Search for a new Z' gauge boson via the $pp \to W^{\pm(*)} \to Z'\mu^{\pm}\nu \to \mu^{\pm}\mu^{\mp}\mu^{\pm}\nu$ process with the ATLAS detector

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On behalf of the ATLAS collaboration

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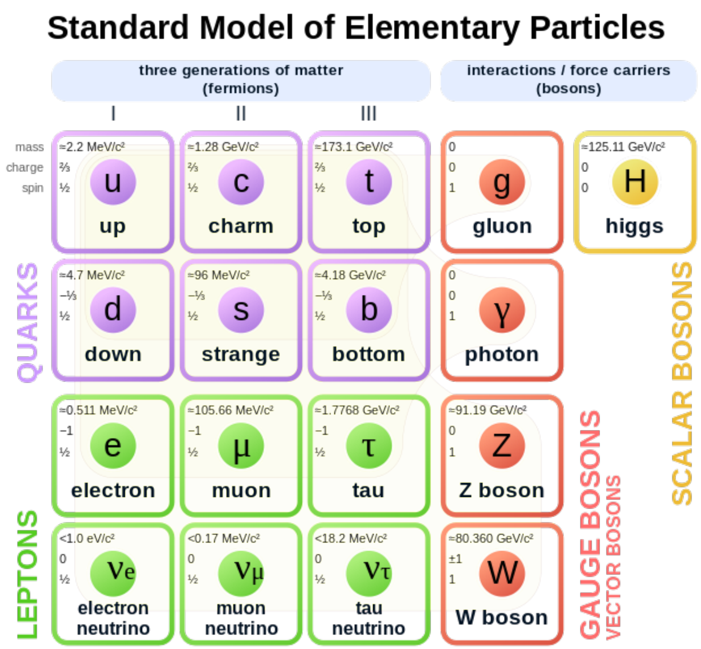
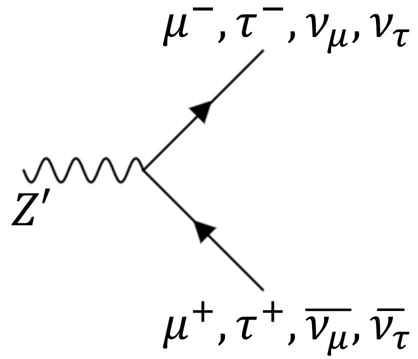
Introduction

- To address the problems in the Standard Model, Grand Unified Theories are required with a larger unification group containing new symmetries.
  - Predicts at least one extra neutral gauge boson, Z'.
- The lepton family numbers L_e, L_μ, L_τ are conserved under the SM.
  - $L_1 \equiv L_e - L_\mu, L_2 \equiv L_e - L_\tau$, and $L_3 \equiv L_\mu - L_\tau$ are anomaly-free and can be gauged with a new neutral gauge boson introduced to the theory.
  - Coupling to the electron is strictly constrained by the very precise $e^+e^- \to e^+e^-$ LEP data.
- Still some potential and opportunities for the $U(1)_{L_\mu - L_\tau}$ model.

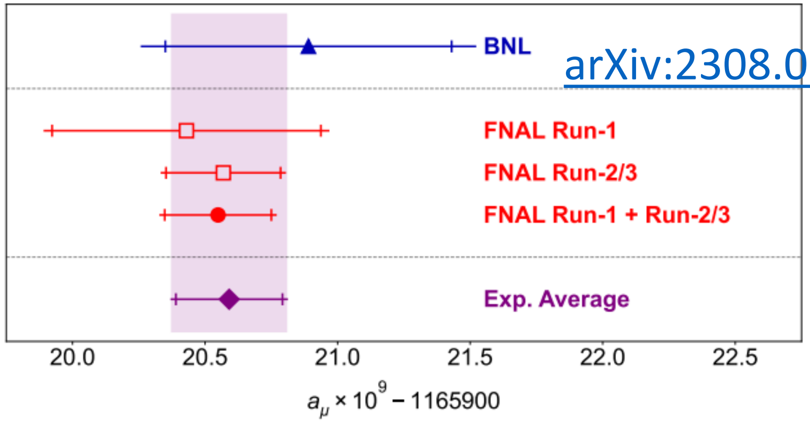




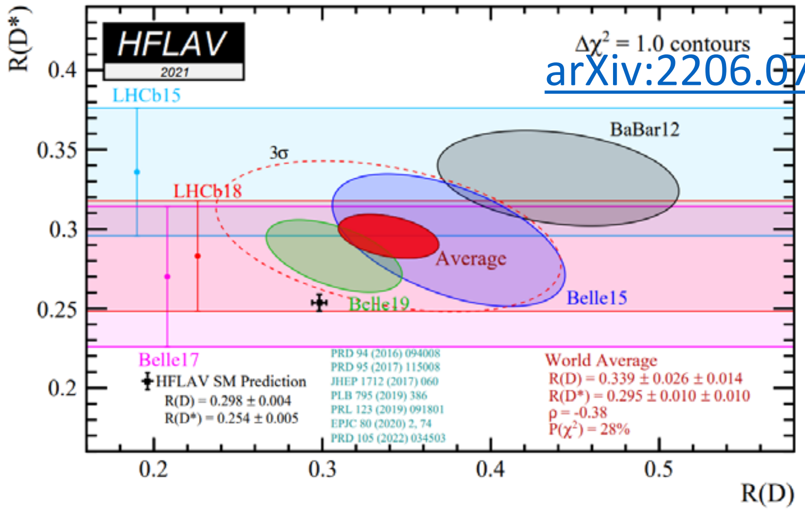
Simplest Z' model

- $U(1)_{L_\mu - L_\tau}$ symmetry is broken with resulting a massive gauge boson Z'.
  - Z' only couples to the leptons of the second and third generation.
  - Model contains two additional parameters $\{g_{Z'}, M_{Z'}\}$

- Potentially address some observed anomalies. Answer the dark matter and neutrino mass problems.
  - Muon anomalous magnetic moment, PhysRevLett.126.141801
  - Semileptonic B decay, arXiv:2206.07501v2
  - Neutrino mass, arXiv:hep-ph/0411190



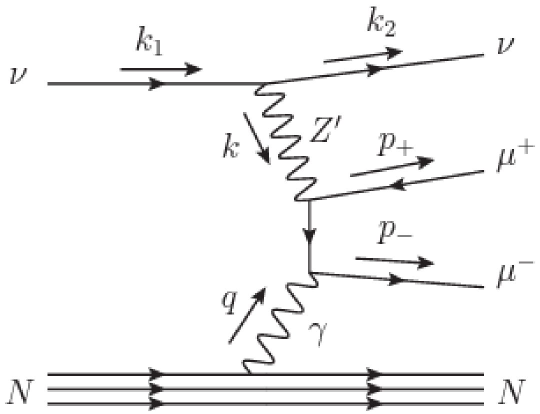
arXiv:2308.06230

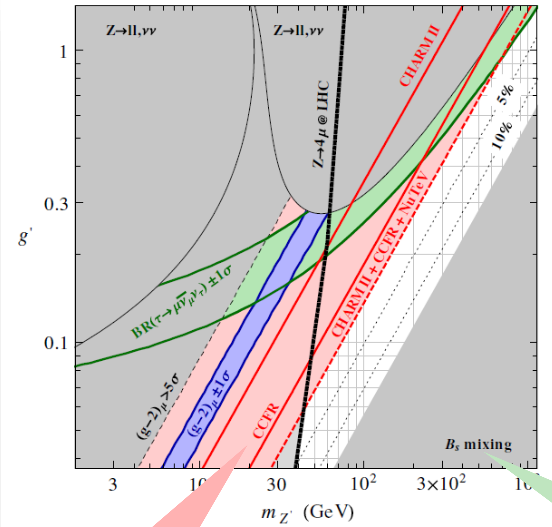


arXiv:2206.07501

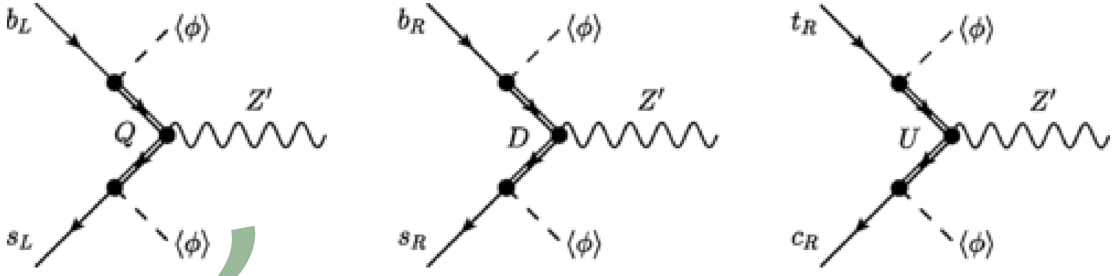
Constraints on Z' parameter space

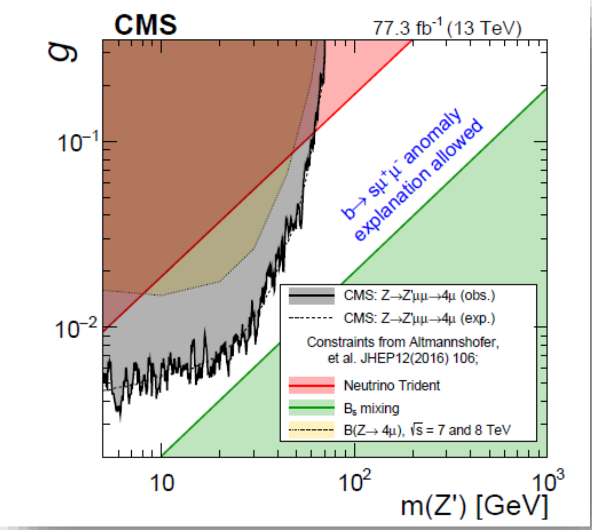
arXiv:1406.2332

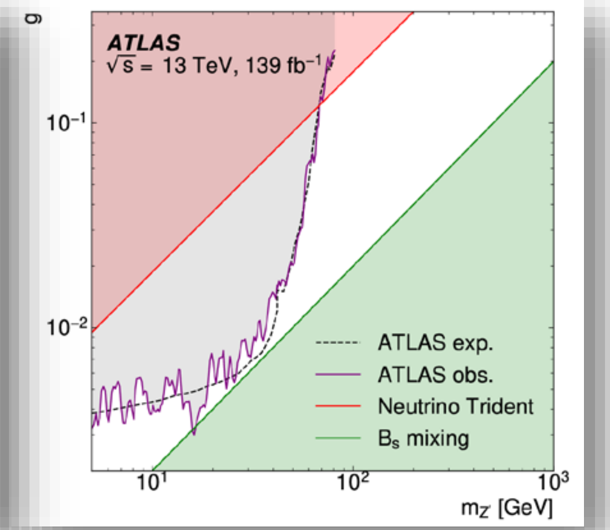




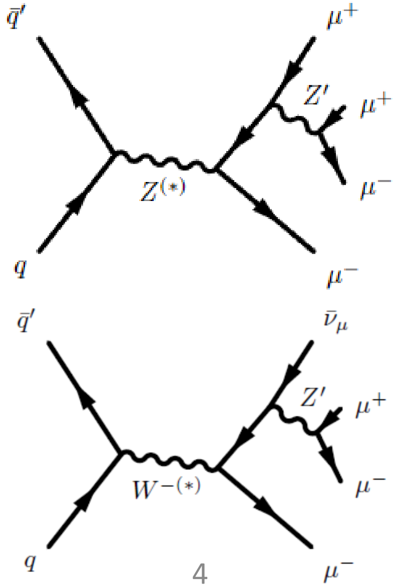
PhysRevD.89.095033







- Previous search with 4μ final state on LHC: CMS, 2019(77.3 fb^{-1}), ATLAS, 2023(139 fb^{-1})
- First time to use the 3μ final state to search this Z'.



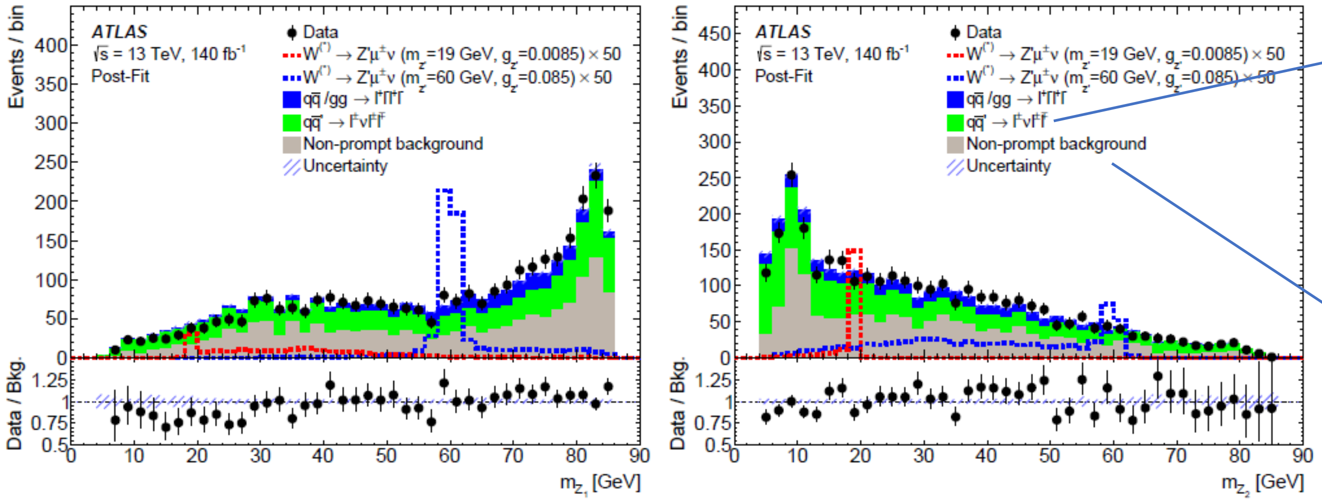
Signal signature

Signal process: $pp \rightarrow W^{(*)} \rightarrow Z'\mu\nu \rightarrow \mu\mu\mu\nu$

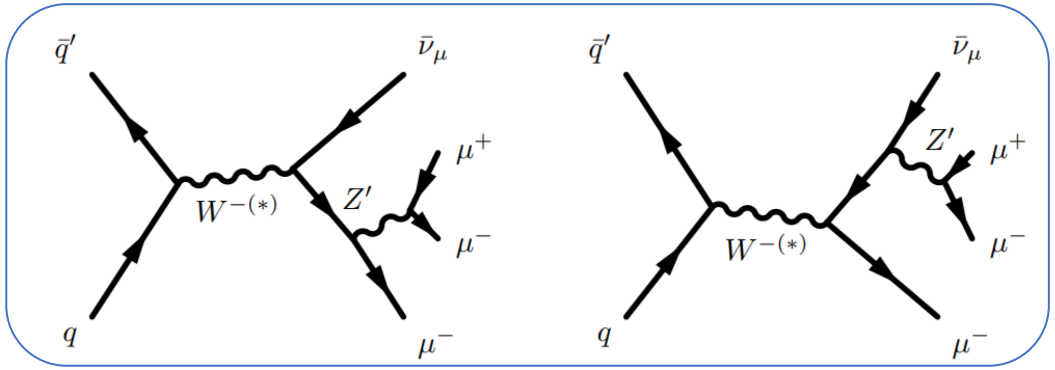
- Experimental signature with a final state of 3μ plus missing transverse momentum

Candidate events in the signal region:

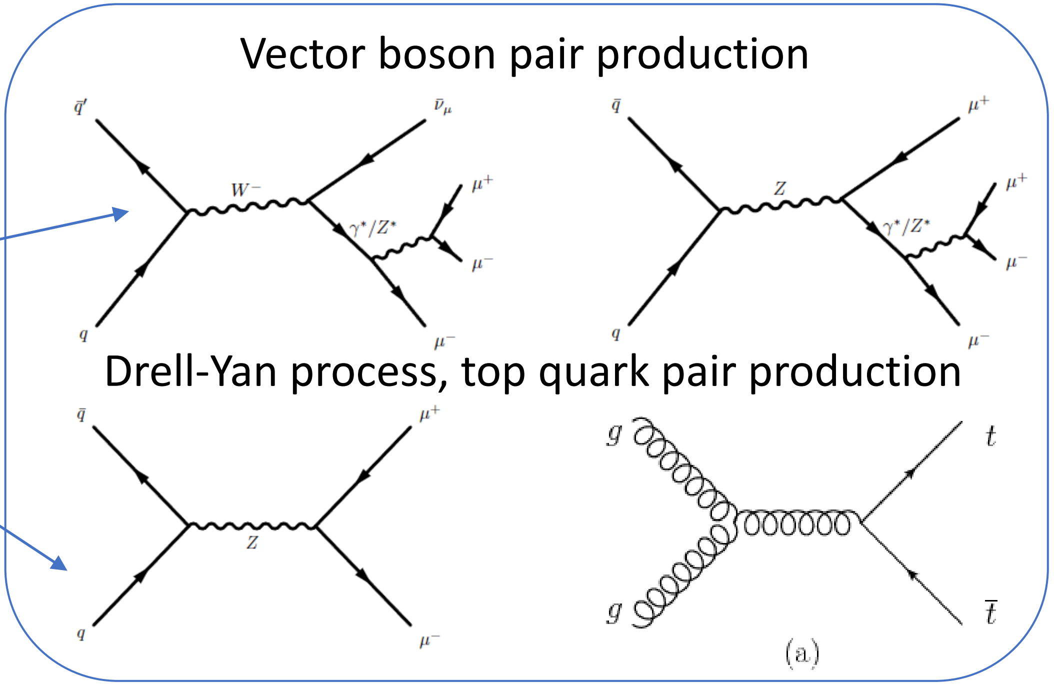
- Exactly three isolated muons
- Large missing transverse momentum
- Focusing on the low mass region ([5, 81] GeV)



Signal



Major background

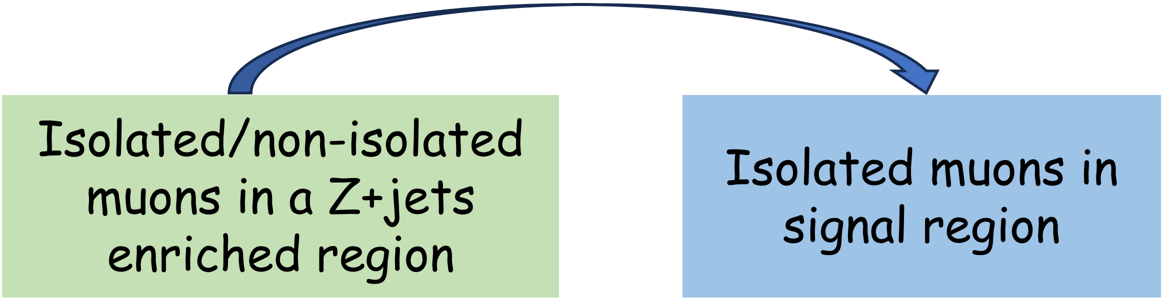


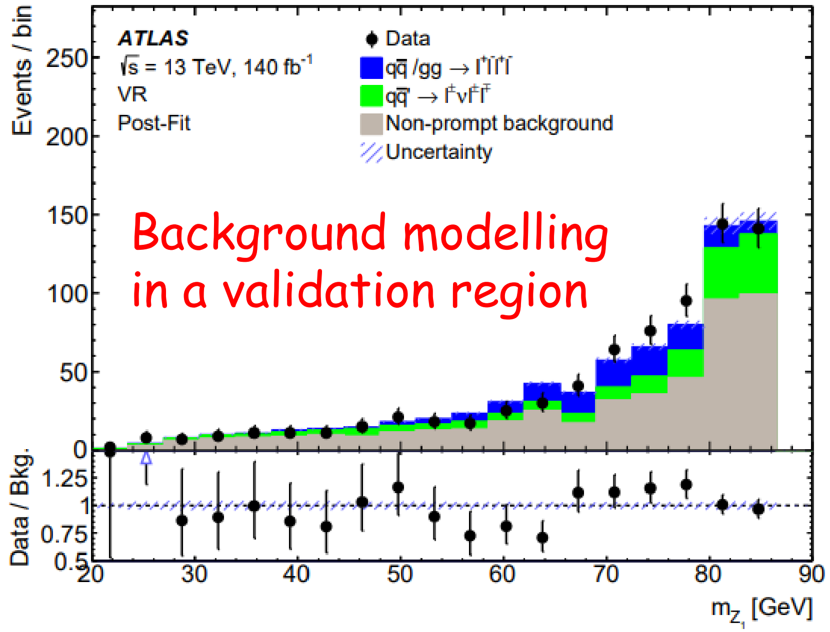
Background modeling

- Prompt background: events containing prompt muons, i.e. Vector boson pair production
  - Estimated by MC simulation
- Non-prompt background: events containing at least one non-prompt muon from hadron decays or misidentification of jets, i.e. Drell-Yan process, top quark pair production
  - Estimated by fake factor method with real data

Regions	Signal region	Z+jets control region	Validation region
Number of isolated muon	3	≥ 2	1
Number of isolated electron	0	0	2
Di-muon (electron) mass	≤ 85 GeV	> 85 GeV & < 100 GeV	≤ 85 GeV

Fake factor: $\frac{N_{\text{isolated muons}}}{N_{\text{non-isolated muons}}}$





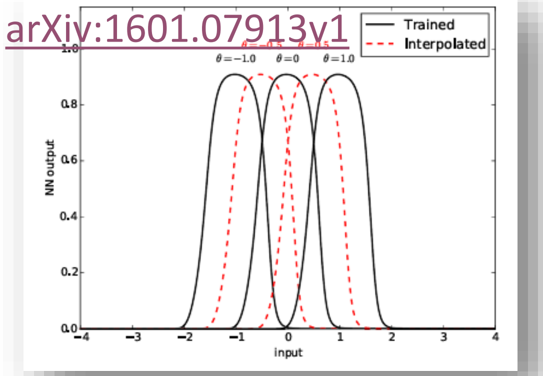
Multivariate analysis

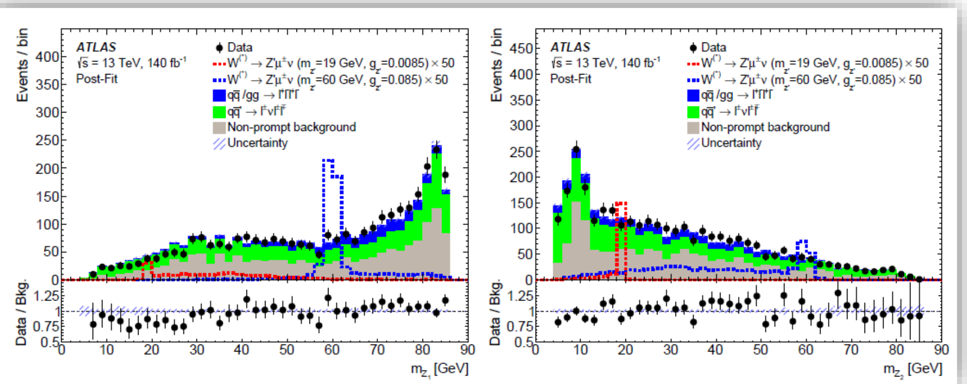
Combine several discriminating variables into a single discriminant

→ Parameterized deep neural network (pDNN):

- One classifier to handle the whole parameter grid
- Convenient to extrapolate to other signal models by varying the mass parameter

arXiv:1601.07913v1

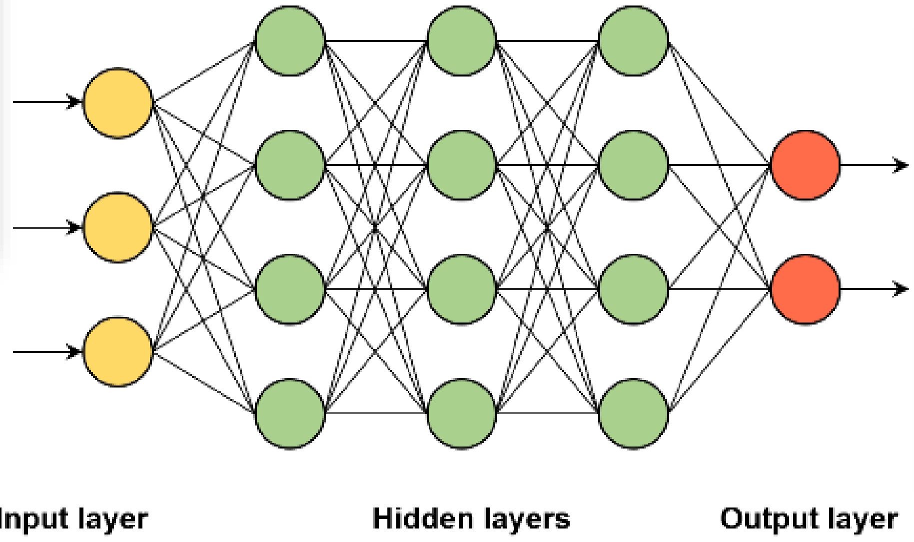


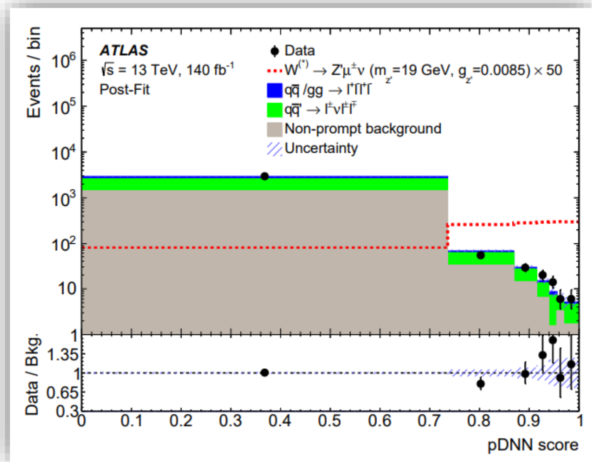


Input features from kinematics of the physics objects in the final state or the mediators

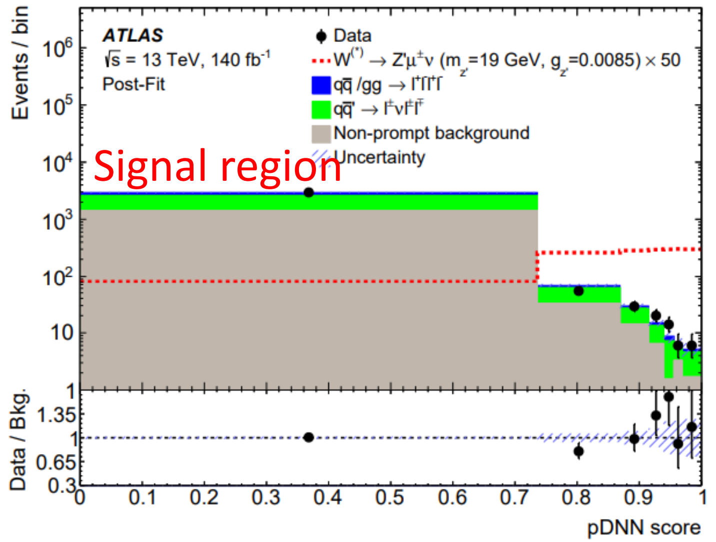
+ mass parameter

(Nominal generated Z′ mass)



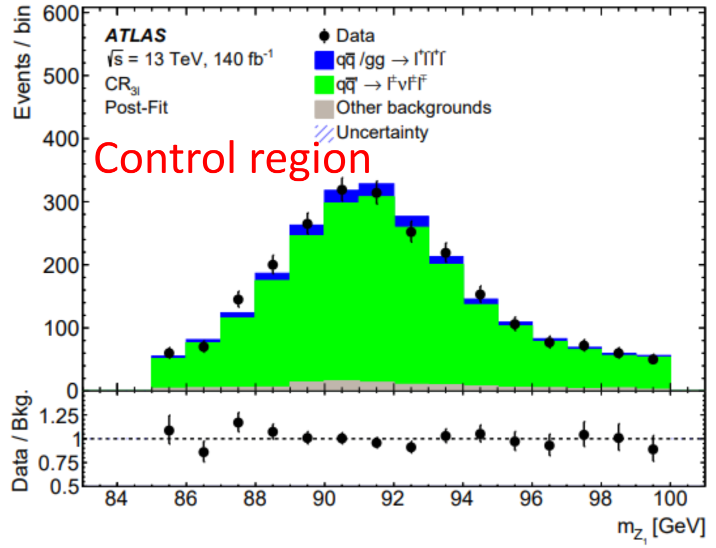


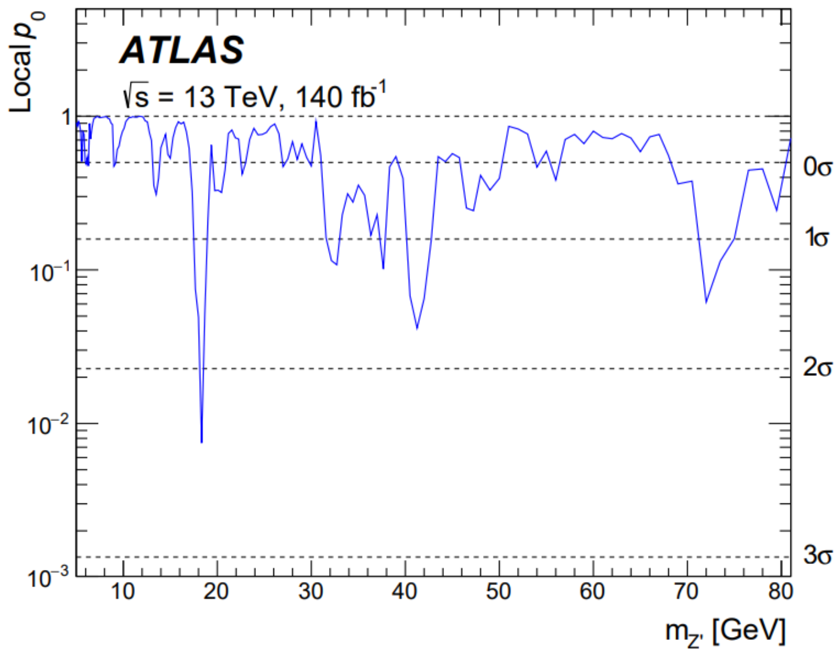
Statistical interpretation

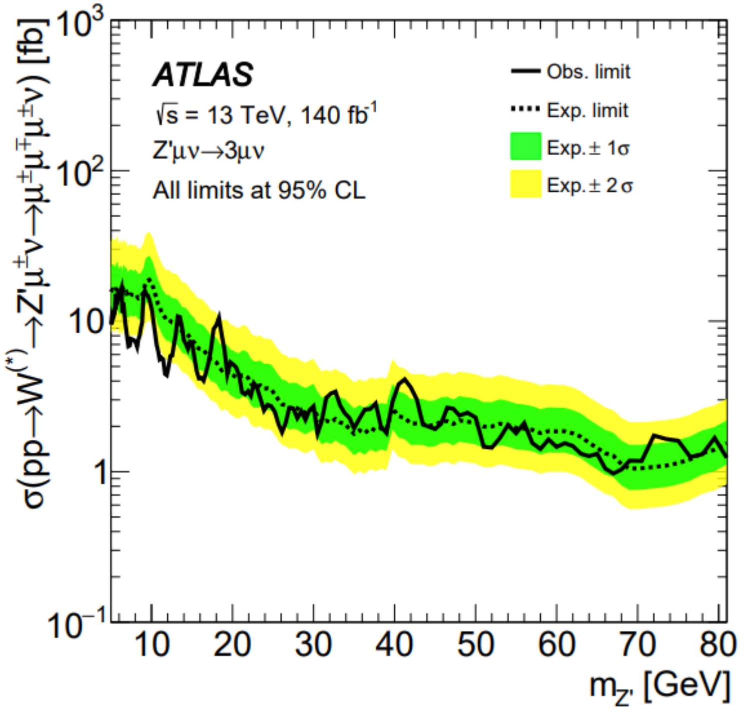


Binned profile-likelihood function

Simultaneous fit



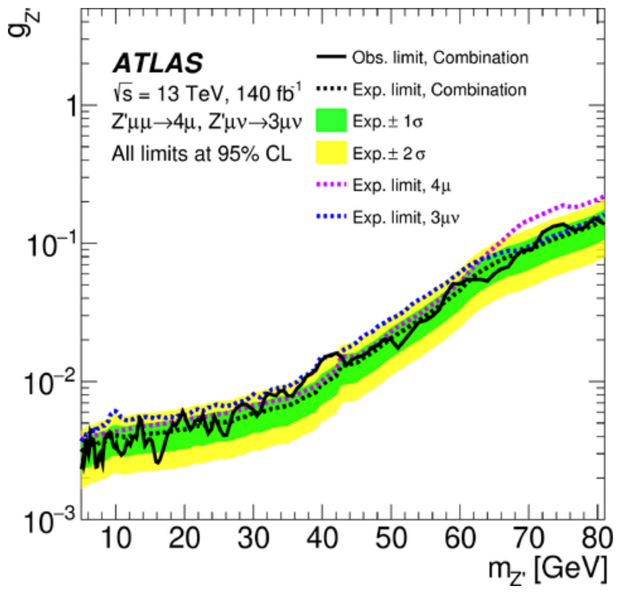


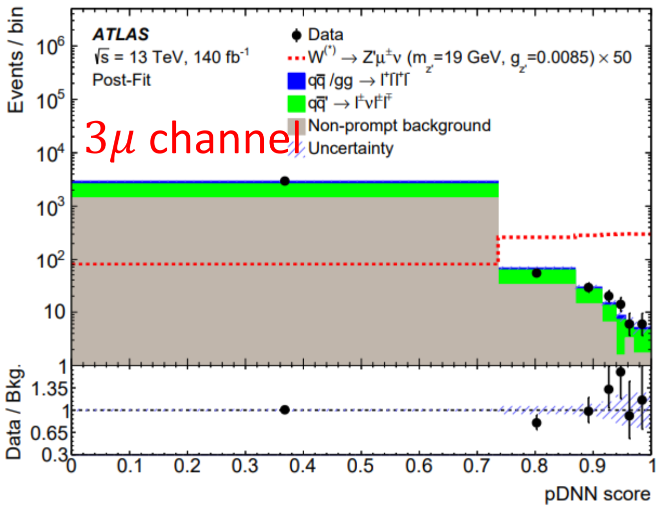


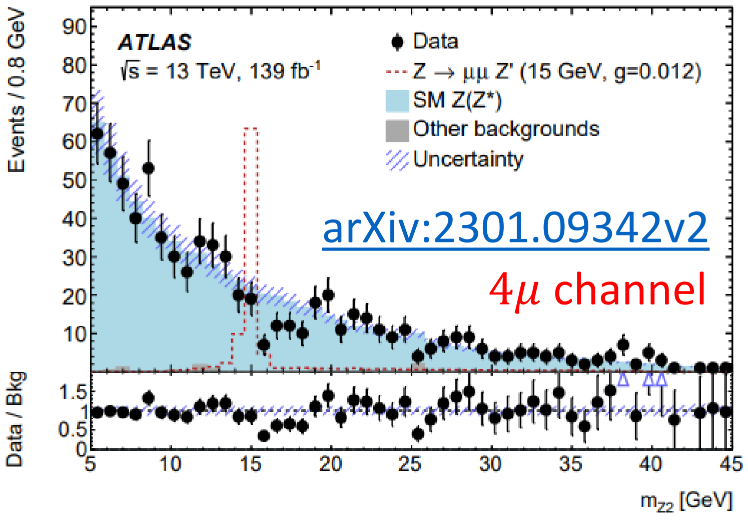
- p_0-values scan in mass range [5, 81] GeV. No significant data excess.
- Set observed (expected) upper limits at 95% CL on cross section.

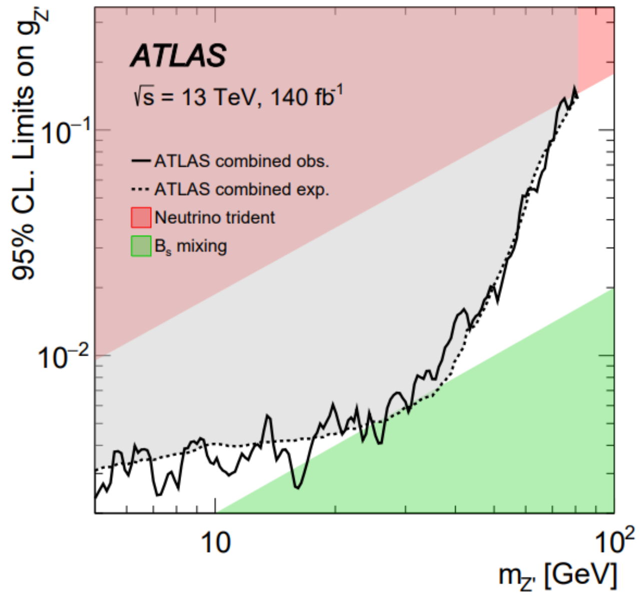
Combination

Statistical combination with the previous search using neutral-current Drell-Yan process (4μ final state)
$\rightarrow$ Common parameter of interest: coupling parameter $g_{Z'}$









Significant improvement relative to the previous search (Up to 40% in the high mass region)

Summary

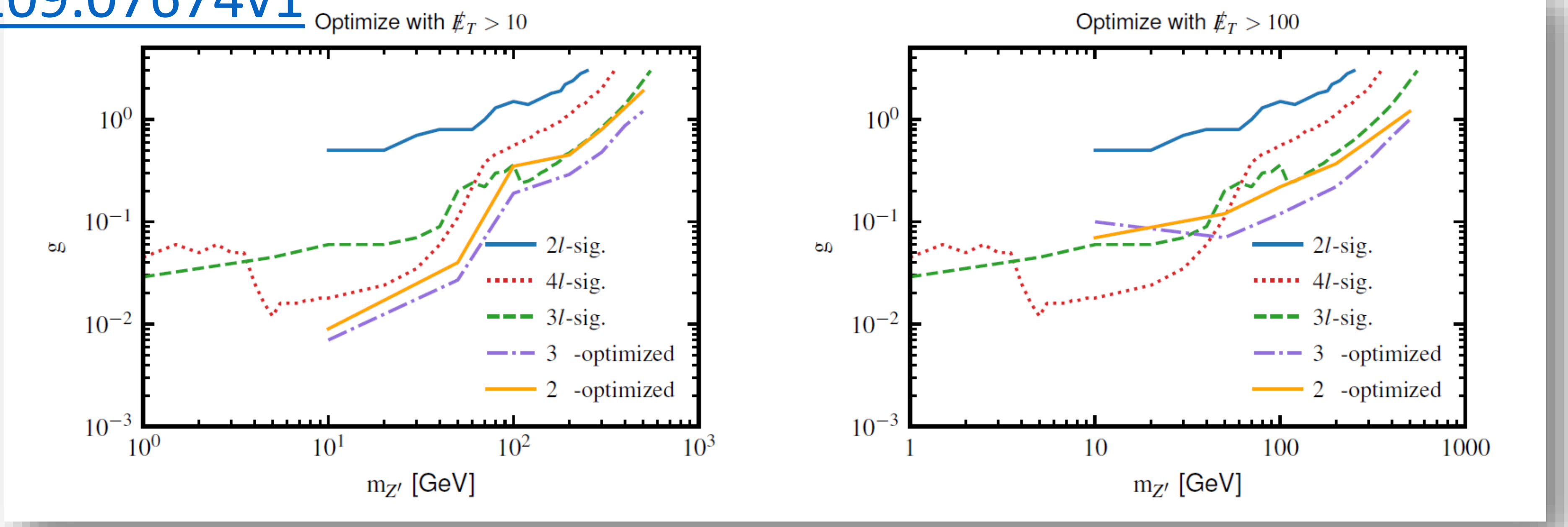
- Search for a $L_\mu - L_\tau$ gauge boson Z' using charged-current Drell-Yan production for the first time at the LHC.
- This search benefits from much higher Z' production cross section compared to the previous search using the neutral-current Drell-Yan process, and has better sensitivity especially in the high mass region.
- The most stringent exclusion limits to date are set in the allowed parameter space of the Z' coupling strength and $m_{Z'}$.
- Using the 3μ final state is expected to be more sensitive in the high mass range beyond Z peak with experiments in high luminosity.

Thank you for your attention!

Back up

Phenomenology study

arXiv:2109.07674v1



- Sensitivity of this Z' search on LHC using $2\mu, 3\mu$ (Simulation only) and 4μ (CMS, 2019) final states.
- The 2μ and 3μ results are optimized with neural network.
- The 3μ result gets significant improvement with the implement of neural network and it's expected to provide the best sensitivity in the high mass region.

Signal information & efficiency

Information of the simulated Z' signals

$m_{Z'}$ [GeV]	$g_{Z'}$	$\Gamma_{Z'}$ [GeV]	σ [fb]	$m_{Z'}$ [GeV]	$g_{Z'}$	$\Gamma_{Z'}$ [GeV]	σ [fb]
5	0.0050	9.553×10^{-6}	28.13	9	0.0065	3.016×10^{-5}	23.22
15	0.0080	7.636×10^{-5}	15.52	19	0.0085	1.092×10^{-4}	10.67
23	0.0090	1.482×10^{-4}	7.397	27	0.0095	1.939×10^{-4}	5.086
31	0.0110	2.985×10^{-4}	4.183	35	0.0120	4.011×10^{-4}	3.001
39	0.0150	6.983×10^{-4}	2.751	45	0.0230	1.894×10^{-3}	2.768
51	0.0370	5.556×10^{-3}	2.803	54	0.0480	9.901×10^{-3}	2.863
60	0.0850	3.450×10^{-2}	3.145	66	0.1800	0.1702	5.483
69	0.2500	0.3432	7.451	75	0.3500	0.7311	9.222
81	0.4000	1.031	8.891				

Selection efficiency

$m_{Z'}$ [GeV]	5	19	39	60	81
Number of identified muons (looser muons) = 3(< 4)	2.7%	7.0%	11.8%	18.8%	36.2%
$p_{T,i} (i = 1, 2, 3) > 20,\ 10,\ 7$ GeV	33.6%	52.8%,	87.4%	85.7%	97.9%
Number of b-jets = 0	98.5%	97.5%	98.5%	98.4%	97.9%
$E_T^{miss} > 15$ GeV	64.1%	72.5%	60.1%	72.2%	92.6%
$m_{Z_1} < 85$ GeV	100%	99.2%	97.8%	72.5%	43.1%
Combined event selection efficiency	0.6%	2.6%	6.0%	8.3%	13.8%