Searches for Invisible Higgs Boson Decays at the ATLAS Experiment

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On behalf of the ATLAS Collaboration

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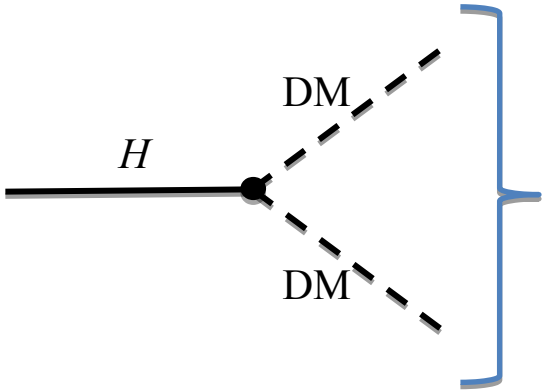
Introduction

- Strong evidence that large fraction of matter in the universe is dark matter (DM)
- Understanding the nature of DM is one of the most important goals of particle physics today
- Several theoretical models predict DM production in pp collisions at the LHC
  - In some of these models the 125 GeV Higgs boson can act as a mediator between DM candidates and the SM particles
  - => Higgs boson can decay into DM particles if kinematically allowed (mDM<mH/2)
  - This decay is "invisible" as the decay products do not interact directly with the detector
  - Search for H→invisible decay in Higgs boson production in association with visible SM particles

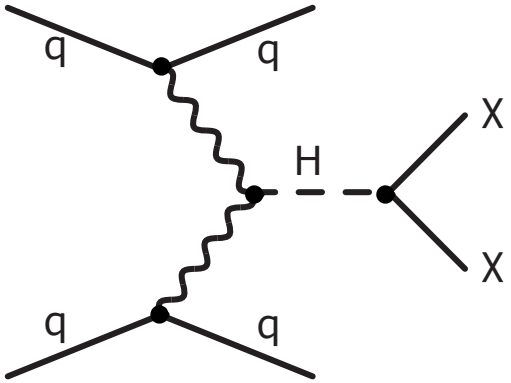
- In SM, branching ratio for Higgs invisible decay (H→ZZ→4ν) ~0.1%
- If DM exists and in the right mass range, we may observe larger BR(H→inv) than SM prediction



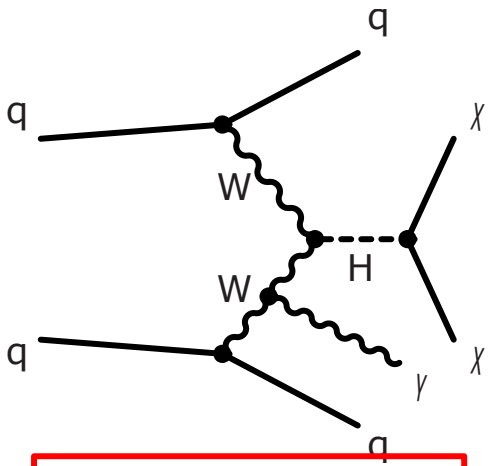
No direct interaction with detector
=> General signature is large imbalance in transverse momentum (missing transverse energy : MET)

H→invisible Decay Searches at ATLAS

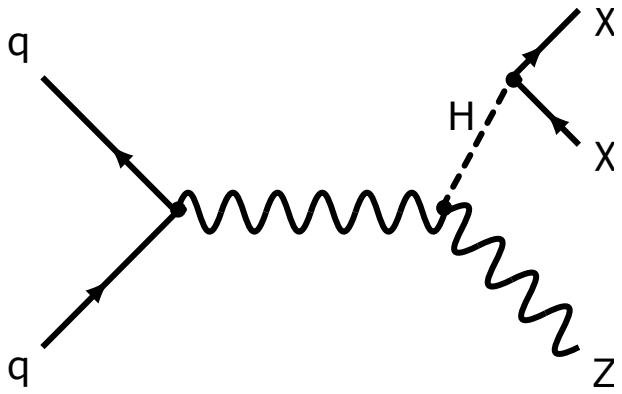
- Searched in the main Higgs boson production processes using the full ATLAS Run-2 data sample (L~139 fb^{-1})
- Assuming SM predicted production cross section values



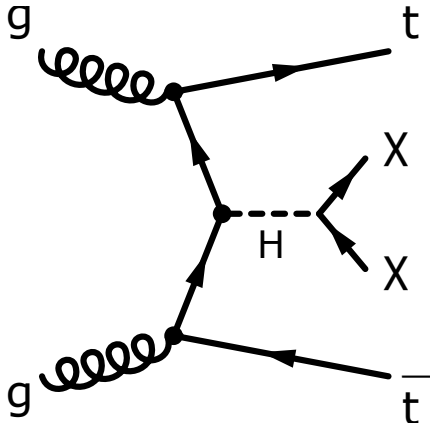
VBF + MET



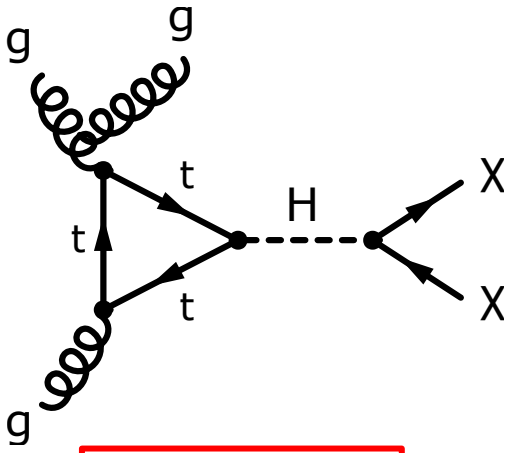
VBF + γ + MET



Z + MET



tt + MET



jets + MET

H→invisible Search in VBF + MET

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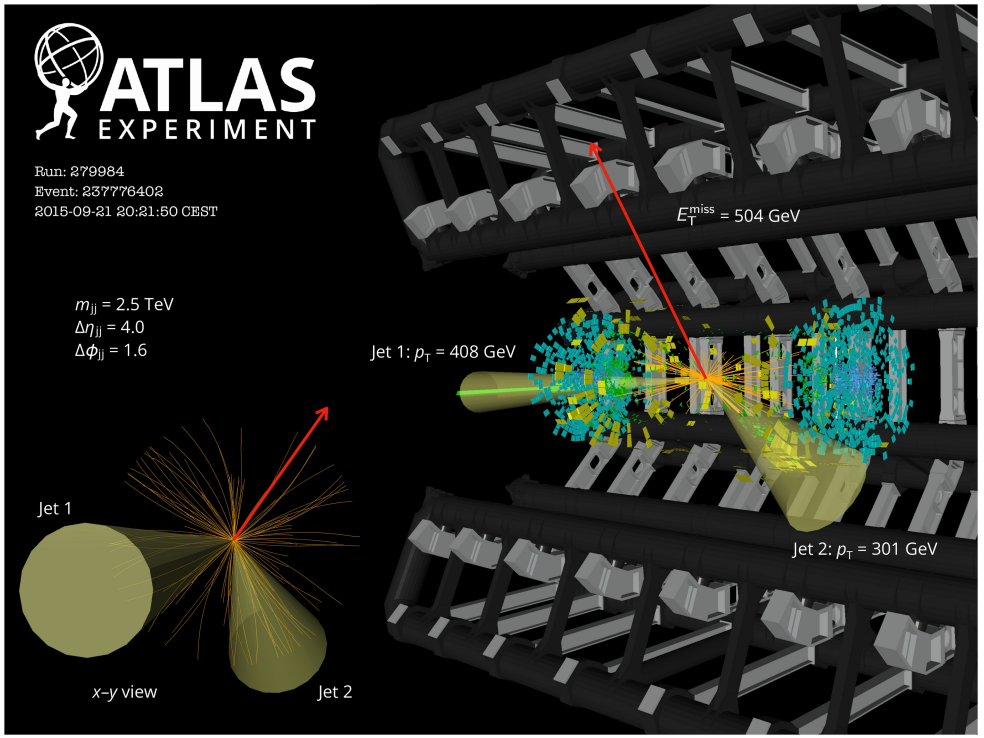
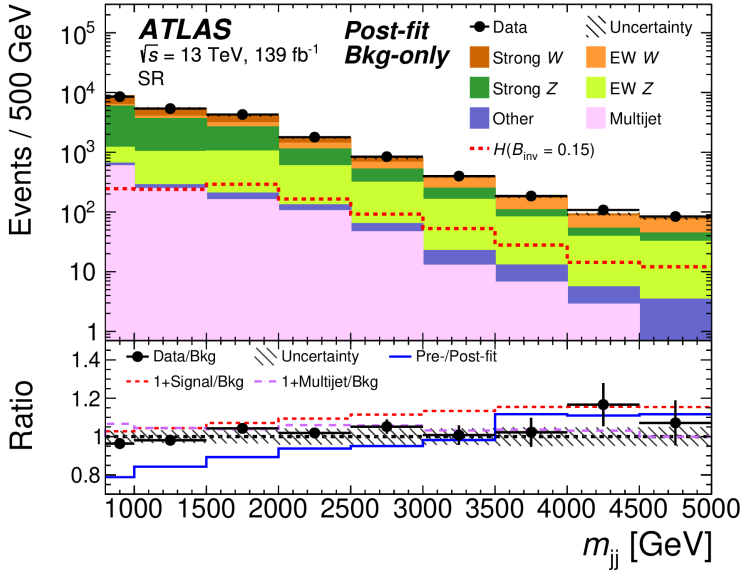
- Most sensitive channel among the five searches
- VBF: 2nd largest Higgs production rate
- Unique signature with two forward jets in opposite detector hemisphere
  - Large separation in pseudorapidity and large mjj mass

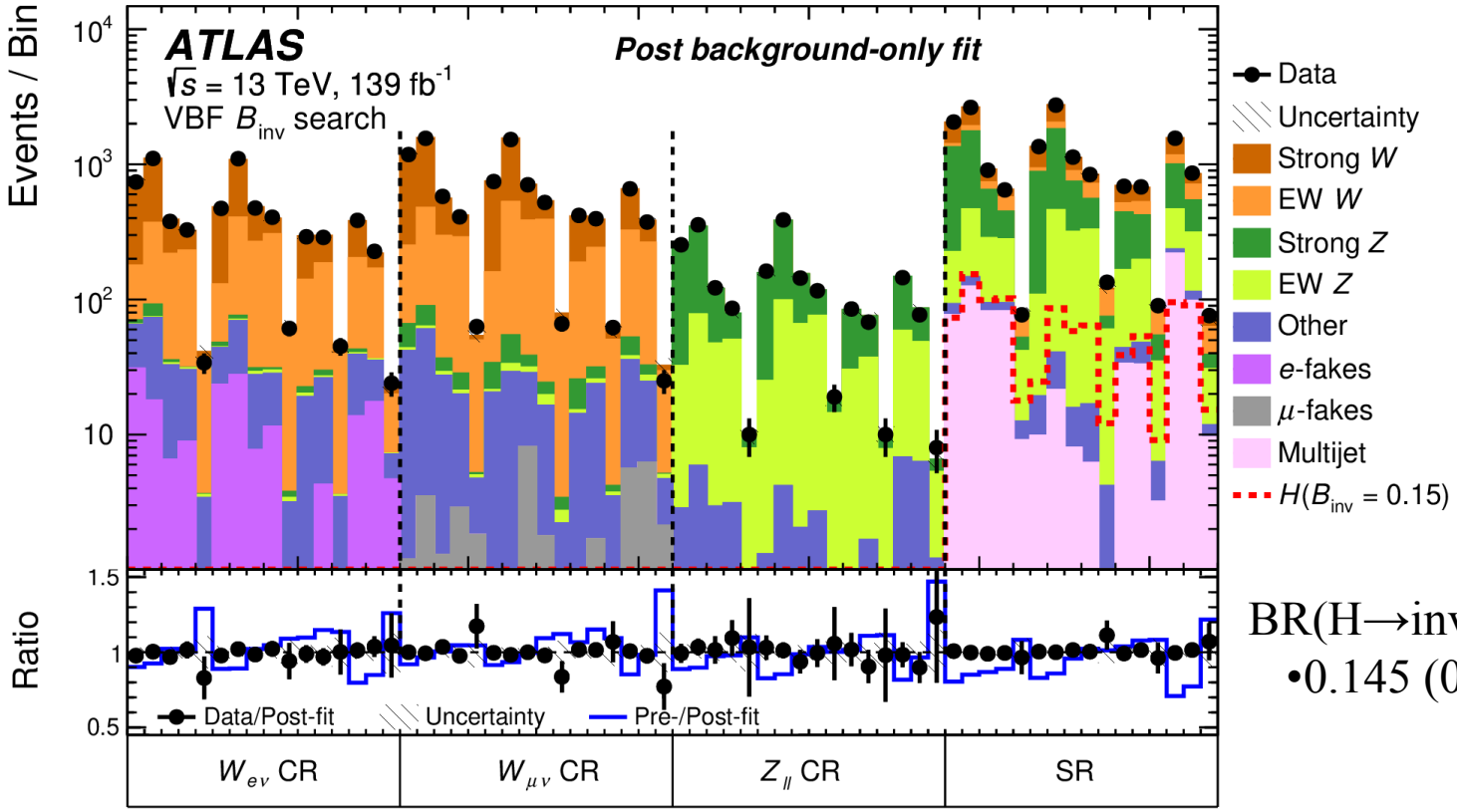


- **Signal selection:**
  - Large MET (>160 GeV)
  - 2 VBF jets not back-to-back in ϕ (Δϕ(j,j)<2)
    - To suppress multi-jet
  - Allow additional 3rd, 4th jets if compatible with VBF FSR
  - Veto events with e, μ and γ
    - To reduce other SM processes
    - To be orthogonal to other H→inv searches



H→invisible Search in VBF + MET

- Dominant background from Z+jets and W+jets production, challenging to model
  - Z→νν , W→lν (l : not identified)
  - Modelling uncertainty constrained by using dedicated W/Z+jets CRs, and theoretical calculation of σ(Z+jet)/σ(W+jet) in phase space of VBF-like signature (arXiv:2004.07652)
    - Significantly improves the sensitivity of this analysis
- Divide SR & CR into 16 bins of MET, mjj, Δϕ(j,j), Njets to maximize signal extraction



BR(H→inv) limit at 95% CL:
- 0.145 ($0.103\ ^{+0.041}_{-0.028}$ expt)

H→invisible Search in VBF + γ + MET

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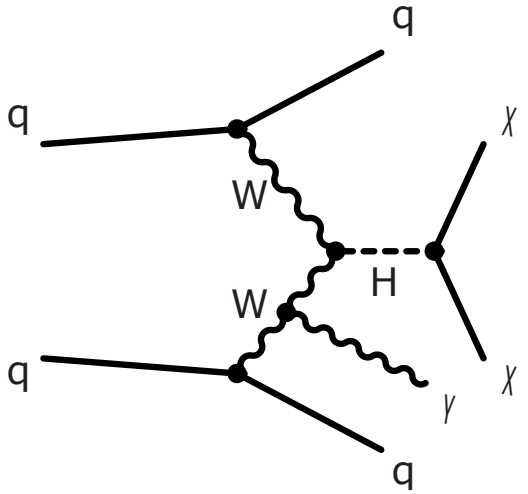
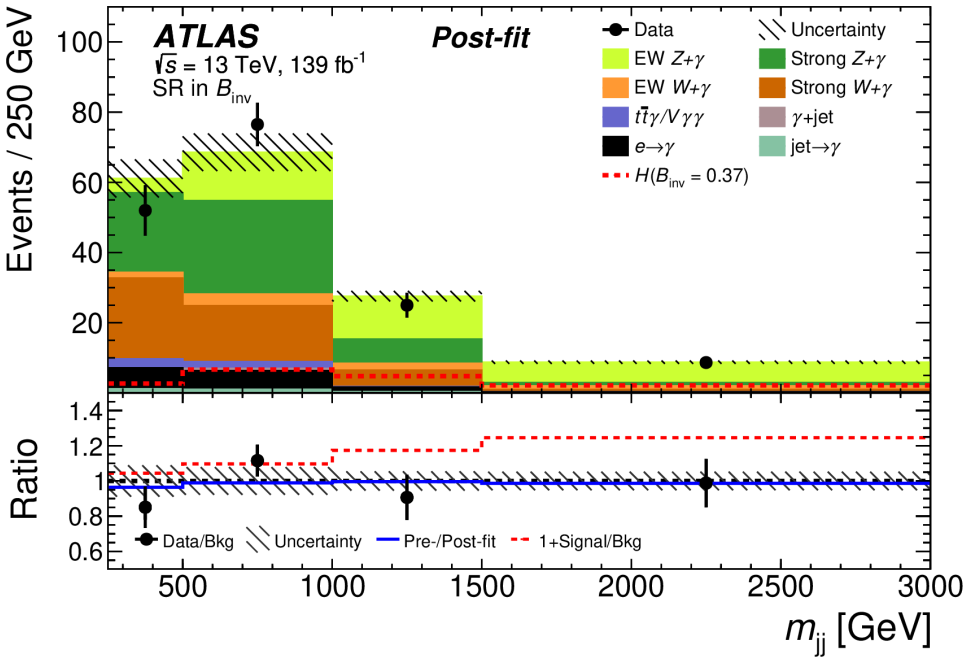
- Signature very similar to the VBF+MET search
  - Except extra photon
- **Advantage :**
  - Better background rejection
  - Higher signal selection efficiency
- **Disadvantage :**
  - smaller production rate



- Photon usually radiated off from scattering W

- Background mainly from:
  - $Z(\rightarrow\nu\nu) + \gamma$ + jets
  - $W(\rightarrow l\nu) + \gamma$ + jets
    - (l : not identified)

- Define CRs to constrain modelling of dominant background



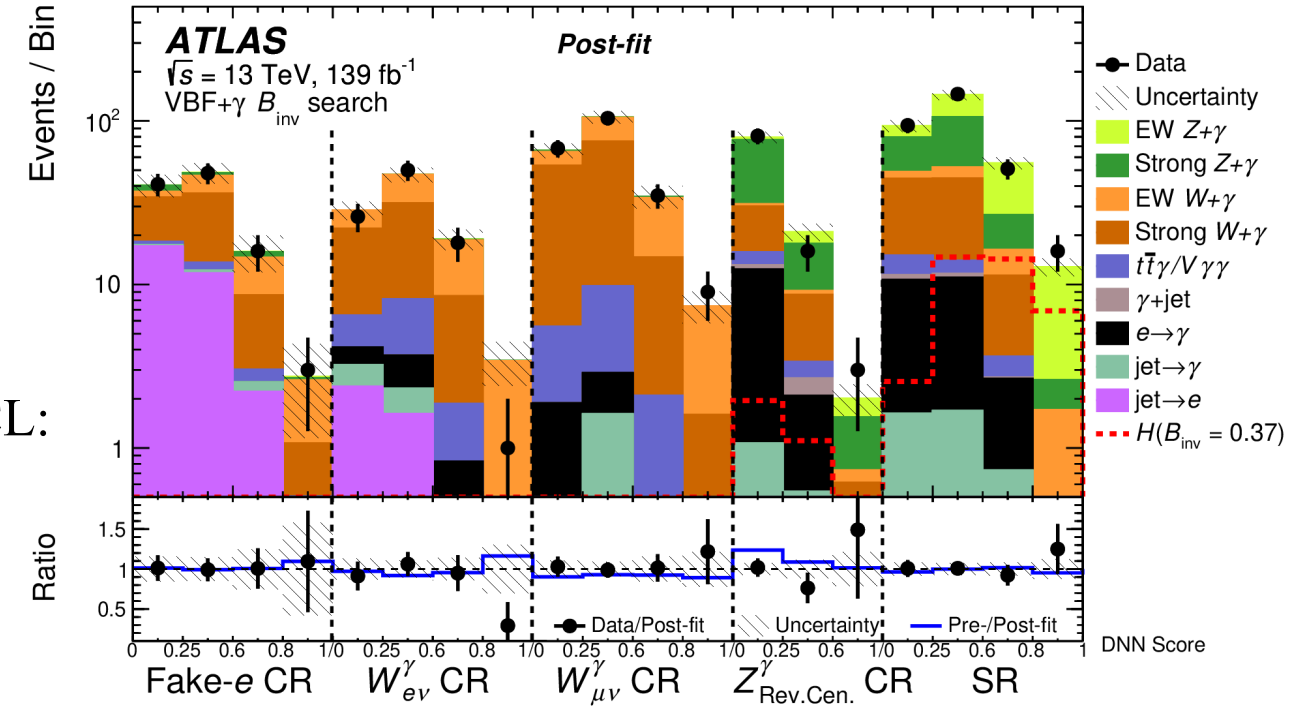
H→invisible Search in VBF + γ + MET

- Perform multivariate analysis (MVA) to improve search sensitivity, using several discriminating features :
  - Kinematics of the VBF jets : angular separation, mjj, pT
  - photon pseudorapidity
  - MET

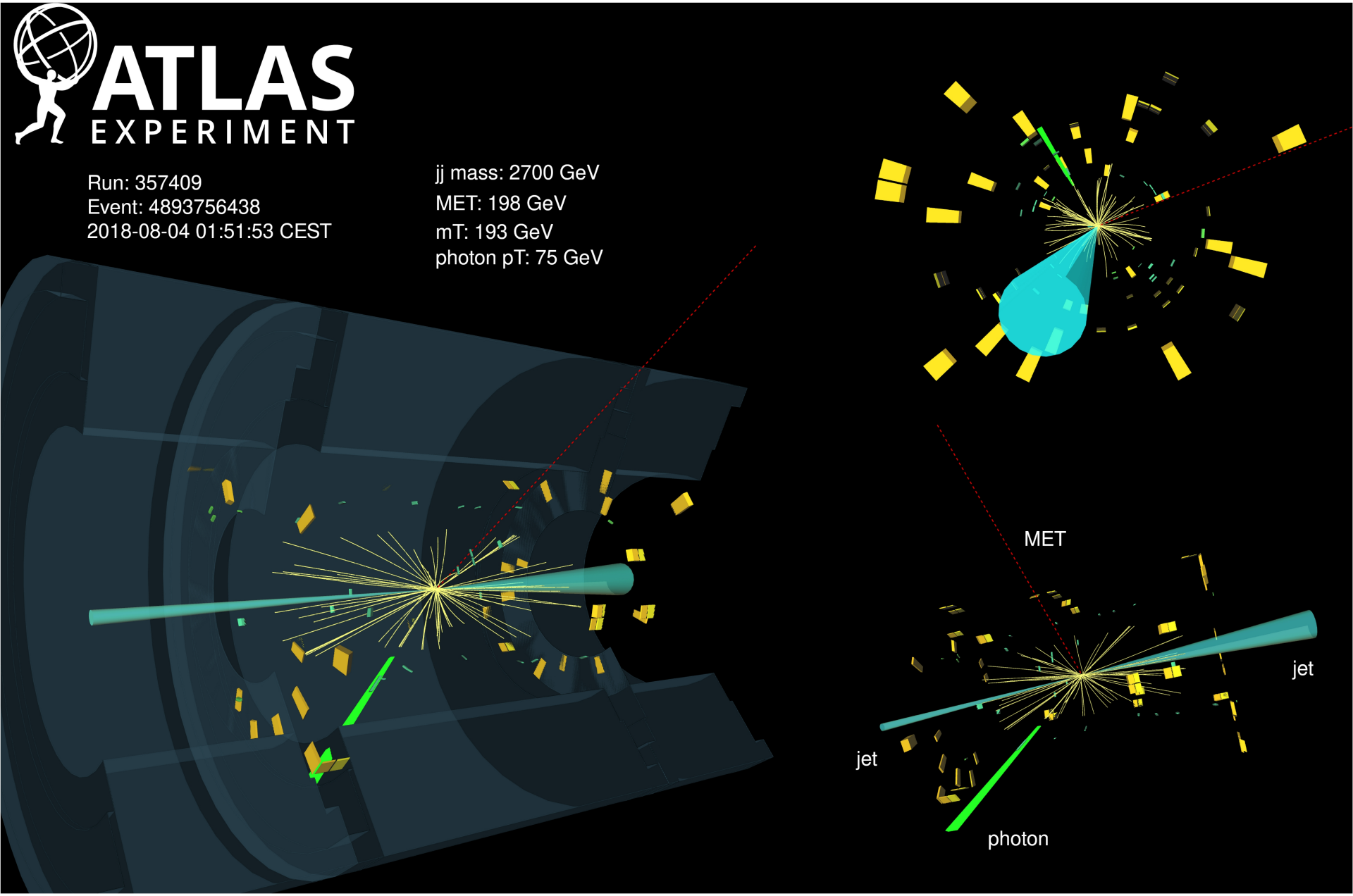
- Uncertainties :
  - Dominant : data statistics
  - MC statistics, jet energy scale/resolution, theory

- BR(H→inv) limit at 95% CL:
  - 0.37 ($0.34\ ^{+0.15}_{-0.10}$ expt)

- Results are limited by statistics, large room for improvement in Run-3 by increasing the data sample



H→invisible Search in VBF + γ + MET



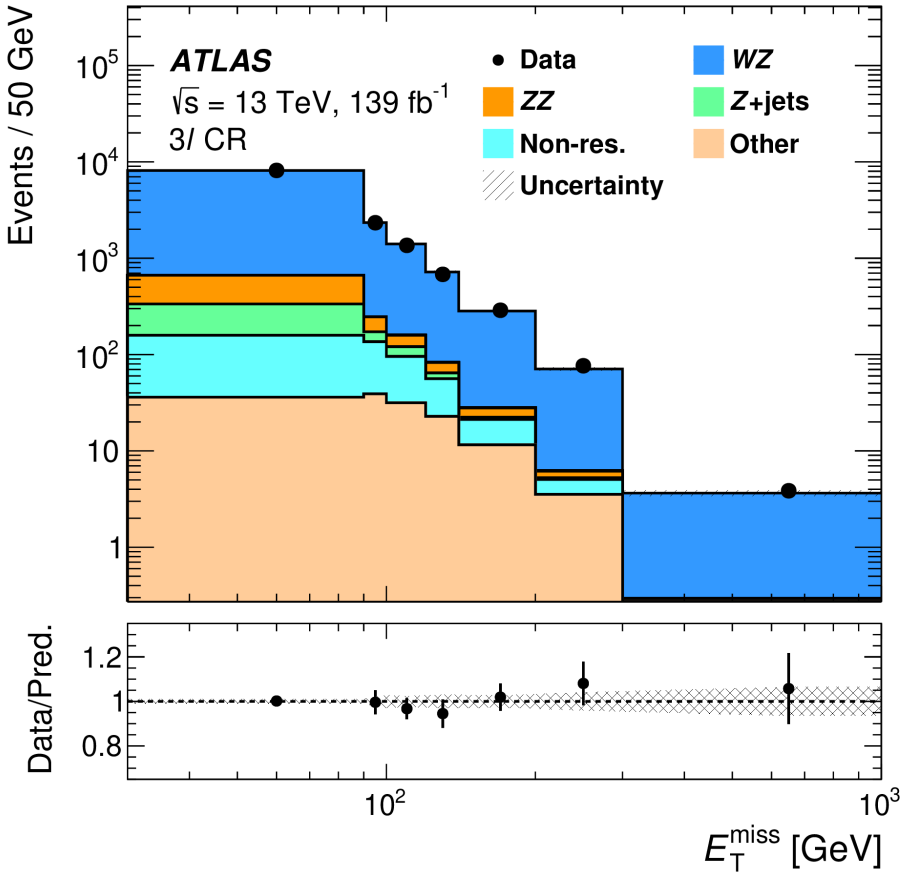
H→invisible Search in Z(ll) + MET

PLB 829 (2022) 137066

- 2nd most sensitive channel for H→inv search at ATLAS

- **Signal selection:**
  - e^+e^- or $\mu^+\mu^-$ pair , consistent with origin from Z decay
  - Large MET (>90 GeV)
  - Veto events with b-tagged jets
    - Suppress top background
    - Orthogonal to tt+MET search

- Main background sources:
  - ZZ, WZ, Z+jets, WW, top
- Define eμ, 4-lepton and 3-lepton control regions to constrain these background sources



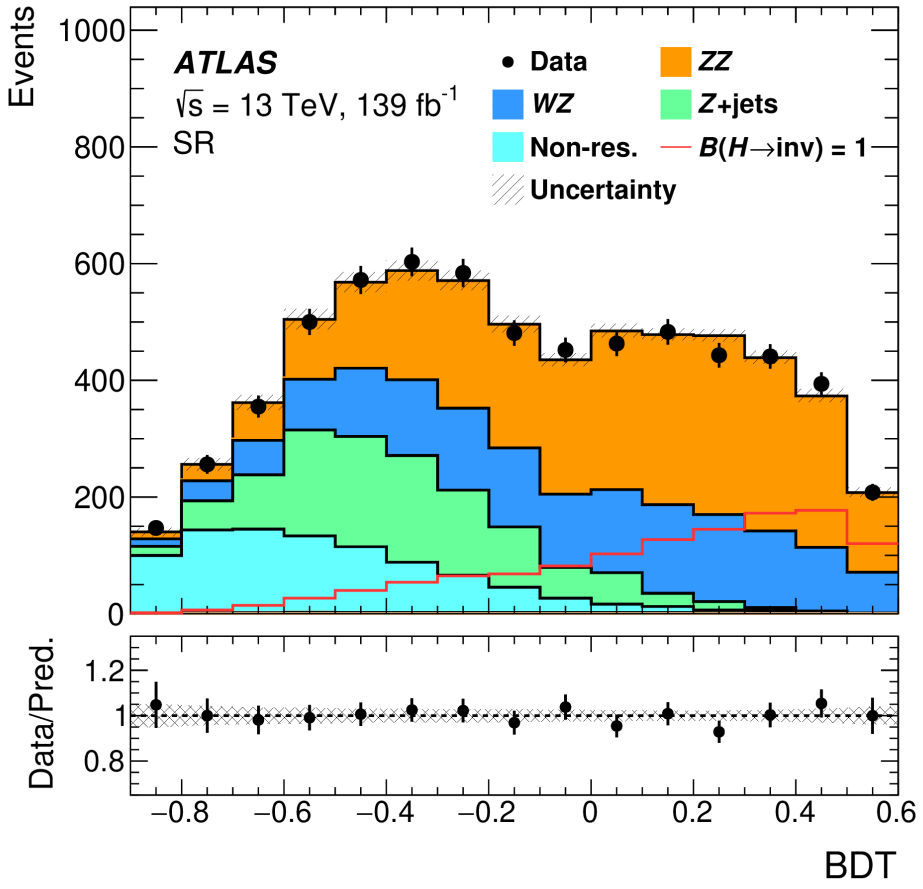
H→invisible Search in Z(ll) + MET

- Enhanced search sensitivity by training a Boosted Decision Tree (BDT) to improve separation between signal and background
- Discriminating variables include :
  - kinematics of the di-lepton system
  - MET significance
  - Scalar sum pT of leptons and jets

- Perform simultaneous fits to distributions in SR and CRs to constrain the backgrounds and to extract the signal

- Dominant uncertainties :
  - Statistical
  - ZZ modelling
  - Jet, MET measurement

- BR(H→inv) limit at 95% CL:
  - 0.19 (0.19 expt)

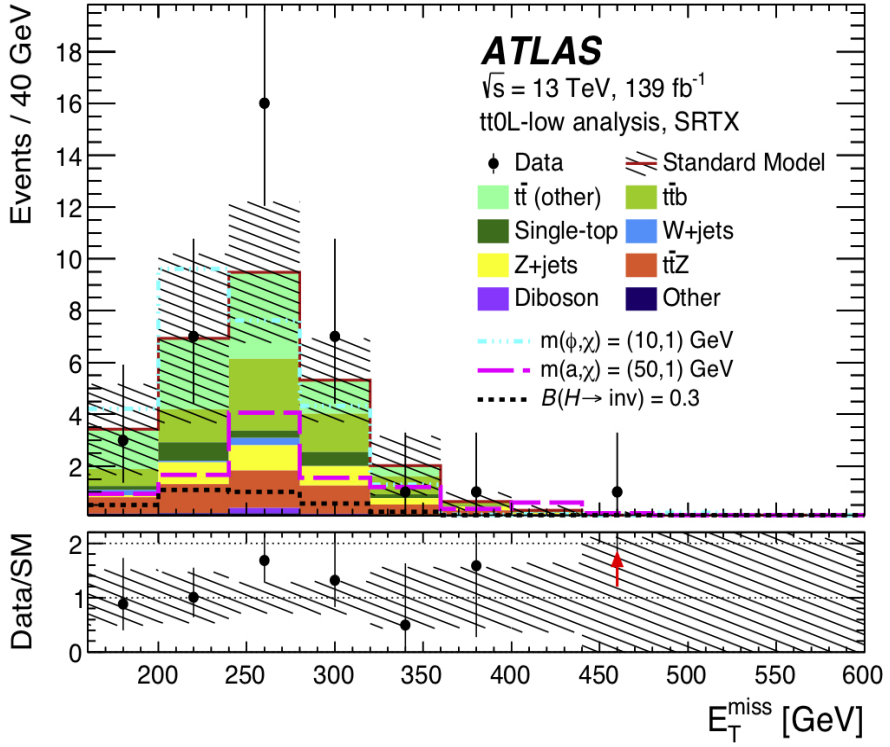


- BDT output used in the profile likelihood fit

H→invisible Search in tt + MET

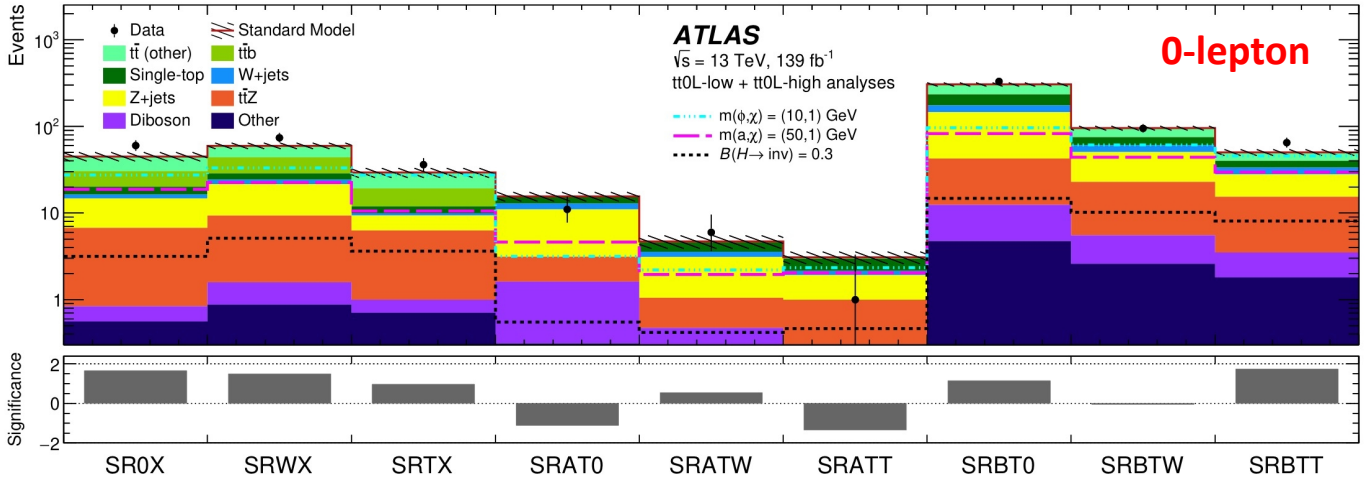
CERN-EP-2022-133

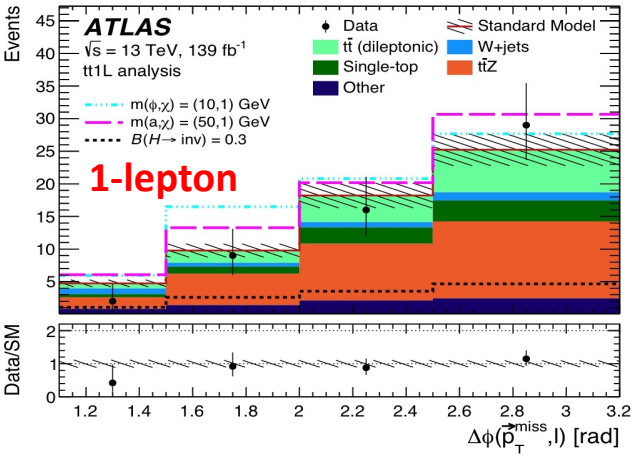
- Search for H→inv decay in Higgs boson production in association with tt pair
  - via combination of results considering 0-, 1- and 2-lepton signatures
- Final state signature :
  - 1 or 2 b-tagged jets
  - Large MET or MET significance
  - Different charged lepton multiplicity
- Event selection developed for each lepton multiplicity : 0-lepton, 1-lepton, 2-lepton
  - 0-lepton : low and high MET sub-channels
- Result in different background contributions from SM processes :
  - 0-, 2-lepton: tt, single-top, ttZ, Z+jets, diboson
  - 1-lepton: tt, single-top, ttZ, W+jets
- Divide the signal region of each leptonic channel into several bins to maximize the signal extraction sensitivity

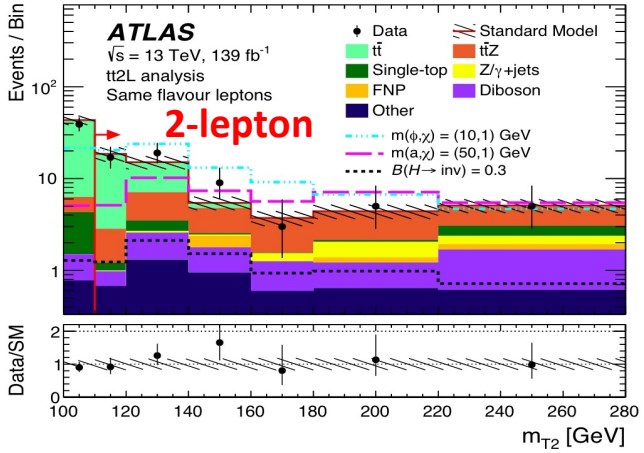


- One of the SR bins of the 0-lepton channel

H→invisible Search in tt + MET







- Combined the three leptonic channels to extract the BR(H→inv) limit
- All channels are statistic limited, can be improved with Run-3 data!

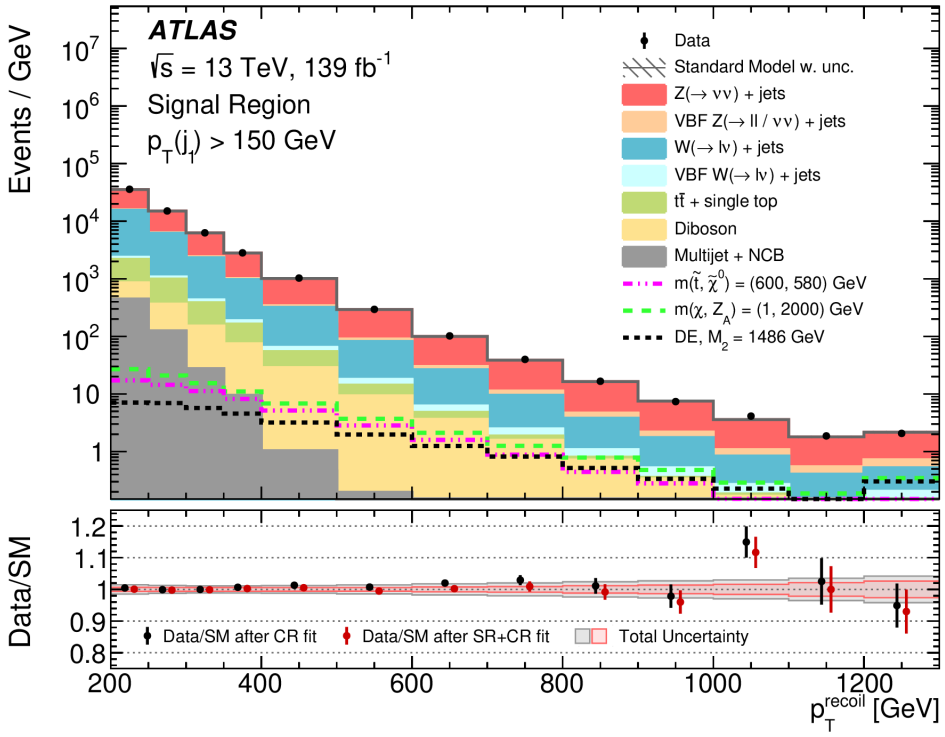
Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.08^{+0.20}_{-0.19}$	0.36	$0.40^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.15}_{-0.15}$	0.38	$0.30^{+0.13}_{-0.09}$

H→invisible Search in jets + MET

PRD 103 (2021) 112006

- Jets+MET : golden signature for DM searches: can interpret results in several models
- Target this final state signature for H→inv search
- Signal contribution mostly from ggF production (73%) with remaining contributions from other production

- **Event selection:**
  - ≥1 high pT central jet, MET>200 GeV
  - Veto events leptons (e,μ,τ) or photon
- **Main background sources:**
  - Z(νν) + jets, W(lν) + jets (l : not iden.)
  - W/Z+jets MC predictions are reweighted to account for higher order QCD & EWK corrections. (EPJC 77, 829 (2017))
- **Discriminating distribution:**
  - p_T^{recoil} : pT of the system recoiling against jets reconstructed in the event

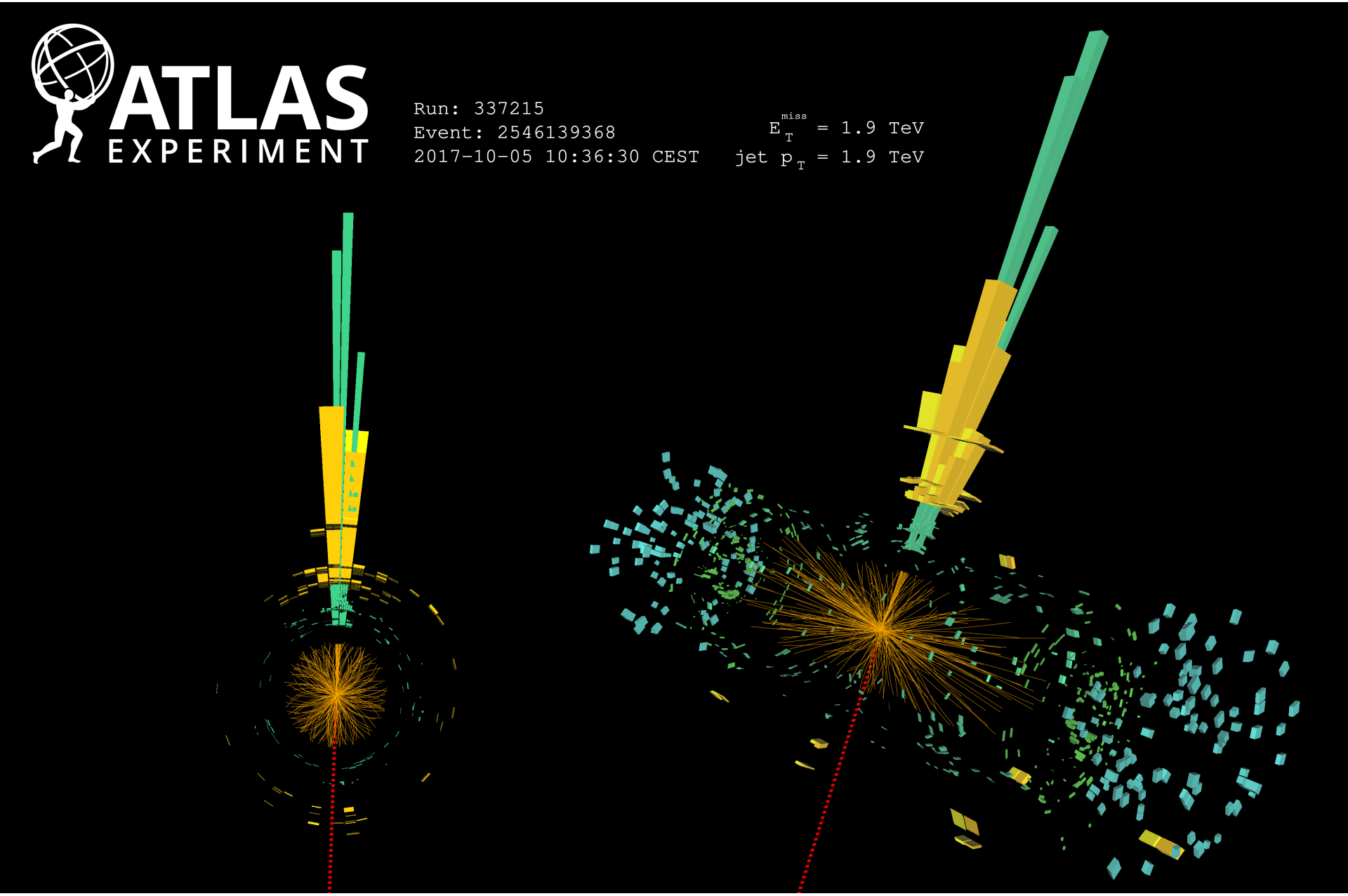


- Simultaneous fit on signal (0-lep) and control regions (1, 2-lep) to constrain backgrounds

BR(H→inv) limit at 95% CL:

- 0.34 (0.39 $^{+0.16}_{-0.11}$ expt)

H→invisible Search in jets + MET



H→invisible Search : Combination

To be submitted to PLB

•Combined all the five Run-2 search results, and also combined with Run-1 results

Run-2 ($\sqrt{s}$=13 TeV, L~139 fb^{-1})
- VBF + MET
- VBF + γ + MET
- Z(ll) + MET
- tt + MET
- jets + MET

Run-1 ($\sqrt{s}$=7,8 TeV, L~25 fb^{-1})
- VBF + MET
- Z(ll) + MET
- W/Z + MET (W/Z: hadronic decay)

Run-2 Combination:

•Small overlap between VBF+MET & jets+MET (~0.2% data), negligible impact on combined results (<0.1%)

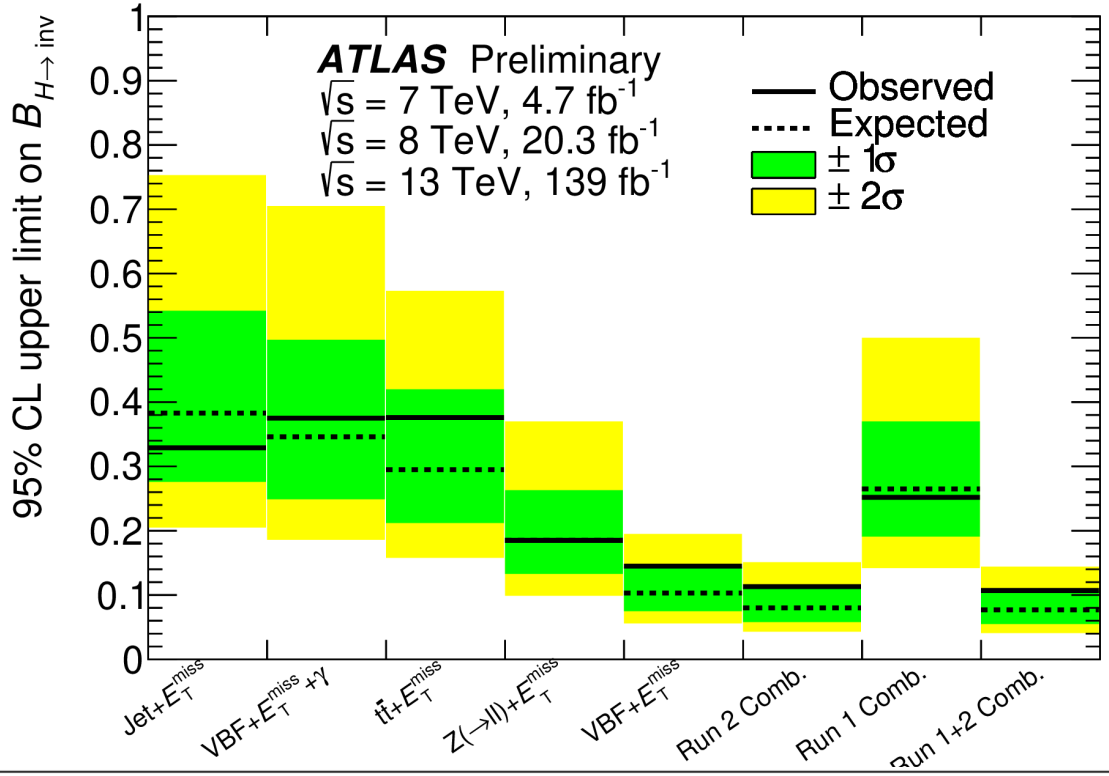
•Correlation :
- •Correlated : Most experiment uncertainties, and some signal uncertainties
- •Uncorrelated : Background modelling (due to differences in leading background, kinematic phase space, and usage of data driven methods)

Run-1 + Run2 Combination:

•Most uncertainties are not correlated

•Only correlate modelling of calorimeter response and jet energy calibration as same methods are applied in both runs

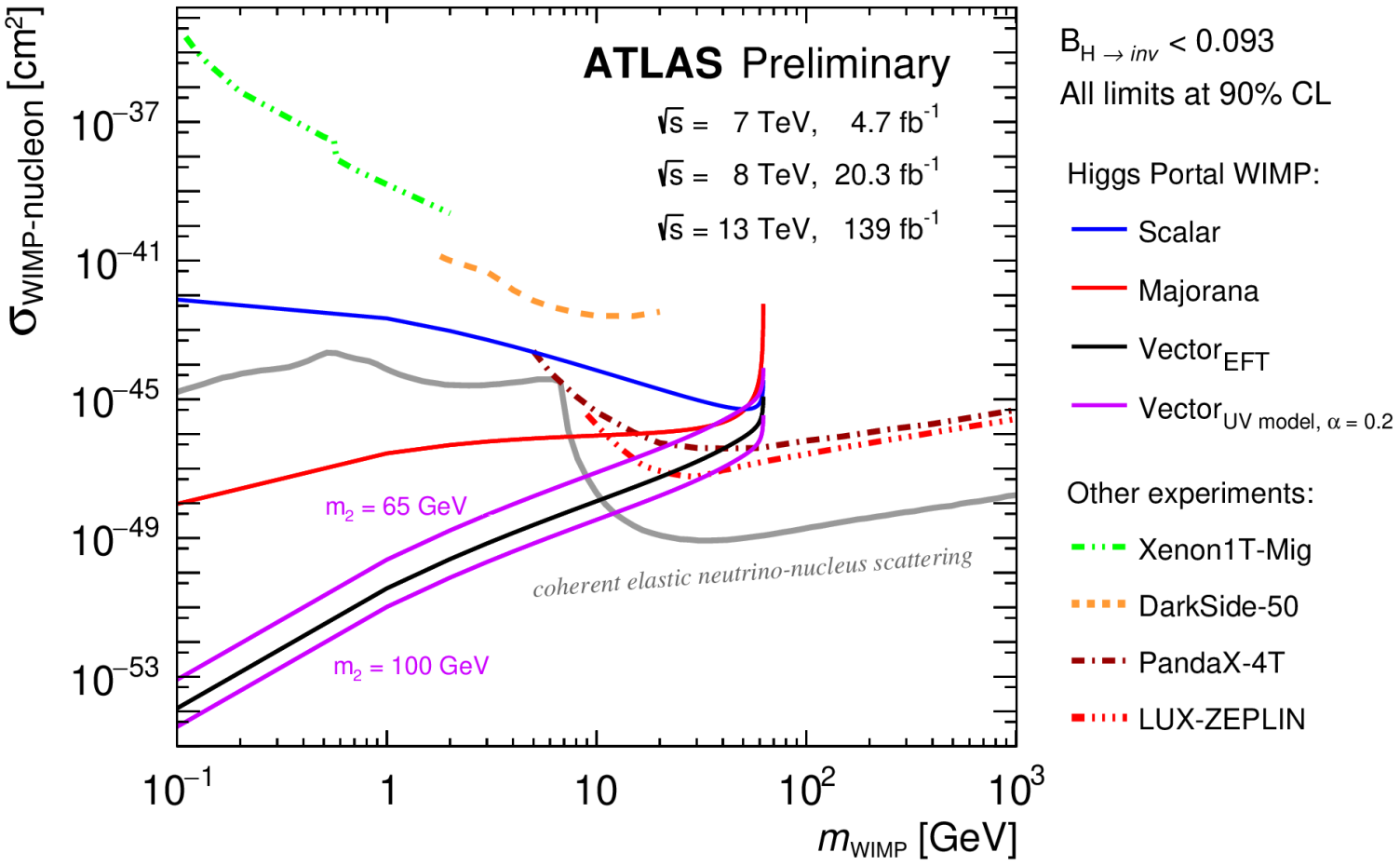
H→invisible Search : Combination



Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

- Run-2 sensitivity is dominated by VBF+MET, adding other channels improve by 22%
- Adding Run-1 results improve sensitivity by 4%
- Leading uncertainty : W/Z+jets modelling (driven by VBF+MET)
- Sub-leading uncertainties : data/MC statistics, leptons/jets measurements, other BG modelling

H→invisible Search : Combination



- Convert the BR(H→inv) limit to the limit on spin independent DM-nucleon elastic scattering cross section
  - Complement direct detection results
- Assume several WIMP (weakly interacting massive particle) hypotheses:
  - Scalar, Majorana fermion, vector

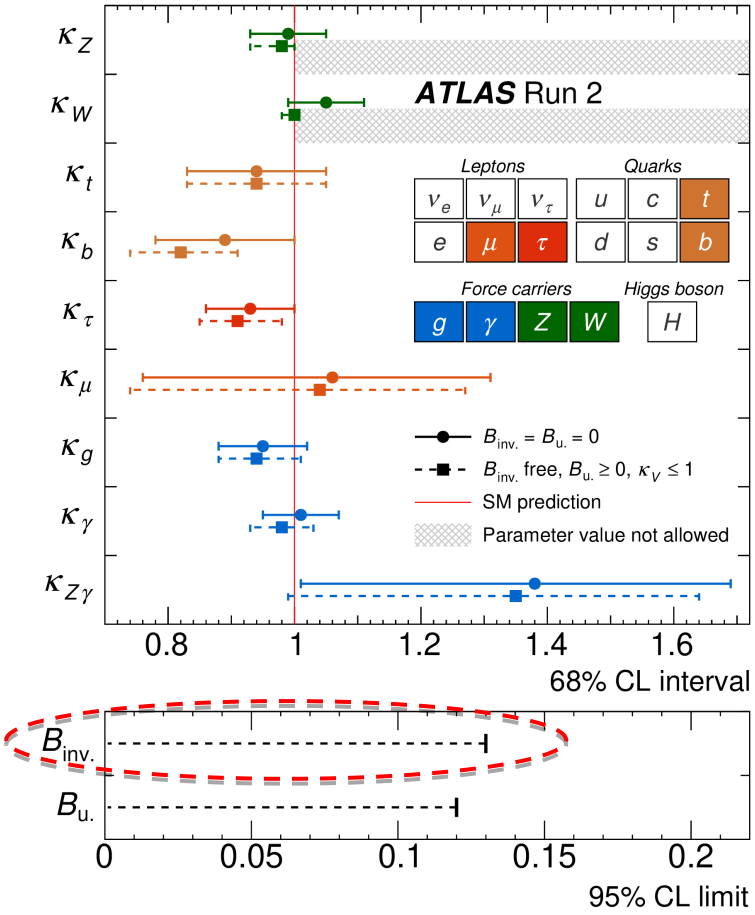
Summary

- Searches for invisible Higgs boson decay can be sensitive to new physics and dark matter (e.g. Higgs portal models)
- Direct H→invisible analysis has been performed with the full ATLAS Run-2 data and in main Higgs production processes
- Latest Run-2 + Run-1 combined limit on BR(H→inv) is **10.7% obs, 7.7% expt.**
  - This is a factor of two improvement over the last combination using partial Run-2 data (~36 fb^{-1}) + Run-1 data
- VBF+MET channel has the best sensitivity
- Several search channels are statistically limited
  - => Large room for improvement in Run-3

Back Up

BR(H→inv) limit from Higgs to visible and invisible decays

- ATLAS has performed a combination by using Run-2 results on Higgs measurements in various Higgs production and decay channels
- Results from direct H→inv searches are also included in the combination
  - Include VBF+MET and Z(ll)+MET

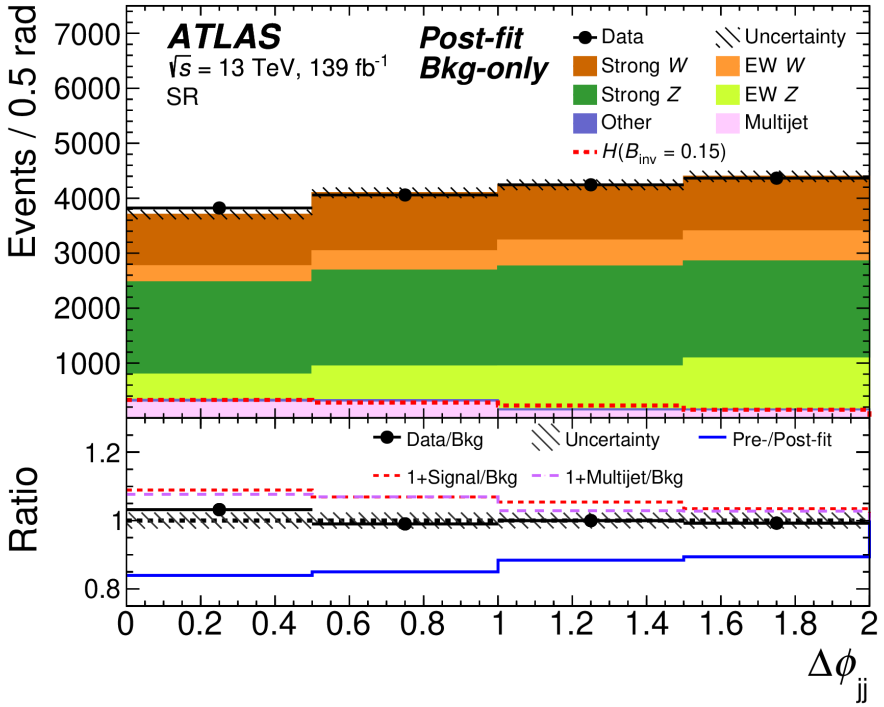


(Reduced coupling strength modifiers, and effective photon, Zγ and gluon couplings)

Nature 607, pages 52-59 (2022)

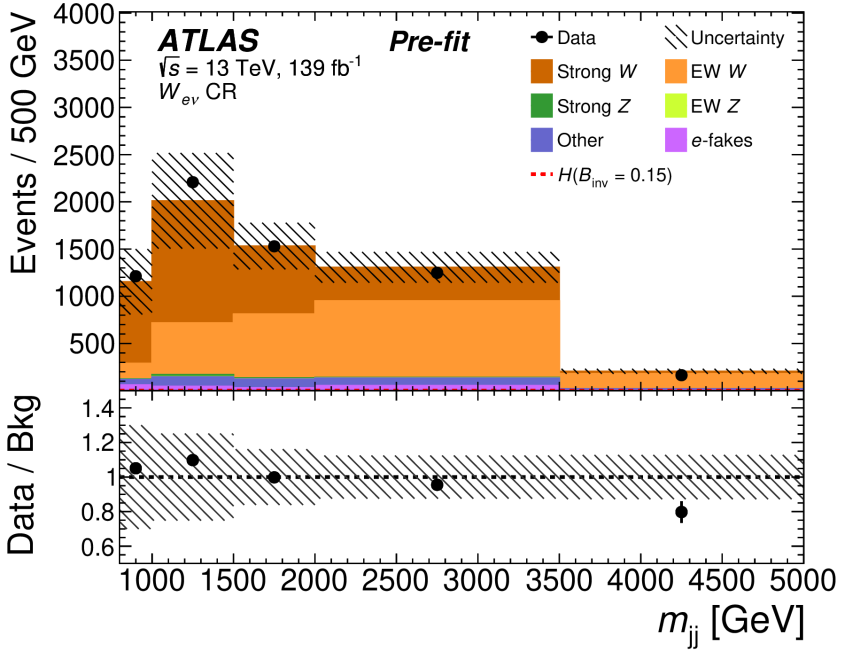
- When allowing invisible non-SM Higgs boson decays to contribute to the Higgs boson decay width :
  - BR(H→inv) limit at 95% CL: 0.13 (0.08 expt)

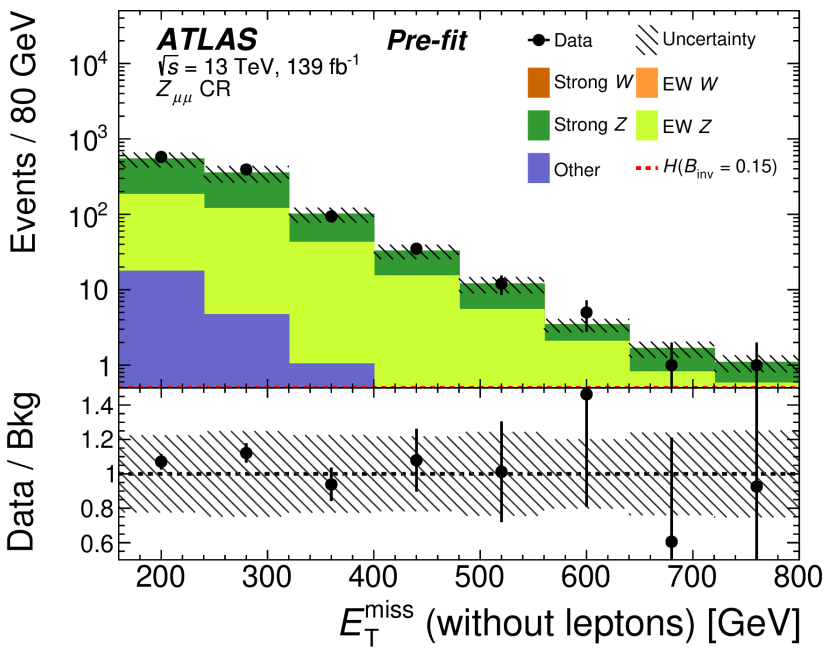
H→invisible Search in VBF + MET



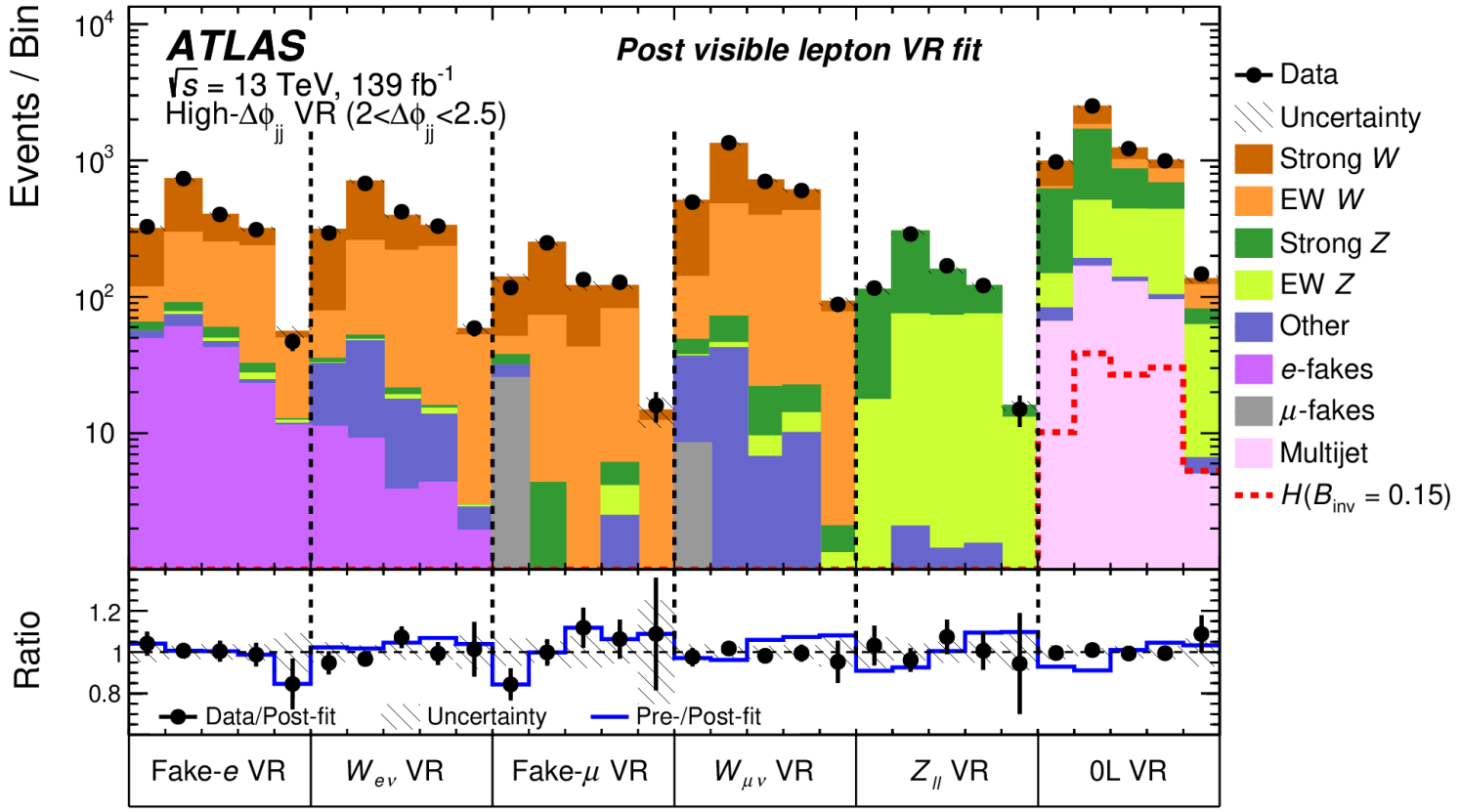
Source	Δ [%]
Jet energy scale	2.1
Jet energy resolution	4.2
Fake leptons	6.5
Lepton ID	5.3
Multijet	5.0
Other	2.8
V+jets theory	4.2
Signal theory	0.6
MC stats.	3.8
V+jets data stats.	9.4
Remaining data stats.	8.7

H→invisible Search in VBF + MET



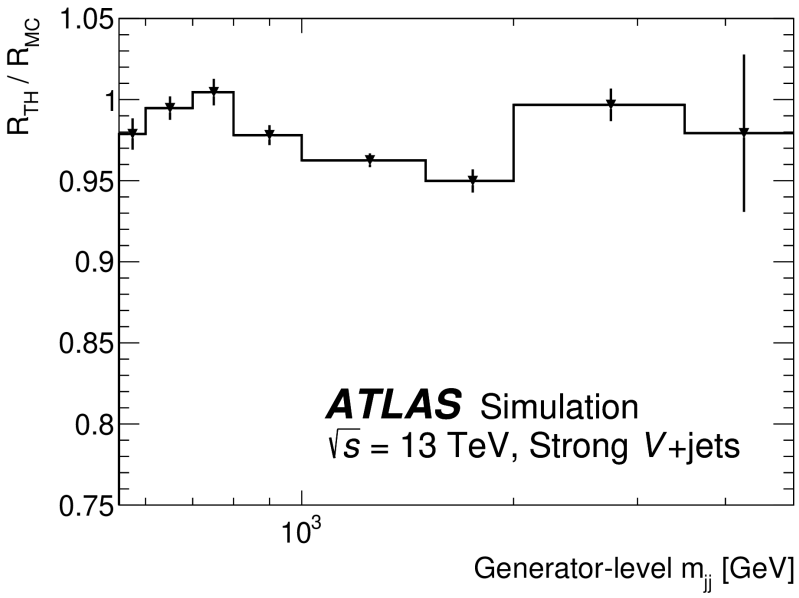


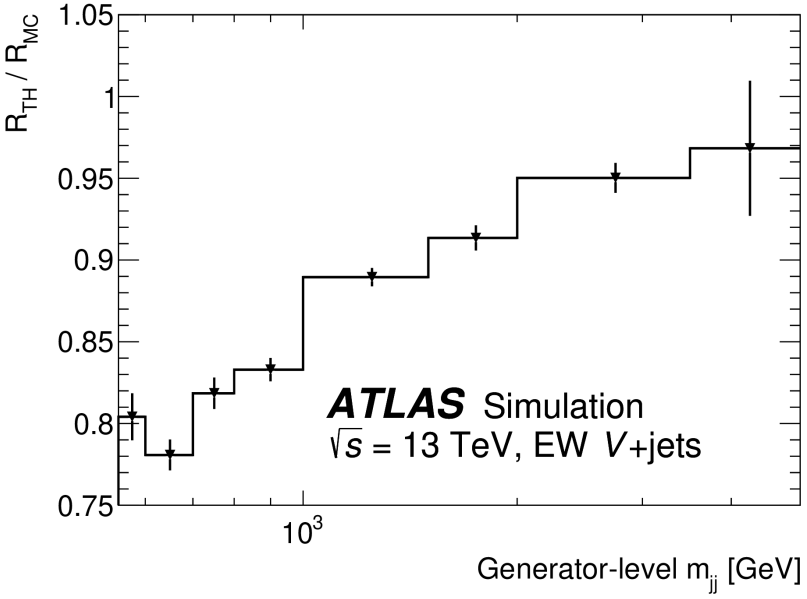
H→invisible Search in VBF + MET



- Validation region :
- MET>200 GeV, 2<Δϕ(j,j)<2.4, njet=2
- 5 bins in mjj

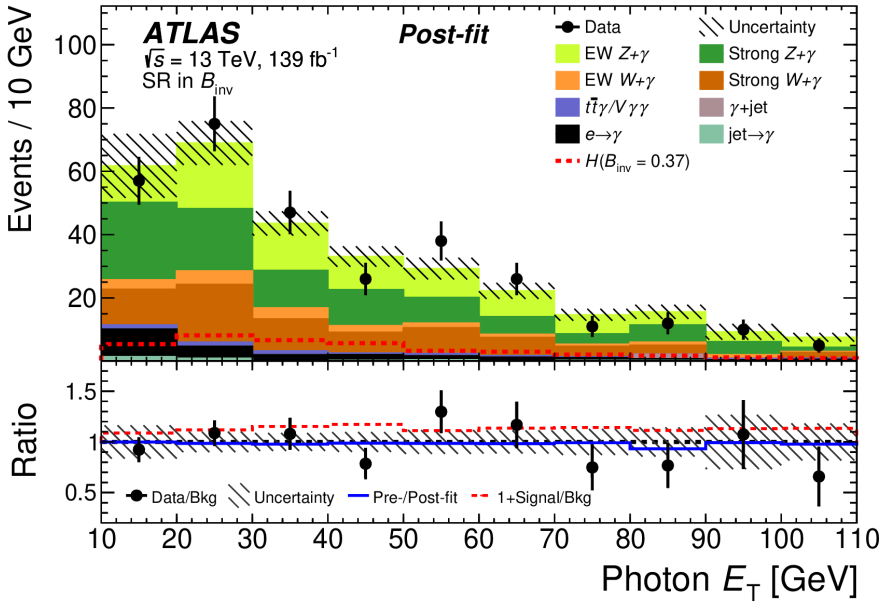
H→invisible Search in VBF + MET





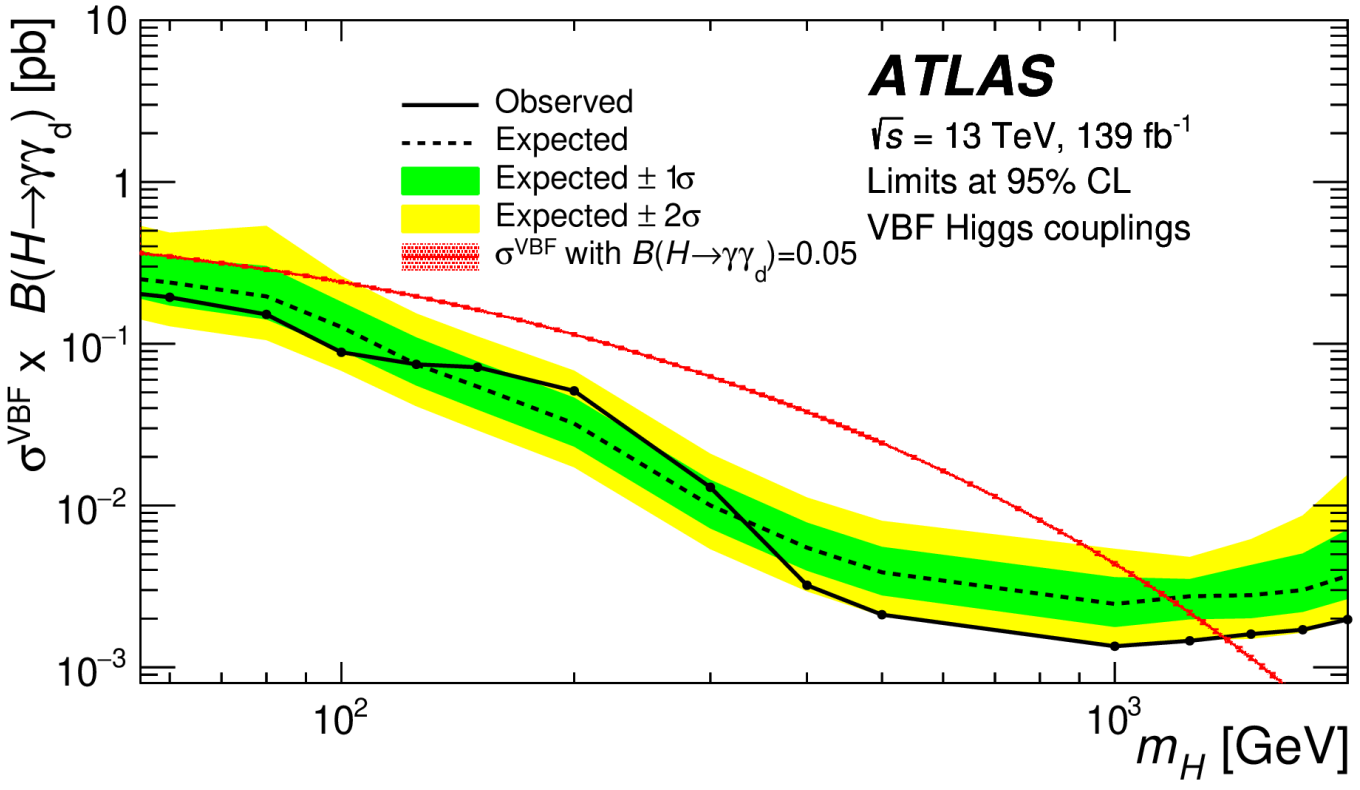
- Main reasons for large correction at low mJJ for EW V+jets are missing NLO s-channel contributions, and missing interference between s- and t-channel processes in the simulated MC samples

H→invisible Search in VBF + γ + MET



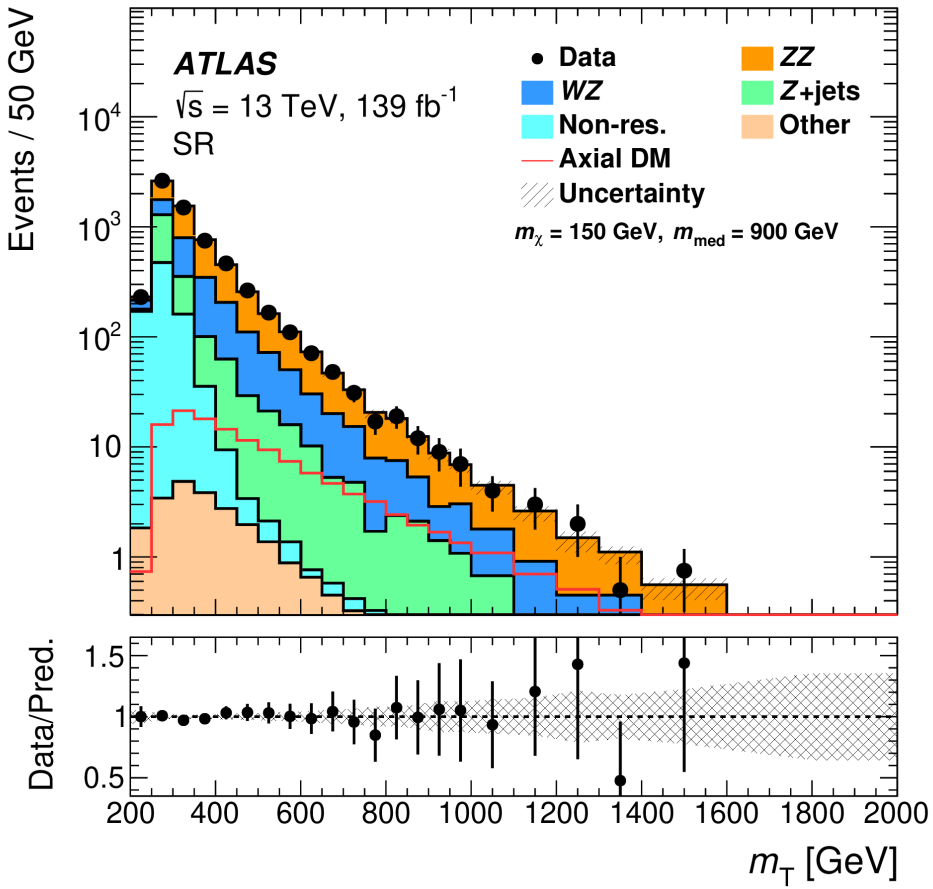
Source	1σ Uncertainty on $\mathcal{B}_{\text{inv}}$
Jet scale and resolution	0.045
$V\gamma$ + jets theory	0.044
pile-up	0.021
Photon	0.031
$e \to \gamma$, jet$\to e, \gamma$ Bkg.	0.034
Lepton	0.003
$E_{\text{T}}^{\text{miss}}$	0.018
Signal theory shape	–
Signal theory acceptance	–
Data stats.	0.11
$W\gamma$ + jets/$Z\gamma$ + jets Norm.	0.013
MC stats.	0.046
Total	0.15

H→invisible Search in VBF + γ + MET



- Dark photon search : $H \rightarrow \gamma\gamma_D$
  - Set limit on $\sigma \times BR(H \rightarrow \gamma\gamma_D)$ as function of a mediator mass (assuming narrow width approximation up to 2 TeV) (for VBF production)
  - Higgs boson produced via ggF and VBF, with mass 125 GeV :
    - $BR(H \rightarrow \gamma\gamma_D)$ limit at 95% CL: 0.018 (0.017 expt)

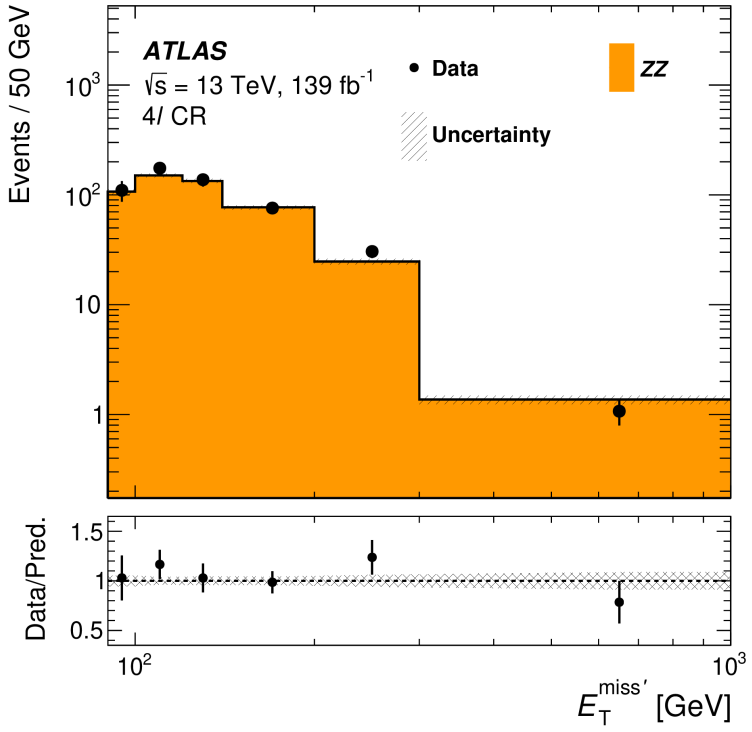
H→invisible Search in Z(ll) + MET

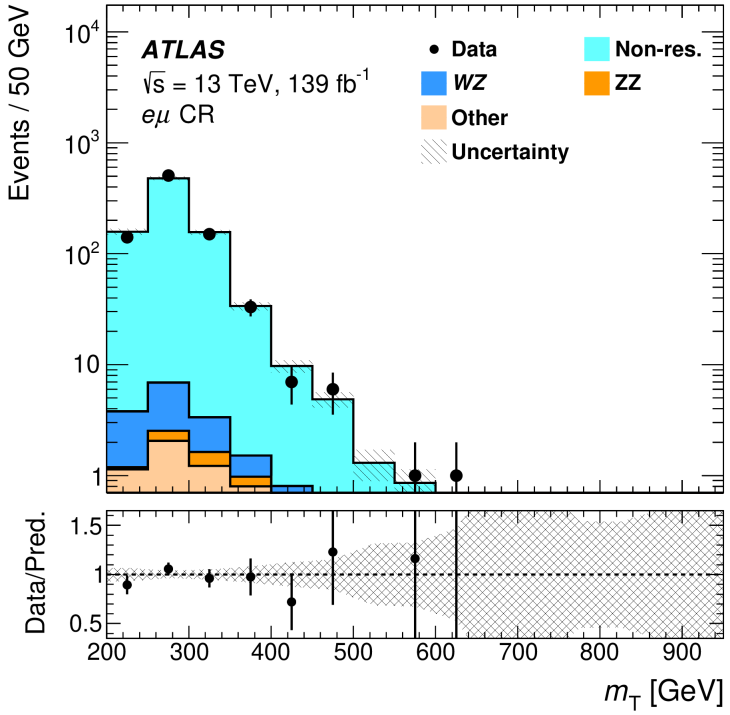


Uncertainty source	$\Delta\mathcal{B}$ [%]
Statistical uncertainty	5.1
Systematic uncertainties	7.4
Theory uncertainties	4.9
Signal modelling	0.4
ZZ modelling	4.4
Non-ZZ background modelling	2.1
Experimental uncertainties (excl. MC stat.)	4.6
Luminosity, pile-up	1.5
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.0
Flavour tagging	0.4
Electrons, muons	1.2
MC statistical uncertainty	1.6
Total uncertainty	9.0

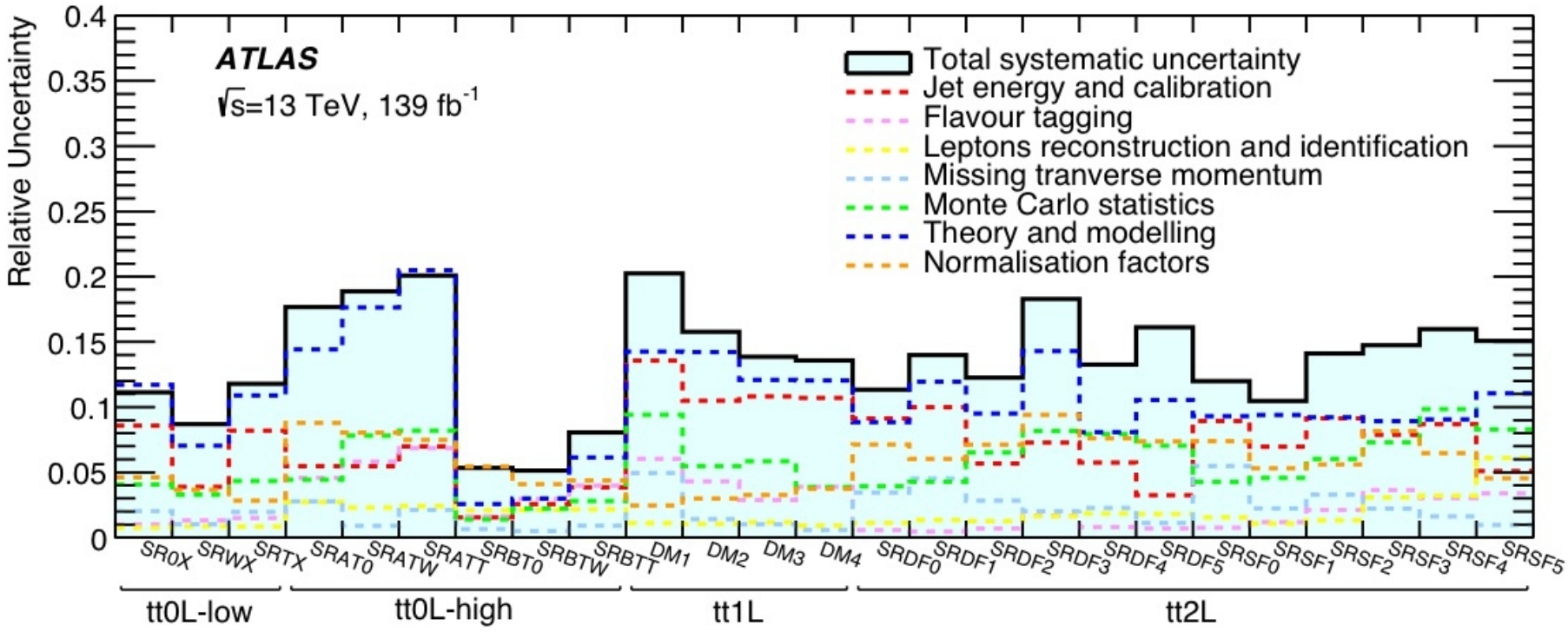
(Transverse mass use in fits for the SR and CR of the DM search considering simplified DM models.)

H→invisible Search in Z(ll) + MET





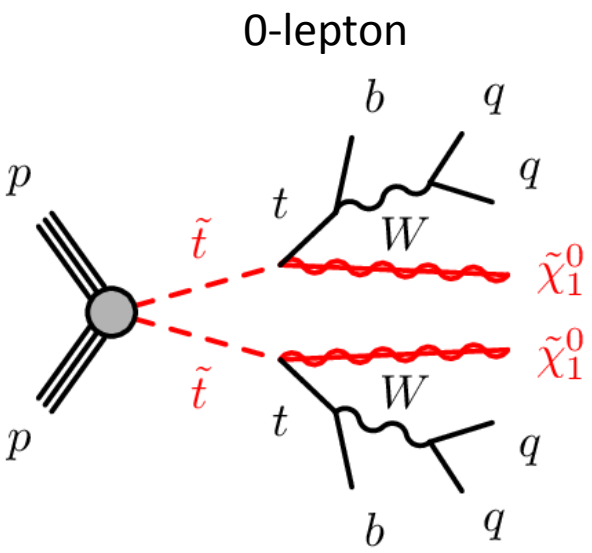
H→invisible Search in tt + MET



Total uncertainties on the BG predictions.

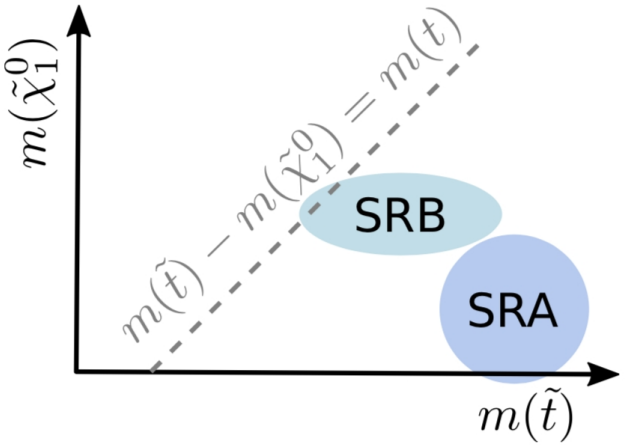
tt2L:
SRDF : different flavor
SRSF : same flavor

H→invisible Search in tt + MET



- ttOL
  - 0 lepton
  - >=4 jets
  - 2 b-tagged jets
  - MET>160 GeV

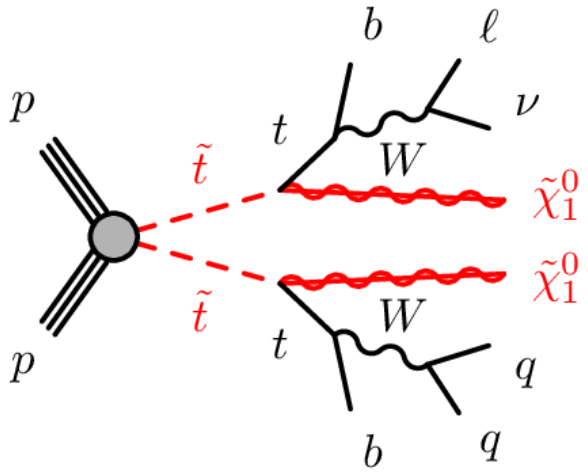
- ttOL-low
  - Pass b-jet trigger or MET trigger
  - 160<MET<250 GeV or MET>250 GeV & METSig<14
  - large-R jet consistent with top or W mass, or no large-R jet requirement (=>TX, WX, 0X)



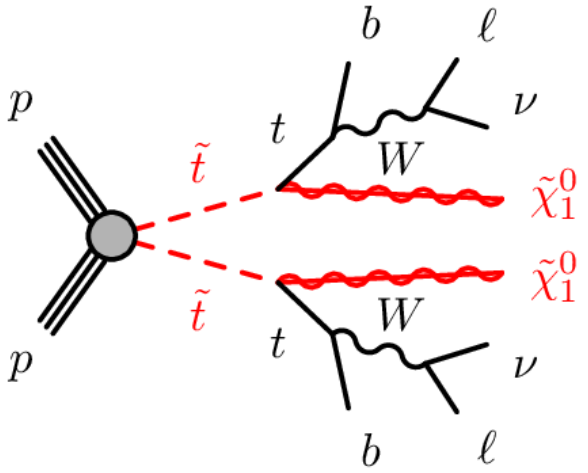
- ttOL-high
  - MET trigger
  - MET>250 GeV & METSig>14
  - >=1 large-R jet
    - leading LR jet mass consistent with top
    - sub-leading LR jet mass either consistent with top or W or neither (=> TT, TW, T0)
  - Events also sub-divided into SRA, SRB categories

H→invisible Search in tt + MET

1-lepton



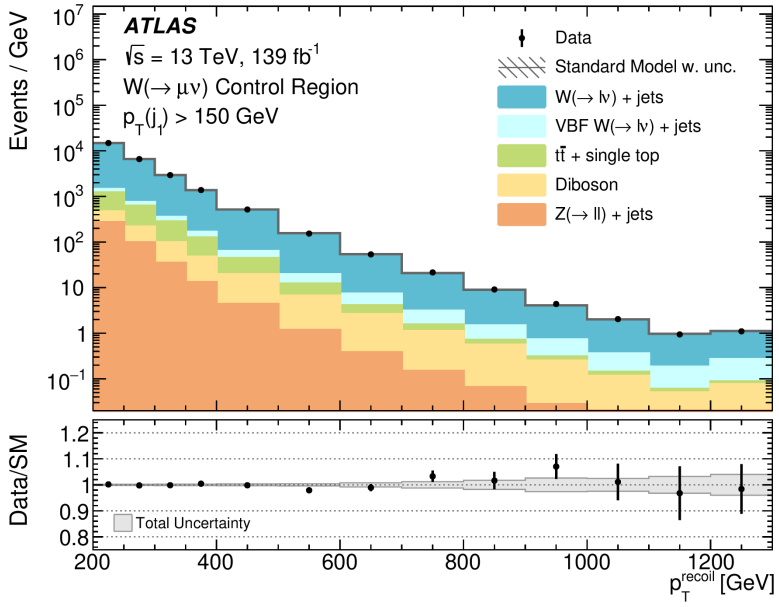
2-lepton

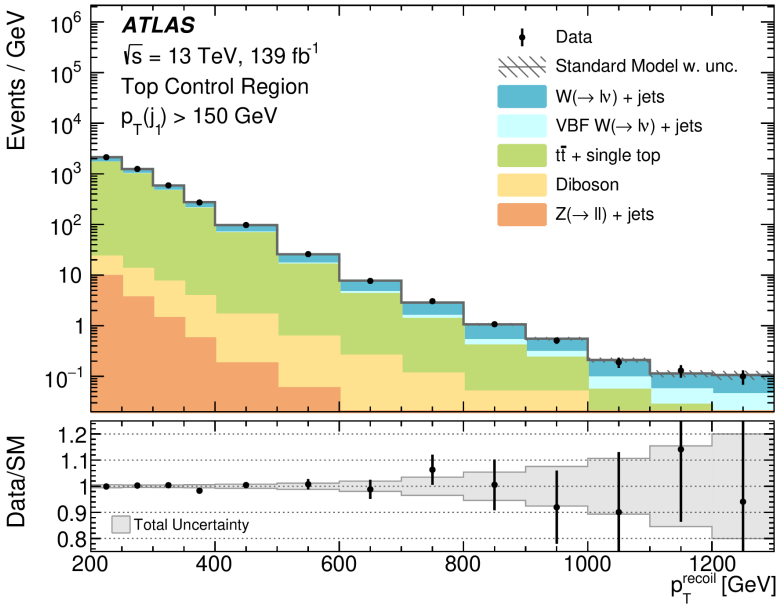


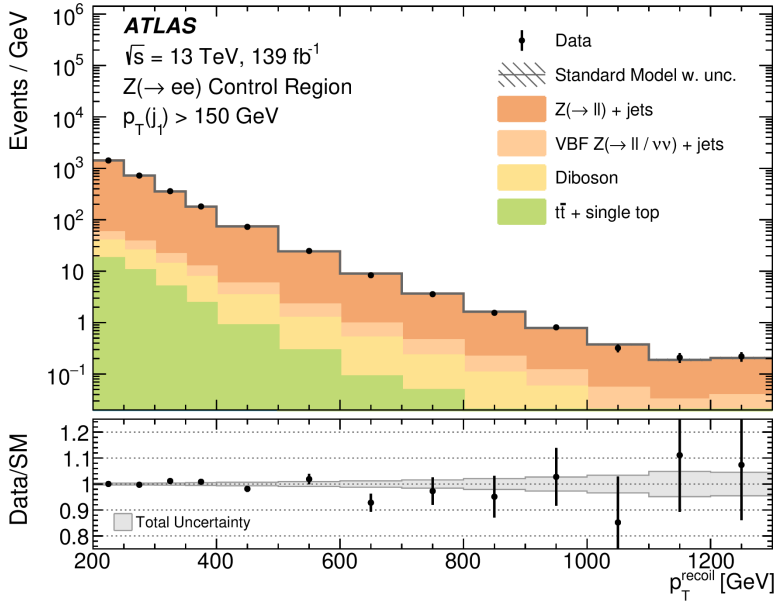
- tt1L
  - >=4 jets
  - 2 b-tagged jets
  - MET>230 GeV
  - >=1 large-R jet, mass consistent with top
  - split selected events into several bins in dphi(lep, MET)

- tt2L
  - 2 opposite sign leptons
  - >=1 b-tagged jets, METSig>12
  - Split into same and different lepton flavours
  - Leptonic stransverse mass (mT2) as the main discriminating variable
    - mT2 : kinematic variable to bound the masses of a pair of identical particles which each decays into a visible and an invisible particle

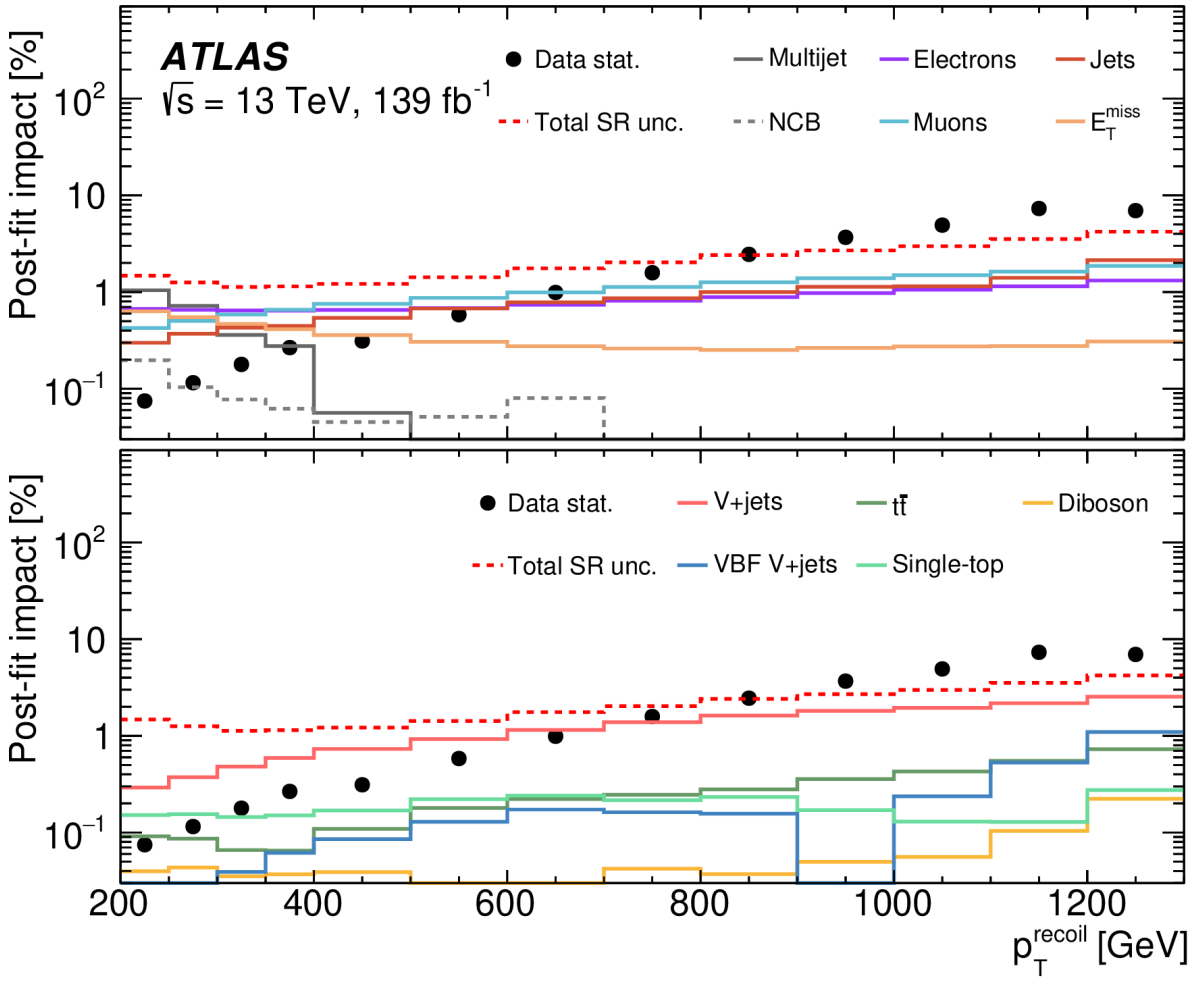
H→invisible Search in jets + MET



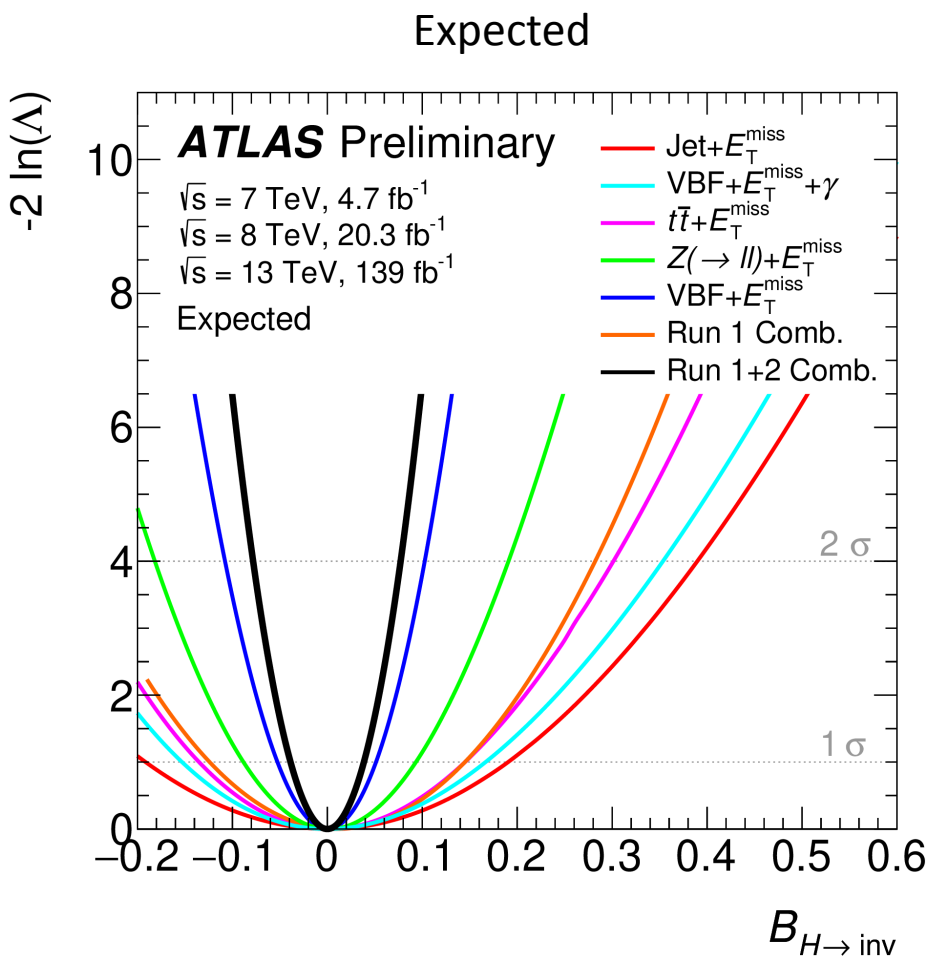


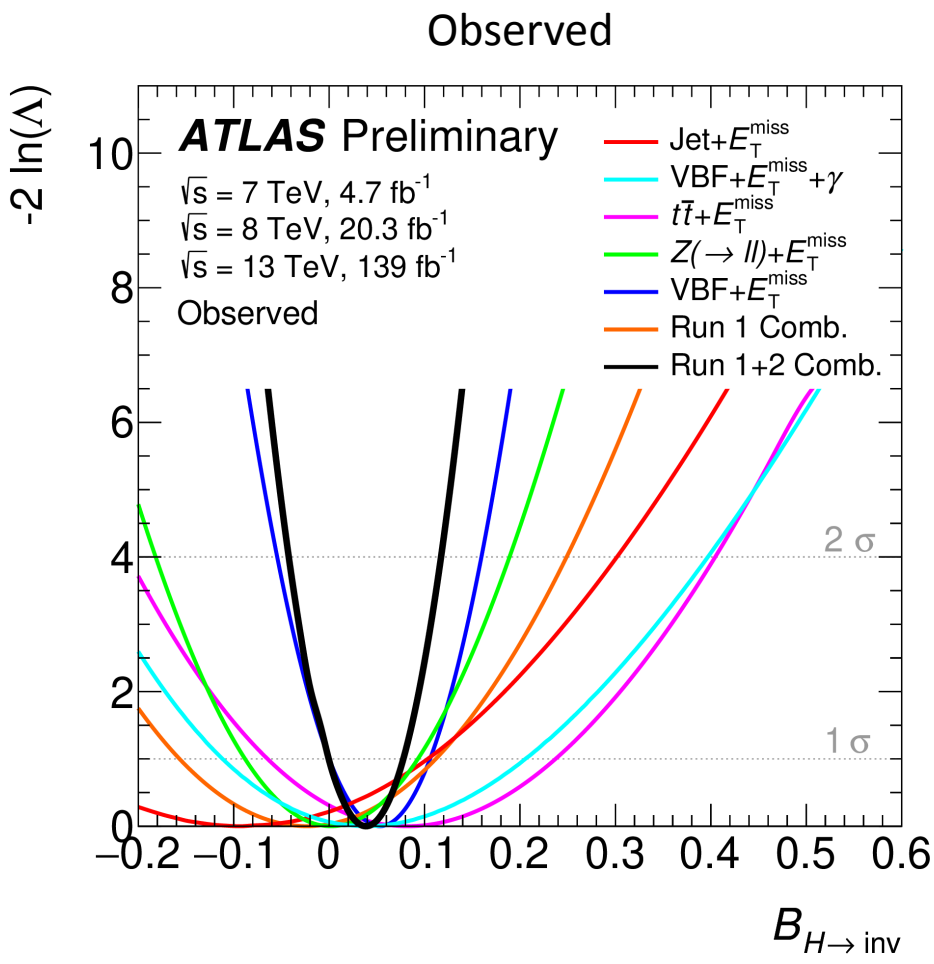


H→invisible Search in jets + MET



H→invisible Search : Combination





H→invisible Search : Combination

Table 2: The expected impact of different categories of systematic uncertainty on $\mathcal{B}_{H\to\text{inv}}$. The evaluation is performed by ignoring a given category of systematic uncertainties and quadratically subtracting the modified uncertainty on the expected best-fit $B_{H\to inv}$ value from the nominal case with the full uncertainty treatment. Due to residual correlations between categories, the quadratic sum of systematic uncertainties can differ from the total uncertainty. The uncertainty due to finite data statistics is obtained by ignoring all systematic uncertainties and the floating background normalisations. The sum of all systematic uncertainties is estimated by quadratically subtracting the above uncertainty and the one from floating background normalisations from the total uncertainty. The uncertainty related to the size of the MC samples ("MC statistics") is included in the experimental uncertainty category. The uncertainties are reported as the upper part of the 68% confidence interval on the observed best-fit $\mathcal{B}_{H\to\text{inv}}$ value.

Source of uncertainty	Run2	Run1+2
Luminosity / pile up	0.005	0.005
Leptons / Photons	0.014	0.013
Jets	0.013	0.013
Flavour tagging	0.002	0.001
E_T^{miss}	0.004	0.003
MC statistics	0.013	0.012
All experimental	0.024	0.023
V+jets modelling	0.019	0.018
Other background Modelling	0.014	0.014
Data-driven Backgrounds	0.011	0.010
Signal Modelling	0.002	0.003
All theory	0.025	0.024
Total systematic uncertainty	0.037	0.035
Data statistics	0.011	0.011
Background normalization	0.012	0.012
Total statistical uncertainty	0.017	0.016
Total uncertainty	0.041	0.039