SEARCHES FOR DARK MATTER WITH THE ATLAS DETECTOR

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Deep Inelastic Scattering 2017, Birmingham

Motivation

Why search for 'dark matter'?

- strong evidence from several observations: rotational velocities in spiral galaxies, galaxy clusters, bullet cluster. . .

- cosmic microwave background: $\sim 26\%$ of universe made up by dark matter

What is dark matter?

- at least gravitional interaction, at most weak interaction with SM sector

- stable on cosmological time scale

$\Rightarrow$ focus on **WIMP** model for dark matter: weakly interacting, massive (non relativistic), stable

$\hookrightarrow$ production at colliders possible
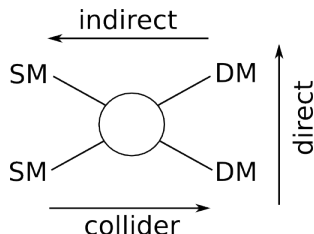
Dark Matter Searches at the LHC

How to look for dark matter?

WIMPs can only be recognised as $\not{E}_T$ at the LHC: need a recoiling object: jets, $W/Z, \gamma$, Higgs boson

focus on **simplified models**

- event signatures denoted as **Mono-X**:

- jet + $\not{E}_T$
- $\gamma + \not{E}_T$
- $W/Z + \not{E}_T$
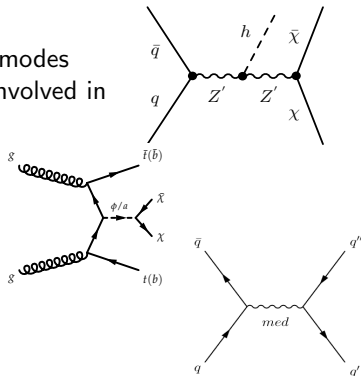↪ different decay modes

- Higgs + $\not{E}_T$
↪ different decay modes
↪ Higgs directly involved in WIMP production

- **dark matter+heavy flavour** production:

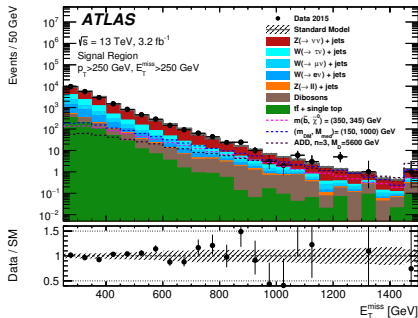- **di-jet** resonant production: mediator can also decay to quarks
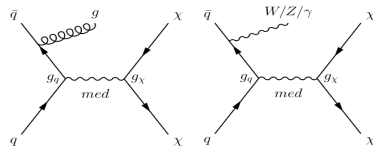
Strategy: search for an abundance of events with high $\not{E}_T$, a high p_T jet and 0 leptons

- at most four jets ($p_T > 30$ GeV)
- $\not{E}_T > 250$ GeV
- leading jet $p_T > 250$ GeV

- control regions defined to estimate W/Z+jets background: lepton veto inverted, $\not{E}_T$ defined to mimic $p_T(W/Z$-boson)
- simultaneous fit to $\not{E}_T$: $\rightarrow \not{E}_T$-dependent scale factors for background normalisation
- dominant background: $Z(\nu\nu)$+jets: normalised via $W(\mu\nu)$+jets scale factor, theory transfer uncertainty applied in signal region

Monojet Search (3.2 fb^{-1})

No excess found: limit on dark matter production via Z'-like mediator:
↪ axial-vector coupling with $g_\chi = 1.0$ and $g_q = 0.25$
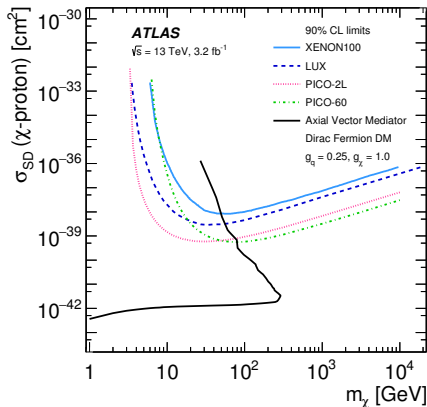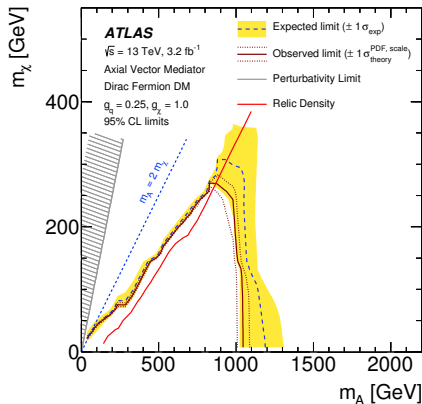
↪ derivation of scattering cross section limit: ATLAS constraint competitive for low DM masses

Similar to monojet: instead of high energetic jet, require high energetic photon
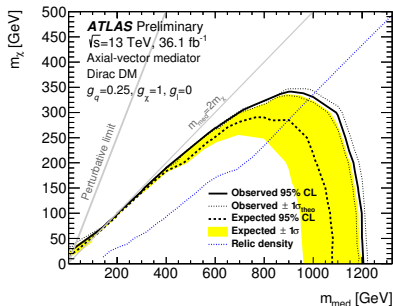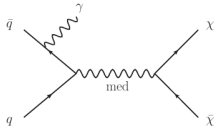
- 1 isolated photon with $p_T > 150$ GeV, no leptons

- $\not{E}_T > 150$ GeV, at most one jet with $p_T > 30$ GeV

- combination of data-driven methods and MC

- fit to $\not{E}_T$: $W/Z\gamma$ backgrounds scale factors

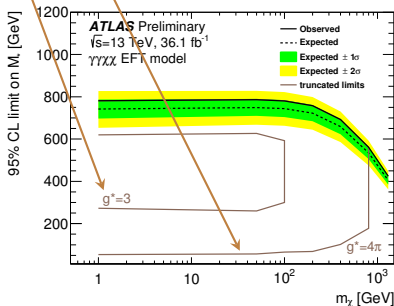- Dominant background $Z(\nu\nu)\gamma$ normalised by $Z(\ell\ell)\gamma$ scale factors
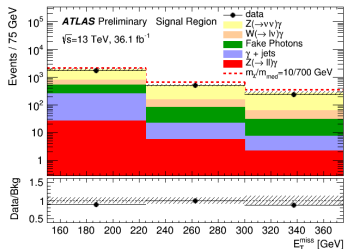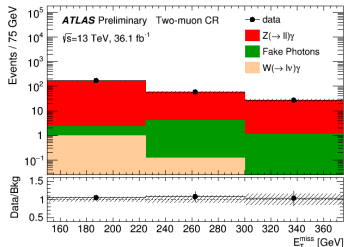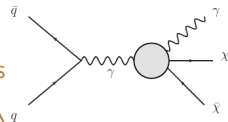
Use binned fit to $\not{E}_T$-distribution to interpret results in terms of DM models:

Axial-vector mediator

Effective Theory: $\gamma\gamma\chi\chi$ interaction


truncated limits

$\hookrightarrow$ analysis sensitivity dominated by statistical uncertainty in control regions

Search for $W/Z+E\!\!\!/_T$ with hadronically decaying W/Z

$\hookrightarrow$ analysis similar to monojet search but with focus on **large-R jets**

- require large-R jets: both decay products of W/Z contained ($R = 1.0$, anti-k_t)
  $\hookrightarrow$ substructure described by jet mass and D_2 (two distinct energy concentrations)

- p_T(large-R jet)> 200 GeV, $|\eta| < 2.0$, $E\!\!\!/_T > 250$ GeV

- no leptons allowed

- dominant background $Z(\nu\nu)+$jets
  $\hookrightarrow$ normalised via $Z(\mu\mu)+$jets estimation
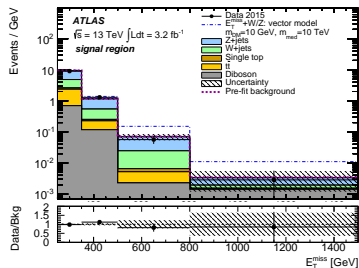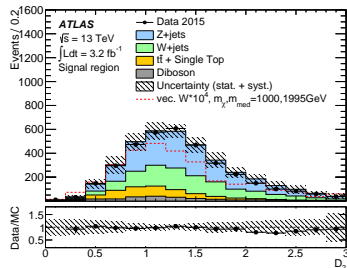
Mono-V($\rightarrow$hadrons) Search (3.2 fb^{-1}) Phys. Lett. B 763, 251

Background-prediction in agreement with data: limits are set on effective field theory and simplified models:
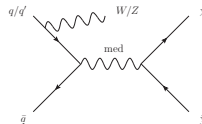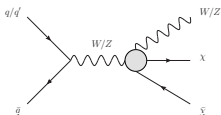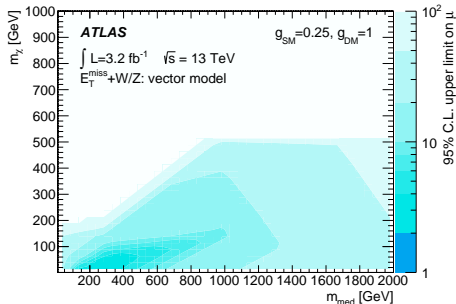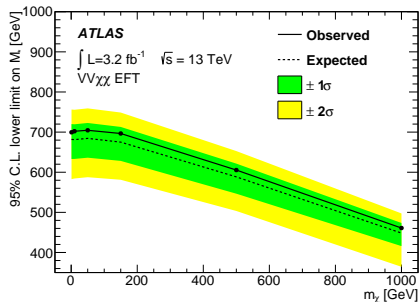
$\hookrightarrow$ main limitations: statistics, modelling of large-R jet observables

Signature: opposite sign leptons and $\not{E}_T$

- require $\not{E}_T > 90$ GeV, boosted Z-boson with $\Delta R(\ell\ell) < 1.8$, b-veto
- dominant background: $ZZ \to \ell\ell\nu\nu$ production
- differential m_{ZZ} cross section corrected to NNLO QCD and NLO EW calculation
- WZ background normalized to NNLO QCD and fitted in control regions with 3 leptons
- Z+jets background data driven, non resonant background from $e\mu$ control regions
- Z+jets uncertainty dominates
- limit on vector mediator in simplified model of WIMP production
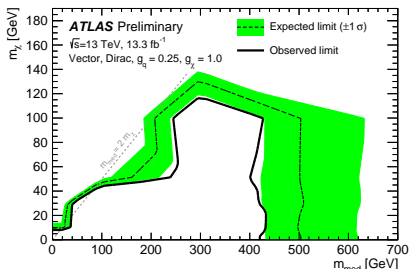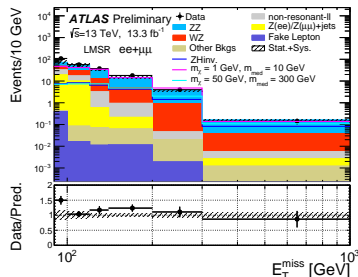
Mono-Higgs, $H \rightarrow \gamma\gamma$ (13.3 fb^{-1})

Higgs involved in WIMP production: different models: coupling to heavy mediator Z', coupling to Z' and pseudo-scalar A^0 (2HDM)

- two photons with $p_T > 25$ GeV, $105 < m_{\gamma\gamma} < 160$ GeV
- categories in $\not{E}_T/\sqrt{\sum E_T}$ and $p_T^{\gamma\gamma}$
  ↪ highest sensitivity to vector mediator (Z'_B) for high $\not{E}_T/\sqrt{\sum E_T}$ and $p_T^{\gamma\gamma}$
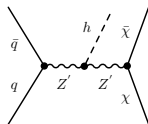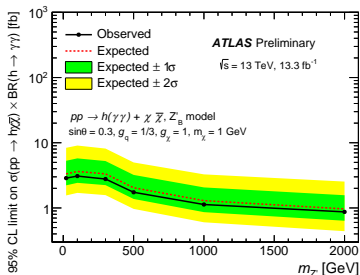
Higgs ISR suppressed due to Yukawa coupling
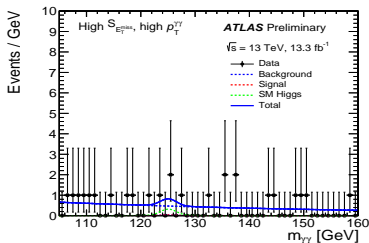
- background in $m_{\gamma\gamma}$ fitted with exponential function+double sided crystal ball (Higgs resonance)
- signal (crystal ball) fitted to 0 → upper cross section limits as function of heavy mediator masses derived

Search similar to mono-$H(\to \gamma\gamma)$: final state now with b-jets

- *resolved* region: two distinct b-jets, $\slashed{E}_T < 500$ GeV

- *merged* region: $\slashed{E}_T > 500$ GeV: boosted Higgs $\to$ large-R jet with substructure

- shape-fit to m_{jj} or m_J in different categories of $\slashed{E}_T$ and #b-jets, two dedicated control regions

- main backgrounds: W/Z+jets, $t\bar{t}$

- dominant uncertainty: b-tagging, luminosity, JES, jet mass

Searches for $b\bar{b} + \not{E}_T$ and $t\bar{t} + \not{E}_T$ production:
$\hookrightarrow$ sensitive to **(pseudo-)scalar** mediator

- **DM+$b\bar{b}$**: ATLAS-CONF-2016-086

  $\hookrightarrow$ exactly two b-jets, 3rd jet veto, no leptons
  $\hookrightarrow$ dominant background $Z(\nu\nu) + b$ reduced by cut requiring separated b-jets, momentum imbalance
  $\hookrightarrow$ 3 CR, $Z(\nu\nu) + b$ constrained from $Z(\ell\ell) + b$
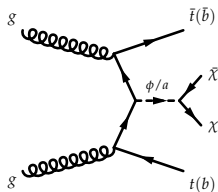
- **DM+$t\bar{t}$**: ATLAS-CONF-2016-077, ATLAS-CONF-2016-050, ATLAS-CONF-2016-076

  $\hookrightarrow$ 0-leptons, 1-lepton or 2-leptons channels
  $\hookrightarrow$ many signal regions defined with help of different variables: $\not{E}_T/\sqrt{H_T}, m_T$, razor variables. . .
  $\hookrightarrow$ dominant background is SM $t\bar{t}$ production: estimated in control regions

DM+Heavy Flavour Searches (13.3 fb^{-1})

Limits shown on **pseudo-scalar** mediator models (similar to scalar mediator):
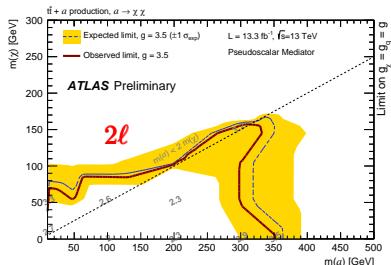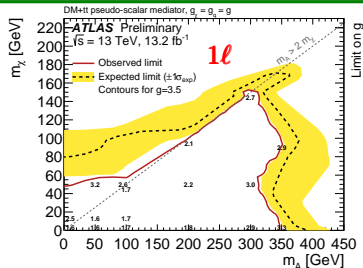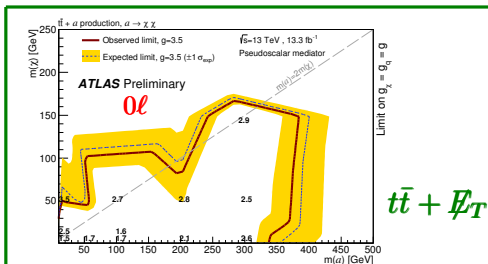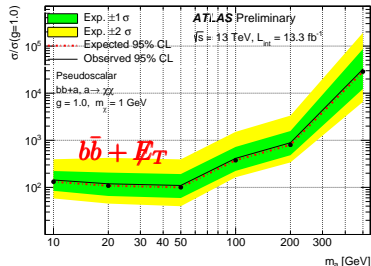
↪ **similar sensitivities**

Search for resonance in di-jet invariant mass spectrum

- see talk by Hanno Meyer zu Theenhausen (Wed. 2 pm)
- limits are set on excited quarks q^*, quantum black holes, W', **Z'**, W^*, generic Gauss-shaped resonances
- in context of simplified models: limit on coupling g_q to standard model particles as a function of the mediator mass $m_{Z'}$
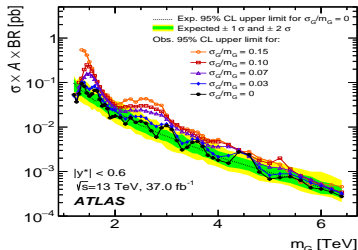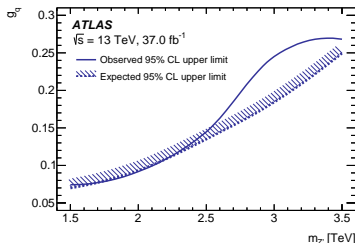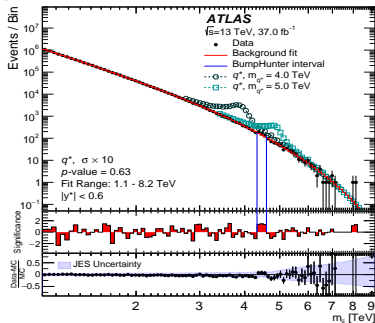
Combination of Exclusions I

Combining dark matter searches in terms of simplified models with an axial-vector mediator model:

With less 'optimistic' coupling to standard model quarks: $g_q = 0.1$:

DM Simplified Model Exclusions   *ATLAS* Preliminary March 2017

Vector mediator, Dirac DM
$g_q = 0.1$, $g_l = 0.01$, $g_{DM} = 1$
All limits at 95% CL

Dijet
Dijet 8 TeV $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Phys. Rev. D. 91 052007 (2015)
Dijet $\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
arXiv:1703.09127 [hep-ex]
Dijet TLA $\sqrt{s}$ = 13 TeV, 3.4 fb^{-1}
ATLAS-CONF-2016-030

E_T^{miss}+X
E_T^{miss}+γ $\sqrt{s}$ = 13 TeV, 36.4 fb^{-1}
CERN-EP-2017-044

Dilepton
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-027
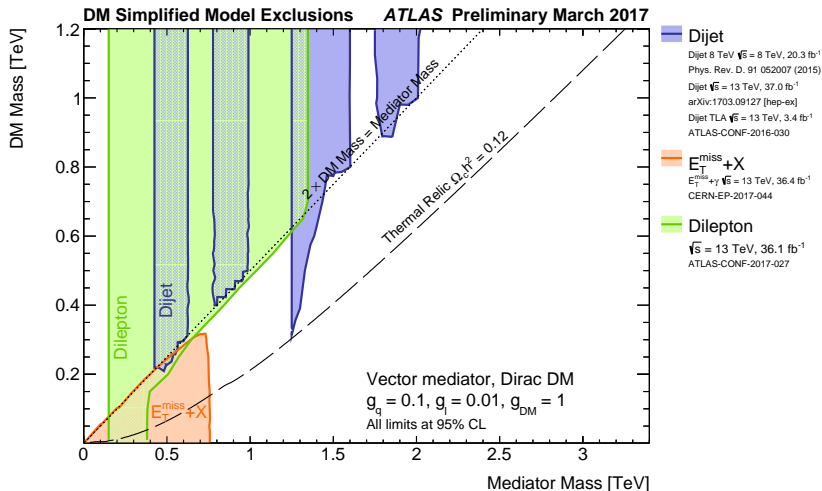
$\rightarrow$ dilepton results shown, coupling suppressed: $g_\ell = 0.01$

Limit on spin-dependent WIMP-proton scattering cross section:

DM Simplified Model Exclusions   *ATLAS* Preliminary March 2017

σ_{SD} (DM-proton) [cm^2]

$E_T^{miss}+\gamma$

PICO-60 C_3F_8

Dijet TLA

Dijet 8 TeV

Dijet

Axial-vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_{DM} = 1$
ATLAS limits at 95% CL, direct detection limits at 90% CL

DM Mass [GeV]

Dijet TLA
$\sqrt{s} = 13$ TeV, 3.4 fb^{-1}
ATLAS-CONF-2016-030

Dijet 8 TeV
$\sqrt{s} = 8$ TeV, 20.3 fb^{-1}
Phys. Rev. D. 91 052007 (2015)

Dijet
$\sqrt{s} = 13$ TeV, 37.0 fb^{-1}
arXiv:1703.09127 [hep-ex]

$E_T^{miss}+\gamma$
$\sqrt{s} = 13$ TeV, 36.4 fb^{-1}
CERN-EP-2017-044

PICO-60 C_3F_8
arXiv:1702.07666v1 [astro-ph.CO]

Summary and Outlook

- a variety of dark matter searches carried out throughout 2015 and 2016 data taking

  $\hookrightarrow$ many new results, many new results to come soon with full 2015+2016 data set

- interpretations focused on simplified models: dark matter production via heavy mediator

  $\hookrightarrow$ **model dependent** approach

  $\hookrightarrow$ complementary sensitivity compared to direct dark matter searches

  $\hookrightarrow$ constraints from di-jet resonance searches

- no evidence for dark matter found so far

 $\hookrightarrow$ stay tuned for new results with 3-10$\times$ increased data sets
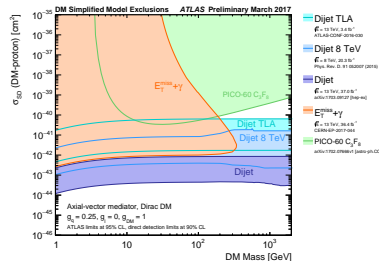
BACKUP

Similar to monojet: instead of high energetic jet, require high energetic photon

- 1 isolated photon with $p_T > 150$ GeV, no leptons

- $\not{E}_T > 150$ GeV, at most one jet with $p_T > 30$ GeV

- 4 control regions to estimate $W/Z\gamma$ and γ+jets background: use low-$\not{E}_T$ region

- fake photon estimation data-driven: ABCD method for jets faking γ, $Ze\gamma/Zee$ ratio measurement for e faking γ
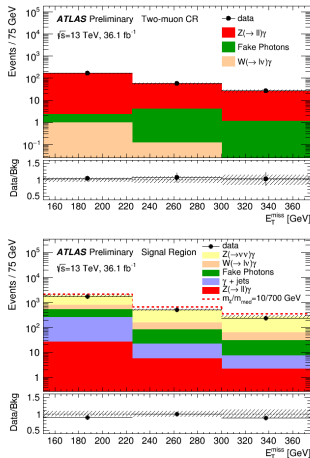

Simultaneous fit in control regions and signal regions to $\not{E}_T$: independent normalisation factors per $\not{E}_T$-bin for $W/Z\gamma$ backgrounds

Dominant background $Z(\nu\nu)\gamma$ normalised by $Z(\ell\ell)\gamma$ scale factors

- require large-R jets: both decay products of W/Z contained ($R = 1.0$, anti-k_t)
  $\hookrightarrow$ substructure described by jet mass and D_2 (two distinct energy concentrations)

- p_T(large-R jet)> 200 GeV, $|\eta| < 2.0$, $\not{E}_T > 250$ GeV, $\Delta\phi(\not{E}_T$,narrow jet$) > 0.6$

- no leptons

- dominant background $Z(\nu\nu)$+jets
  $\hookrightarrow$ three control regions defined
  $\hookrightarrow$ simultaneous fit to $\not{E}_T$-distribution performed: single normalisation factors for W/Z+jets, $t\bar{t}$ backgrounds
  $\hookrightarrow$ $Z(\nu\nu)$+jets normalised with $Z(\mu\mu)$+jets scale factor
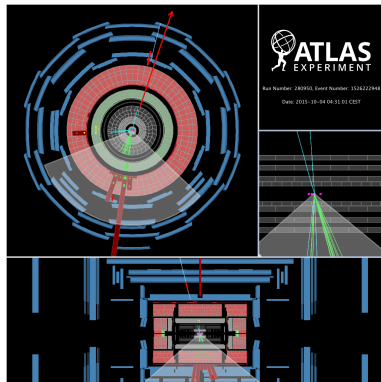
Search for resonance in di-jet invariant mass spectrum

- background completely data-driven: *sliding window fit* with $f(x) = p_1(1-x)^{p_2}x^{p_3}$
- limits are set on excited quarks q^*, quantum black holes, W', **Z'**, W^*
- limits are also set on generic Gauss-shaped resonances with mass m_G (truth level)
- in context of simplified models: limit on coupling g_q to standard model particles as a function of the mediator mass $m_{Z'}$