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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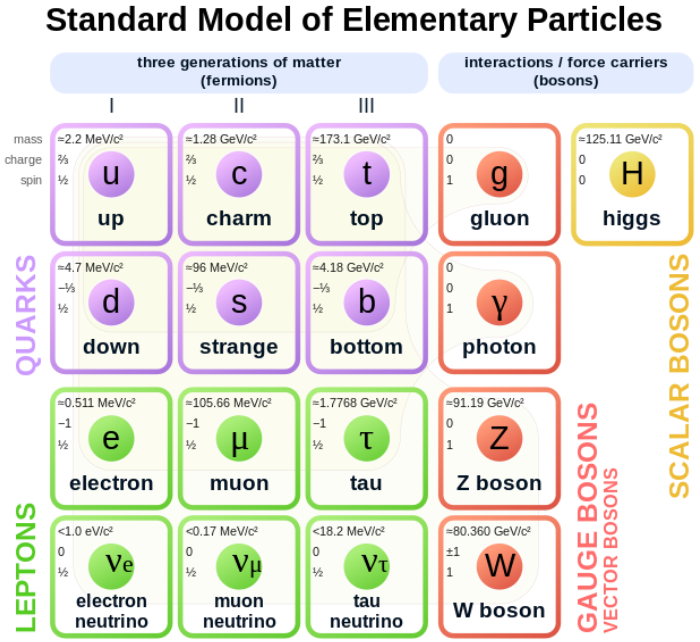
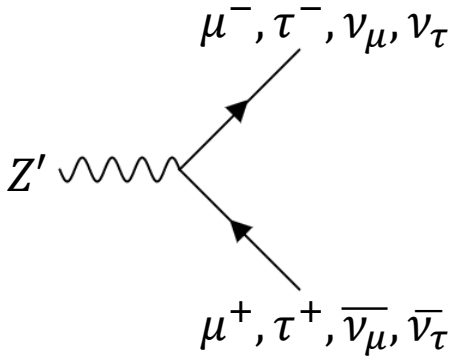
Introduction

- Different models have predicted the existence of Z' to address the problems in the Standard Model
  - Grand Unified Theories 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 Standard Model
- $L_1 \equiv L_e - L_\mu, L_2 \equiv L_e - L_\tau$, 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

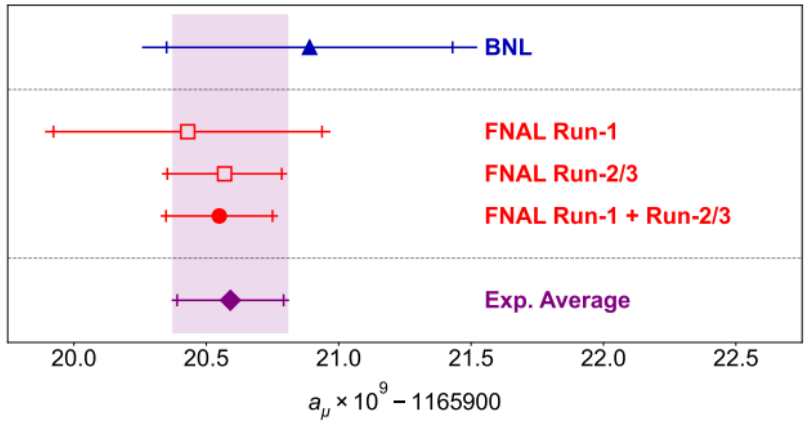




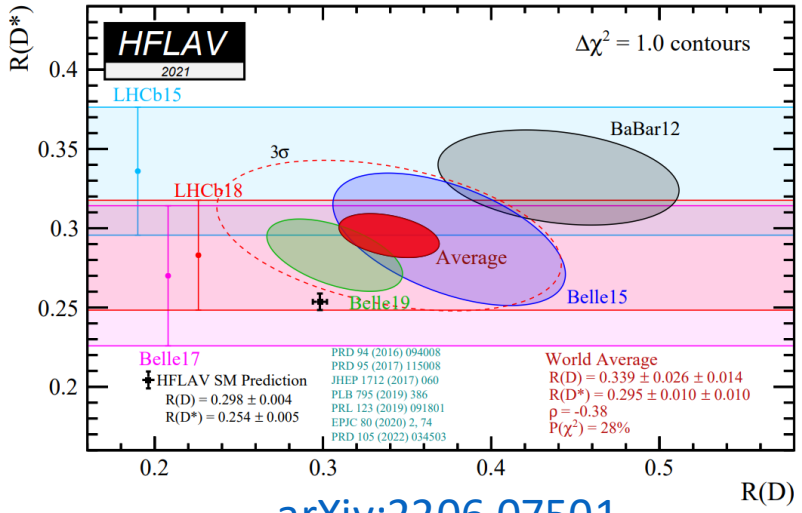
The Simplest Z' model

- $U(1)_{L_\mu - L_\tau}$ 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 which could answer the dark matter and neutrino mass problems
  - PhysRevLett.126.141801:Muon anomalous magnetic moment
  - arXiv:2206.07501v2:Semileptonic B decay
  - arXiv:hep-ph/0411190:Neutrino mass



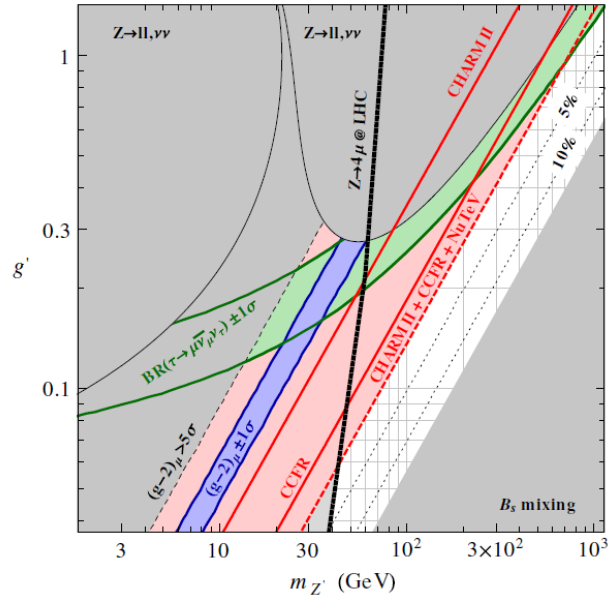
arXiv:2308.06230

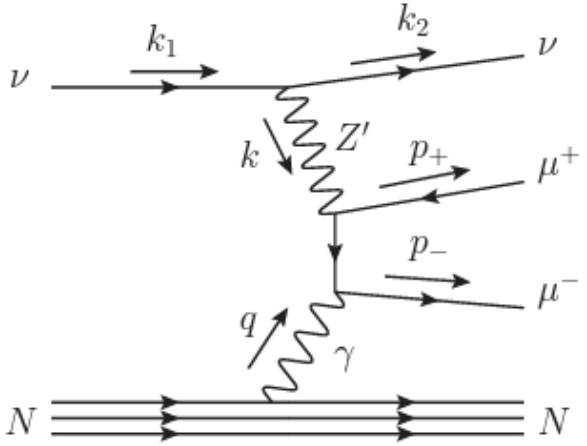


arXiv:2206.07501

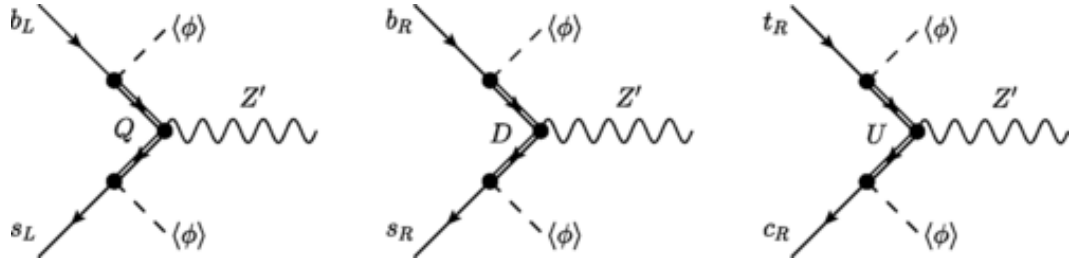
Constraints on Z' parameter space

- Contribution to neutrino trident production
  - arXiv:1406.2332 Neutrino Trident Production: A Powerful Probe of New Physics with Neutrino Beams
  - Providing **upper** bounds
- Correction to B_s meson oscillations
  - PhysRevD.89.095033 Quark flavor transitions in $L\mu - L\tau$ models
  - Providing **lower** bounds





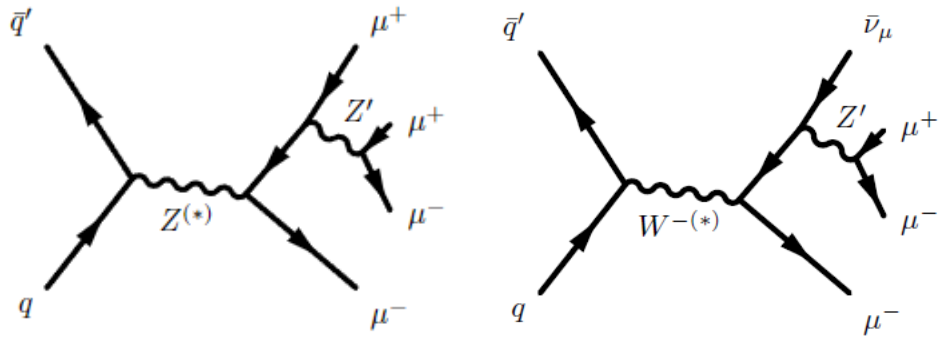
Contribution to neutrino trident production
CCFR measurement

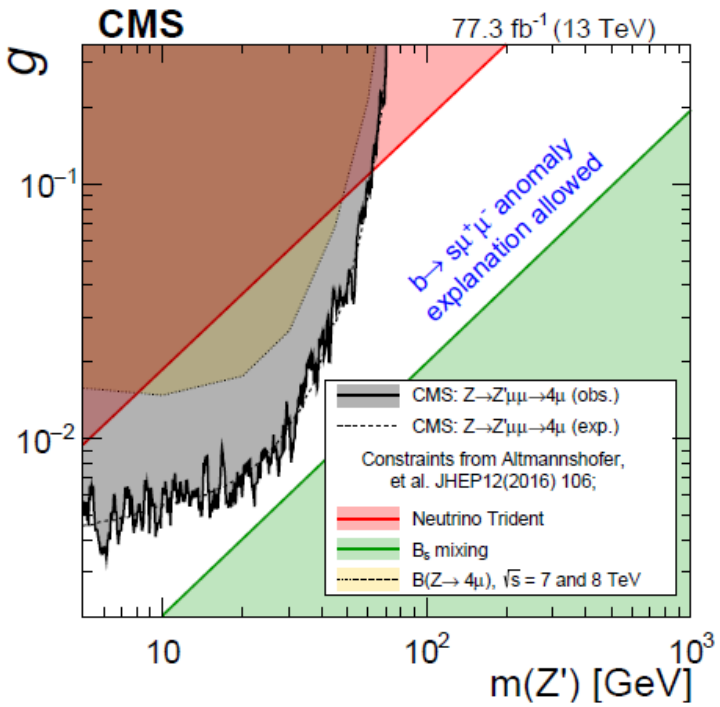


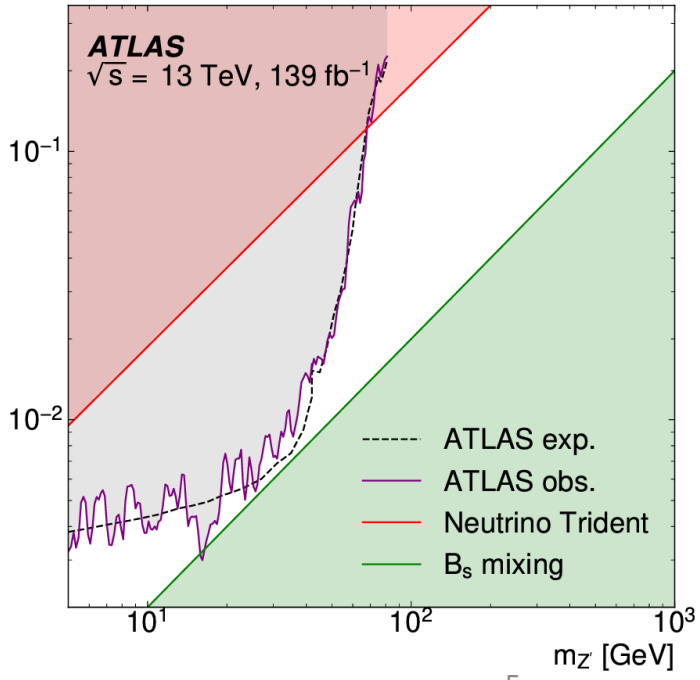
Correction to B_s meson oscillations
LHCb measurement

Constraints on Z' parameter space

- Large cross section of Drell-Yan process on LHC
- Previous search with $\boldsymbol{4\mu}$ final state on LHC
  - CMS, 2019 ($77.3\ fb^{-1}$)
  - ATLAS, 2023 ($139\ fb^{-1}$)
- **First** time to use the $\boldsymbol{3\mu}$ **final state** to search this $\boldsymbol{Z'}$
  - Expected to provide better sensitivity in the high mass region
  - PhysRevD.110.072008

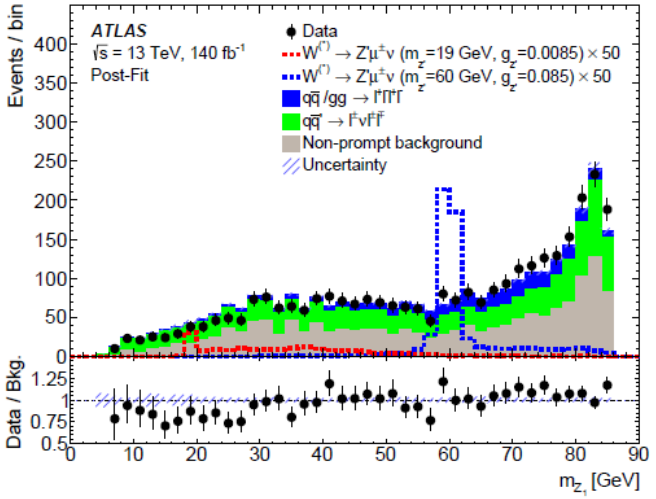


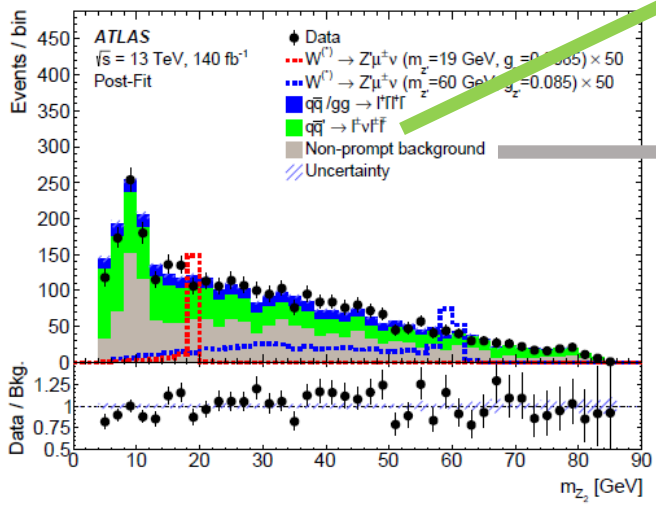


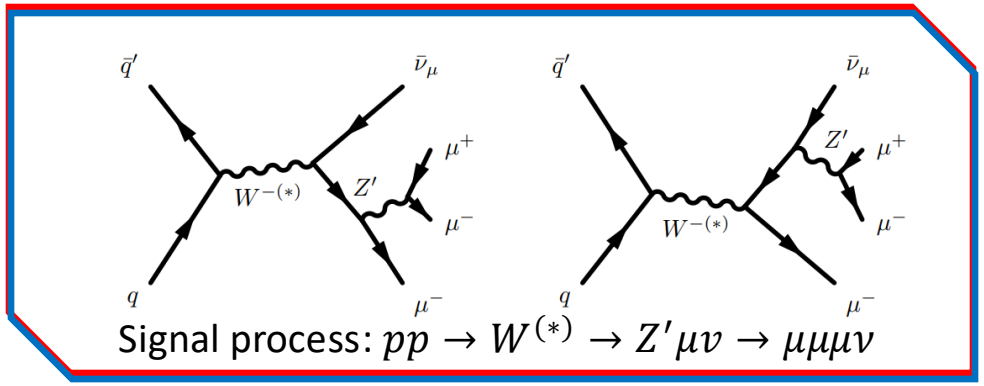


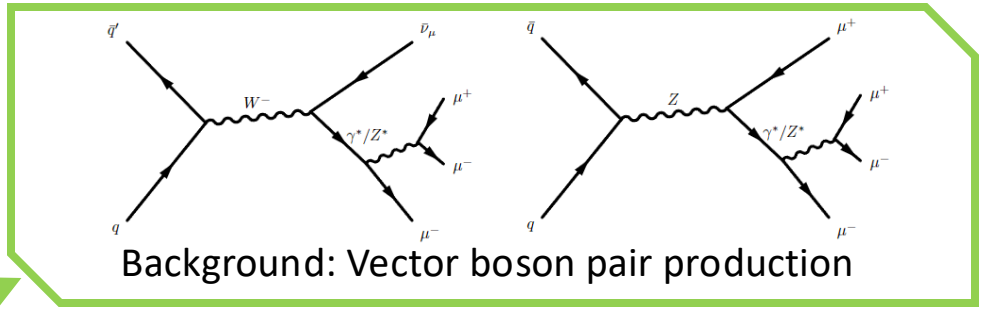
Signal signature

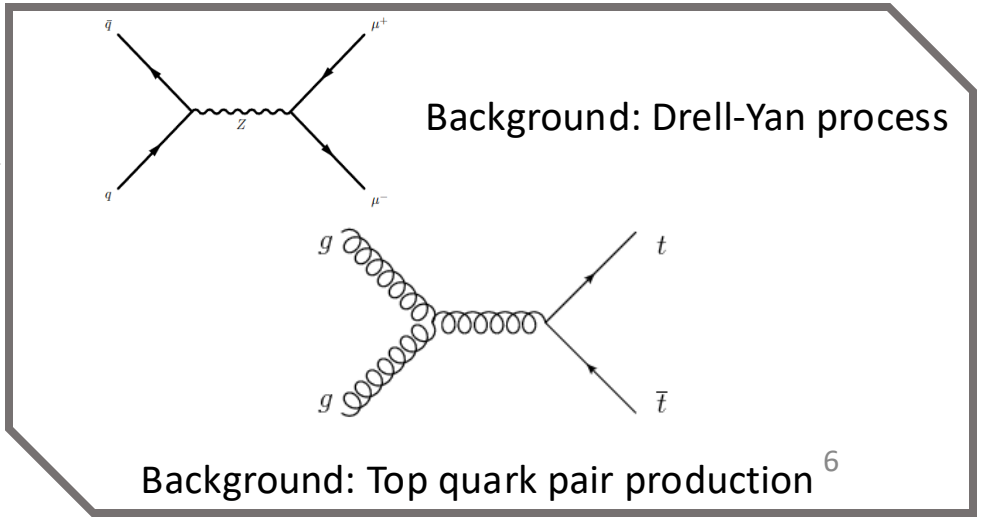
- Signal process: $pp \to W^{(*)} \to Z'\mu\nu \to \mu\mu\mu\nu$
  - 3μ plus missing transverse momentum
- Major background
  - Vector boson pair production
  - Drell-Yan process, Top quark pair production
- Candidate events in the signal region:
  - Exactly three isolated muons and large missing transverse momentum
  - Focusing on the low mass region: [5, 81] GeV





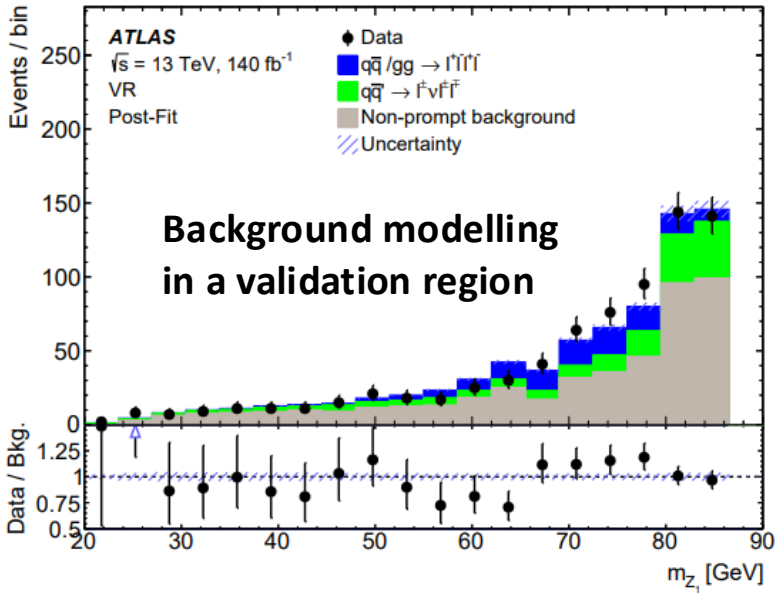






Background modeling

- Prompt background: events containing prompt muons
  - 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
  - Drell-Yan process, top quark pair production
  - Estimated by fake factor method with real data



Isolated/non-isolated muons in a Z+jets enriched region → **Isolated muons in signal region**

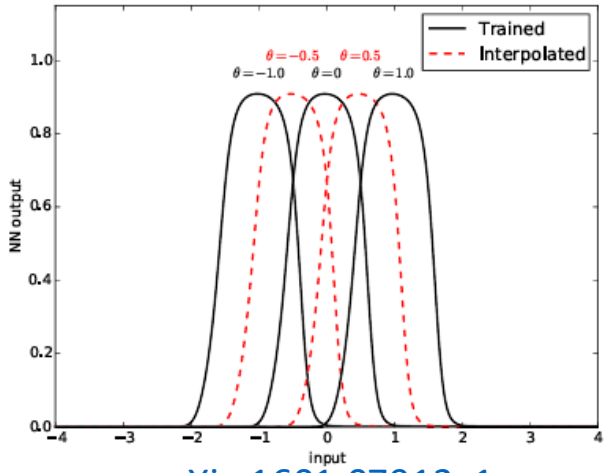
Fake factor: $\frac{N_{\text{isolated muons}}}{N_{\text{non-isolated muons}}}$

Signal Region:
Three isolated muons
Di-muon mass below Z peak

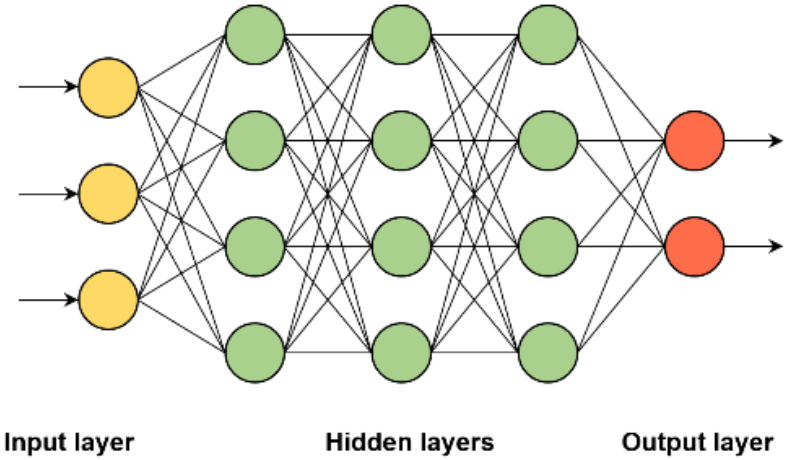
Z+jets Control Region:	Validation Region:
Two isolated muons and one additional muon, around Z peak	Two isolated electrons and one isolated muon, below Z peak

Multivariate analysis

- Parameterized deep neural network (pDNN): Combine several discriminating variables into a single discriminant
  - One classifier to handle the whole parameter grid
  - Convenient to extrapolate to other signal models
- Input features
  - Muon kinematics, missing transverse momentum
  - Di-muon mass of leading muon pair Z_1 and sub-leading muon pair Z_2, angle between muons with muon pairs
  - Scalar(Vector) sum of transverse momentum of all physics objects
- The reconstruction of Z' mass resonance depends on their truth mass
  - Two different classifiers for low-mass and high-mass regions

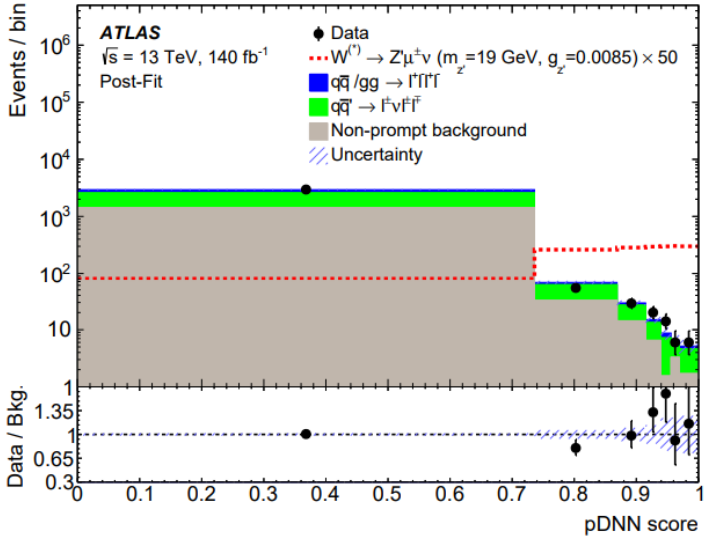


arXiv:1601.07913v1

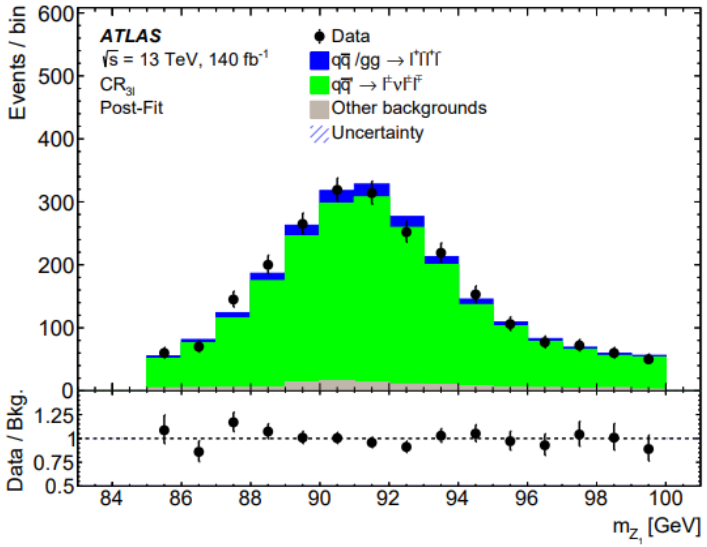


Statistical interpretation

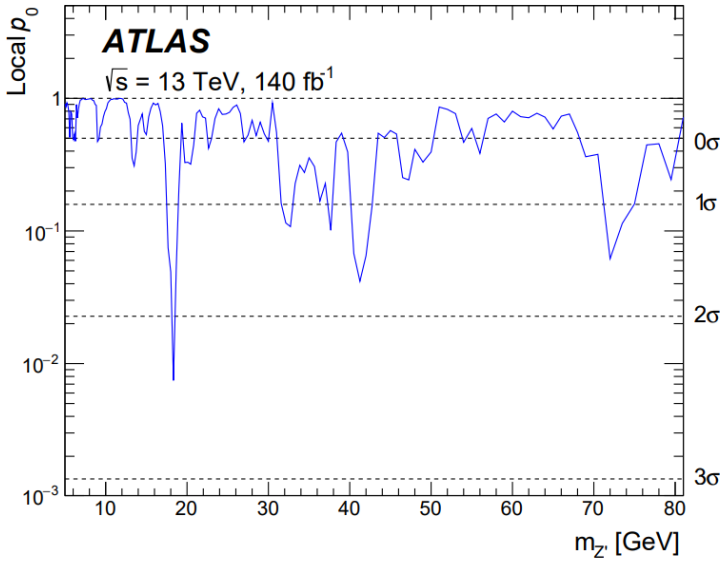
- Binned profile-likelihood function and simultaneous fit
- p_0-values scan in mass range [5, 81] GeV
  - no significant data excess
- Set observed (expected) upper limits at 95% CL on cross section

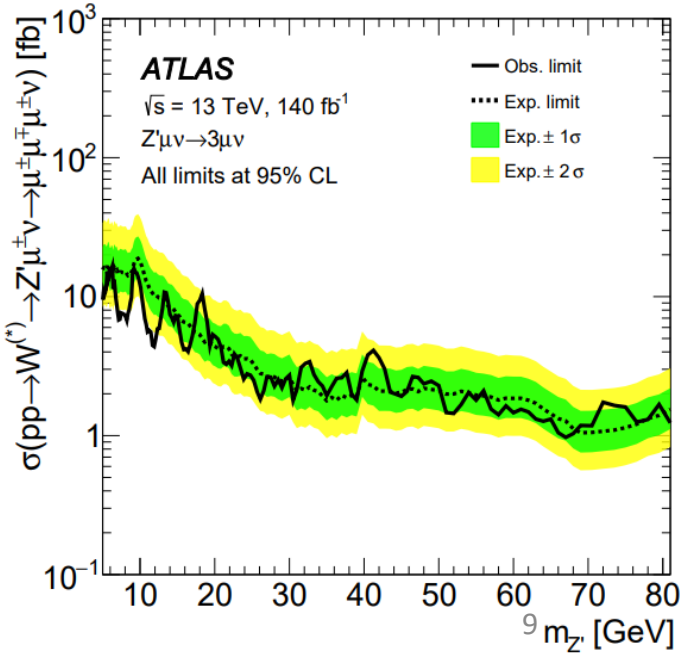


Signal region



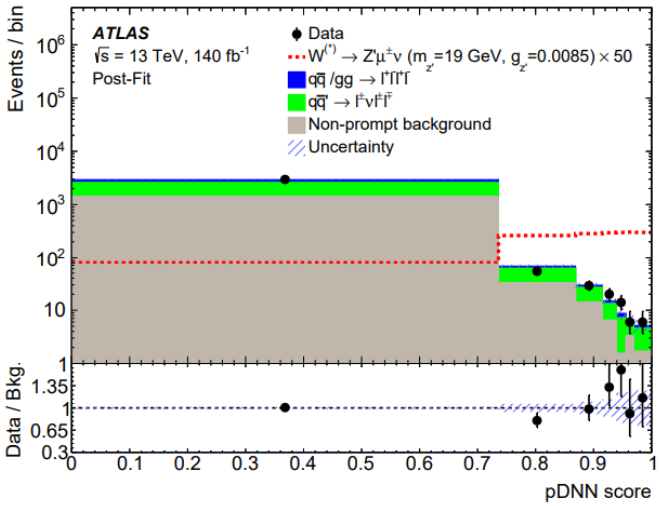
Control region



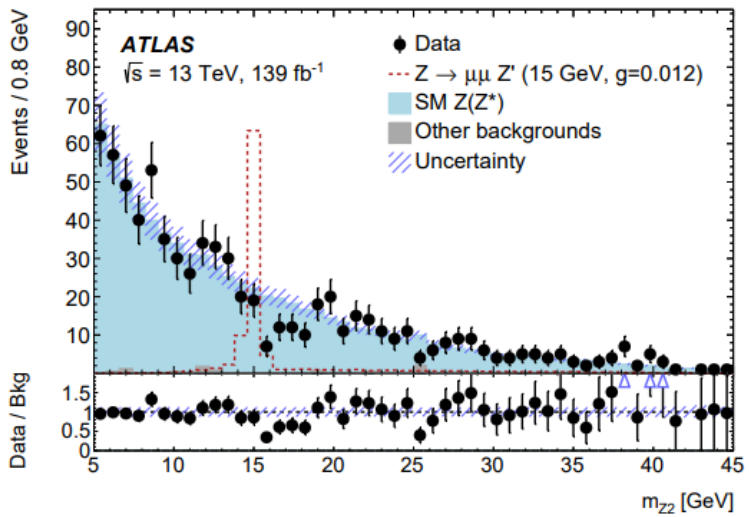


Combination

- Statistical combination with previous search using neutral-current Drell-Yan process (4μ final state)
  - Common POI: coupling parameter $g_{Z'}$
- Significant improvement relative to the previous search
  - Up to **40%** in the high mass region

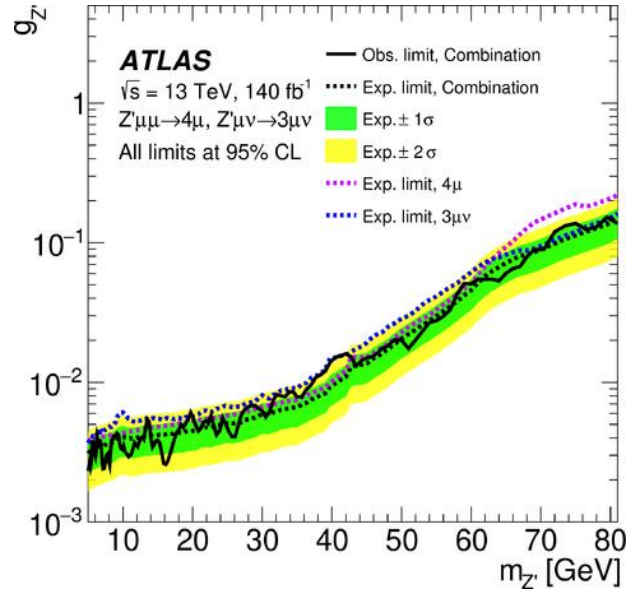


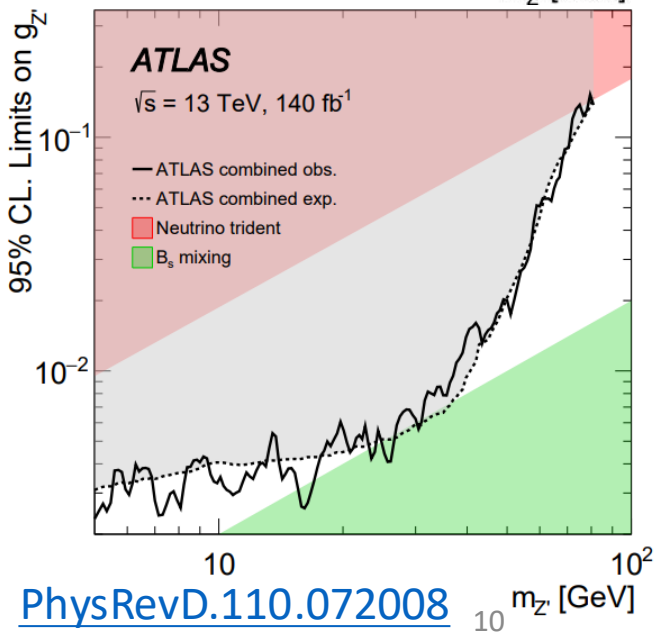
3μ channel



4μ channel

arXiv:2301.09342v2





PhysRevD.110.072008

Summary

- Search for a $L_\mu - L_\tau$ gauge boson Z' using charged-current Drell-Yan production for the first time at the LHC
- Benefits from much higher Z' production cross section compared to the previous search using the neutral-current Drell-Yan process
  - 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

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Thank you for your attention!

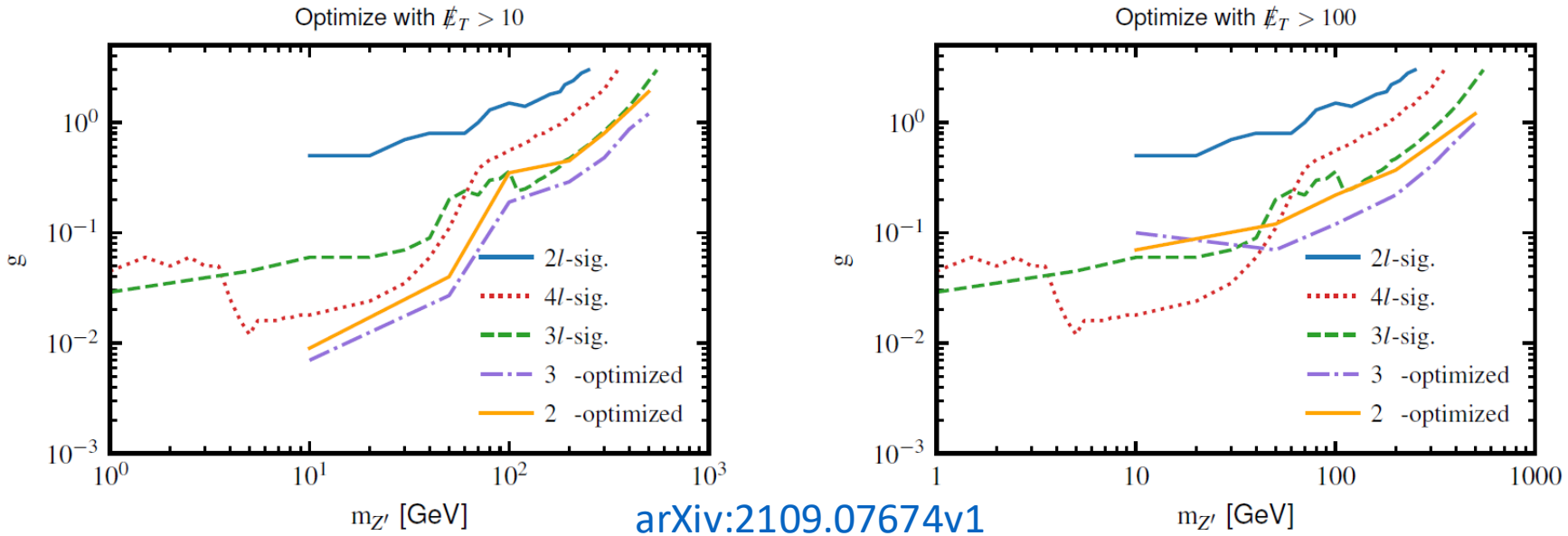
Backup - Simulated Z' signal information

$m_{Z'}$ [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				

Backup - 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%

Backup - 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
- 2μ and 3μ results are optimized with neural network
- 3μ result gets significant improvement with the implement of neural network
  - expected to provide the best sensitivity in the high mass region