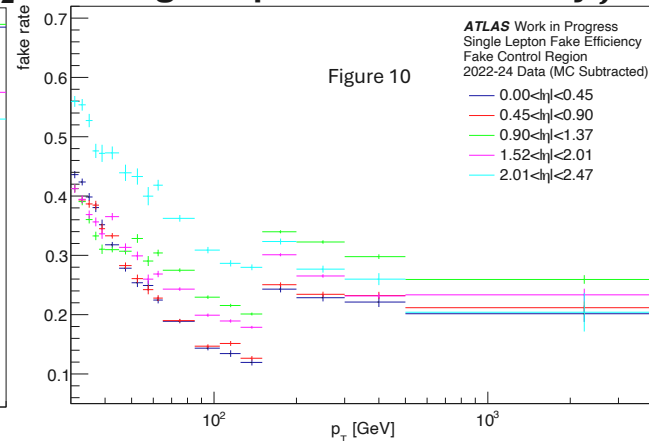
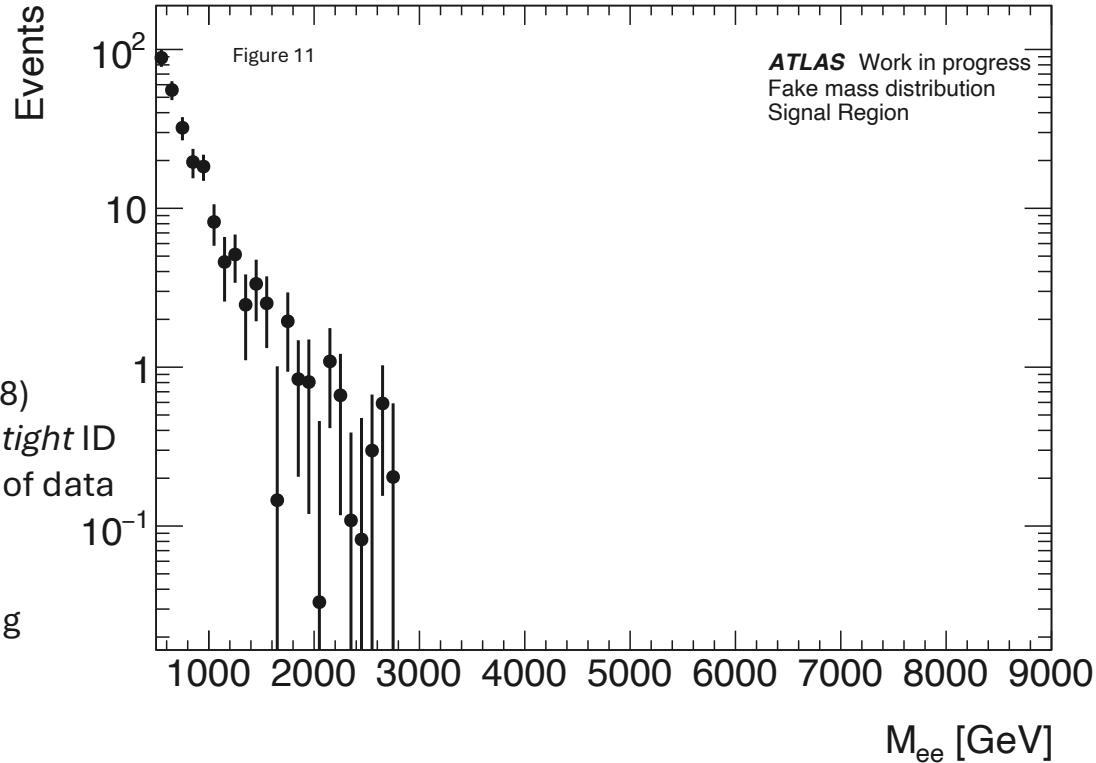


Figure 10

$$N_{TT}^{fake} = w_{TT}(r_1, r_2, f)N_{TT} + w_{TL}(r_1, r_2, f)N_{TL} + w_{LT}(r_1, r_2, f)N_{LT} + w_{LL}(r_1, r_2, f)N_{LL}$$

- Equation (see slide 7 for details) prescribes weights assigned to data events based on:
 - p_T and $|\eta|$
 - Corresponding values for r_1 , r_2 , and f (see slide 8)
 - Whether candidate objects in pair pass *loose* or *tight* ID
- Mass distribution of fakes obtained from reweighting of data events
- Constitutes $\sim 1\%$ of total background
- Distribution forms part of input to process of selecting analytic function for background modelling



- Cross-section times branching fraction ($\sigma \cdot B$) computations can be made for all signal models using reweighted high-statistics Drell-Yan samples
- After normalizing by target luminosity, can compute total $\sigma \cdot B$ by integrating mass spectrum $\sigma \cdot B = \frac{N}{L}$
- Compute fiducial $\sigma \cdot B$ by doing the same after applying fiducial cuts:

$$\begin{aligned}
 p_T^{lead}, p_T^{sublead} &> 30 \text{ GeV} \\
 |\eta_{lead}|, |\eta_{sublead}| &< 2.5 \\
 m_{\ell\ell} &> M_{pole} - 2\Gamma
 \end{aligned}$$

⇒ One-sided mass cut to remove low-mass tail from distribution, allow reinterpretation within common fiducial volume

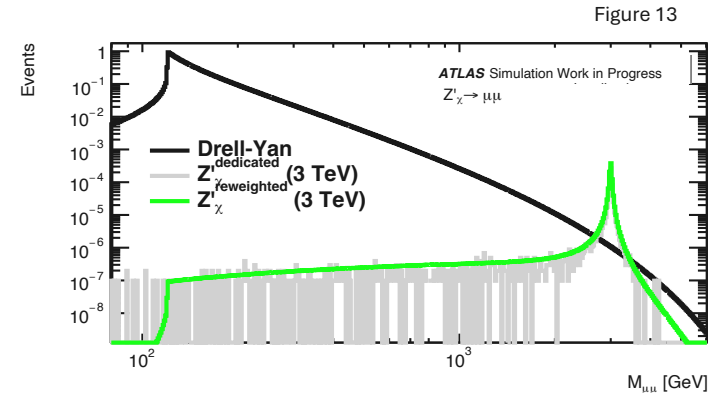
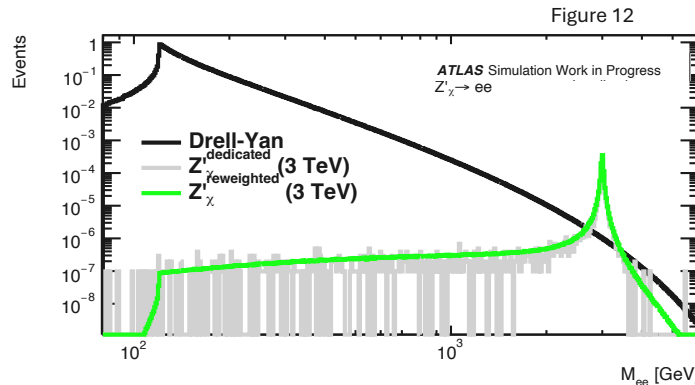


Figure 14

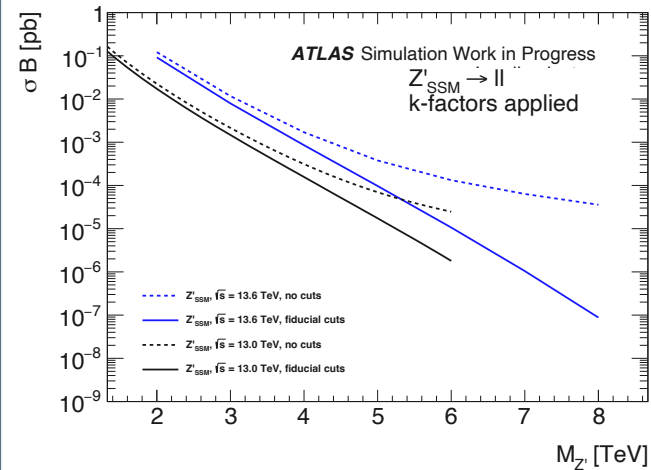


Figure 15

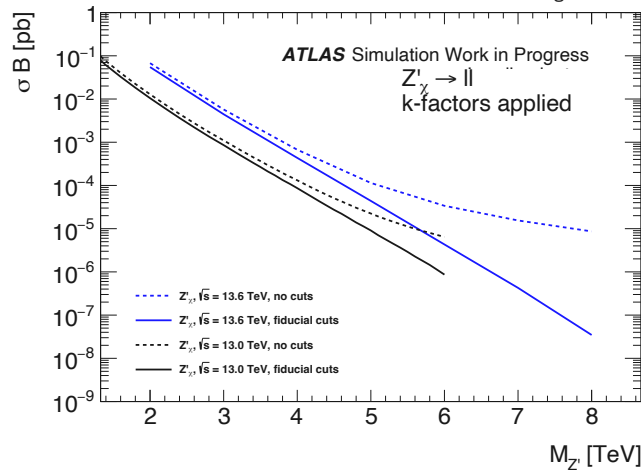
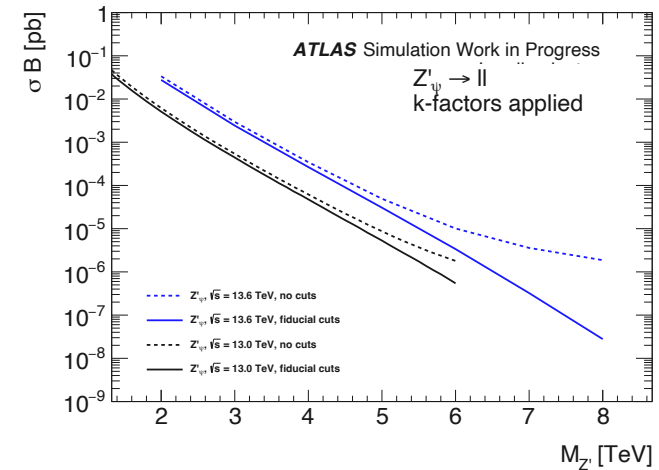


Figure 16



- Run 3 ($\sqrt{s} = 13.6 \text{ TeV}$) $\sigma \cdot B$ roughly 20% greater than Run 2 ($\sqrt{s} = 13.0 \text{ TeV}$)
- Effect of fiducial cuts is to reduce model dependence at the cost of some $\sigma \cdot B$ – good for reinterpretation
- Next step: use σB curves to compute expected limits on the three signal models

- Presented summary of some contributions to Run 3 search for new dilepton resonances:
 - Fake electron background estimation
 - Computation of cross-sections; will be used to set limits on benchmark models
- Analysis in and advanced stage; will set the best limits yet on the Z' mass and cross-section!
- Will follow up with legacy paper combining the full Run 3 dataset with Run 2
- Watch this space and others for exciting things from the exotics group in ATLAS!