SEARCH FOR Z' RADIATING FROM THE DARK MATTER AT THE LHC

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Quy Nhon, 24 July 2024

Outline:

1. Introduction
2. The Model
3. Methods for Simulation and Analysis
4. Results
5. Summary

Work with **R. Primulando, Q.M.B. Soesanto, B. Dirgantara, B.E. Gunara**

The details can be found in arXiv : 2404.12781

PROBLEMS IN SM

Incomplete to be the description of the Universe!

Several major problems to answer:

1. Dark Matter (26% of mass-energy present in the Universe, SM only accounts for ~5%) and Dark Energy (69%)[1]
2. Neutrino masses, observed from experiments on neutrino oscillation
3. Matter-antimatter symmetry
4. Gravity is not included

1. https://sci.esa.int/web/planck/-/51557-planck-new-cosmic-recipe

LHC is suited to scrutinize the coupling of Dark Matter with quarks.

DM itself is invisible.

- The detector detects the recoils of DM with visible objects : Monojet, monophoton, etc
- ATLAS search for Monojet with axial-vector mediator Z_A (Phys. Rev. D 103, 112006)
- Robust constraint but substantial background.

- Dark sector can have dark gauge group, DM radiates dark gauge bosons. Can resemble monojet.
- If dark gauge bosons have interaction with SM gauge bosons, it can decay to SM particles.

PROPOSED MODEL

Fermionic DM χ and new corresponding gauge group $U(1)_D$.

$$\mathcal{L}_{\text{Dark}} = g_D X_\mu \bar{\chi} \gamma^\mu \chi$$

Kinetic mixing term of $U(1)_D$ with SM $U(1)_Y$,

$$\mathcal{L}_{\text{kin.mixing}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} X^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu}$$

This mixing will yields (after diagonalization) two massive neutral gauge bosons, Z and Z'.

We introduce new variables (used also in Phys. Rev. D 106, 015027) :

$$\kappa = \frac{\epsilon}{\cos\theta_W},$$
$$\eta = \frac{\kappa}{\sqrt{1-\kappa^2}},$$

We have bounds on ϵ, upper limit is in the order of $O(10^{-3})$ (Phys. Rev. Lett. 124, 131802).

Due to the mixing, in case of $m_{Z'} < 2m_\chi$, Z' will exclusively decay into SM particles. The decay width of $Z' \to f^+f^-$ is given by:

$$\Gamma_{Z'\to f^+f^-} = \frac{m_{Z'}}{12\pi} N_c \sqrt{1-\frac{4m_f^2}{m_{Z'}^2}} \left[\left(c_V^2 + c_A^2\right)\left(1-\frac{m_f^2}{m_{Z'}^2}\right) + 3(c_V^2 - c_A^2)\frac{m_f^2}{m_{Z'}^2}\right]$$

We are interested in the case where the final state are dilepton pairs + MET.

The production of DM is through a simplified model, similar to the one used in LHC monojet analysis (Phys. Rev. D 103, 112006).

The Lagrangian is given by:

$$\mathcal{L}_{q-\chi} = g_Q(\bar{u}\gamma^\mu\gamma^5 u + \bar{d}\gamma^\mu\gamma^5 d)Z_A{}^\mu + g_\chi \bar{\chi}\gamma^\mu\gamma^5\chi Z_A{}^\mu$$

The mediator Z_A will connect the quark and DM sectors.

Our focus is directed towards a process in which DM radiates Z', succeeded by the subsequent decay of Z' into lepton pairs. This process is termed as "Darkstrahlung" (JHEP 1509 (2015) 079).

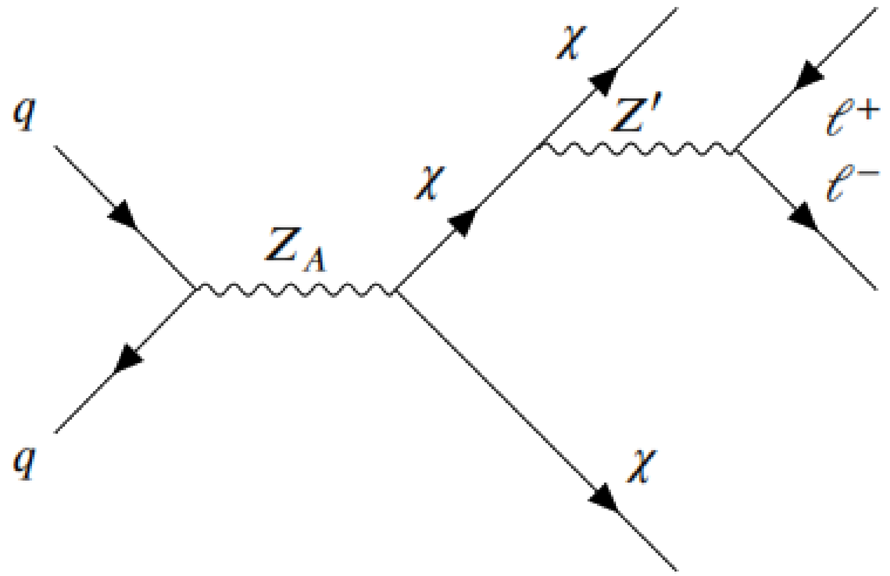


Fig 1. The Darkstrahlung Process

SEARCH FOR DILEPTON + MET FINAL STATE AT THE LHC

- ATLAS Search for Dilepton Resonance (https://cds.cern.ch/record/2870113)
- ATLAS Slepton Search (*Eur. Phys. J. C* **80**, 123, 2020)
- CMS Slepton Search (*J. High Energ. Phys.* 04, **2021**, 123)

Important selection criteria on these experiments:

ATLAS Dilepton Resonance	ATLAS Slepton	CMS Slepton
Low ET miss (55 GeV), $m_{ll} > 180$ GeV	High ET miss (110 GeV), $m_{ll} > 121.2$ GeV	Low ET miss (50 GeV), Two region, $20 < m_{ll} < 65$ GeV and $m_{ll} > 120$ GeV

TOOLS USED IN THIS WORK

Process	Software
Parton-level events	MadGraph v5 aMC@NLO (+ FeynRules 2.0)
Shower and Hadronization	Pythia 8.3
Detector Response	Delphes v3 (+ FastJet)
Event Selection and Analysis	MadAnalysis 5

LIKELIHOOD AND CHI-SQUARE VALUES

In order to calculate the bounds for our model, we follow the strategy of GAMBIT (*Eur. Phys. J. C* **77**, 795, 2017).

The likelihood of observing a signal in particular bin i, s_i is

$$\mathcal{L}_i(n_i|s_i, b_i) = \int_0^\infty \frac{(\xi(s_i + b_i))^{n_i}\, e^{-\xi(s_i+b_i)}}{n_i!} P_i(\xi)\, d\xi,$$

With n, b are number of observed and predicted background, respectively.
The probability is defined as :

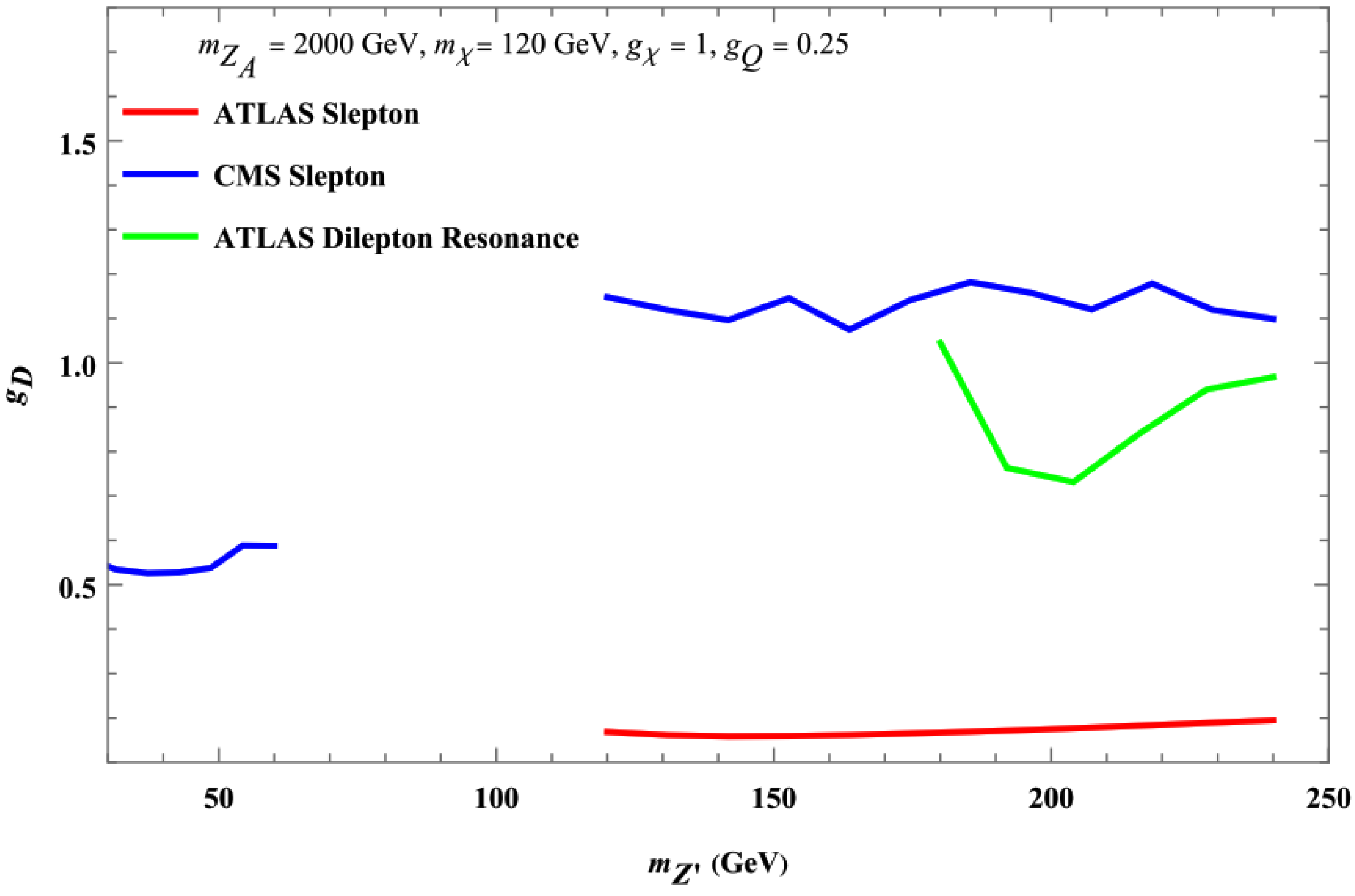
$$P_i(\xi) = \frac{1}{\sqrt{2\pi\sigma_i}} \frac{1}{\xi} \exp\left[-\frac{1}{2}\left(\frac{\ln \xi}{\sigma_i}\right)\right]$$

and finally the chi-square values are given by :

$$\chi^2 = -2 \sum_i (\ln \mathcal{L}(n_i|s_i, b_i) - \ln \mathcal{L}(n_i|s_i = 0, b_i))$$

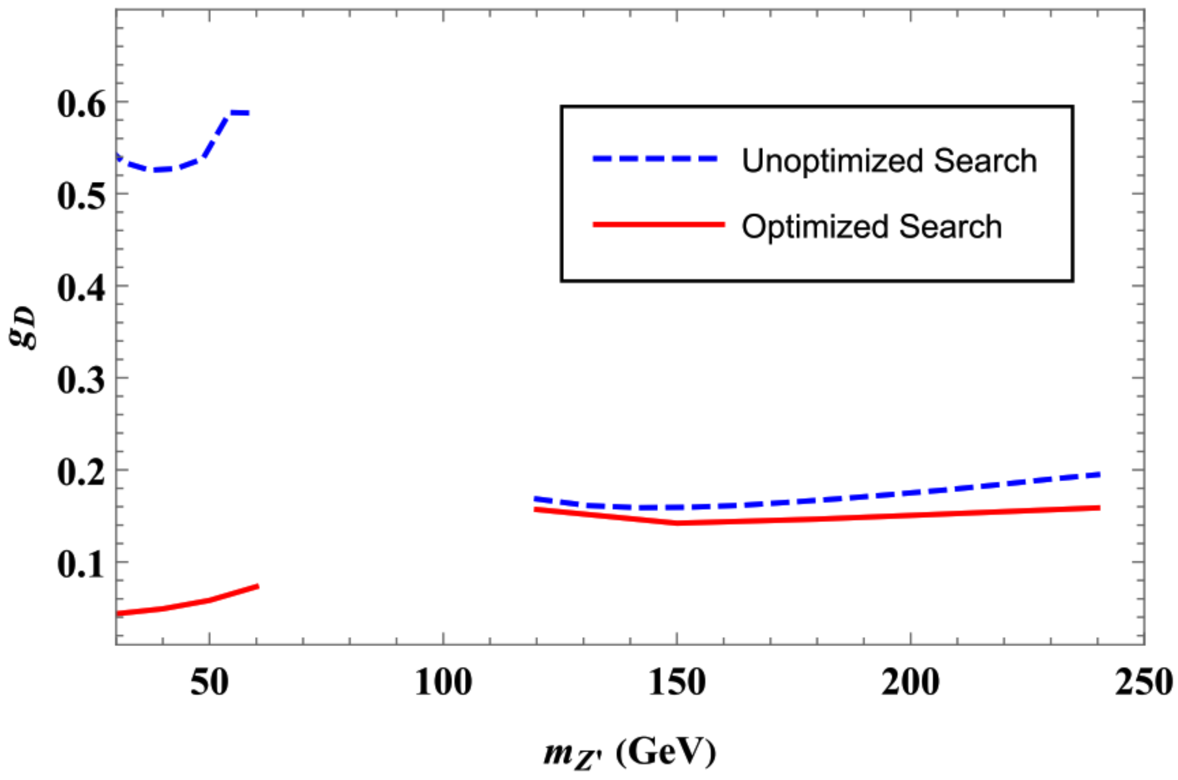
RESULTS

Recasted bounds from ATLAS dilepton resonance, ATLAS Slepton, and CMS Slepton is shown below.
We chose a benchmark of $m_{Z_A} = 2$ TeV, $m_\chi = 120$ GeV, $g_Q = 0.25$ and $g_\chi = 1$, corresponding to ATLAS monojet analysis.

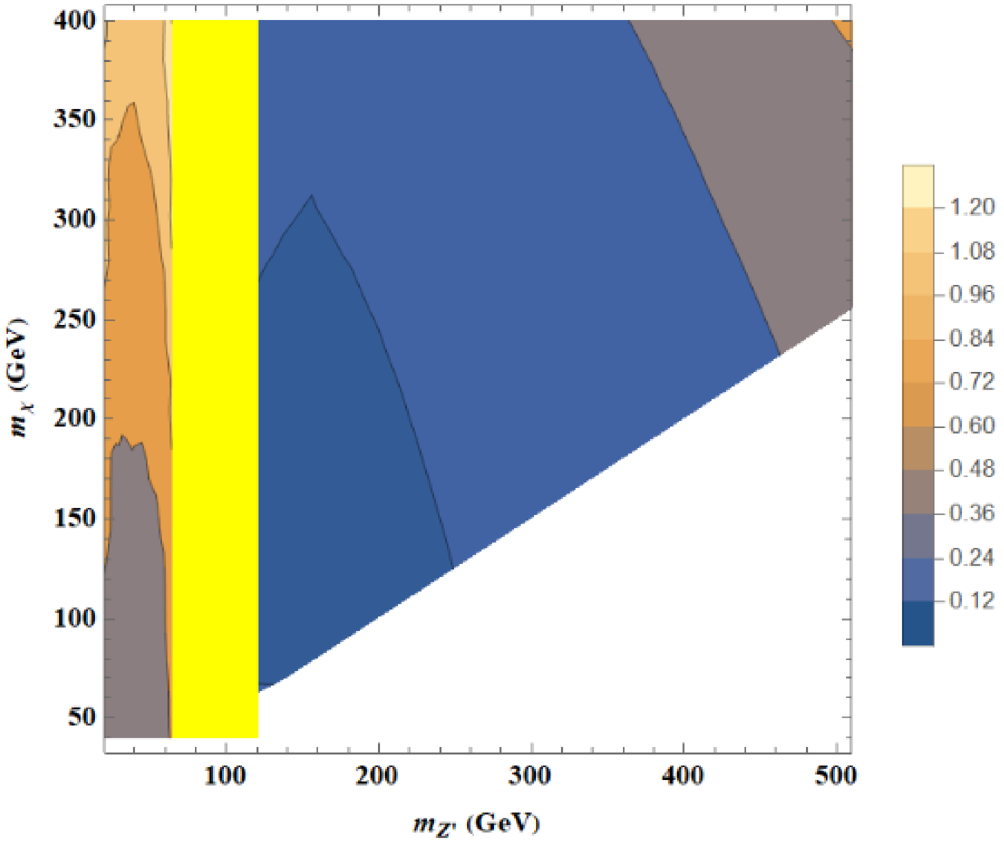


Logically, ATLAS Dilepton Resonance search should gives stronger constraints!
Not the case, because of low E^{T}_{miss}

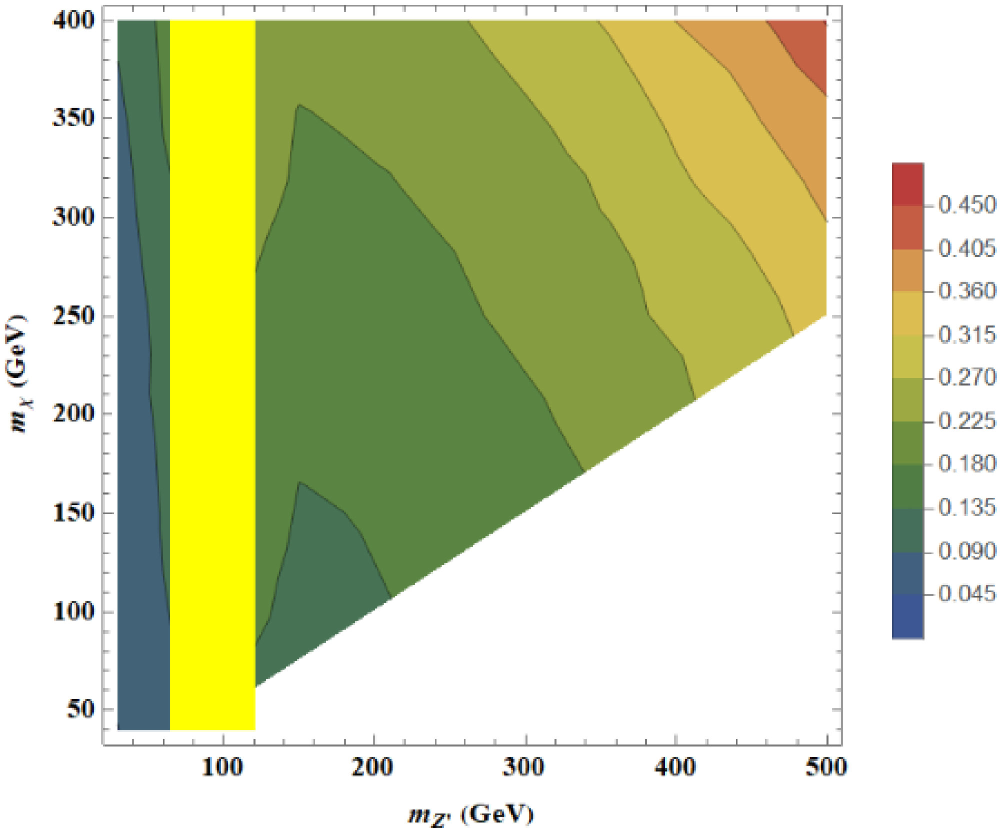
We proposed that ATLAS Dilepton Resonance could be improved by implementing a stronger cut on missing energy.
This is the simulation result with additional cuts : $|m_{ll} - m_{Z'}| < 5$ GeV and $E^{T}_{miss} > 250$ GeV.



This optimization also gives stronger bounds on g_D for various values of $m_{Z'}$ and m_χ.



(a) Unoptimized bounds



(b) Optimized bounds

SUMMARY

- We discussed LHC constraints for our model, where the dark sector consists of a dark matter charged under new hidden $U(1)$ symmetry.
- Recasting of LHC searches (ATLAS Dilepton Resonance + ATLAS Slepton + CMS Slepton) has been performed.
- Higher cut on E_{miss}^{T} and choosing narrow region for m_{ll} can improve the constraints.


Спасибо
Gracias
شكرا
Obrigado
Спасибо
Dank U
Grazie
Ευχαριστώ
Danke
Ευχαριστώ
Obrigado
Merci
Thank You
Ngiyabonga
Dank U
Diolch
Thank You
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Dank U
Terima Kasih
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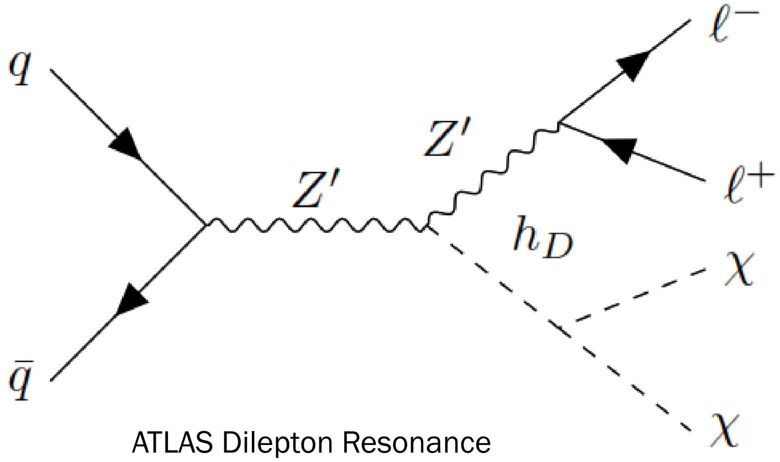
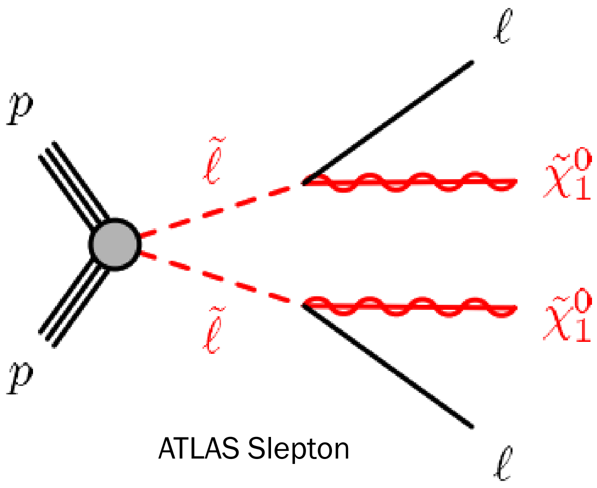
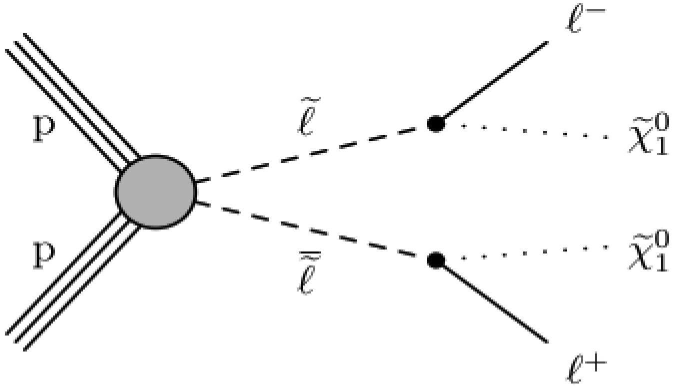
BACKUP



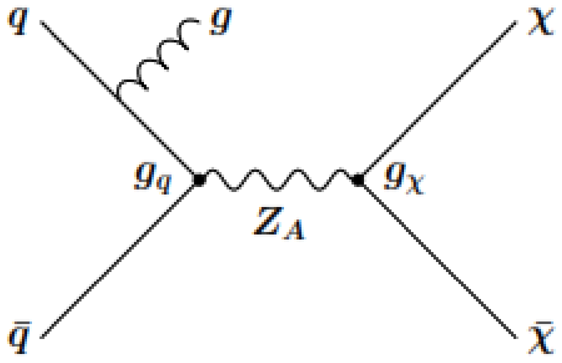
ATLAS Dilepton Resonance



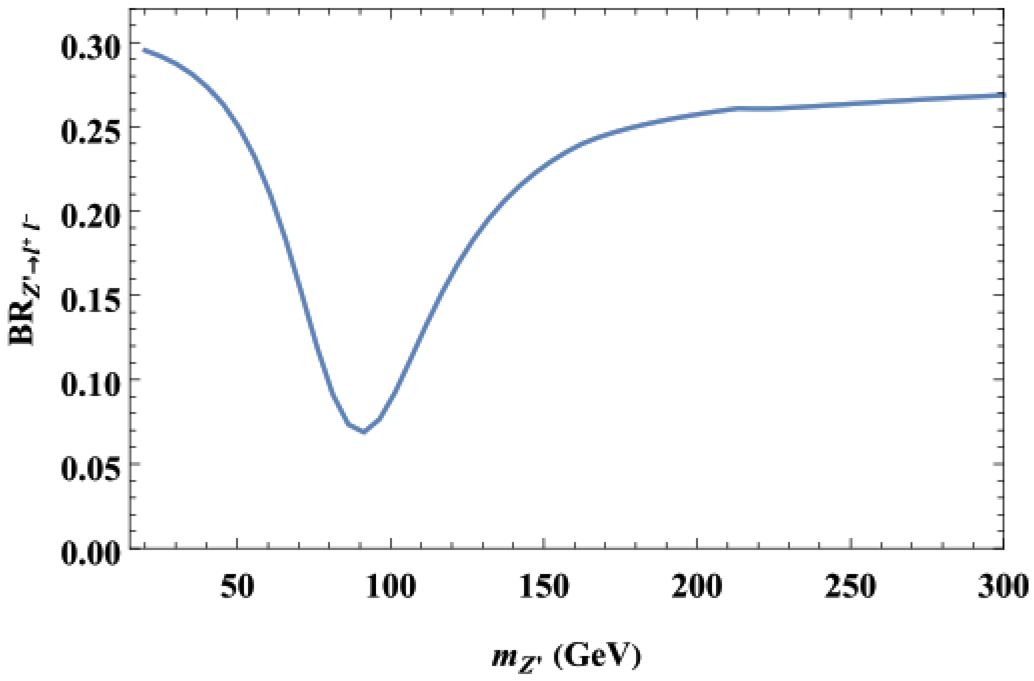
ATLAS Slepton



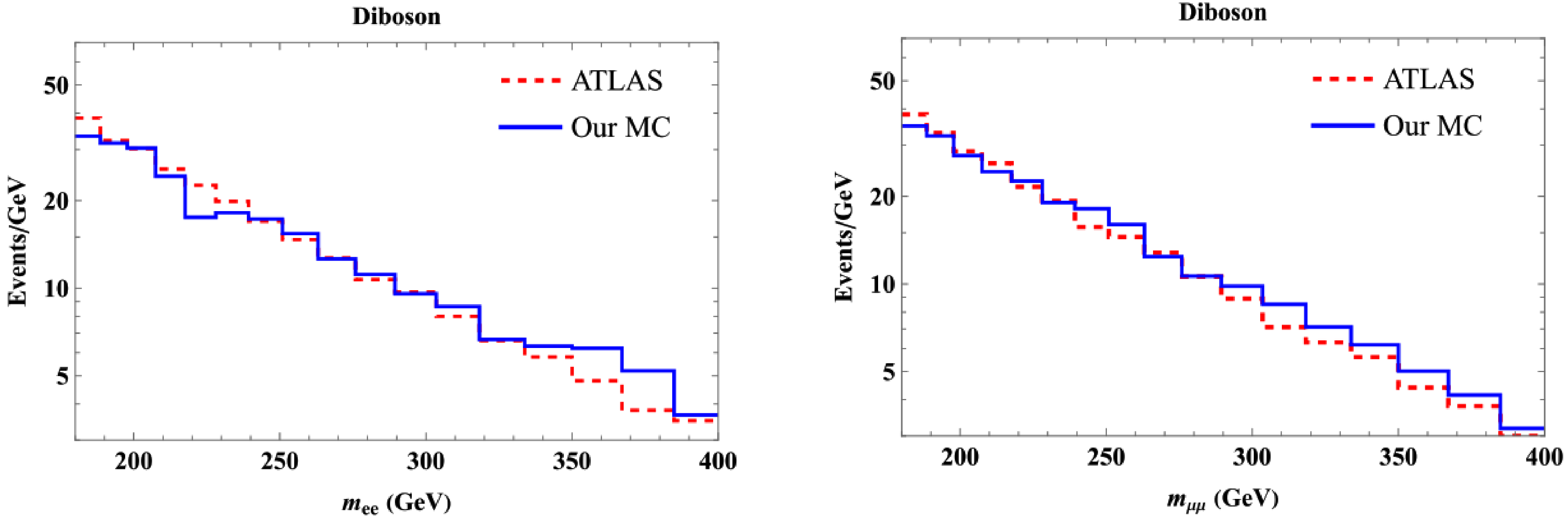
CMS Slepton



ATLAS Monojet Search

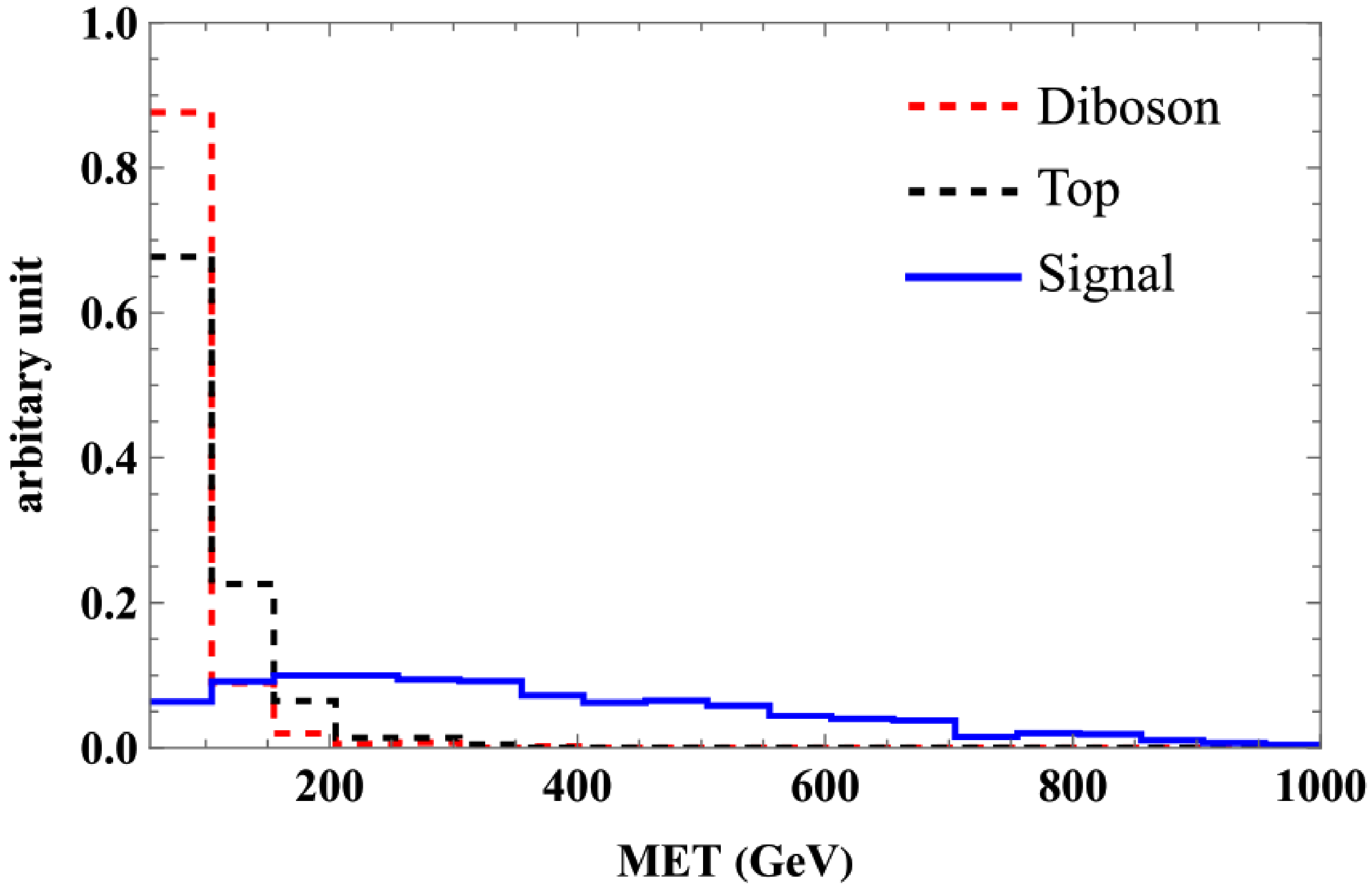


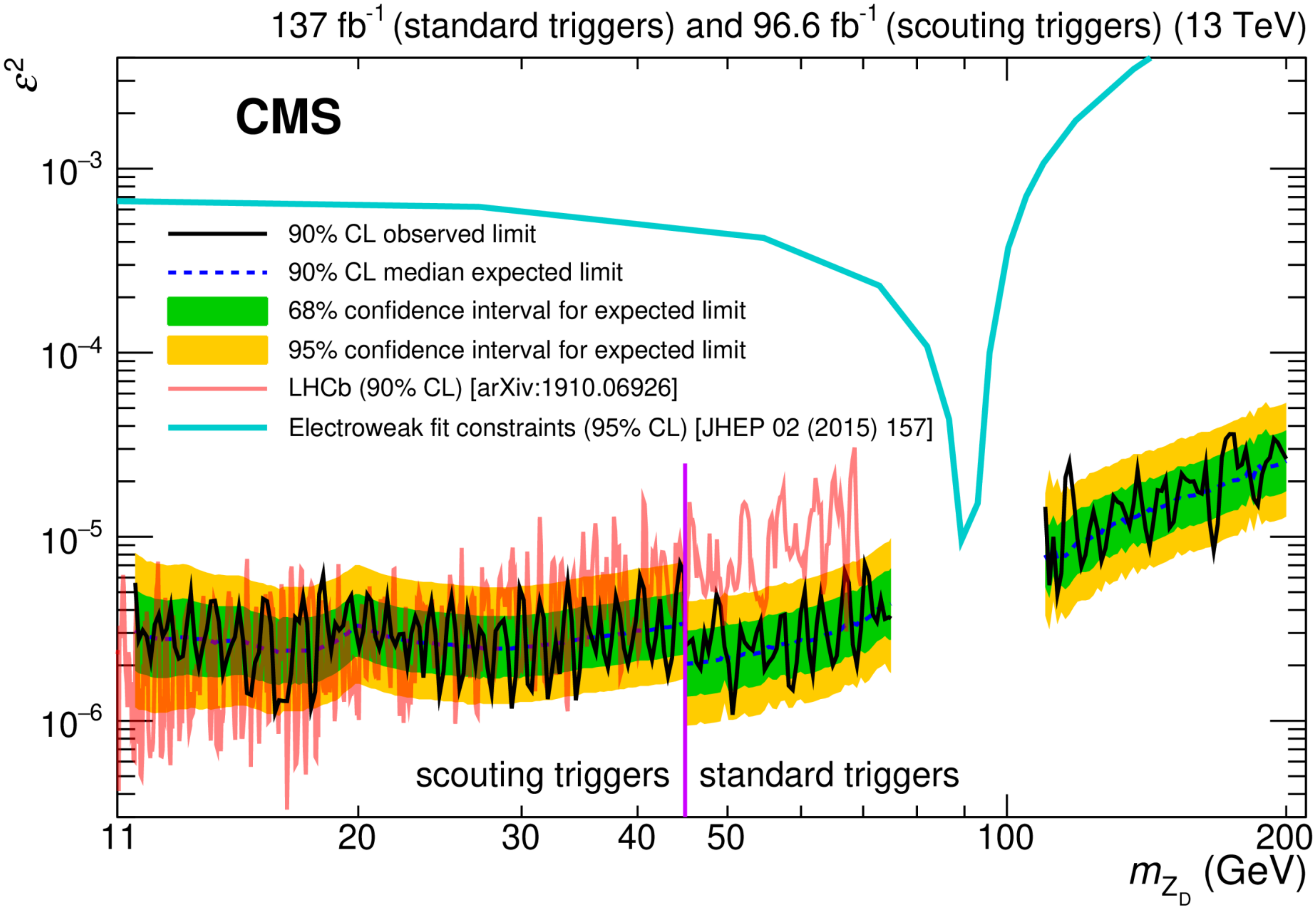
0.30
0.25
0.20
0.15
0.10
0.05
0.00
50
100
150
200
250
300
$BR_{Z' \to l^+ l^-}$
$m_{Z'}$ (GeV)



(a) *ee* channel

(b) $\mu\mu$ channel


1.0
0.8
0.6
0.4
0.2
0.0
arbitary unit
200
400
600
800
1000
MET (GeV)
Diboson
Top
Signal


137 fb^{-1} (standard triggers) and 96.6 fb^{-1} (scouting triggers) (13 TeV)
CMS
90% CL observed limit
90% CL median expected limit
68% confidence interval for expected limit
95% confidence interval for expected limit
LHCb (90% CL) [arXiv:1910.06926]
Electroweak fit constraints (95% CL) [JHEP 02 (2015) 157]
scouting triggers
standard triggers
ε^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
11
20
30
40
50
100
200
m_{Z_D} (GeV)