Search for invisible particles in association with jets using the ATLAS detector

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Motivation for MET+X analysis

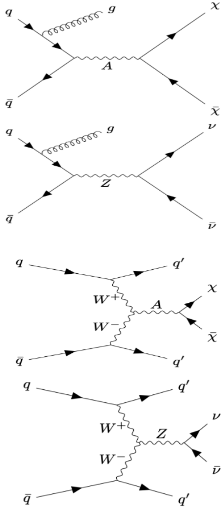
- Dark Matter particles (e.g. WIMPs) could be produced at the LHC and remain undetected leaving a clear missing energy signature

- This can be inferred via momentum imbalance in the transverse plane if produced in association with SM particles (e.g. jets)

- Dominant source of missing energy in the SM is $Z \rightarrow \nu\bar{\nu}+$ jets (however $W \rightarrow \ell\nu+$ jets contributes due to out of acceptance leptons)

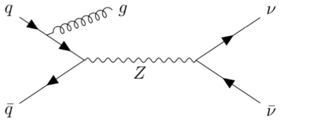
MONOJET LIKE

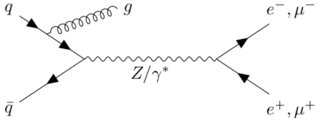
VBF-LIKE

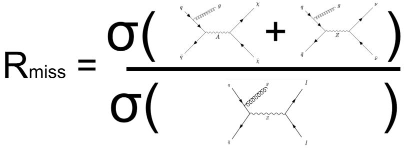


Analysis idea

- We take the charged leptons to not be reconstructed and construct a pseudo p_T^{miss} for the $Z \to \ell^+\ell^-$ and $W \to \ell\nu+$ jets events
- Similarities of these processes to $Z \to \nu\bar{\nu}+$ jets are exploited in the control regions
- Measure the detector corrected differential cross sections as a function of p_T^{miss} and jet kinematics
- Measure the ratio in addition to the individual processes, leads to cancellation of most theoretical and experimental uncertainties



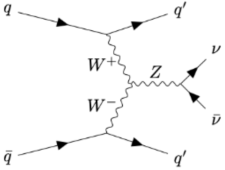




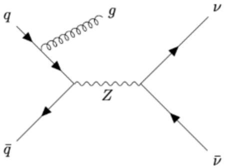
- Looking at different observables, such as p_T^{miss} or m_{jj}, and constraining various DM models or even the Higgs Boson decaying invisibly
- We can then exclude many different DM models at a 95 % confidence limit or even set a constraint on BR(H $\rightarrow$ inv)

Event selection
pTmiss > 200 GeV,
Jet |y| < 4.4, Jet pT > 30 GeV

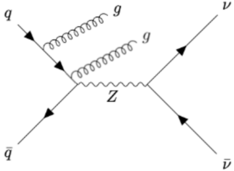
VBF-like
Njets ≥ 2, mjj ≥ 200 GeV
pTj1 ≥ 80 GeV, pTj2 ≥ 50 GeV
$\Delta\eta$jj > 1



Monojet-like
Njets ≥ 1,
pTj1≥ 120 GeV, pTj2≥ 30 GeV

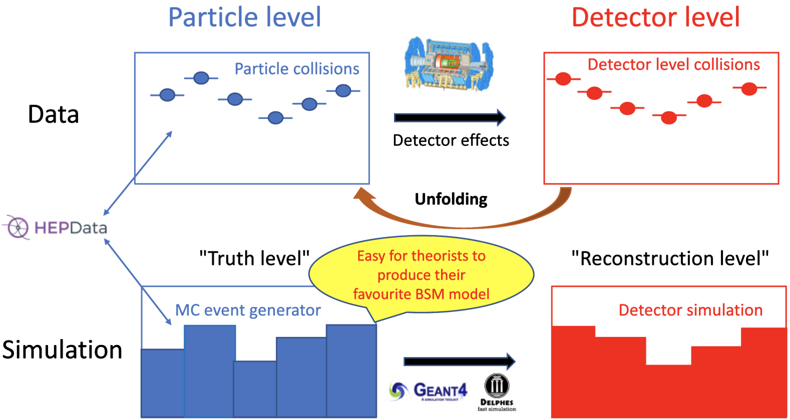


2 Jet Inclusive
Njets ≥ 2,
pTj1≥ 110 GeV, pTj2≥ 50 GeV



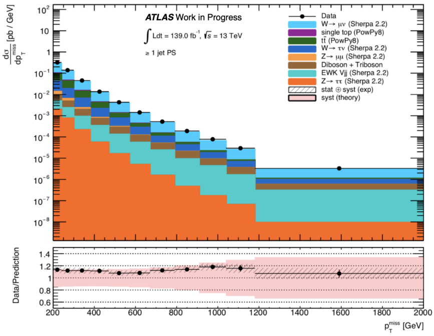
Unfolding

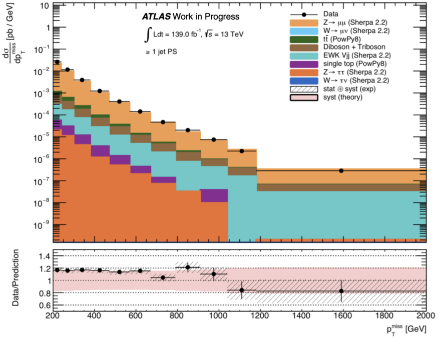
- Particle level measurements of SM processes are common in collider physics, they can be used to set limits on BSM models
- Iterative unfolding is performed on the detector level data [1]



Unfolded Observables

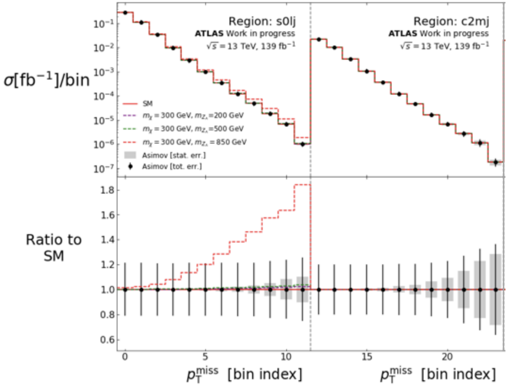
- Unfolded p_T^{miss} observable in the one muon and two muon control region for the monojet-like phase space [2]
- Main contribution in the one muon control region is $W \to \mu\nu$ and in the two muon control region it is $Z \to \mu\mu$

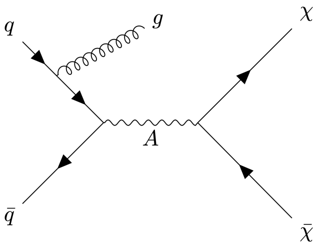




Monojet like phase space: p_T^{miss} distributions

- Axial-vector DM model ($g_q = 0.25$, $g_\chi = 1.0$) in general gets bigger in tails of p_T^{miss} spectrum in the signal region but no presence in control regions
- Includes theory and experimental systematic uncertainties
- QCD scale is the largest systematic uncertainty





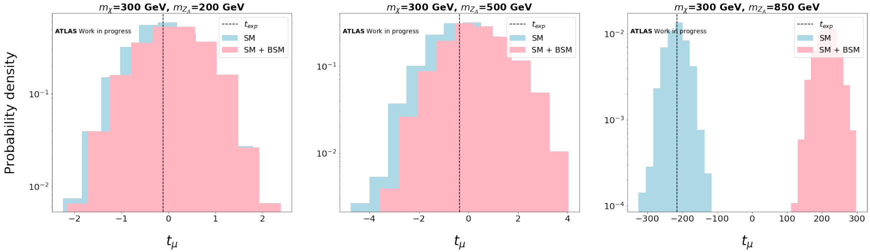
Test statistic, t_μ

- The test statistic is given by:

$$\lambda(\vec{\mu}) = \frac{\operatorname{argmax}_{\vec{\theta}} \mathcal{L}(\vec{x} \mid \vec{\mu}, \vec{\theta})}{\operatorname{argmax}_{\vec{\theta}} \mathcal{L}(\vec{x} \mid \mu_{SM}, \vec{\theta})} \tag{1}$$

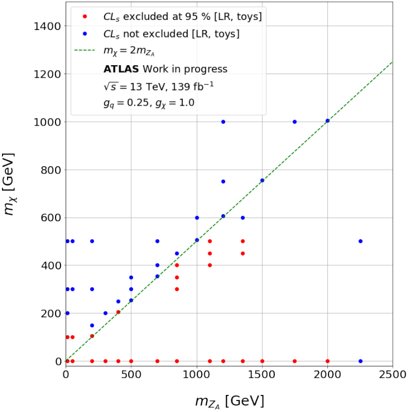
$$t_{\vec{\mu}} = -2\ln\lambda(\vec{\mu}) = \chi^2_\mu - \chi^2_{SM} \tag{2}$$

- Probability distribution functions for the test statistic, t_μ, for axial-vector DM models (m_χ=300 GeV; m_{Z_A}=200 GeV, 500 GeV, 850 GeV)



Expected CL_s limits

- Comparison of current expected CLs limits (left) of the axial-vector mediator model to the limits obtained with the recent MET + jets analysis for the axial-vector mediator (right, Figure 5a from CERN-EP-2020-238)



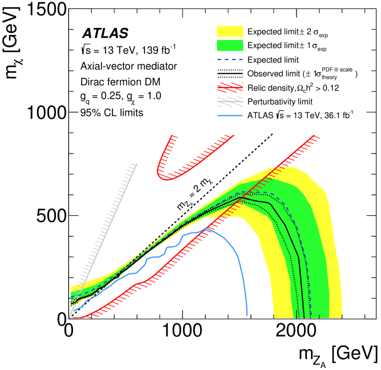
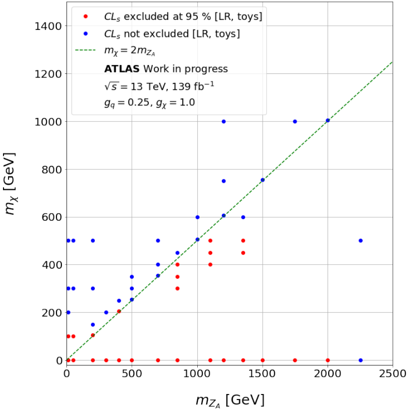


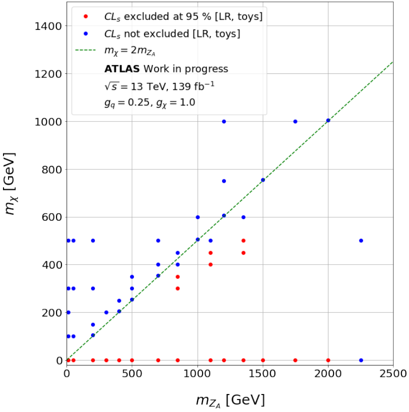
Figure 5a, CERN-EP-2020-238

Effect of control regions

- Calculate the CL_s with and without control regions to see the effect of constraining the systematic uncertainties



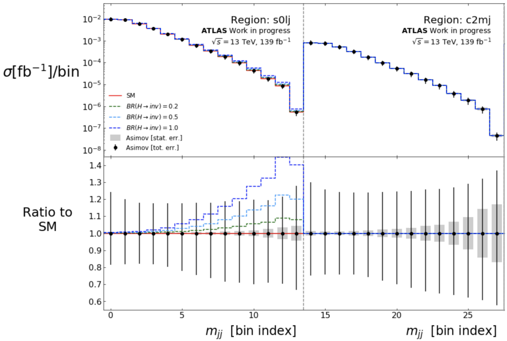
With control regions

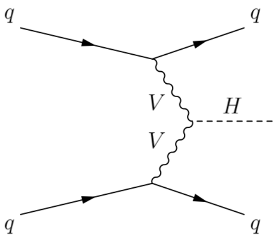


No control regions

VBF phase space: m_{jj} distribution

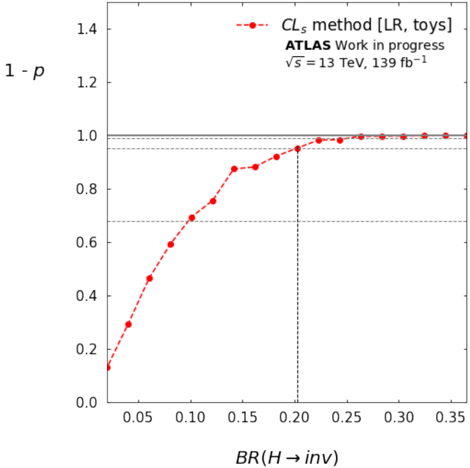
- VBF Higgs with varying branching fractions to invisible particles, in general this model gets bigger in tails of m_{jj} spectrum in the signal region but no presence in control regions
- Includes theory and experimental systematic uncertainties
- m_{jj} shape correction is the largest systematic uncertainty





CL_s limit on $\mathrm{BR}(\mathrm{H} \to \mathrm{inv})$

- $\mathrm{BR}(\mathrm{H} \to \mathrm{inv})$ excluded above 0.2 at a confidence level of 95 % for the VBF Higgs channel
- Compare to recent ATLAS result, where VBF $\mathrm{BR}(\mathrm{H} \to \mathrm{inv})$ excluded above 0.13 at 95 % CL [3]



Summary & outlook

- Idea of this analysis is to measure the detector corrected differential cross sections as a function of p_{T}^{miss} and jet kinematics in three different phase spaces

- We have set preliminary expected limits on the axial-vector mediator model and Higgs to invisible branching ratio; this will be updated once the final MC at particle level is available

- Next steps:
  - Calculate the observed limit using unfolded data
  - Look at other BSM models with $p_{\mathrm{T}}^{\mathrm{miss}}$ as signature e.g. SUSY and Leptoquarks
  - Add in different observables which have been measured, such as $\Delta\phi_{jj}$, and see how our sensitivity changes

Thank You!

References

- [1] https://inspirehep.net/literature/1672893
- [2] https://discovery.ucl.ac.uk/id/eprint/10119246/1/VasilisKonstantinidesThesis.pdf
- [3] https://cds.cern.ch/record/2715447

Likelihood function

The likelihood function used, assuming all statistical and systematic uncertainties are Gaussian:

$$\mathcal{L}\left(\vec{x} \mid \vec{\mu}, \vec{\theta}\right) = \frac{1}{\left(\sqrt{2\pi}\right)^k \, |\mathrm{Cov}|} \cdot e^{-\frac{1}{2}\chi^2\left(\vec{x}, \vec{\mu}, \vec{\theta}\right)} \cdot \prod_i \mathcal{G}\left(\theta^{(i)}\right) \tag{3}$$

where k is the number of PoIs and

$$\chi^2\left(\vec{x}, \vec{\mu}, \vec{\theta}\right) = \left(\vec{x} - \vec{p}^{\,\mathrm{mod}}\left(\vec{\mu}\right) + \sum_i \theta^{(i)} \cdot \vec{\epsilon}^{\,(i)}\right)^{\mathrm{T}} \mathrm{Cov}^{-1} \left(\vec{x} - \vec{p}^{\,\mathrm{mod}}\left(\vec{\mu}\right) + \sum_i \theta^{(i)} \cdot \vec{\epsilon}^{\,(i)}\right) \tag{4}$$

- χ^2 test-statistic
- Cov is the covariance matrix describing statistical and systematic uncertainties
- The SM + BSM model prediction at a particular hypothesis $\vec{\mu}$ is denoted by $\vec{p}^{\,\mathrm{mod}}\left(\vec{\mu}\right)$
- $\epsilon^{(i)}$ is the absolute uncertainty amplitude associated with a nuisance parameter $\theta^{(i)}$

Test statistic, t_μ

- To test the hypothesised value of μ we consider the ratio of the likelihoods of the signal and SM hypotheses:

$$\lambda(\vec{\mu}) = \frac{\mathrm{argmax}_{\vec{\theta}}\mathcal{L}(\vec{x} \mid \vec{\mu}, \vec{\theta})}{\mathrm{argmax}_{\vec{\theta}}\mathcal{L}(\vec{x} \mid \mu_{SM}, \vec{\theta})} \tag{5}$$

- The test statistic is then given by:

$$t_{\vec{\mu}} = -2\ln\lambda(\vec{\mu}) = \chi^2_\mu - \chi^2_{SM} \tag{6}$$

- This is equal to the $\Delta\chi^2$ between the two hypotheses assuming that all statistical and systematic uncertainties are modelled as Gaussian

CL_s method

- The confidence level is defined as the probability of $t_{\vec{\mu}}$ being higher than what was observed, assuming the signal model to be true:

$$CL(\vec{\mu}) = \int_{t_{\vec{\mu},obs}}^{\infty} f(t_{\vec{\mu}}|\vec{\mu})dt_{\vec{\mu}} \tag{7}$$

- Whereas $CL(\vec{\mu})$ was defined by testing the signal hypothesis against the SM, assuming the signal hypothesis is true

- Now define CL_b by using the same LR to test the signal hypothesis, assuming the SM is true

- Define CL_s to be a ratio of these two quantities:

$$CL_s(\vec{\mu}) = \frac{CL(\vec{\mu})}{CL_b} \tag{8}$$

CL_s results

- Any gridpoint with value above 0.95 is excluded at a 95% confidence level, values with zero are non-available samples