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Search for a new gauge boson Z' in 4muon events with the ATLAS detector

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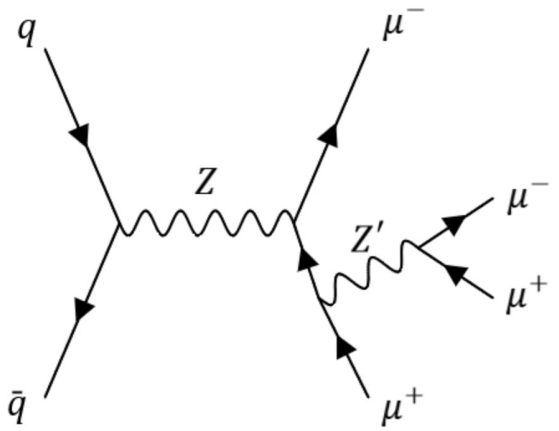
Motivation

- A new gauge boson Z' is predicted by well-motivated gauged $L_\mu - L_\tau$ models, which extend the SM to **address the observed muon anomalous magnetic dipole moment (Link) and the B physics anomalies (Link1, Link2).**
- In the $L_\mu - L_\tau$ model the Z' boson couples only to the 2nd and 3rd generation leptons. The Lagrangian of the Z' and interactions is:

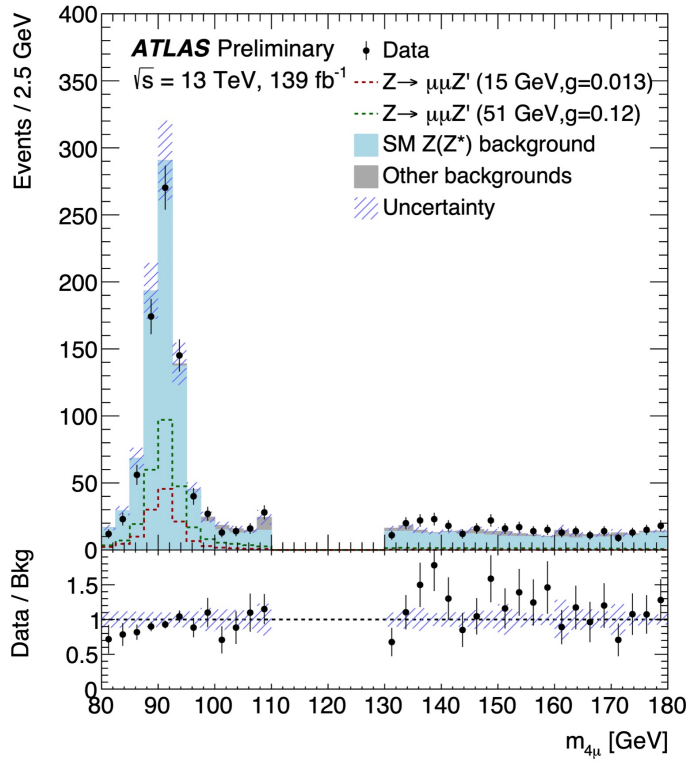
$$L_{Z'} = -\frac{1}{4} Z'_{\alpha\beta} Z'^{\alpha\beta} + \frac{1}{2} M_{Z'}^2 Z'^{\alpha} Z'_{\alpha} - g_{Z'} Z'_{\alpha} (\bar{l}_2 \gamma^{\alpha} l_2 + \bar{\mu} \gamma^{\alpha} \mu - \bar{l}_3 \gamma l_3 - \bar{\tau}\, \gamma^{\alpha} \tau)$$

  Where $Z'_{\alpha\beta} = \partial_\alpha Z'_\beta - \partial_\beta Z'_\alpha$ is the field strength tensor, and $l_i = (\nu_i, e_i)^T$ ($i = 2, 3$ for the 2nd and 3rd lepton doublet)
- Z' couples to the 2nd and 3rd generation left-handed leptons (μ, τ and neutrinos) and right-handed muon and tau singlet as shown in Lagrangian above, where $g_{Z'} = \varepsilon g_1$, is the U(1) coupling const. ($g_1 = 0.351\ @m_Z$), and ε is the fraction. A dedicated search for Z' will be performed in $\{m_{Z'}, g_{Z'}\}$ parameter space of the model.
- At the LHC, Z' could be produced in the final-state radiation of muon or tau leptons. We use radiative Drell-Yan production around Z to search for the Z' in this analysis.

Analysis Design



- Basic selections to select 4muon events in the mass region of 80 to 180 GeV, excluding Higgs region
  - H->WW/ZZ->mvmv/mmvv->mmvvZ'->mmmmvv would have different kinematic than other mass region due to MET
  - H->mm->mmZ'->mmmm would have too small cross section
- Events further split into low mass ($m_{Z'}$ < 42 GeV) and high mass ($m_{Z'}$ > 42 GeV) region
  - In the low mass region, Z' would likely peak at sub-leading dimuon pair
  - In the high mass region, Z' would likely peak at leading dimuon mass
- Two pDNN are trained. One for low mass, one for high mass
  - For final limit setting, cut on DNN score and then fit on the leading (sub-leading) dimuon mass for high (low) mass Z'

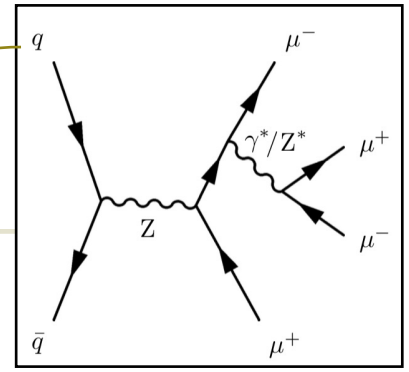


Data and MC Samples

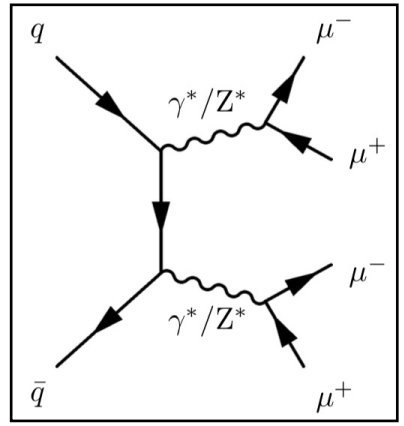
- **Data**
  - Full run-2 datasets with $139\ fb^{-1}$ collected in ATLAS detector
- **Signal Samples**
  - Leading Order (LO) Universal Feynman rules Output (UFO) model with MadGraph + Pythia8
  - Mass points from 5 GeV to 75 GeV
    - "low mass": [5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 27, 31, 39] GeV - 13 mass points
    - "high mass": [42, 45, 48, 51, 54, 57, 60, 63, 66, 69, 72, 75] GeV - 12 mass points
- **Background Samples**
  - background component depends on the $m_{4\mu}$ region we are looking at
  - >95% background from SM single resonant $Z \rightarrow 4\mu$ (s-channel)
  - ~4% background from SM t-channel ZZ production from $q\bar{q}$
  - $gg \rightarrow ZZ$: negligible under the Z peak. ~6% level in Z off-shell region
  - Other minor backgrounds (with mis-identified muons): Z+jets, ttbar

Major irreducible backgrounds
Sherpa 2.2.2

dominant (>95%)



small (~4%)



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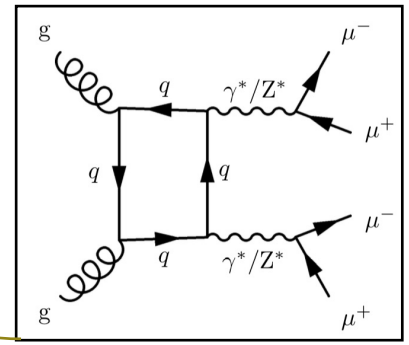


Signal Simulation

Table 1: Summary of the chosen Z' hypotheses and corresponding coupling, width, and cross-section (calculated at LO accuracy in QCD) at each mass point.

$m_{Z'}$ [GeV]	g	Γ [GeV]	σ [fb]	$m_{Z'}$ [GeV]	g	Γ [GeV]	σ [fb]
5	0.0080	2.45×10^{-5}	9.96	42	0.0900	2.71×10^{-2}	13.38
7	0.0085	3.99×10^{-5}	7.06	45	0.1000	3.58×10^{-2}	11.72
9	0.0090	5.78×10^{-5}	5.60	48	0.1100	4.62×10^{-2}	9.96
11	0.0095	7.89×10^{-5}	4.65	51	0.1200	5.84×10^{-2}	8.24
13	0.0100	1.03×10^{-4}	3.95	54	0.1600	1.10×10^{-1}	10.07
15	0.0120	1.72×10^{-4}	4.45	57	0.2000	1.81×10^{-1}	10.73
17	0.0140	2.65×10^{-4}	4.80	60	0.2665	3.39×10^{-1}	12.92
19	0.0160	3.87×10^{-4}	5.00	63	0.3330	5.56×10^{-1}	13.70
23	0.0240	1.05×10^{-4}	7.30	66	0.4000	8.40×10^{-1}	13.62
27	0.0320	2.20×10^{-3}	8.50	69	0.4670	1.20	13.16
31	0.0400	3.95×10^{-3}	8.72	72	0.5335	1.63	12.74
35	0.0600	1.00×10^{-2}	12.82	75	0.6000	2.15	12.65
39	0.0800	1.99×10^{-2}	14.77				

- ✓ The decay width highly depends on the coupling values
- ✓ Coupling values used in the generation were chosen following rough estimate of the expected limit

Event Selections and Efficiency

Table 2: The Z' signal event selection efficiencies compared to the events passing the previous cut level for several representative mass points. The overall signal efficiencies are the products of the 4μ MC filter and pre-selection efficiencies described in this section.

$m_{Z'}$ [GeV]	5	42	63	72
MC simulation filter efficiency	32.8%	57.7%	61.0%	64.7%
Number of identified muons ≥ 4	47.3%	74.1%	70.8%	72.4%
$p_{\mathrm{T}}^{i}(i = 1,4) > 20,\ 15,\ 8,\ 3$ GeV	60.0%	82.6%,	90.3%	93.6%
$\Delta R(\mu_i, \mu_j) > 0.2$ & vertex requirement	87.2%	95.4%	96.2%	96.6%
Isolation	54.2%	76.9%	79.2%	84.1%
$m_{4\mu}$ within [80, 110] or [130, 180] GeV	91.9%	88.8%	58.9%	33.5%
Combined event selection efficiency	12.3%	39.9%	28.7%	18.4%
Overall 4μ signal efficiency	4.1%	23.0%	17.5%	11.9%

Low efficiency in the low and high mass end due to

- ✓ Muon kinematic cut for low end
- ✓ Production phase space limit for high end

Systematics and Modelling Check

- From experimental sources due to imperfect measurement
  - Muon measurement (energy, identification), trigger and isolation efficiency, pile-up, luminosity
  - In total ~4% for the background, 4% to 8% for signal (depending on Z' mass)
- From theoretical sources due to limited accuracy
  - PDFs, alphaS, QCD scale, parton shower
  - In total ~5.5% for the dominant SM Z(Z*) -> 4muon process. Below 2% for signal
- In addition, since LO signal is used, thus the modelling of the 4muon system kinematics has been checked using data, by studying SM Z->mm.

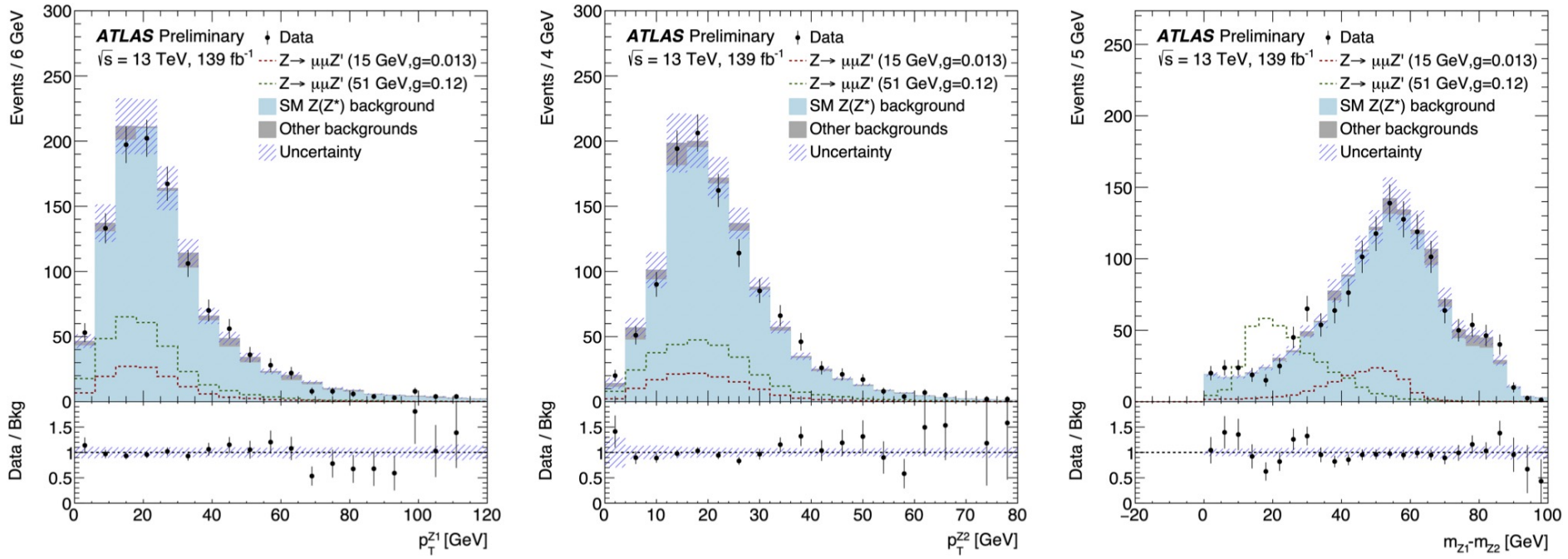
Background Estimation

- Dominant background from SM Z(Z*) process. Modelled with MC, and constraint with data for normalization
- Other minor prompt 4muon background. Modelled with MC
- Non-prompt background (top, Zjet). Estimated with data-driven method

Table 3: The selected 4μ events in data and the estimated backgrounds and their combined statistical and systematic uncertainties.

Data	Total background	$qq \to ZZ^*$ from MC	$gg \to ZZ^*$ from MC	$ttV + VVV + H$ from MC	Reducible background from data
1131	1148 ± 70	1065^{+70}_{-69}	15.6 ± 2.5	6.2 ± 2.9	$61.1^{+8.3}_{-9.1}$

Kinematic Distributions



(a) (b) (c)

Figure 2: Distributions of $p_{\mathrm{T}}^{Z_1}$ (a), and $p_{\mathrm{T}}^{Z_2}$ (b), and the mass difference of the Z_1 and Z_2 candidates (c). Small background contributions are denoted as "other backgrounds", including 4μ events containing non-prompt muons estimated from data and from ttV, VVV, and Higgs boson production processes.

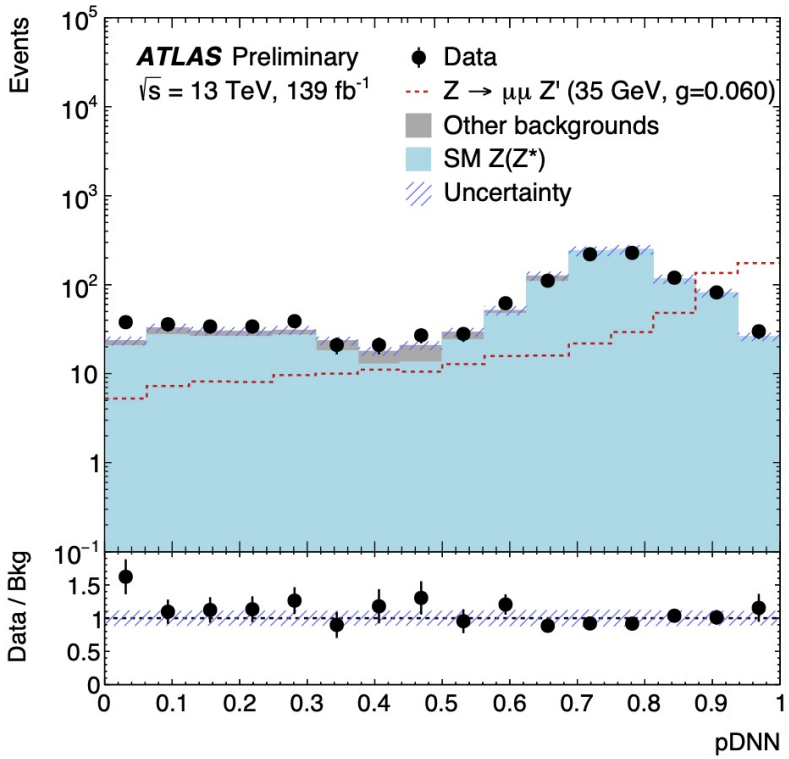
Multi-variable Analysis

- Parametrized deep neutral network (pDNN) used
  - Allows the training of one single classifier for multiple signal mass hypotheses in the interested search region
  - Two independent pDNN trained. One for low mass signal and another for high mass, since signal and background kinematics, as well as background component are different

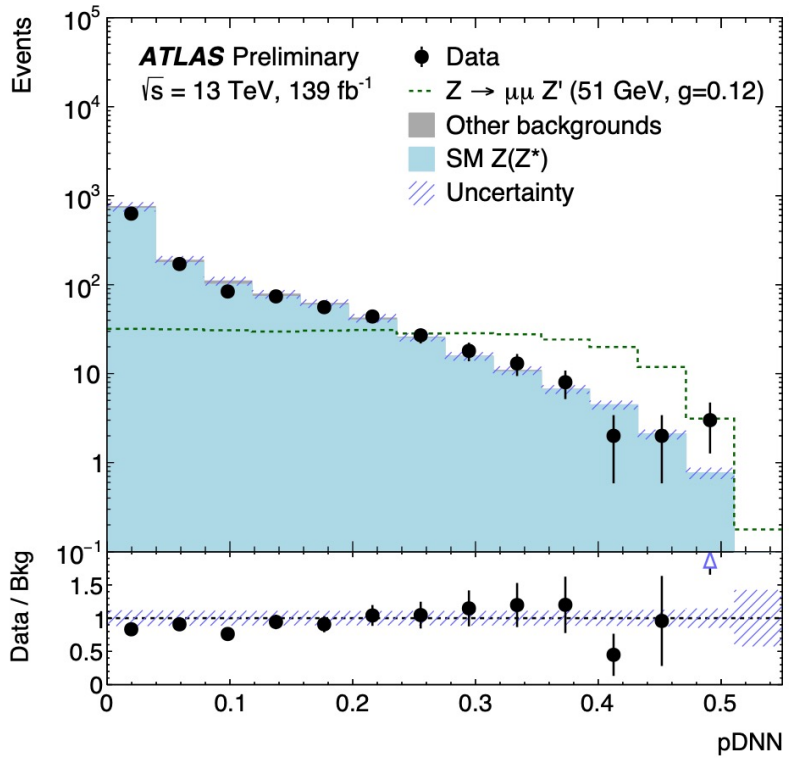
Input variables

variable	description
Mass (θ)	parametrized signal mass feature
$p_{\mathrm{T}}^{i}, \eta^{i}$, (i =1,4)	transverse momentum p_{T} and η of μ_i (i=1,4)
p_{T,Z_i}, (i=1,2)	transverse momenta p_{T} of the Z_1 and the Z_2
$M_{Z1} - M_{Z2}$	subtraction between the mass of two di-muon pairs
$\Delta_R(\mu_i^+, \mu_i^-), i = 1, 2$	ΔR of the di-muon formed Z_i (i=1,2)
$\Delta_\eta(\mu_i^+, \mu_i^-), i = 1, 2$	$\Delta\eta$ of the di-muon formed Z_i (i=1,2)
$M_{4\mu}$	invariant mass of 4 muons
$p_{\mathrm{T},\,4\mu}$	transverse momenta of the 4 muons system

pDNN Score



(a) low mass: $m_{Z'} \leq 42$ GeV



(b) high mass: $m_{Z'} \geq 42$ GeV

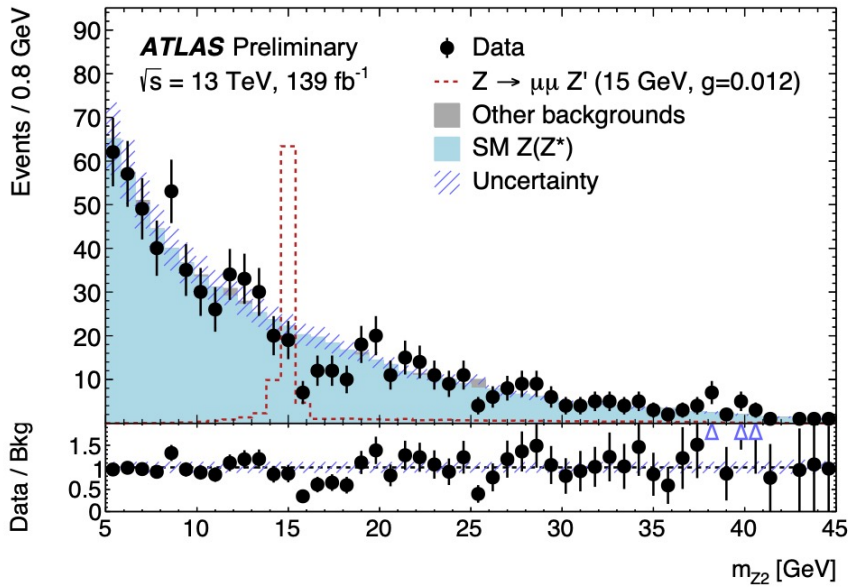
Figure 3: The pDNN output discriminant variable distributions for low mass (a) and high mass (b) with a signal sample at 35 GeV and 51 GeV, respectively.

Further cut on pDNN scores to enhance expected significance

Cut values have been optimized for each signal mass point

- ✓ Ranges from 0.42 to 0.72 for low mass
- ✓ Ranges from 0.12 to 0.16 for high mass

Dimuon Mass after pDNN Cut



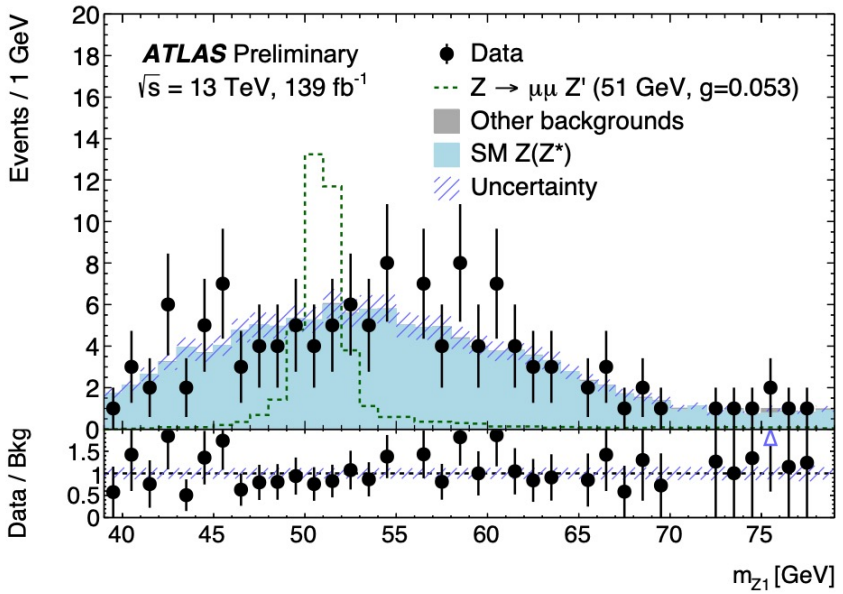


Figure 4: Mass spectra of m_{Z2} (left) and m_{Z1} (right) for the pDNN-selected events with a signal sample at 35 GeV and 51 GeV, respectively.

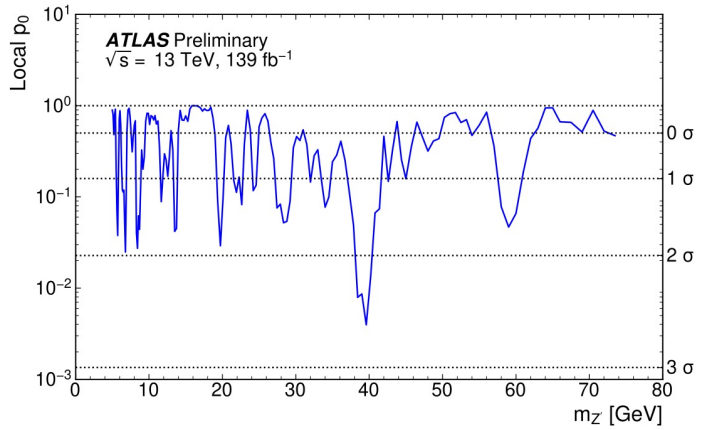
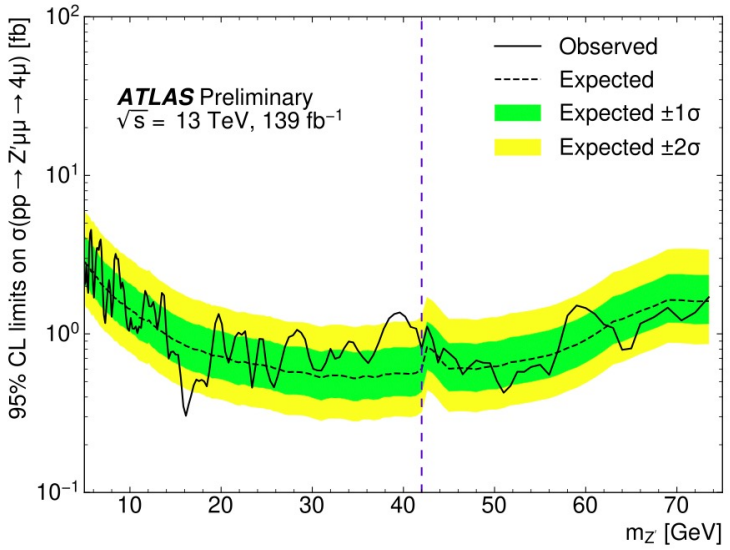


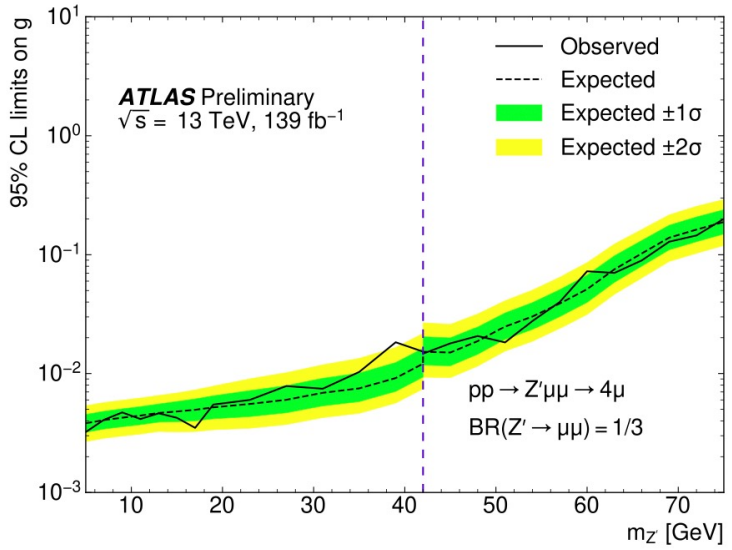
Figure 5: The p_0-value scan across the Z' mass signal regions.

Largest deviation at 39.6 GeV
- ✓ Local: 2.65σ
- ✓ Global: 0.52σ

Observed and Predicted 95% CL Limits on Cross Section and Coupling

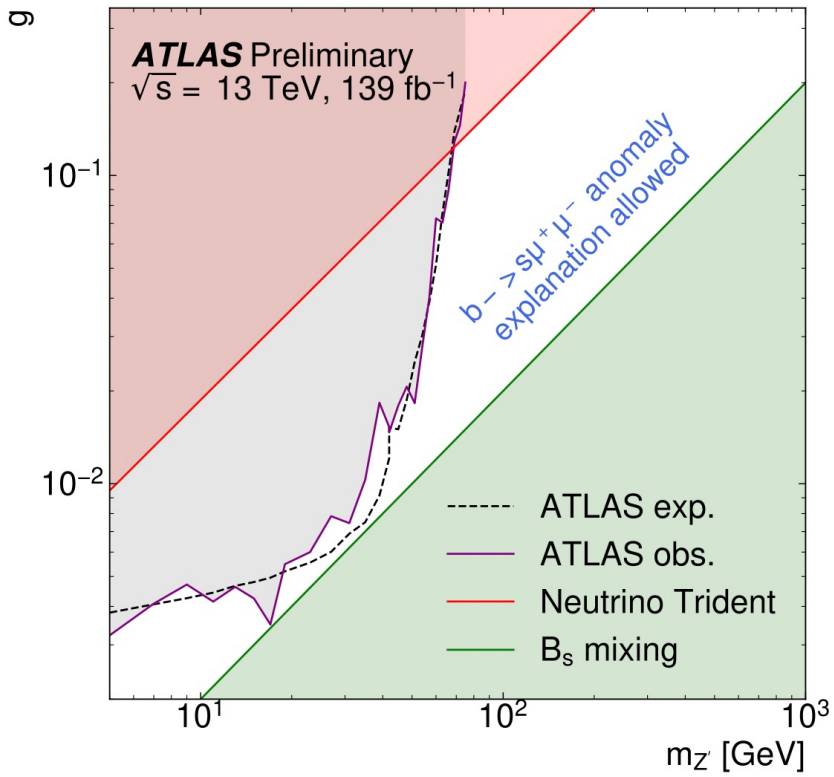


(a)



(b)

Figure 6: 95% CL upper limits (expected and observed) on the cross-sections times branching fraction (a) and coupling parameter (b). The discontinuity at 42 GeV represents the border of the low/high mass classifiers.



Neutrino Trident: Phys. Rev. Lett. 66 (24 1991) 3117
B_s mixing: JHEP 12 (2016) 106

Summary

- A search of a new gauge boson Z', trying to address several flavor related anomalies observed in recent years
- Full Run 2 data used. CONF note released for ICHEP 2022
  - ATLAS-CONF-2022-041

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