Search for invisible Higgs-boson decays in events with vector-boson fusion signatures using 139 fb^{-1} of proton–proton data recorded by the ATLAS experiment

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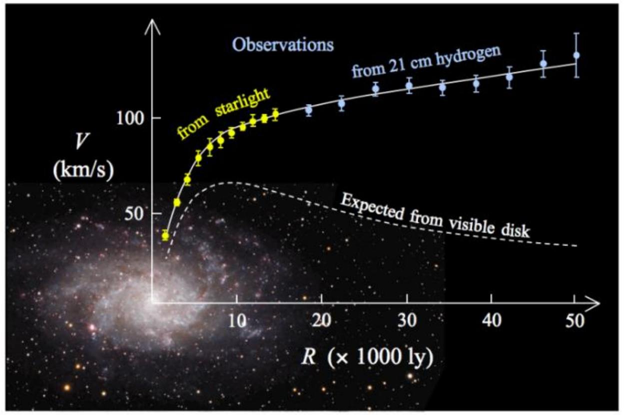
Outline

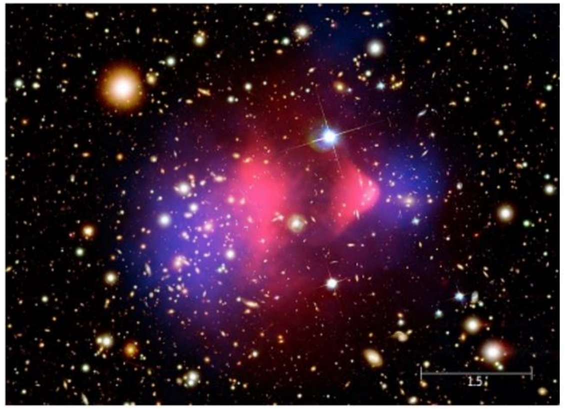
- Introduction
- Data and Simulation
- Event Selection
- Systematic Uncertainty
- Statistical Model
- Results and Conclusions

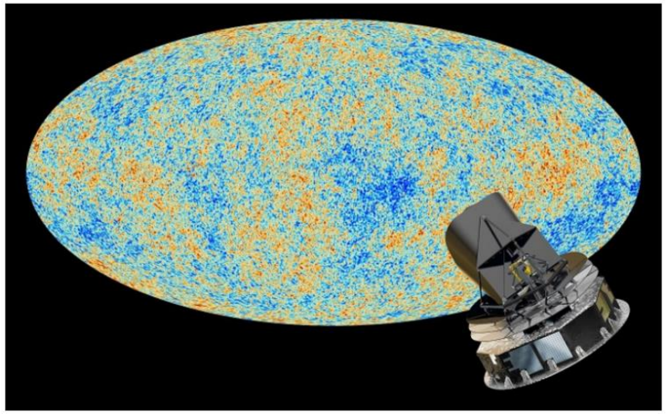
Introduction

- Evidences of the existence of dark matter
  - galactic rotation curve
  - mass distribution of galaxy cluster
  - cosmic microwave background radiation

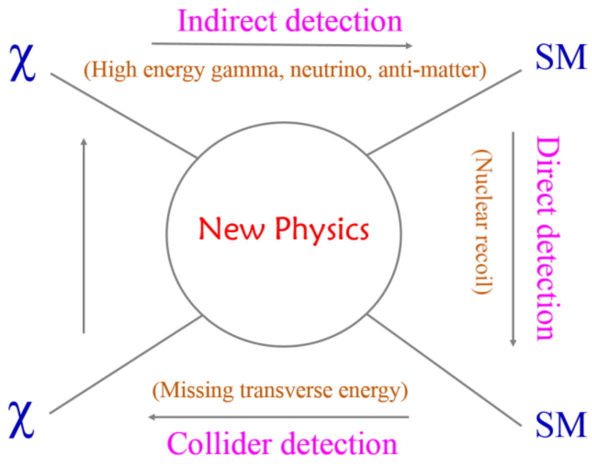
- Candidate particles of dark matter: Axion, sterile neutrino, WIMPs





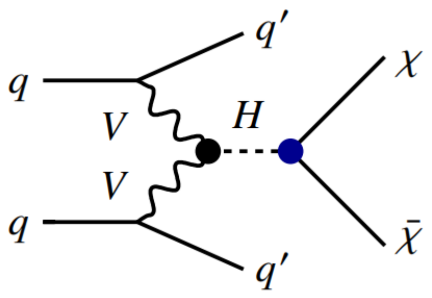


- Experiments for dark matter search(WIMPs)
  - direct search (like PandaX)
  - indirect search(like DAMPE)
  - search in collider(like LHC)

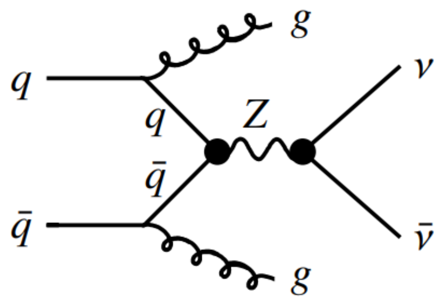


Introduction

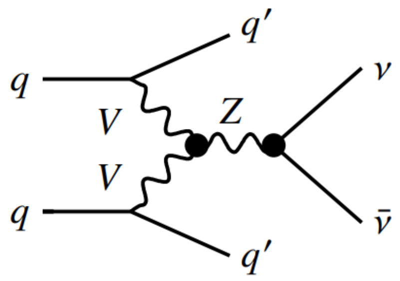
- A direct search for the decay of the Higgs boson into invisible particles(B_{inv})
- Higgs boson might decay into $\chi\chi$(B_{BSM})
- Complementary to indirect constraints from measurements of visible decays
- Search channel
  - VBF(main channel), ggF, VH



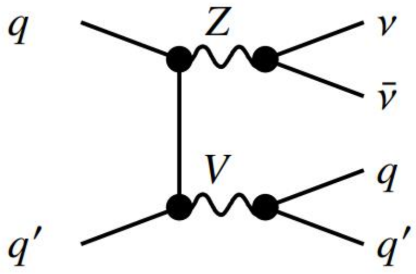
(a) Signal process



(b) Example diagram for strong Z+jets background process



(c) Example diagram for electroweak VBF Z+jets background process



(d) Example diagram for electroweak diboson Z+jets background process

Data and Simulation

- Data
  - 2015-2018, $\sqrt{s} = 13\mathrm{TeV}$, L=139fb^{-1}
- Triggers
  - MET trigger (>70-110GeV)
  - single-lepton triggers (20-26GeV)
  - dilepton triggers
  - single-jet triggers with jet p_T thresholds (15 GeV ~400 GeV)
- Event simulation

$$E_{x(y)}^{\text{miss}} = -\sum_{i\in\{\text{hard objects}\}} p_{x(y),i} - \sum_{j\in\{\text{soft signals}\}} p_{x(y),j}$$

$$\mathbf{E}_\mathrm{T}^{\text{miss}} = (E_x^{\text{miss}}, E_y^{\text{miss}}),$$

$$E_\mathrm{T}^{\text{miss}} = |\mathbf{E}_\mathrm{T}^{\text{miss}}| = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2},$$

$$\phi^{\text{miss}} = \tan^{-1}(E_y^{\text{miss}}/E_x^{\text{miss}}).$$

Process	Generator	ME order	PDF	Parton shower	Tune
Strong V+jets	Sherpa 2.2.1 and Sherpa 2.2.7 (m_{jj}-filtered)	NLO (up to 2 jets), LO (up to 4 jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
Electroweak V+jets	Herwig 7.2.1	NLO (for 2 jets)	MMHT2014nlo	Herwig angular-order and Pythia 8 dipole recoil	Herwig 7.2
V+jets α_{EW}^3 interference	MadGraph5_aMC@NLO	LO	PDF4LHC15	Pythia 8	
Strong VV+jets (including $gg \to VV$+jets)	Sherpa 2.2.1 or Sherpa 2.2.2	NLO (up to 1 jet), LO (up to 3 jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
Electroweak VV+jets	Sherpa 2.2.1 or Sherpa 2.2.2	LO	NNPDF3.0nnlo	Sherpa MEPS@LO	Sherpa
$t\bar{t}$	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8	A14
QCD multijet	Pythia 8.230	LO	NNPDF2.3lo	Pythia 8	A14
ggF Higgs	Powheg NNLOPS	NNLO	PDF4LHC15nnlo	Pythia 8	AZNLO
VBF Higgs	Powheg	NLO	PDF4LHC15	Pythia 8 dipole recoil	AZNLO
VH Higgs	Powheg Box v2	NLO	PDF4LHC15	Pythia 8	AZNLO

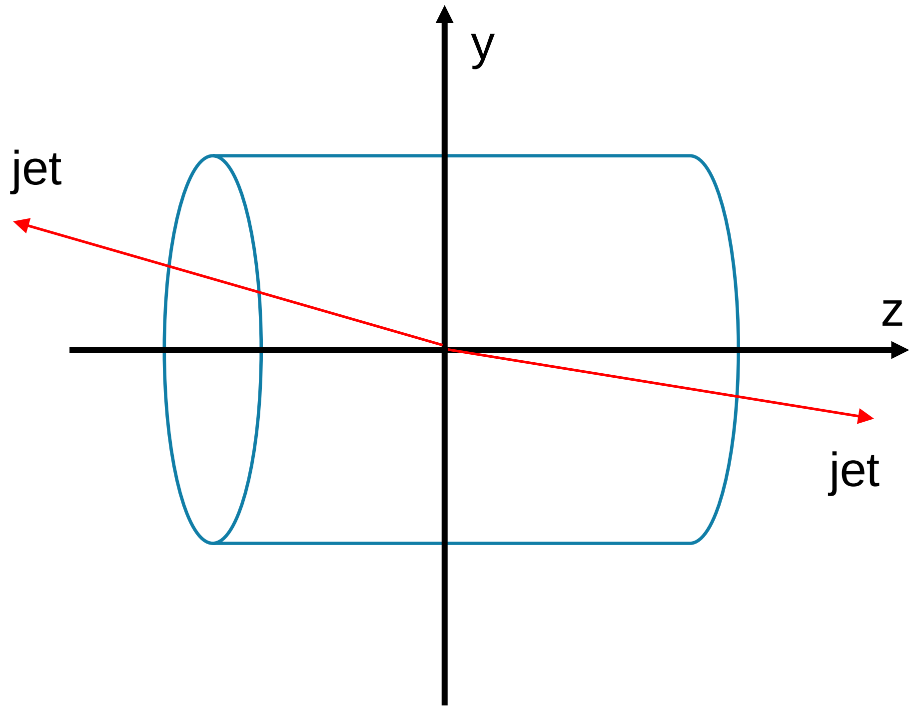
Event selection

- Signature from vector-boson fusion
  - the two leading jets
    - opposite hemisphere of the detector
    - more forward than jets from non-VBF
    - smaller values of the azimuthal separation $\Delta\phi_{jj}$
  - third or fourth jet (radiation from VBF)
    - smaller values of C_i

$$C_i = \exp\left(-\frac{4}{\left(\eta^{j1}-\eta^{j2}\right)^2}\left(\eta^i - \frac{\eta^{j1}+\eta^{j2}}{2}\right)^2\right)$$

    - smaller invariant mass

$$m_i^{rel} = \frac{\min\{m_{j1,i}, m_{j2,i}\}}{m_{jj}}$$



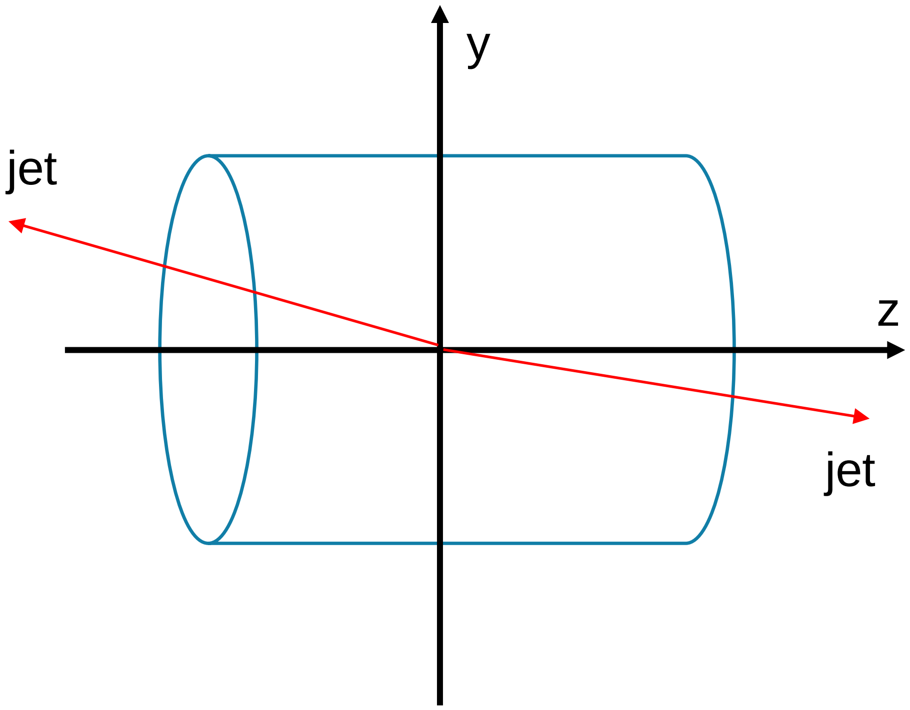
Event selection

- Event selection

• no lepton candidate, nor a photon
• two, three or four jets with p_{T} >25 GeV   • p_{T}(all jets)>140 GeV

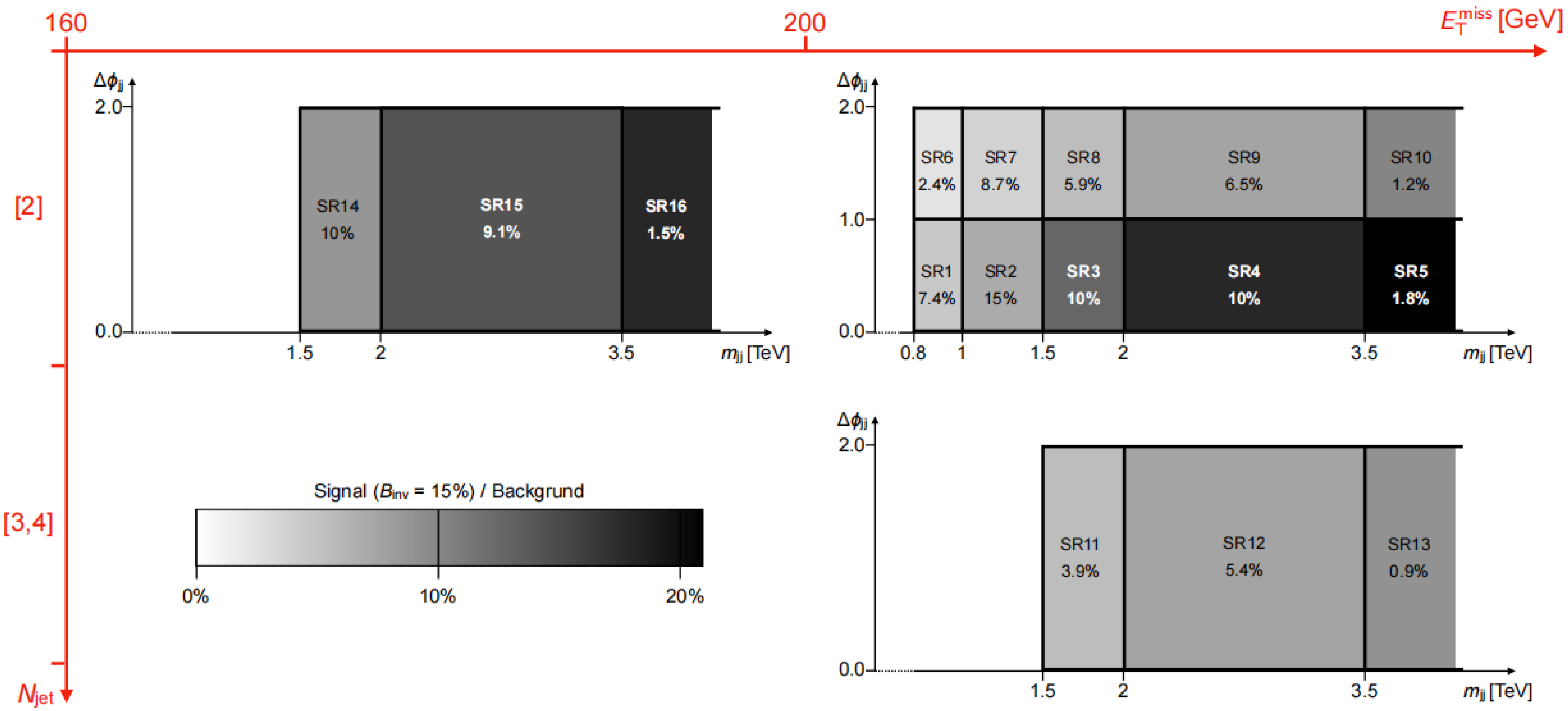
• leading and sub-leading jets have p_{T}>80 GeV and 50>GeV
  • not back-to-back($\Delta\phi_{\mathrm{jj}} < 2$)
  • $\eta_{\mathrm{j1}} \cdot \eta_{\mathrm{j2}} < 0$
  • large pseudorapdidity separation ($\Delta\eta_{\mathrm{jj}}$>3.8)
  • large invariant mass (m_{jj}>0.8 TeV)

• MET>160 GeV



- separated into 16 bins of different signal purity (m_{jj} , $\Delta\phi_{\mathrm{jj}}$)
- CRs defined in kinematic regions analogous to the SR but containing selected $Z(\rightarrow$ll) + jets and $W(\rightarrow$ lv) + jets events

Event selection



Systematic uncertainties

- Theoretical uncertainties
  - matrix elements
  - parton shower matching uncertainties
  - the uncertainty of the proton PDFs
  - for minor backgrounds from $t\bar{t}$, VV, VVV, and VBF($H\rightarrow\tau^{+}\tau^{-}$or $H\rightarrow W^{*}W$), the theoretical uncertainties have been found to be negligible

- Experimental uncertainties
  - luminosity(1.7%)
  - trigger efficiency
  - the used physics objects
    - electron: reconstruction and isolation efficiencies
    - jets: energy scale and resolution
    - pile-up tagging efficiencies

Statistical model

- Method: maximum-likelihood fit
  - a product of terms for the Poisson probabilities
    - signal region
    - pile-up control region
    - V+jets control region
    - fake-e(mu) control region
    - uncertainty
  - contain a total of 58 free parameters and 105 observed event count

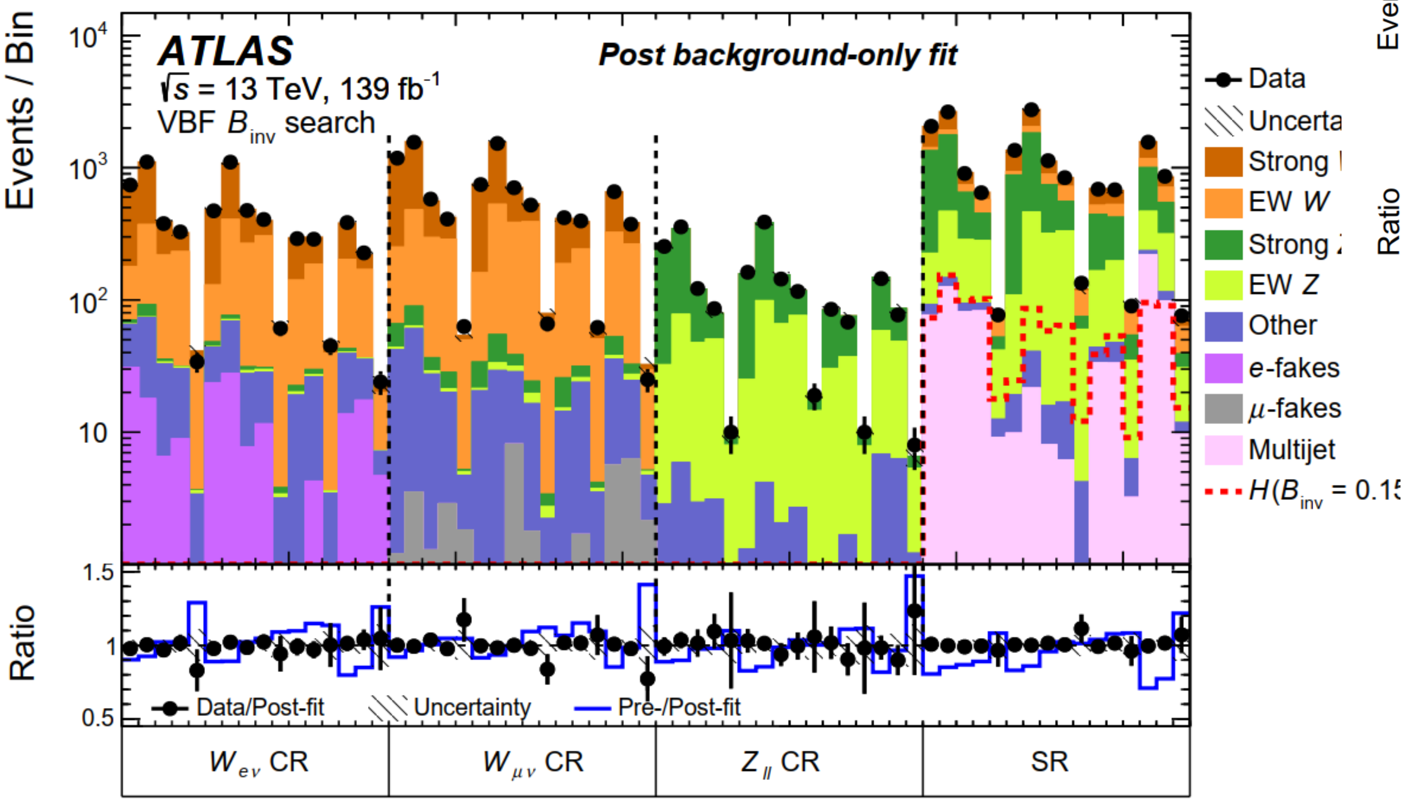
$$\mathcal{L}(\mu, \vec{\beta}_V, \vec{n}_{\text{PU-MJ/fake-}e\text{/fake-}\mu}, \vec{\theta}) = \mathcal{L}^{\text{SR}} \cdot \mathcal{L}^{\text{PU-CR}} \cdot \mathcal{L}^{V\text{+jets-CR}} \cdot \mathcal{L}^{\text{fake-CR}} \cdot \mathcal{L}^{\text{NP}}$$

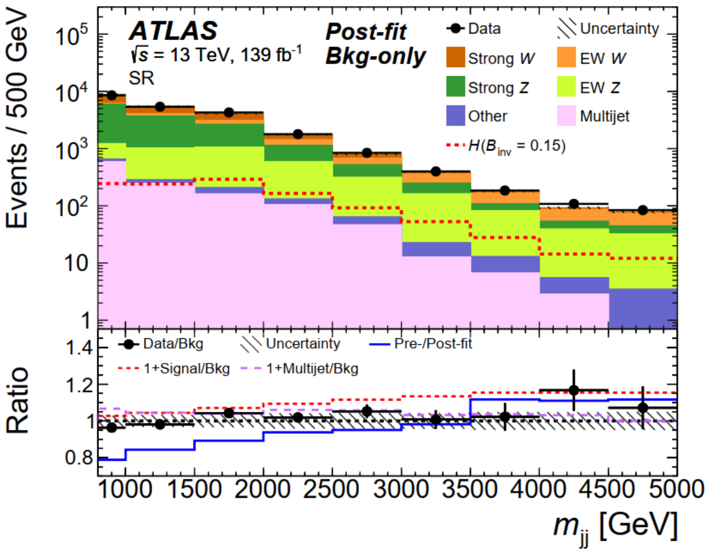
$$\mathcal{L}^{\text{SR}} = \prod_i \mathcal{P}\left(N_i^{\text{SR}} \mid \beta_i \cdot B_{Z,i}^{\text{SR}} + \beta_i \cdot B_{W,i}^{\text{SR}} + B_{\text{MJ},i}^{\text{SR}} + B_{\text{other},i}^{\text{SR}} + \mu \cdot S_i^{\text{SR}}\right)$$

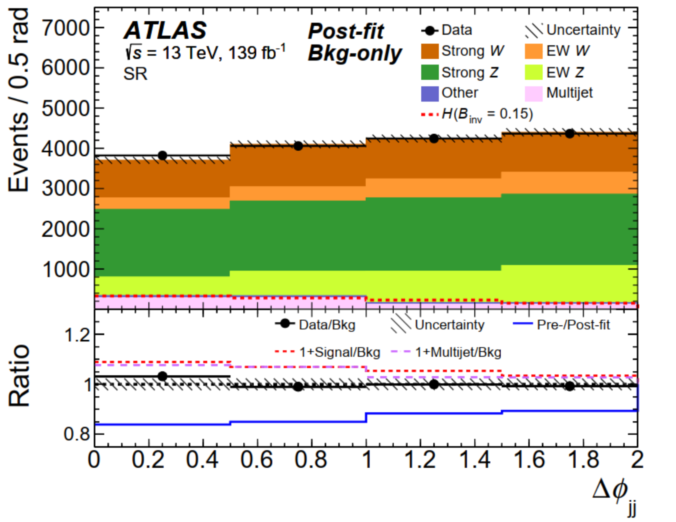
- Asymptotic formulae for the CLs frequentist approach are used to set an upper limit on μ at 95% CL

Results and Conclusions

- Post-fit results of all SR and CR bins with μ set to zero, excluding the zero-lepton bins
  - good agreement between the predicted and observed yields is observed
  - fitted value of the signal strength μ is 0.053 ± 0.052







Results and Conclusions

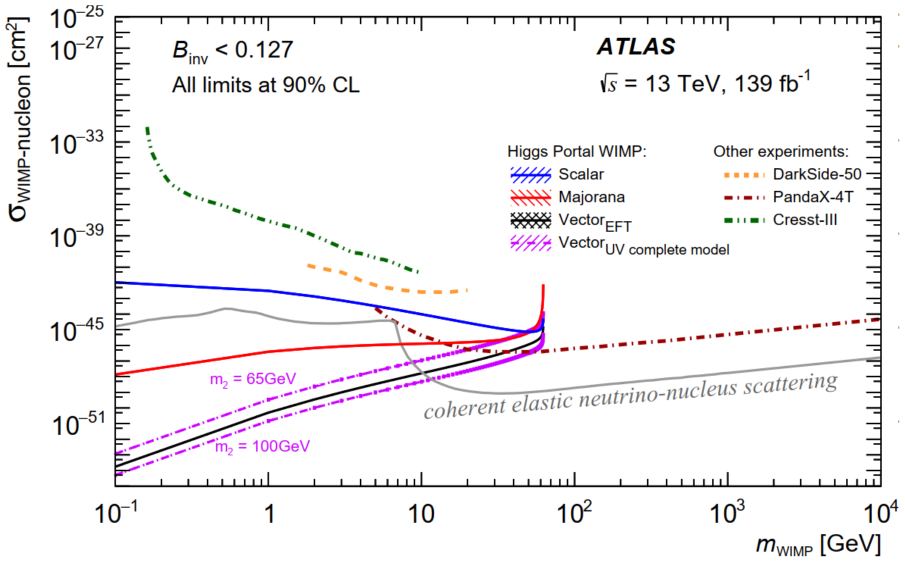
- Fit result does not show any significant signal contribution

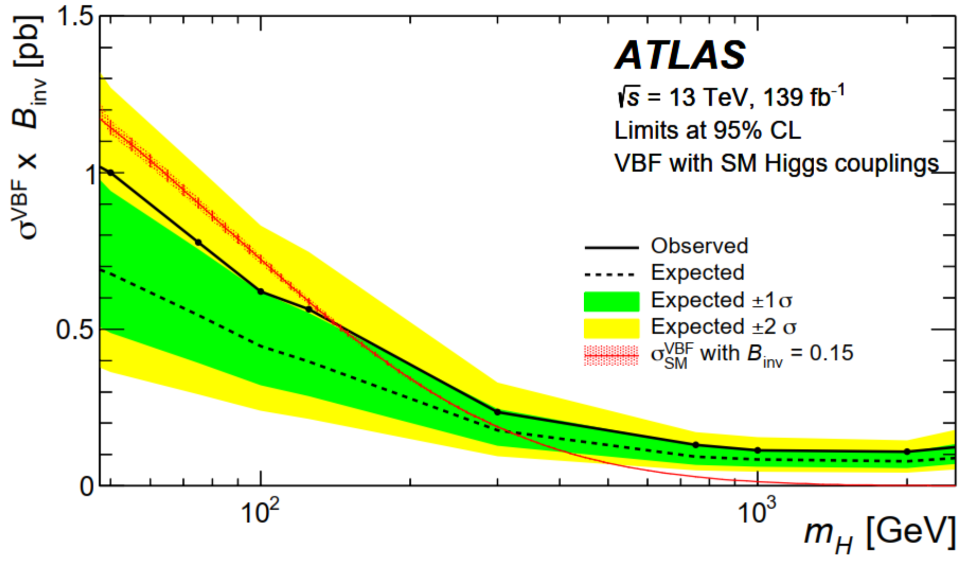
Observed	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ
0.145	0.103	0.144	0.075	0.196	0.055

previous search 0.37 (0.28)

- The limit on B_{inv} can set a limit on the spin-independent WIMP–nucleon cross section
  - scale WIMP ($3 \cdot 10^{-43} - 1 \cdot 10^{-45}$) cm^2
  - Majorana fermion WIMP ($4 \cdot 10^{-47} - 7 \cdot 10^{-45}$) cm^2
  - vector-like WIMP ($5 \cdot 10^{-51} - 3 \cdot 10^{-46}$)cm^2

- The 95% CL upper limit on ($\sigma^{VBF} \cdot B_{inv}$) is 1.0 pb at a mediator mass of 50 GeV and strengthens to 0.1 pb for a mediator mass of 2 TeV





Summary

A search for Higgs bosons invisible decay was presented:

- Data(2015-2018, $\sqrt{s} = 13\mathrm{TeV}$, 139fb^{-1}, ATLAS)
- Triggers (MET, lepton, jets)
- Event selection (VBF signature)
- Background estimation (V+ jets and Multijet background)
- Systematic uncertainty (theoretical and experimental uncertainties)
- Maximum-likelihood fit and Asymptotic formulae
- Fit result does not show any significant signal contribution

THANKS

Data and Simulation

Table 1: Summary of generators used for simulation. The details and the corresponding references are provided in the body of the text.

Process	Generator	ME order	PDF	Parton shower	Tune
Strong V+ jets	Sherpa 2.2.1 and Sherpa 2.2.7 (m_{jj}-filtered)	NLO (up to 2 jets), LO (up to 4 jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
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Data and Simulation

To be considered as a 'signal lepton' stemming from a leptonic decay of a vector boson or a τ-lepton, the leading lepton has to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and fulfil a 'loose' isolation criterion. For events with one lepton, i.e. for the control samples used to constrain the background from $W(\rightarrow \ell\nu) + \text{jets}$ processes, the lepton identification uses a 'tight' ('medium') criterion for electrons (muons) [115, 116]. If two leptons are required, as in the $Z \rightarrow \ell\ell$ control region, the identification uses 'loose' criteria for electrons and muons. Furthermore, the lepton has to be compatible with originating from the primary vertex.

Event selection

- Signature from vector-boson fusion
  - the two leading jets
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    - more forward than jets from non-VBF
    - smaller values of the azimuthal separation $\Delta\phi_{jj}$

- Event selection
  - no lepton candidate, nor a photon
  - two, three or four jets with p_T >25 GeV
    - p_T(all jets)>140 GeV
  - leading and sub-leading jets have pT>80 GeV and 50>GeV
    - not back-to-back($\Delta\phi_{jj} < 2$)
    - $\eta_{j1} \cdot \eta_{j2} < 0$
    - large pseudorapdidity separation ($\Delta\eta_{jj}$>3.8)
    - large invariant mass (m_{jj}>0.8 TeV)
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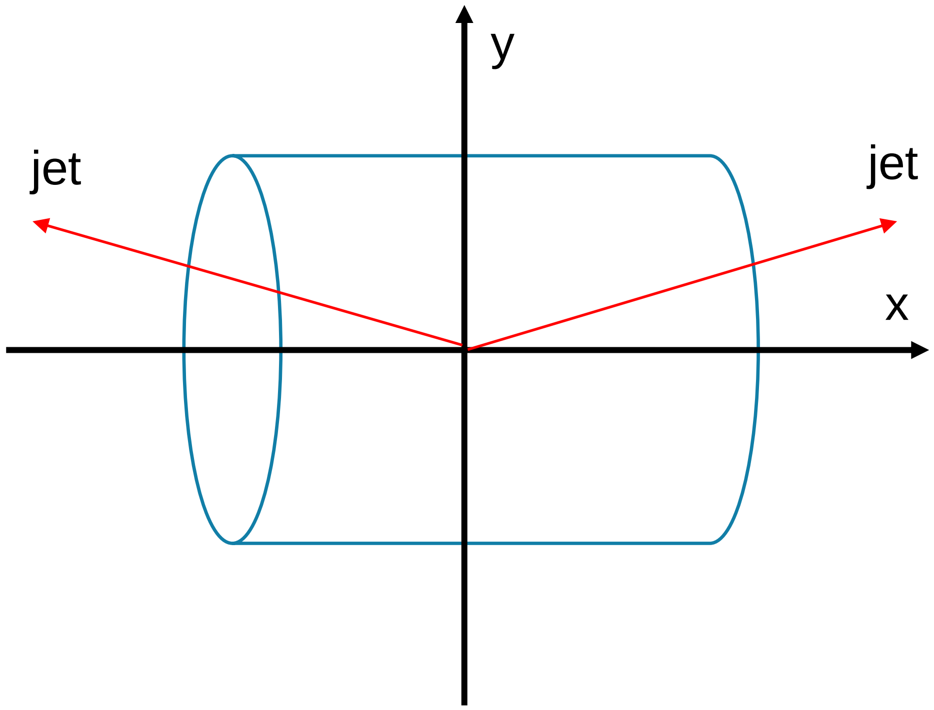

- CRs defined in kinematic regions analogous to the SR but containing selected $Z(\rightarrow ll)$ + jets and $W(\rightarrow l\nu)$ + jets events

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  • large invariant mass (m_{jj}>0.8 TeV)

• MET>160 GeV

Event selection

Table 5: Observed and expected background event yields with associated uncertainties in the signal region (SR) and control regions ($Z_{\ell\ell}$ CR, $W_{e\nu}$ CR, $W_{\mu\nu}$ CR, fake-e CR, fake-μ CR, pile-up CR) prior to the likelihood fit. Minor backgrounds from $t\bar{t}$, VV, VVV, and VBF $H \to W^*W$ / $\tau^+\tau^-$ are combined and labelled 'other'. The uncertainties in the backgrounds include the statistical, experimental, and theoretical uncertainties, taking into account the correlations between the individual SR and CR bins. The predicted signal yields (VBF, ggF, and VH) for $\mathcal{B}_{\text{inv}} = 15\%$ (the observed limit) are presented for comparison. For all CRs with leptons, the contribution from the predicted signal is negligible.

Process	SR	$Z_{\ell\ell}$ CR	$W_{e\nu}$ CR	$W_{\mu\nu}$ CR	Fake-e CR	Fake-μ CR	Pile-up CR
Z strong	6030 ± 2050	1220 ± 440	42 ± 14	143 ± 21	160 ± 57	40 ± 14	$42 \pm ^{59}_{42}$
Z EWK	2630 ± 260	618 ± 74	12.1 ± 1.8	28.3 ± 3.3	23.5 ± 3.3	15.3 ± 2.8	7.2 ± 3.1
W strong	3710 ± 1300	-	3260 ± 1180	5170 ± 1850	1810 ± 650	1010 ± 370	$49 \pm ^{92}_{49}$
W EWK	1610 ± 150	-	2360 ± 190	3410 ± 240	1400 ± 140	822 ± 69	22.9 ± 7.7
Fake-e	-	-	191 ± 70	-	1100 ± 330	-	-
Fake-μ	-	-	-	43 ± 15	-	130 ± 51	-
Multijet	830 ± 190	-	-	-	-	-	1890 ± 110
Other	180 ± 46	46 ± 25	346 ± 82	351 ± 71	67 ± 13	89 ± 27	19.5 ± 9.0
Total bkg.	14 990 ± 2990	1880 ± 510	6210 ± 1260	9150 ± 1890	4560 ± 760	2110 ± 390	2030 ± 110
H (VBF)	886 ± 81						3.9 ± 1.3
H (ggF)	106 ± 41			Predicted signal for $\mathcal{B}_{\text{inv}} = 15\%$			$1.0 \pm ^{1.5}_{1.0}$
H (VH)	0.9 ± 0.2						-
Data	16 490	2051	6361	9294	4563	2110	2033